THE USE OF THE RESISTIVITY PIEZOCONE (RCPTU) FOR THE GEOENVIRONMENTAL CHARACTERIZATION OF SULPHIDE BEARING TAILINGS AND NATIVE SOILS

by

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ABSTRACT

Recent advances in the in-situ testing of sulphide bearing mine tailings have included the development of a resistivity piezocone (RCPTU) and improved water sampling technologies. The RCPTU measures the bulk resistivity of the soil, in addition to all other standard piezocone (CPTU) measurements. The bulk resistivity profile permits assessment of pore water chemistry with correlation to pore water samples and the standard CPTU measurements give accurate estimates of stratigraphy and key geotechnical parameters and hydrogeological characteristics. Also, use of the RCPTU in combination with discrete pore water sampling technologies can permit the development of relationships between bulk resistivity measurements and specific pore water constituents. The technology is repeatable, rapid and economical when compared to traditional drilling and sampling site investigation techniques.

A significant area of concern in the mining industry is acid rock drainage (ARD). ARD is the contaminant drainage which results from oxidation of sulphide minerals and it can represent a serious hazard to surrounding surficial and groundwater systems. The evolution of ARD creates elevated electrical conductivity of tailings pore water which can be readily detected by the RCPTU bulk resistivity measurements. In addition to environmental issues, there are significant geotechnical considerations in the construction of large dams for tailings storage. One fundamental consideration is the potential for a flow failure of the tailings impoundment due to liquefaction of the tailings under both static and dynamic loading conditions. There is a significant challenge in adequately characterizing these impoundments for their geochemical, hydrogeological and geotechnical nature. The potential to use a single procedure for determining many varied engineering design parameters is highly attractive.

Results of a field testing program carried out at sulphide bearing tailings impoundments of three Canadian mines are presented with respect to environmental and geotechnical characterization issues. Site-specific relationships between bulk resistivity measurements and pore water chemistry are developed. CPTU data is used to assess hydrogeological characteristics at specific sites and estimate movement of ARD contaminated pore water. CPTU-based methods are used to assess the susceptibility of liquefaction of tailings, considering both static and dynamic load conditions. Finally, recommendations are made with regard to the use of the RCPTU as a component of an overall geoenvironmental characterization plan for the evaluation of sulphide bearing tailings impoundments.

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LIST OF SYMBOLS

A	-	Cross-Sectional Area
a_{max}	-	Maximum Earthquake Acceleration at Ground Surface
ARD	-	Acid Rock Drainage
APL	-	Aqueous Phase Liquid
B_q	-	Dynamic Pore Pressure Ratio
$C_{v,h}$	-	Coefficient of Consolidation
CEC	-	Cation Exchange Capacity
CRR	-	Cyclic Resistance Ratio
CSR	-	Cyclic Stress Ratio
CPTU	-	Standard Piezocone; Cone Penetration Test
D_r	-	Relative Density
e	-	Void Ratio
e_c	-	Critical Void Ratio
f_s	-	CPT Friction Sleeve
F	-	Stress Normalized Rf
F	-	Formation Factor
FC		Fines Content
FS	-	Factor of Safety
g	-	Gravity
i	-	Hydraulic Gradient
I	-	Current
I_c	-	Soil Behaviour Type Index
IP	-	Induced Polarization
k	-	Resistivity Module Calibration Factor
K	-	Hydraulic Conductivity
l	-	Path Length of Flow
M	-	Molar
M	-	Earthquake Magnitude
m	-	Shape Factor
$m_{v,h}$	-	Coefficient of Compressibility
MCE	-	Maximum Credible Earthquake
n	-	Porosity
N	-	Standard Penetration Test Resistance

$(N_1)_{60}$	-	SPT N Value Corrected For Overburden Stress and Rod Energy
NAPL	-	Non-Aqueous Phase Liquid
Pa	-	Atmospheric Pressure (101.3 kPa)
q_c	-	CPT Penetration Resistance
q_{c1}	-	Stress Normalized q_t
$(q_{c1})_{ecs}$	-	q_{c1} Corrected For Fines Content
q_t	-	q_c Corrected For In-Situ Water Pressures
Q	-	Stress Normalized q_t
Q_p	-	Normalized Q_p
R	-	Resistance
RCPTU	-	Resistivity Piezocone; Resistivity Cone Penetration Test
Rf	-	CPT Friction Ratio
SH	-	Strain Hardening
SPT	-	Standard Penetration Test
SS	-	Strain Softening
S_u	-	Undrained Shear Strength
U	-	CPTU Dynamic Pore Pressure
U_0	-	Equilibrium Pore Pressure
U1	-	U Measured at the Cone Tip
U2	-	U Measured Behind the Cone Tip
U3	-	U Measured Behind the Cone Friction Sleeve
V	-	Voltage
v	-	Groundwater Velocity
σ_{vo}	-	Total Overburden Stress
σ_{vo}'	-	Effective Overburden Stress
ϕ'	-	Peak Friction Angle
ρ_b	-	Bulk Soil Resistivity
ρ_f	-	Pore Water Resistivity
Ω-m	-	Measure of Resistivity
μS/cm	-	Measure of Conductivity
Ψ	-	State Parameter
γ_w	-	Unit Weight of Water (9.81 kN/m^3)

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1.0 INTRODUCTION

Site characterization is the key component of any subsurface investigation of the prevailing physical and geochemical conditions. The overall framework for characterizing the prevailing physical and geochemical conditions is termed geoenvironmental characterization.

The University of British Columbia In-Situ Testing Group (UBC ISTG) has been developing and documenting in-situ tools for site characterization for over 15 years. The standard piezocone (CPTU) has been a principle focus of research and development. The CPTU has proven to be an excellent means of logging stratigraphy for most soils and provides accurate estimates of key geotechnical parameters and hydrogeological characteristics. The primary geotechnical applications of CPTU technology were expanded to include environmental engineering with the development of a resistivity piezocone (RCPTU) in 1988 (Campanella and Weemees, 1990). The RCPTU measures the bulk resistivity of the soil and pore water, which can be used to infer pore water quality. In addition, use of the RCPTU in combination with discrete pore water sampling technologies can facilitate the development of site-specific relationships between bulk resistivity measurements and pore water chemistry.

Mine tailings represent a significant challenge for adequate geoenvironmental characterization. Some mine tailings, particularly from large ore operations that contain sulphide minerals, pose significant environmental problems due to processes such as acid rock drainage (ARD). ARD is the contaminant drainage, often containing high concentrations of sulphates, heavy metals and acidity, which results from the oxidation of sulphide minerals. Additionally, there are inherent geotechnical stability considerations in large tailings impoundments, as many of these are hydraulically constructed entirely with tailings. One fundamental consideration is the potential for a flow failure of the tailings impoundment due to liquefaction of the tailings, under both static and dynamic loading conditions. There can be

a significant challenge in adequately characterizing these impoundments for their geochemical, hydrogeological and geotechnical nature. Traditional methods of drilling and discrete sampling followed by laboratory analysis are expensive, time intensive, and provide a small statistical sample of the subsurface. The RCPTU, which provides a near-continuous log of requisite engineering parameters, can provide a rapid, technically sound and cost-effective alternative for adequate geoenvironmental characterization of sulphide bearing tailings impoundments.

A geoenvironmental site characterization program using RCPTU in conjunction with discrete depth pore water sampling was carried out at sulphide bearing tailings impoundments of three Canadian mines. The objective of this work was to develop a technical understanding of the environmental and geotechnical considerations which confront safe storage of sulphide bearing tailings, and to assess the capability of the RCPTU for characterization of sulphide bearing tailings with respect to both environmental and geotechnical parameters. More specifically, the environmental component of this work focused on the application of the RCPTU to evaluate ARD processes in sulphide bearing tailings, whereas the primary geotechnical component was the evaluation of liquefaction susceptibility of tailings using CPTU-based methods. Field test data are presented to demonstrate specific applications of the RCPTU, and recommendations are made with respect to the use of the RCPTU as a component of an overall geoenvironmental characterization plan for the evaluation of sulphide bearing tailings impoundments.

To meet the stated objective of this thesis a research program was formulated and is summarized as follows:

- Gather available literature and consult acknowledged experts on the following subjects:

(a). environmental and geotechnical issues confronting safe storage of sulphide bearing tailings, particularly ARD processes affecting tailings pore water chemistry and soil liquefaction.

(b). geoenvironmental site characterization methods, including in-situ testing techniques and conventional drilling and sampling techniques.

(c). electrical conduction in soil and water, and the application of resistivity techniques for the delineation of ARD contamination.

(d). CPTU-based techniques for evaluating the liquefaction susceptibility of soils, considering both static and dynamic loading conditions.

- Design, implement and interpret results from relevant field and lab testing programs.

- Provide a thorough evaluation of the geoenvironmental characterization site investigation techniques upon completion of the testing programs.

2.0 EVALUATION OF SULPHIDE BEARING TAILINGS IMPOUNDMENTS

2.1 GENERAL

Tailings may be defined as crushed rock particles that are either produced or deposited in a slurry form as a result of mineral extraction processes. Sulphide bearing tailings are tailings that contain sulphide minerals. The properties of tailings are dependent upon the characteristics of the host rock and the procedures employed for mineral extraction.

Currently, the most common method for tailings disposal is on-land impoundments. In 1993, of the 150 operating mines in Canada, almost all mines practised on-land disposal, with the exception of three operations which have unconfined disposal on an ocean or lake bottom (Giancola, 1993). Generally the tailings impoundment is constructed by building a dyke at the downstream end of the tailings area, or entirely surrounding the planned impoundment area if the topography is flat. The tailings are deposited hydraulically behind the dam and the process water is either decanted, evaporated, recycled to the mill for reuse or some combination thereof. This results in a tailings beach and a zone of fines associated with the ponded decant water. As the level of the tailings rises, the height of the impoundment is raised to increase the impoundment volume.

There are three general methods of constructing new raises on tailings dams, namely upstream, downstream and centerline construction (Vick, 1983). Historically upstream construction methods were used extensively. The upstream method (Figure 2.1a), in which dykes used for successive raises are constructed on settled tailings, is subject to instability due to high seepage rates, excessive settlement and liquefaction susceptibility. Modern tailings dams are generally constructed by the downstream or centerline methods, Figures 2.1b and

2.1c. These methods incorporate the principles of conventional water retention dams to produce a physically more stable design.

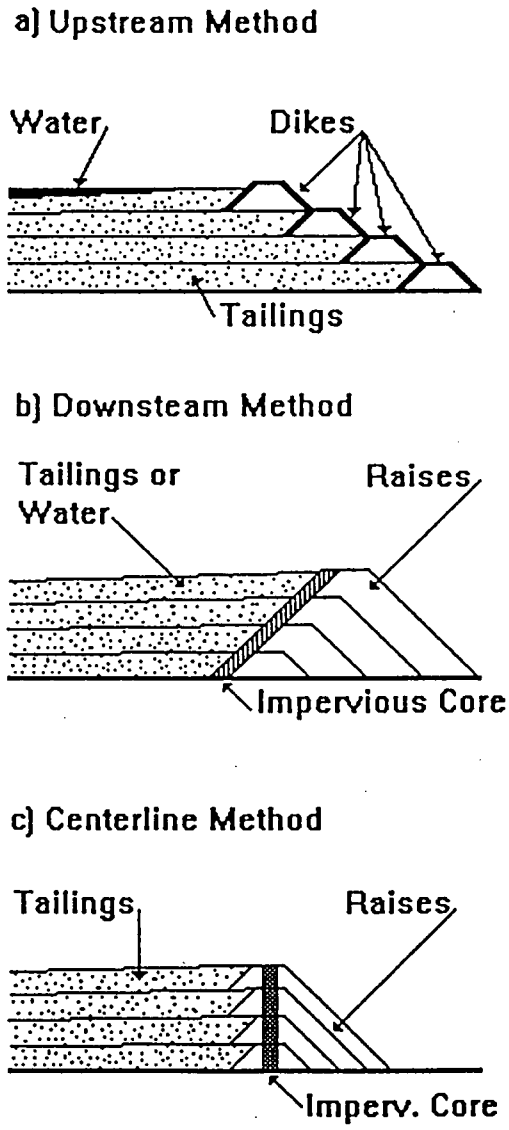


Figure 2.1: Tailings Dam Construction Methods (After Klohn, 1980)

2.2 PORE WATER CHEMISTRY

Pore water chemistry is controlled by the influence of pore water contaminants, which strictly speaking include all substances other than H_2O. Types of pore water contaminants can be broken down into two categories: aqueous phase liquids (APL's) and non-aqueous phase liquids (NAPL's). APL's are those contaminants which occur as dissolved species (ions) in the pore water, whereas NAPL's have low solubilities in water and include organic substances such as gasoline and PCB's. NAPL contaminants would not be expected to be an environmental issue at a sulphide bearing tailings impoundment, unless localized dumping of such substances had occurred.

The pore water of sulphide bearing tailings contains a variety of dissolved ionic species, and these dissolved constituents may be classified as APL contaminants. The pore water chemistry of a specific pore water sample is influenced by a number of factors, which are listed below:

- water chemistry of the effluent with which the tailings are discharged to the impoundment;
- tailings mineralogy;
- water chemistry of external sources (such as surface waters and precipitation) which infiltrate the tailings impoundment;
- pore water transport processes; and
- chemical and biological reactions.

Of the above factors governing pore water chemistry of sulphide bearing tailings, it is chemical and biological reactions which often have the largest influence. The oxidation of sulphide minerals by means of chemical and biological reactions can pose a serious detriment

to pore water quality through a process referred to as acid rock drainage (ARD). The evolution and potential implications of this process are discussed in Section 2.2.1.

The designation of dissolved constituents contained in tailings pore water as APL contaminants does not give a measure as to the potential impact the pore water may have on a receiving environment. The potential impact of the tailings pore water is dependent upon the type and concentration of the dissolved ionic species. In Canada discharge from tailings impoundments must meet the criteria laid out in the Metal Mining Liquid Effluent Regulations and Guidelines under the federal Fisheries Act. The present limits are shown in Table 2.1 (Environment Canada, 1992). In addition, many mines are subject to more stringent requirements on discharge by provincial regulations.

Table 2.1: Authorized Levels of Deleterious Substances Prescribed in the Metal Mining and Liquid Effluent Regulations (After Environment Canada, 1992)

Parameter	Max. Authorized Monthly Arithmetic Mean	Max. Authorized Composite Sample	Maximum Authorized Grab Sample
pH	6.0	5.5	5.0
Arsenic	0.5 mg/L	0.75 mg/L	1.0 mg/L
Copper	0.3 mg/L	0.45 mg/L	0.6 mg/L
Lead	0.2 mg/L	0.3 mg/L	0.4 mg/L
Nickel	0.5 mg/L	0.75 mg/L	1.0 mg/L
Zinc	0.5 mg/L	0.75 mg/L	1.0 mg/L
Total Suspended Matter (TSM)	25.0 mg/L	37.5 mg/L	50.0 mg/L
Radium-226	10.0 pCi/L	20.0 pCi/L	30.0 pCi/L

2.2.1 ACID ROCK DRAINAGE (ARD)

Acid rock drainage (ARD) is the single largest environmental concern currently facing the Canadian mining industry (Filion and Ferguson, 1989). ARD is the contaminated drainage that occurs as a result of the natural chemical and biological oxidation of reactive sulphide minerals when exposed to air and water.

The primary sources of ARD at a mine site involve sulphide bearing mine rock which has been disturbed and for which the exposed surface area has been increased. These sources include:

- underground mine workings;
- open pits;
- mine waste dumps
- tailings impoundments
- roads, dams etc. constructed from mine waste; and
- exposed rock faces in rock cuts for roads etc.

After oxidation of the sulphide minerals has occurred, water flushes the oxidation sites and flows along the drainage paths, reacting with the surrounding soil and rock material. This results in changes in pH and contaminant concentrations of the drainage. Acidic drainage may be neutralized by alkaline material in the flow paths. Thus, the drainage in the initial stages of ARD development may be of neutral pH, but contain significant concentrations of dissolved ionic constituents (typically sulphates and heavy metals) from the oxidation process and reactions along the flow paths. This drainage can cause a detrimental effect on water quality in the receiving environment. Table 2.2 presents typical examples of water quality affected by ARD processes. The discrepancies between the water quality data and federal restrictions shown in Table 2.1 are readily apparent.

Table 2.2: Examples of Water Quality Affected by ARD Processes (After Frytas et al, 1992)

Water Quality Parameter	Seepage From Abandoned Uranium Mine Tailings Pond in Ontario	Waste Rock Dump Seepage From Active Mine in B.C.	Mine Water From Underground Copper Mine in B.C.
pH	2.0	2.8	3.5
Sulphate (mg/l)	7440	7650	1500
Acidity (mg/l)	14600	43000	-
Mn (mg/l)	5.6	78.3	6.4
Cu (mg/l)	3.6	89.8	16.5
Al (mg/l)	588	359	-
Pb (mg/l)	0.67	2.0	0.1
Cd (mg/l)	0.05	0.5	0.14
Zn (mg/l)	11.4	53.2	28.5
As (mg/l)	0.74	25	0.05
Ni (mg/l)	3.2	8.0	0.06

2.2.1.1 Generation of ARD

There exists a variety of sulphide minerals which are susceptible to oxidation processes and subsequent generation of ARD. Some common sulphide minerals include pyrite (FeS_2), pyrrhotite (Fe_7S_8), pentlandite ($(Fe, Ni)_9S_8$ and galena (PbS). By means of example, the chemical reaction for oxidation of the sulphide mineral pyrite can be expressed as follows:

[2.1] $$FeS_2 + \frac{15}{4}O_2 + \frac{7}{2}H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+$$

As shown in equation [2.1] oxidation of sulphide minerals requires sulphide minerals, oxygen and pore water. The implication of this with respect to ARD in tailings is that oxidation of sulphide minerals and subsequent acid generation generally occurs in the unsaturated zone of tailings. In the saturated tailings the low diffusion coefficient of oxygen through water [Steffen Robertson and Kirsten, 1990] prevents significant oxidation of sulphide minerals. However, ionic constituents produced in the unsaturated zone may be transported to the saturated tailings, and any remaining acidity may result in additional dissolution of ionic constituents in the saturated tailings.

The net result of the ARD process is that hydrogen ions are produced resulting in an increase in acidity and subsequent dissolution of ionic constituents. Drainage water pH is an indication of the development of ARD: over time, pH drops in stages. In the near neutral pH range, most of the oxidation is chemical (by oxygen) and the acidity that is released is quickly neutralized by alkalinity contained in the mine waste. As this alkalinity is consumed, the pH drops (in stages depending upon the alkali minerals). Generally at this stage, while sulphate, acidity, and later iron concentrations increase, the concentrations of other metals (such as copper) are limited by pH-solubility controls. At pH values of approximately 4.5, the much more rapid biologically catalyzed oxidation predominates, increasing the rate of acid production. Solution pH values are acidic and elevated sulphate, acidity and heavy metals concentrations are present in the drainage. The evolution of ARD can be separated into three stages as shown in Table 2.3 and summarized below:

- chemical oxidation with minimal acidity;
- biological oxidation becomes significant with acidity increasing and ultimately
- oxidation is very rapid and the solution becomes acidic.

Table 2.3: Stages in the Formation of Acid Rock Drainage (After Broughton et al., 1992)

	STAGE I (Onset of Sulphide Mineral Oxidation)	STAGE II (Acidic Conditions Occurring)	STAGE III (Buffering Agents Depleted)
Unsaturated (Vadose) Zone	·chemical oxidation buffered ·sulphate levels elevated ·ferric hydroxide precipitates	·biochemical oxidation ·acid runoff ·high Fe^{3+}, SO_4^{2-} ·elevated heavy metals	·biochemical oxidation ·acid runoff ·high Fe^{3+}, SO_4^{2-} ·high heavy metals
Saturated Zone	·neutral seepage ·sulphate levels elevated	·neutral seepage ·high Fe^{3+}, SO_4^{2-} ·high acidity ·low heavy metals	·acid seepage ·high Fe^{3+}, SO_4^{2-} ·high acidity ·high heavy metals

It is important to note that elevated levels of sulphate (SO_4^{2-}) are characteristic of all three stages of ARD formation. Sulphate concentration, which is not restricted under water quality regulations, can be used to assess sulphide oxidation processes. Elevated sulphate concentrations, in the absence of elevated heavy metals concentrations and acidic conditions, are likely indicative of Stage I ARD formation. Identification of sulphide oxidation processes prior to the onset of acidic conditions permits the implementation of appropriate abatement strategies to mitigate the effects of ARD.

2.2.1.2 Generation of ARD in Sulphide Bearing Tailings

The development and progression of ARD in sulphide bearing tailings is relatively well-understood. Blowes et al. (1994), Blowes et al. (1988), Coggans et al. (1991) and Dubrovsky et al. (1984) each provide details with respect to the evolution and effects of ARD processes in sulphide bearing tailings for specific sites.

ARD generation in sulphide bearing tailings impoundments generally occurs when the impoundment is inactive or after closure. In operating tailings impoundments the tailings are usually saturated. The pore water inhibits movement of oxygen through the tailings which limits acid generation. However, after termination of active discharge into the impoundment the water levels within the tailings drop, and air is permitted to fill the voids. Infiltration of surface water reacts with the oxygen and sulphide minerals resulting in acid generation in the unsaturated tailings and subsequent generation of ARD. A one-dimensional model showing the vertical progression of oxidation and the resulting contaminant migration is shown in Figure 2.2.

Surface water infiltrating through the tailings enters a zone of partial saturation, Z1. The water progresses from this zone to the saturated zone (Z2) below the water table. Progression into Z2 causes the original process water to move downwards into the underlying soil where it mixes with the groundwater. The zone of oxidation, Z3, indicates the depth to which oxidation of the sulphide tailings has taken place, and correspondingly the depth to which acid generation has occurred. Water becomes acidic as it infiltrates through Z3 and dissolves ionic constituents until it reaches Z4 where it may be neutralized by alkalies if present in the tailings. Consumption of the sulphides in the oxidation zone allows oxygen to progress to a greater depth in the tailings, resulting in a progression of ARD contamination. This process advances with time and Z4 eventually penetrates the foundation soils, where ARD mixes with the groundwater.

In addition to movement of ARD downward through the tailings, transport in the horizontal direction is often more pronounced. The manner in which tailings are deposited produces a layered effect which results in much higher values of hydraulic conductivity (K) in the horizontal direction. The ratio of horizontal to vertical hydraulic conductivity (K_h/K_v) can range from 10-1000 for many tailings impoundments (Davies, 1996).

Acid generation in tailings impoundments is a long process (Lawrence, 1994). Even after acid generation is initiated a period of time (possible tens of years) will transpire before ARD is released into the groundwater. Thus, tailings at a mine site may appear to be innocuous for a long time, when in fact they represent a significant environmental liability.

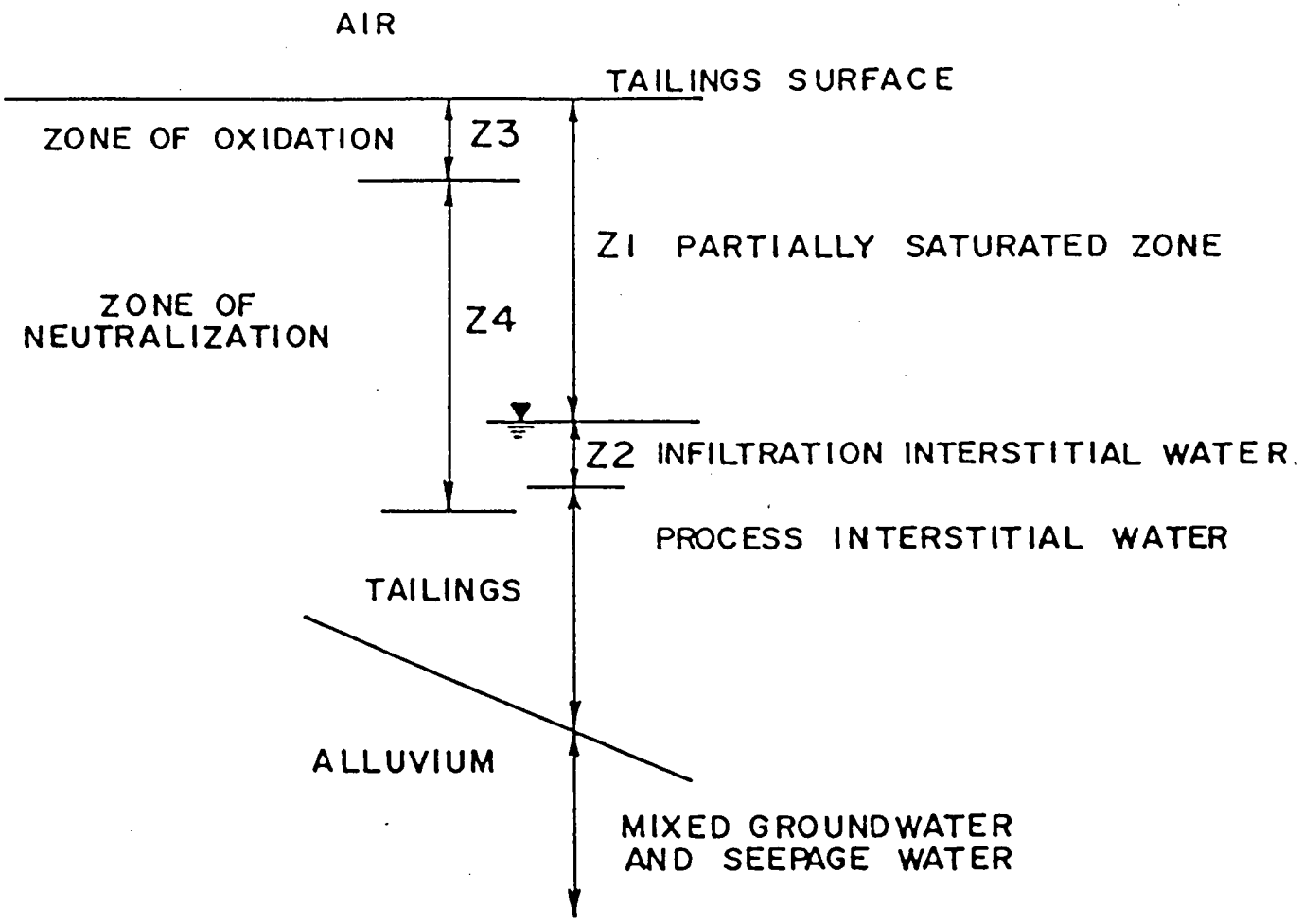


Figure 2.2 One-Dimensional Water Quality Model For a Tailings Impoundment (After A. Robertson, 1987)

2.3 SOIL LIQUEFACTION

Static and transient load stability considerations are usually the primary geotechnical engineering concern with respect to design, construction and operation of a tailings impoundment. Table 2.4 provides a summary of historical tailings dam failures, which in many cases caused significant economic and environmental damage as well as human injury and loss of life. Common features of each of the tailings dam failures presented in Table 2.4 are the use of upstream construction methods and the significant flow movement of tailings due to liquefaction of the tailings. The term liquefaction encompasses two distinct phenomena: flow liquefaction and cyclic liquefaction (Robertson, 1994), each of which are discussed in the following two sections.

2.3.1 FLOW LIQUEFACTION

Flow liquefaction is synonymous with strain softening (SS) of sand in undrained shear, as illustrated in Curve 1 in Figure 2.3. Straining beyond the peak undrained shear strength results in a drop in strength to an ultimate condition referred to as steady state (equivalent to the residual strength of the soil). Steady state conditions imply increasing deformations under constant effective stress. A soil can also exhibit limited strain softening (LSS) behaviour to a quasi-steady state, as shown in Curve 2. This behaviour may result in significant deformations due to the level of strain required to mobilize increased strength. Finally, Curve 3 is an example of a strain hardening (SH) soil in which shear strength increases with increasing strain, and subsequently liquefaction is not a consideration.

There is the potential for a flow liquefaction failure of a tailings dam if the tailings dam is entirely or partially composed of a SS soil. If a tailings dam is entirely composed of SS soil and

Table 2.4: Summary of Tailings Flow Failures (adapted from Vick, 1991)

Tailings Dam	Failure Cause	Volume Displaced (m^3)
El Cobre, Old	seismic	1.4×10^6
El Cobre, New	seismic	355 000
Hierro Viejo	seismic	850
Los Maquis	seismic	21 000
La Patangua	seismic	36 000
Bellavista	seismic	71 000
Ramayana	seismic	140
Cerro Negro 3	seismic	86 000
Barahona	seismic	2.8×10^6
Veta de Agua	seismic	280 000
Cerro Negro 4	seismic	500 000
Mochikoshi 1	seismic	80 000
Mochikoshi 2	seismic	3000
Churchrock	piping	76 000
Bafokeng	piping	3×10^3
Southwest US	stability	-
Texas	seepage	100 000
Mike Horse	overtop	150 000
Western Nuc.	overtop	40
Union Carbide	overtop	11 000
Kimberly	stability	1.5×10^6
Stava	stability	200 000
Bilbao	stability	140 000
Deneen	overtop	38 000
Blackpool	stability	11 000
Cholwich	stability	18 000
Tyrone	stability	2.1×10^6
United Nuc.	pipeline	36 000
Union Carbide	-	360
Edgemont	-	140
Grootvlei	stability	-
Captains Flat	-	40 000

the in-situ gravitational shear stresses are greater than the steady state strength of the soil a catastrophic flow slide can occur if a triggering mechanism causes flow liquefaction. If a tailings dam is partially composed of SS and SH soil a flow failure can occur if the SS soil is triggered to strain soften and the SH soil cannot support the gravitational shear stresses. Triggering mechanisms include both cyclic and monotonic undrained loading. In addition,

Sasitharan et al. (1994) have shown that flow liquefaction can be triggered by certain types of drained monotonic loading (e.g. a slow rise in the water table).

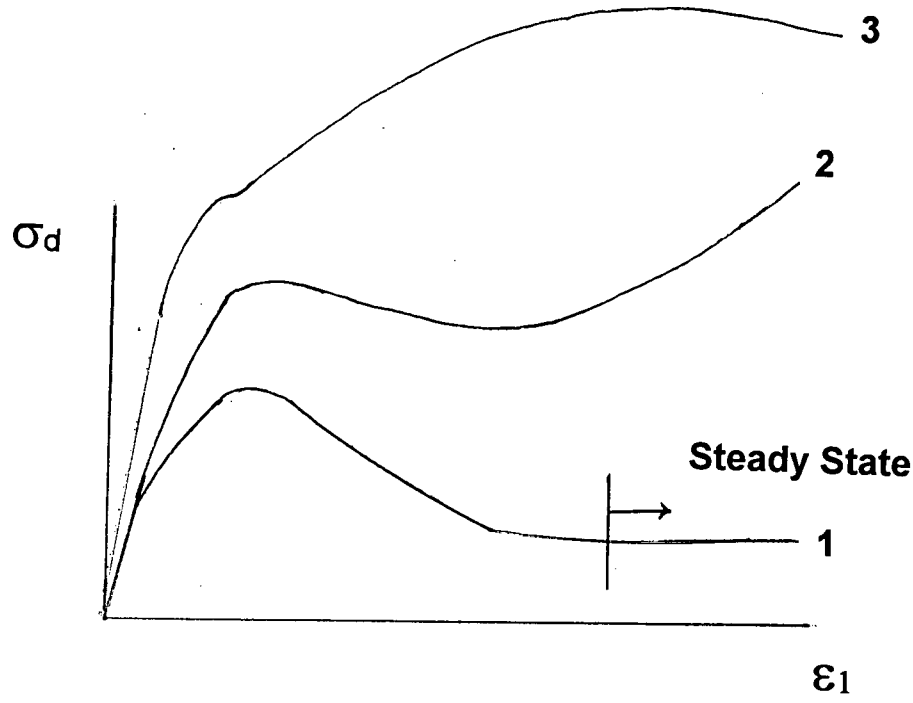


Figure 2.3: Undrained Behaviour of Sand

2.3.2 CYCLIC LIQUEFACTION

The principle concerns with respect to dynamic loading of a tailings dam are cyclic liquefaction under earthquake loading and the potential for a resultant flow liquefaction failure. During cyclic undrained loading almost all granular soils develop positive pore pressures due to the contractant response of the soil at small strains. If there is shear stress reversal, the effective stress can progress to the point of zero effective stress, as illustrated in

Figure 2.4. When a soil element reaches the condition of essentially zero effective stress, the soil has very little stiffness and large deformations can occur during cyclic loading. When cyclic loading stops, the deformations due to cyclic liquefaction essentially stop, except for those due to local pore pressure redistribution (Robertson, 1994). However, the reduction in shear strength (to residual values) of soils that experienced cyclic liquefaction can produce conditions favourable for flow liquefaction. Therefore, deformations of tailings dams under cyclic loading may be attributed to the effects of both cyclic liquefaction and flow liquefaction.

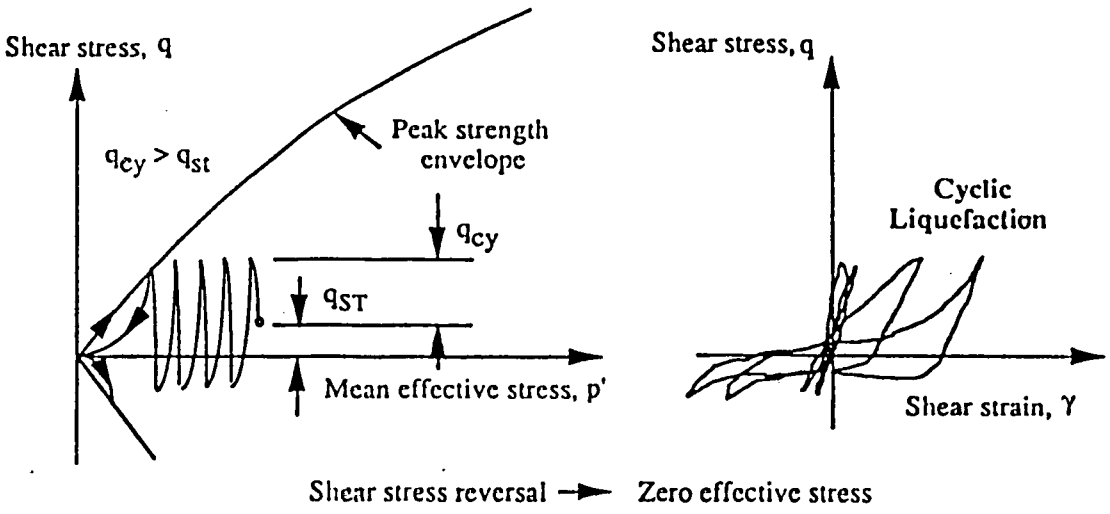


Figure 2.4: Undrained Cyclic Behaviour of Sand

3.0 IN-SITU TESTING METHODS

In-situ testing, and more specifically CPT technology, can provide an accurate and cost-effective method for geoenvironmental characterization in appropriate ground conditions. Appropriate ground conditions include sands, silts, clays and some sands and gravels. Mine tailings, consisting of predominately sand to clay-sized materials, are highly amenable to CPT technology. Campanella et al. (1984), Woeller et al. (1989) and each demonstrate the use of the CPTU for geotechnical and hydrogeological characterization of tailings with specific case examples. The CPTU is effective in identifying the physical regime, but geoenvironmental characterization also requires assessment of geochemical conditions. The recent development of a resistivity piezocone (RCPTU) and improved water sampling technologies provide a means of assessing the geochemical properties of sulphide bearing tailings. Campanella et al. (1994) provided an overview of the use of the RCPTU for environmental characterization of sulphide bearing tailings, and used some of the field data presented in this thesis. The following sections provide details concerning the CPT technology used in this study.

3.1 RESISTIVITY CONE PENETRATION TEST (RCPTU)

The resistivity cone penetration test (RCPTU) records the same measurements as the cone penetration test (CPTU) (which is described in Section 3.3), and in addition measures the bulk resistivity of the soil. Bulk resistivity measurements are made by a module (referred to as a resistivity module) which resides behind the standard cone. This section describes the theoretical basis and operation of the resistivity module for bulk resistivity measurement of soils, and focuses on the application of the resistivity module for assessment of ARD contamination in sulphide bearing tailings.

3.1.1 RESISTIVITY MEASUREMENT IN SOILS

The term bulk resistivity is used to describe resistivity measurements of the soil, pore water and gas phase. Bulk resistivity measurements are affected by the following factors (Urish, 1981):

- degree of saturation
- ionic composition of the pore water
- porosity
- temperature
- shape of pore size
- cation exchange capacity (CEC) of matrix materials

In saturated soils, the bulk resistivity is primarily influenced by electrical conduction through the pore water, which is a function of the ionic composition of the pore water and the pore volume. In the unsaturated zone the effect of the soil matrix resistivity (which is much larger than that of the pore fluid) increases relative to the electrical conduction of the pore water (Frolich and Parke, 1990). This, coupled with the fact that air in the voids acts as an insulator, generally results in much higher values of bulk resistivity in the unsaturated zone. Interpretation of bulk resistivity measurements in the unsaturated zone is complicated by the difficulty of discerning the relative influence of pore water saturation and pore water chemistry on the measurements.

For the case of saturated soils, the bulk resistivity can be related to the pore water resistivity through application of Archie's Equation (Archie, 1942, Telford et al., 1976). This empirical formula assumes that bulk resistivity is directly related to pore water resistivity and the geometry of the pore spaces in the soil. A term commonly used to relate soil resistivity to pore

water resistivity is the formation factor (F), which is a function of the pore geometry. Archie's Equation can be expressed as follows:

[3.1] $$F = \frac{\rho_b}{\rho_f} = n^{-m}$$

where,

F = Apparent Formation Factor

ρ_b = Bulk Resistivity

ρ_f = Pore Water Resistivity

n = Porosity

m = Constant related to soil behaviour type

For sands the value of m is approximately 1.5, and for various clays m has been found to range from approximately 1.8 - 3.0 (Jackson et al., 1978)

The term apparent formation factor implies that surface conduction effects and other intergranular pore water effects may contribute to the measured bulk resistivity. The intrinsic formation factor of a soil is function of only the pore geometry, which has been found to be a function of particle shape (Jackson et al., 1978).

Archie's Equation is recognized to be an over-simplification of the relationship between bulk resistivity and pore water resistivity, but is still valid under the condition that the pore water is highly conductive and the soil particles are non-conductive relative to the pore water (Urish, 1981). Based upon the discussion in Section 2.2.1, ARD contamination can result in significant ionic loading of the pore water, which results in a corresponding increase in the electrical conductivity of the pore water. Also, the relative electrical conductivity of the generally non-

plastic tailings is negligible in comparison with that of the pore water. Thus, for the case of saturated sulphide tailings affected by ARD processes, it appears that Archie's Equation is likely valid.

3.1.1.1 Influence of Pore Water Affected by ARD Contamination on Bulk Resistivity Measurements

At low frequencies, similar to that employed by the UBC resistivity module, conduction in pore water takes place by electrolytic conduction . A current is produced when the ions migrate due to the application of an electric field. In general, the more ions present in the pore water the greater the electrical conductivity, and subsequently the lower the bulk resistivity (as resistivity is the direct inverse of conductivity). However, the relationship between the electrical conductivity of an electrolyte and the ionic constituents is complicated by the effect of viscous drag (Keller, 1982). Viscous drag opposes the mobility of individual ions, which limits the electrical conductivity of the pore water. The main factors affecting viscous drag include the following:

(a).Temperature - fluid viscosity is a function of temperature and therefore conductivity of a particular ion will increase with an increase in temperature.

(b).Ionic concentration - conductivity increases with increased ionic concentration, but there also is an increased tendency towards collisions which retard migration of the ions.

(c).Ion Size - the tendency for smaller ions to have a higher mobility due to a decreased incidence of collisions is complicated by the tendency of charged ions to attract a layer of water molecules, and thus increase overall size.

(d).Ion Valence - the greater the valence the more charge transferred per ion, which results in higher electrical conductivity of the pore water.

As was discussed in Section 2.2.1, pore water affected by ARD contamination contains a variety of ionic constituents, which act to increase the electrical conductivity of the pore water. Assuming the temperature of a given pore water sample remains constant, changes in pore water electrical conductivity can be attributed to factors (b) through (d). As the ARD process advances from Stage 1 - Stage 3 the concentration and type of ionic constituents in the pore water increases significantly. The relative activity of some common pore water ions are shown in Table 3.1. The high mobility and correspondingly high relative activity of the hydrogen ion (H^+) is readily apparent. Initially, in Stage 1 ARD the principle contributor to elevated electrical conductivity of the pore water is due to increased sulphate concentrations. As ARD progresses to Stage 2 and Stage 3 development, increases in types and concentrations of heavy metal ions and increases in acidity result in significant increases in pore water electrical conductivity.

Table 3.1: Relative Electrical Activity of Common Ionic Species (After King and Sartorelli, 1991)

Major Cations	Specific Conductance	Major Anions	Specific Conductance
H^+	34.8	OH^-	19.7
K^+	7.5	SO_4^{2-}	8.0
NH_4^+	7.5	Cl^-	7.7
Ca^{2+}	6.1	NO_3^-	7.1
Na^+	5.0	HCO_3^-	4.6

3.1.1.2 Influence of Soil Type on Bulk Resistivity Measurements

Changes in soil stratigraphy are generally less influential on bulk resistivity measurements than pore water chemistry. Changes in stratigraphy are often marked by changes in bulk resistivity, but the influence of these changes is often limited by changes in electrical conductivity of the pore water. However, under amenable soil conditions and relatively low pore water conductivity, changes in stratigraphy can be linked directly to changes in bulk resistivity, as evidenced in Figure 3.1. Kokan (1992) found that the peaks in friction ratio (Rf) (indicative of changes in soil lithology) corresponded with changes in bulk resistivity. From 3-12 m the peaks in Rf corresponded with increased organic content, from 12-15 m the peaks in Rf were representative of organic-rich soil with increased clay content and beneath a depth of 15 m the peaks in friction ratio were indicative of clayey-silt layers. The decrease in bulk resistivity in the organic and clay soils can be attributed to surface conduction effects of the soils. The observed influence of soil type on bulk resistivity is largely recognizable due to the relatively low pore water conductivity at the site (as evidenced by the majority of bulk resistivity measurements of > 30 Ω-m).

For the case of sulphide bearing tailings, it is unlikely that soil type would have a significant influence on bulk resistivity measurements. Stratigraphic variations in the tailings would likely be minimal considering the relative uniformity of the tailings and surface conduction effects of the generally non-plastic tailings would be negligable in comparison with the electrical conductivity of tailings pore water affected by ARD processes.

3.1.2 DESCRIPTION OF UBC RESISTIVITY MODULE

The description contained herein of developments in UBC resistivity module design includes developments to 1994, and more recent changes to the equipment are not described. The

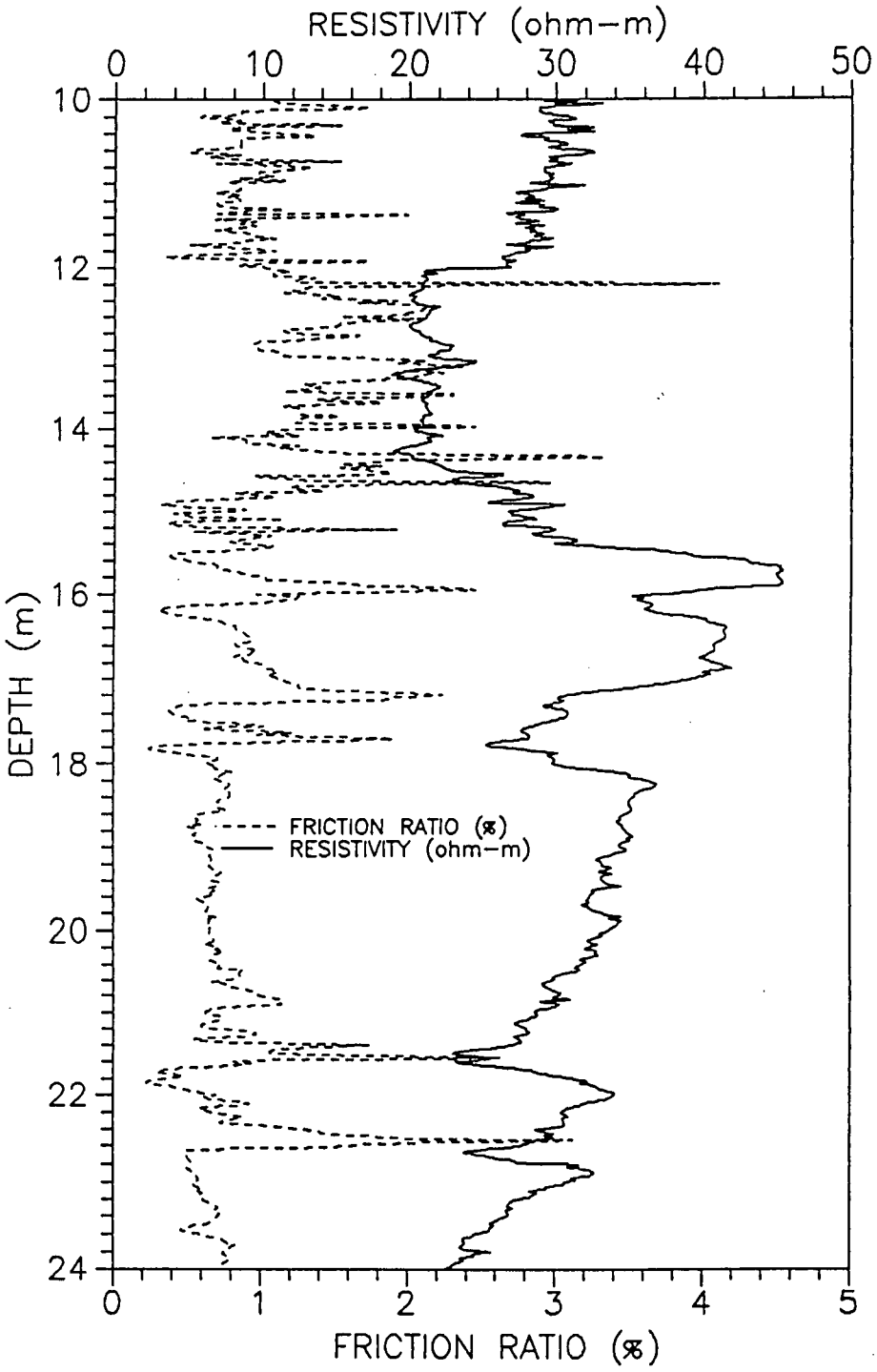


Figure 3.1: Comparison of Bulk Resistivity and Friction Ratio (After Kokan, 1992)

measurement of resistance to electrical current flow in soils is a relatively new development in penetration technology (Weemees, 1990). Resistivity cone penetrometers are available on a limited but increasing commercial basis (Van de Graff and Zuidberg, 1985, Horsnell, 1988, Woeller et al., 1993, and Rossabi, 1993). The RCPTU consists of a resistivity module which resides behind a standard cone. The addition of the resistivity module permits assessment of pore water quality by measuring bulk resistivity, while still providing all other standard CPTU measurements.

A schematic of one of the UBC resistivity modules (RES1) used in this study is shown in Figure 3.2. The diameter of the resistivity module is 44 mm. Three different sets of brass electrode spacings of 10, 25, and 75 mm are used for measurement. Smaller distances between the electrodes allow for possible detection of thinner layers of contrasting resistivity. Wider spacing provides a greater penetration of the electric field into undisturbed soil and provides a more averaged resistivity response. The performance of the module is related to the thickness, width, and composition of the electrodes (Kokan, 1992). The electrodes should have stable and linear conductive properties at varying current levels. Brass electrodes have been found to offer the best compromise between conduction and wear characteristics (Weemees, 1990). The two outer electrodes have widths of 5.0 mm while the three inner electrodes have widths of 2.5 mm. Delrin, a plastic, is used as the insulator separating the electrodes.

The outer electrode spacing also acts to supply a constant peak excitation current of 1000 Hz to the resistivity module. Research by Weemees (1990) found that this frequency eliminates polarization of the current supply electrodes. Polarization is the process where ions accumulate at the electrodes thus increasing the measured resistance. The applied frequency is also within the range of 25-3000 Hz suggested by the American Society for Testing and Materials (1982) for conductivity testing of water.

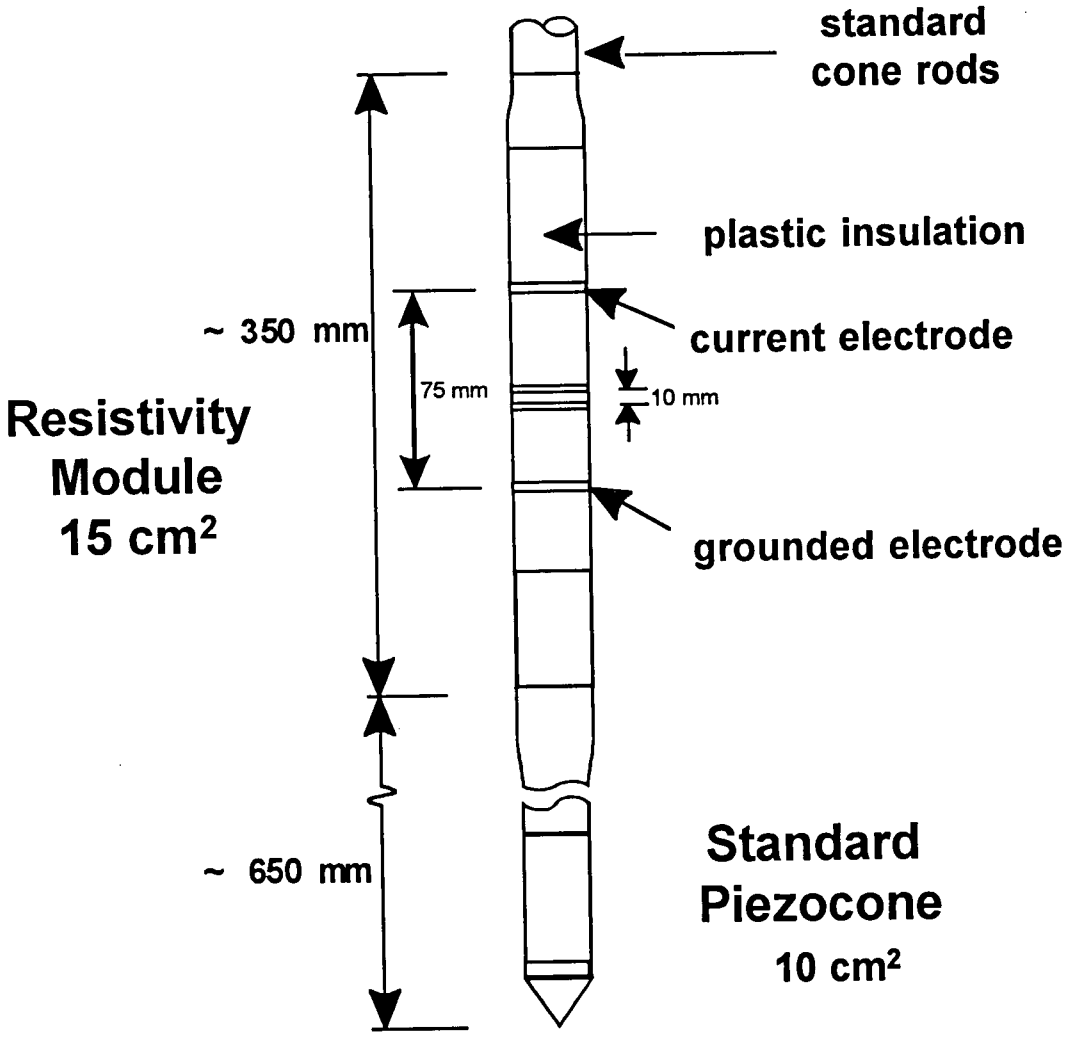


Figure 3.2 Schematic of Resistivity Piezocone (RCPTU)

A signal generator was used to apply an excitation voltage at 1000 Hz. This excitation voltage controls the amount of current supplied to the electrodes. The required excitation current depends on how conductive the soil is, so that lower resistivity soils require a higher excitation current.

The resistivity module does not directly measure resistivity, but rather measures resistance. For a given excitation current, measured voltages across the different electrode spacings are converted to resistance through Ohm's Law:

[3.2] $V = IR$

where,

V = Potential Difference (V)

I = Excitation Current (A)

R = Resistance (Ω)

Resistance is not a fundamental material property, but rather is a function of resistivity and geometry (specifically length (L) and cross-sectional area (A)) of the different electrical conducting material being measured. Resistance is related to resistivity, ρ, through the following relationship:

[3.3] $$R = \frac{\rho * L}{A}$$

Weemees (1990) proposed a calibration factor, k, to account for the influence of the electrode configuration on measured resistance. Assuming that (1) the soil acts as a homogeneous, isotropic media, (2) the electrodes act as perfect conductors and (3) the electronic circuitry of

the resistivity module acts as a perfect current supply source, the geometry factor (A/L) would be constant, k, and equation [3.3] would reduce to the following equation:

[3.4] $\rho_b = R * k$

Laboratory calibrations were carried out to determine this relationship for the different electrode configurations.

3.1.3 CALIBRATION OF UBC RESISTIVITY MODULE

Calibration procedures require submerging the resistivity module in constant temperature solutions of known resistivity. Typically calibration work is carried out by starting with de-ionized water and then potassium chloride (KCl) is added to the water in small quantities. This permits calibration of the resistivity module over a wide range of resistivities. The resistivity of the solution was recorded using a hand-held conductivity meter (Omega model CDH-30). The conductivity meter was calibrated with a 0.01 Molar (M) solution of KCl and then checked with a 0.10 M solution. The submerged resistivity module measures potential difference across the three electrode spacings for the different solution resistivities. Given that the excitation current remains constant, the potential difference measurements can be directly related to solution resistivity using equation [3.4] to determine calibration factors for each electrode spacing.

Figure 3.3 presents calibration data for the resistivity module used during field testing at INCO and Falconbridge mine sites (referred to as RES1). RES1 is a non-isolated resistivity module, in which the power supply to the resistivity module is not completely separate from that of the cone. This results in non-linear calibrations due to grounding and impedance effects (Kokan, 1992). The calibration for an excitation voltage of 0.1 V (Figure 3.3a) is highly

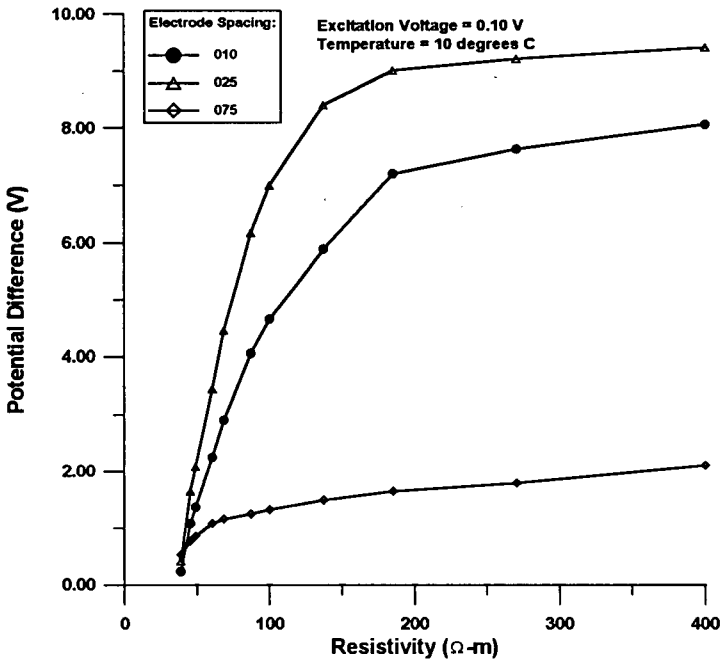


Figure 3.3a: RES1 Resistivity Module Calibration Curve - Low Excitation

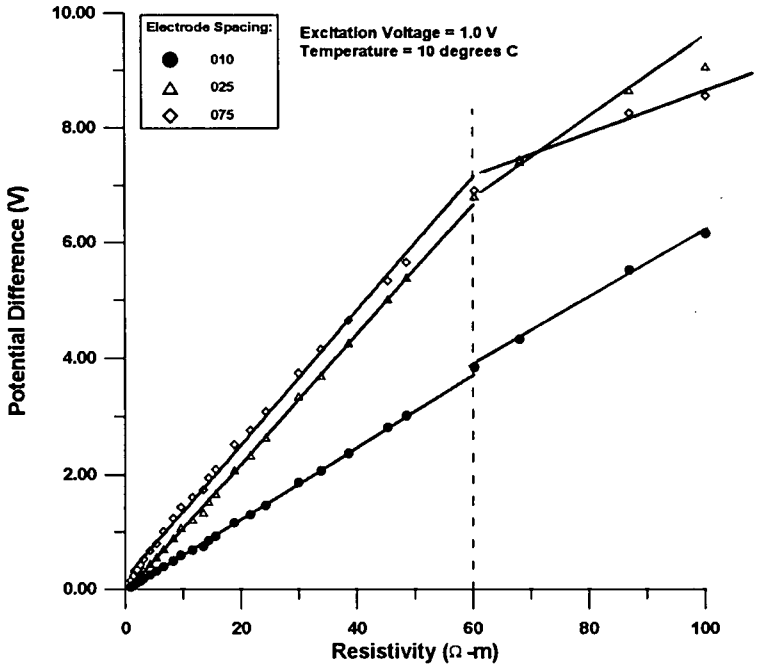


Figure 3.3b: RES1 Resistivity Module Calibration Curve - High Excitation

non-linear, particularly for the 10 mm and 25 mm electrode spacings. However, the calibration for a higher excitation voltage of 1.0 V (Figure 3.3b), required for measurement of lower resistivity, exhibits a more linear response for resistivities up to 100 Ω-m. The calibration data for each electrode spacing for the 1.0 V excitation can be approximated by two linear relationships; the first from 0-60 Ω-m and the second from 60-100 Ω-m. As the purpose of this study was to delineate low resistivity ARD, it was anticipated that the resistivity module would be operated at an excitation voltage of 1.0 V.

Recent improvements in resistivity module design have eliminated the non-linear calibrations. An isolated resistivity module (referred to as RES2) has a power supply totally independent of the cone power supply, which prevents grounding losses to the cone body. Figure 3.4 presents calibration data for the improved resistivity module (referred to as RES2), which was used during testing at the Gibraltar mine site. For the low excitation voltage (0.5 V) the calibrations are linear for resistivities up to 350 Ω-m and have a lower boundary of approximately 1 Ω-m, as shown in Figure 3.4a. For the higher excitation voltage (5.0 V) the calibrations are linear to 40 Ω-m and have a lower boundary of approximately 0.01 Ω-m, as shown in Figure 3.4b. This represents a significant improvement over previous resistivity module performance.

3.1.4 APPLICATION OF RCPTU FOR ASSESSMENT OF ARD CONTAMINATION

The application of resistivity techniques for delineation of contamination requires that there be a contrast between the natural resistivity of the subsurface (background values) and the resistivity of contaminated zones. Contaminants can provide this contrast and influence the bulk resistivity measurements by changing the resistivity of the pore water. Dissolved aqueous phase liquids (APL's) typically act to decrease the resistivity

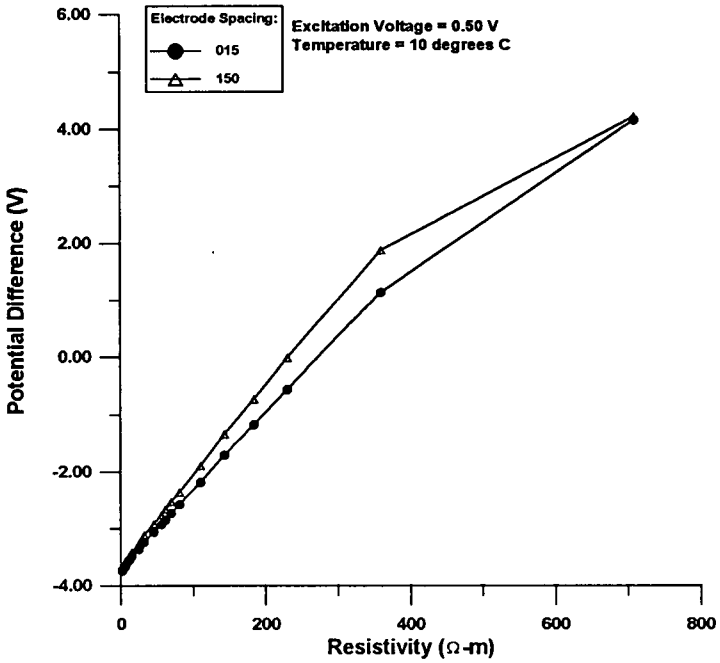


Figure 3.4: RES2 Resistivity Module Calibration Curve - Low Excitation

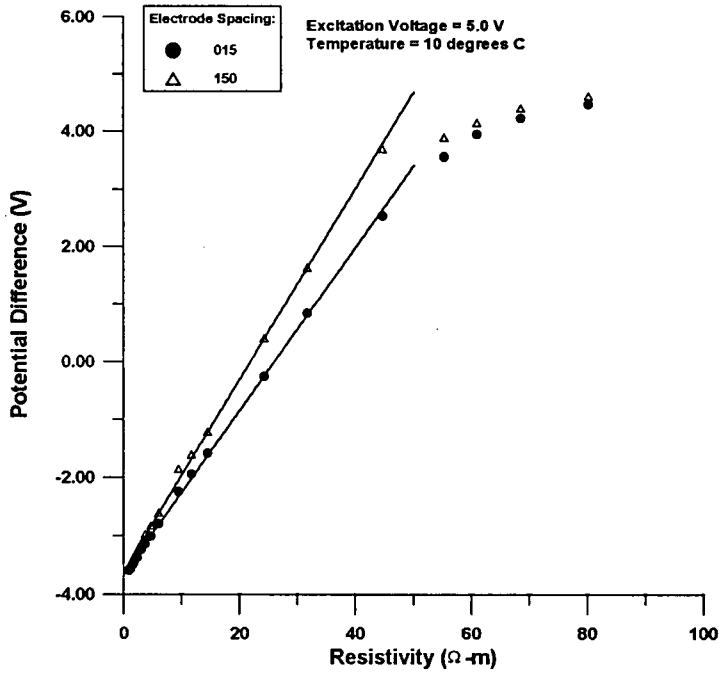


Figure 3.4b: RES2 Resistivity Module Calibration Curve - High Excitation

of the pore water (i.e. ARD leachate from mine tailings) and insulating organic non-aqueous phase liquids (NAPL's) increase bulk resistivity by blocking paths of conduction through the pore space of the soil (i.e. organic contaminants).

The UBC ISTG has carried out RCPTU tests at a variety of sites since 1988. Results to date clearly demonstrate the capability of the RCPTU to produce repeatable and accurate profiles of resistivity. A summary of typical resistivity measurements of fluids and bulk soil-fluid mixtures is shown in Table 3.2. Values of conductivity, which are simply the reciprocal of resistivity values, are also shown due to the widespread convention of using conductivity in the environmental sciences. The conversion between resistivity and conductivity is as follows:

[3.5] Conductivity ($\mu S/cm$) = 10000 / Resistivity (Ω-m)

As can be seen in Table 3.2, the RCPTU is capable of delineating highly conductive pore water. Based on this experience, it was believed that the RCPTU would be effective in identifying highly conductive pore water associated with ARD contamination. The use of resistivity measurements to delineate zones where ARD is developing or occurring is relatively well-documented. For example, Ebraheem et al. (1990) and King and Sartorelli (1991) show how high ionic loading of both early stage and low pH, fully developed ARD is well defined by surface geophysics. However, the ability to carry out resistivity soundings and avoid the non-unique solution interpretation of surface geophysics is a large advantage of the RCPTU.

The use of the RCPTU for assessment of ARD contamination requires consideration of bulk resistivity measurements in both the unsaturated and saturated zones. In the unsaturated zone the effects of conductive pore water affected by ARD contamination are countered by the insulative effects of air also contained in the voids, making interpretation of bulk resistivity measurements difficult. It is reasonable to expect that bulk resistivity measurements in the

Table 3.2: Summary of Typical Resistivity (Conductivity) Measurements of Bulk Soil Mixtures and Pore Fluid (Campanella et al., 1994)

Material	Bulk Resistivity ρ_b, Ω-m	Fluid Resistivity ρ_f, Ω-m	Bulk Conductivity μS/cm	Fluid Conductivity μS/cm
Sea Water	-	0.2	-	50000
Drinking Water	-	>15	-	<665
McDonald Farm Site Clay	1.5	0.3	6700	33300
Laing Bridge Site Clay	20	7	500	1430
Colebrook Site Clay	25	18.2	400	550
232 Ave. Clay	8	-	1250	-
Strong Pit Clay	35	-	285	-
Kidd 2 Site Clay	14	12.5	715	800
McDonald Farm Site Sand	5-20	1.5-6	2000-500	6700-1670
Laing Bridge Site Sand	5-40	1.5-10	2000-250	6700-1000
Colebrook Site Sand	70		143	
Strong Pit Site Sand	115		89	
Kidd 2 Site Sand	1.5-40	0.5-21	6700-225	20000-475
Typical Landfill Leachate	1-30	0.5-10	10000-330	20000-1000
Industrial Site- Inorganic Contaminants in Sand	0.5-1.5	0.3-0.5	20000-6500	33000-20000
100 % Ethylene Dichloride (ED)	-	20400	-	0.5
50% ED/50% Water in Sand	700	-	14	-
17% ED/83% Water in Sand	275	-	36	-
Industrial Site - Organic Contaminants in Sand	125	-	80	-
BC Place Parcel 2, PAH's (Coal Gas Plant)	200-300	-	50-33	-
BC Place Parcel (Wood Waste)	300-600	-	33-66	-

unsaturated zone would be highly variable, owing to the effects of changing pore water chemistry and variable saturated conditions. Therefore, interpretation of bulk resistivity measurements in the unsaturated zone requires a qualitative approach, as one must attempt to decipher the influences of these countering factors. However, this qualitative approach can be strengthened if pore water samples can be collected and subsequent chemical analyses carried out. For the field test work carried out at INCO and Falconbridge mine sites pore water samples were collected in the unsaturated zone using a modification of the immiscible displacement technique developed by Patterson et al., (1978).

In the saturated zone the interpretation of bulk resistivity measurements is more straightforward. For the case of sulphide bearing tailings changes in bulk resistivity are predominately due to changes in pore water chemistry. The influence of changes in soil type are not as significant, due to the relatively uniform nature of the tailings and the generally low plasticity (and hence low surface conduction effects) of the tailings.

As was discussed in Section 3.1.1.1, under constant temperature conditions the factors affecting electrical conductivity of the pore water are ion concentration, ion size and ion valence. Of primary importance in mapping ARD contamination as it progresses from Stage 1 - Stage 3 ARD, is monitoring increases in concentrations of specific ionic constituents (sulphate, specific metals, H^+). Research by Ebraheem et al. (1990) demonstrates a direct relationship between total dissolved solids (TDS) (a measure of the total dissolved ionic loading of the pore water) and bulk resistivity, as shown in Figure 3.5. Therefore, it appears reasonable that the development of ARD and its characteristic increase in ionic loading of the pore water can be linked directly to bulk resistivity measurements. Moreover, based upon relative values of bulk resistivity measurements and identification and quantification of specific ionic constituents from pore water samples, the approximate stage of ARD can likely be identified. For instance, bulk resistivity measurements which correspond to water samples having elevated sulphate concentrations, but with low heavy metals and acidity, are likely indicative of Stage 1 ARD. However, bulk resistivity measurements which correspond to pore water samples having elevated concentrations of sulphates, metals and acidity are likely characteristic of more advanced Stage 2 and/or Stage 3 ARD processes. While it is acknowledged that ion size and ion valence also influence electrical conductivity of the pore water, consideration of these factors appears less critical to the evaluation of ARD processes than the overall increase in ionic loading with ARD progression.

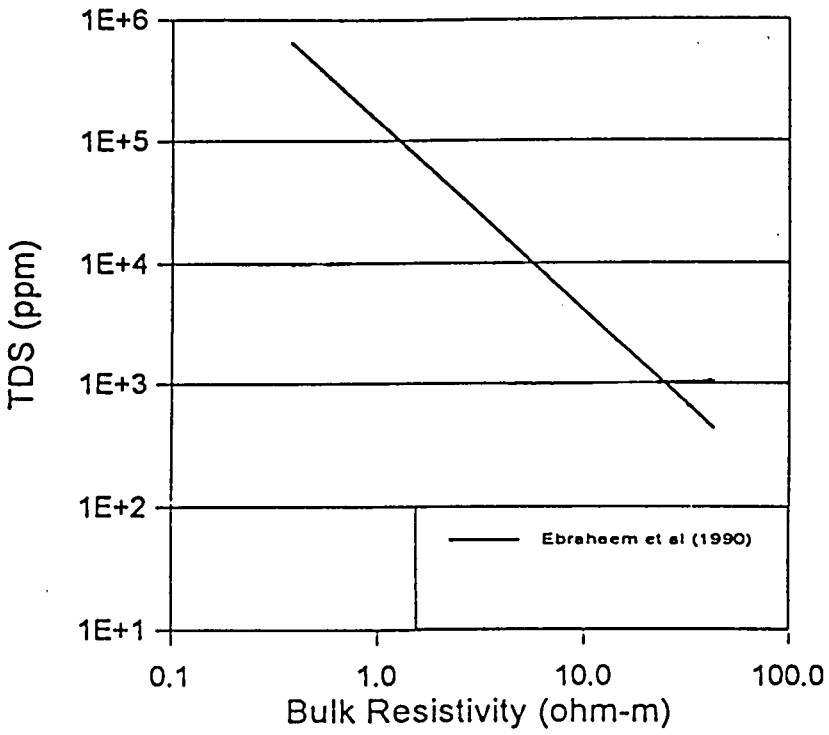


Figure 3.5: Observed Relationships Between Total Dissolved Solids and Bulk Resistivity (After Ebraheem et al., 1990))

3.2 BAT PORE WATER SAMPLING TECHNOLOGY

The BAT pore water sampler, named after its inventor (B.A. Torstennson, 1984), was used to collect pore water samples during the field investigation program for this study. The system consists of a sampling tip that is accessed through sterile evacuated glass sample tubes (volume = 35 ml) and a double-ended hypodermic needle set-up. The tube sampler is lowered by a cable through standard AW water sampling rods. The BAT sampler is pushed into the ground in the same manner as the piezocone. The UBC modified BAT sampling tip consists of a probe slightly larger in diameter than the resistivity module (50 mm vs. 44 mm). This permits undisturbed sampling down the same alignment as a previous CPTU sounding, or the sampling tip may be pushed on its own. Everard (1995) demonstrated that there is no

difference in sample integrity in pore water samples collected from sampling down a previous CPTU sounding versus pore water samples collected from the BAT pushed on its own. A schematic of the UBC modified BAT pore water sampler is shown in Figure 3.6. Recent modifications to the design of the UBC modified BAT pore water sampler were made following completion of field work for this thesis. Campanella (1995) gives a detailed description of these recent changes.

The first pore water sample at a depth is generally purged and after the second pore water sample is retrieved to the ground surface preliminary chemical tests can be carried out on site (e.g. pH, conductivity and temperature) and the samples stored for future chemical analyses. After sampling is carried out at a specific depth, the probe is then pushed to the next depth and the procedure repeated. There is no limit to the number of samples that can be taken at one location. The time to retrieve a sample is dependent upon the hydraulic conductivity of the soil unit being investigated.

The United States Environmental Protection Agency (US EPA) have conducted many field trials and comparisons of existing water sampling technologies (Blegen et al., 1988). They have recognized the BAT technology as being superior in obtaining high quality pore water samples for geoenvironmental characterizations. BAT groundwater sampling can be used to significantly enhance the application of the RCPTU. RCPTU logs can be used to target potential areas of contamination and identify permeable soil strata, which facilitates cost-effective pore water sampling. After pore water samples have been collected, comparisons between bulk resistivity logs and specific chemical properties of the samples can potentially enable the formation of site-specific relationships. Such relationships can improve the interpretation of any future RCPTU soundings at a site, which makes the technology attractive for monitoring water quality changes over time.

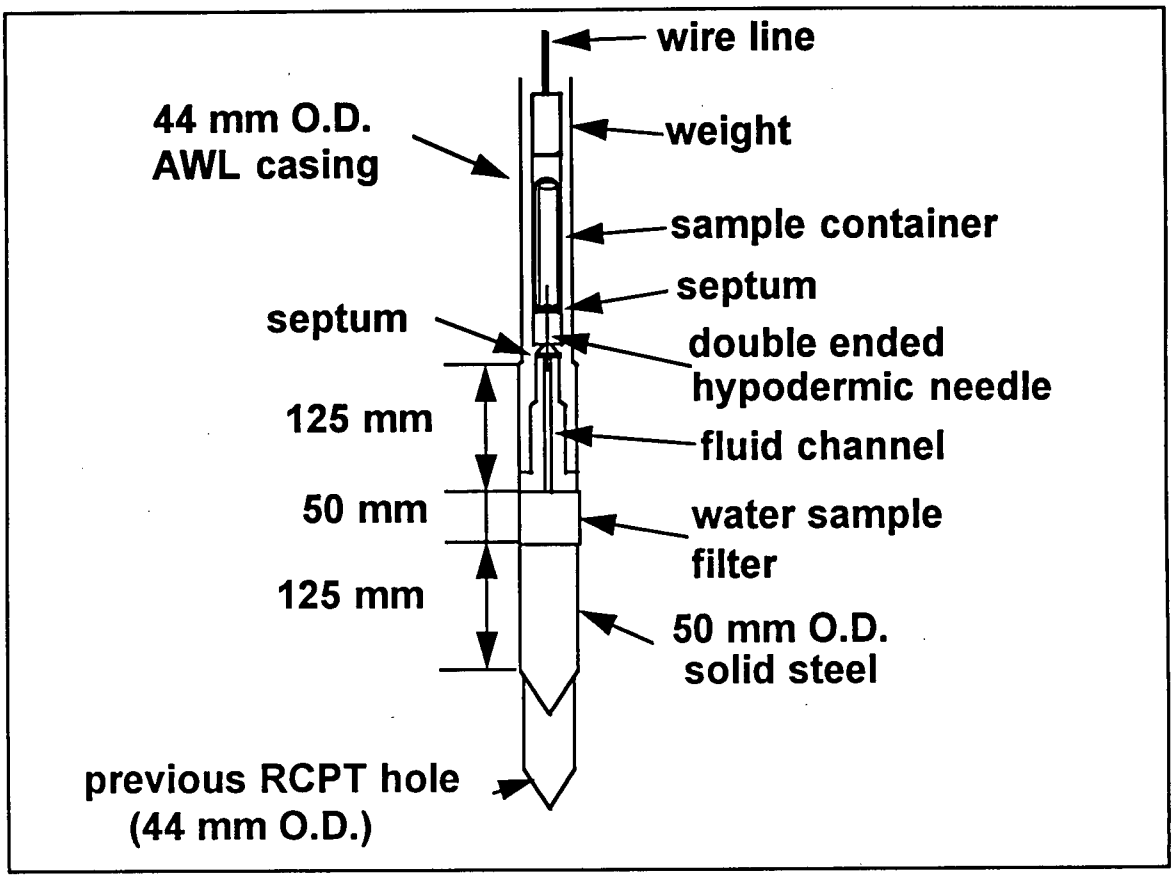


Figure 3.6: Schematic of UBC-Modified BAT Pore Water Sampler

3.3 CONE PENETRATION TEST (CPTU)

The cone penetration test represents a repeatable means of delineating soil stratigraphy and determining physical geotechnical parameters. The designation of the U in CPTU implies pore pressure measurements are recorded, as compared to a CPT test which is not equipped to measure pore pressure. A schematic of the standard cone is shown in Figure 3.7. The cone has a standard (ASTM D-3441) 10 cm^2, 60° conical tip, a 150 cm^2 friction sleeve and pore pressure transducers which allow the CPTU to measure tip resistance (q_c), friction sleeve stress

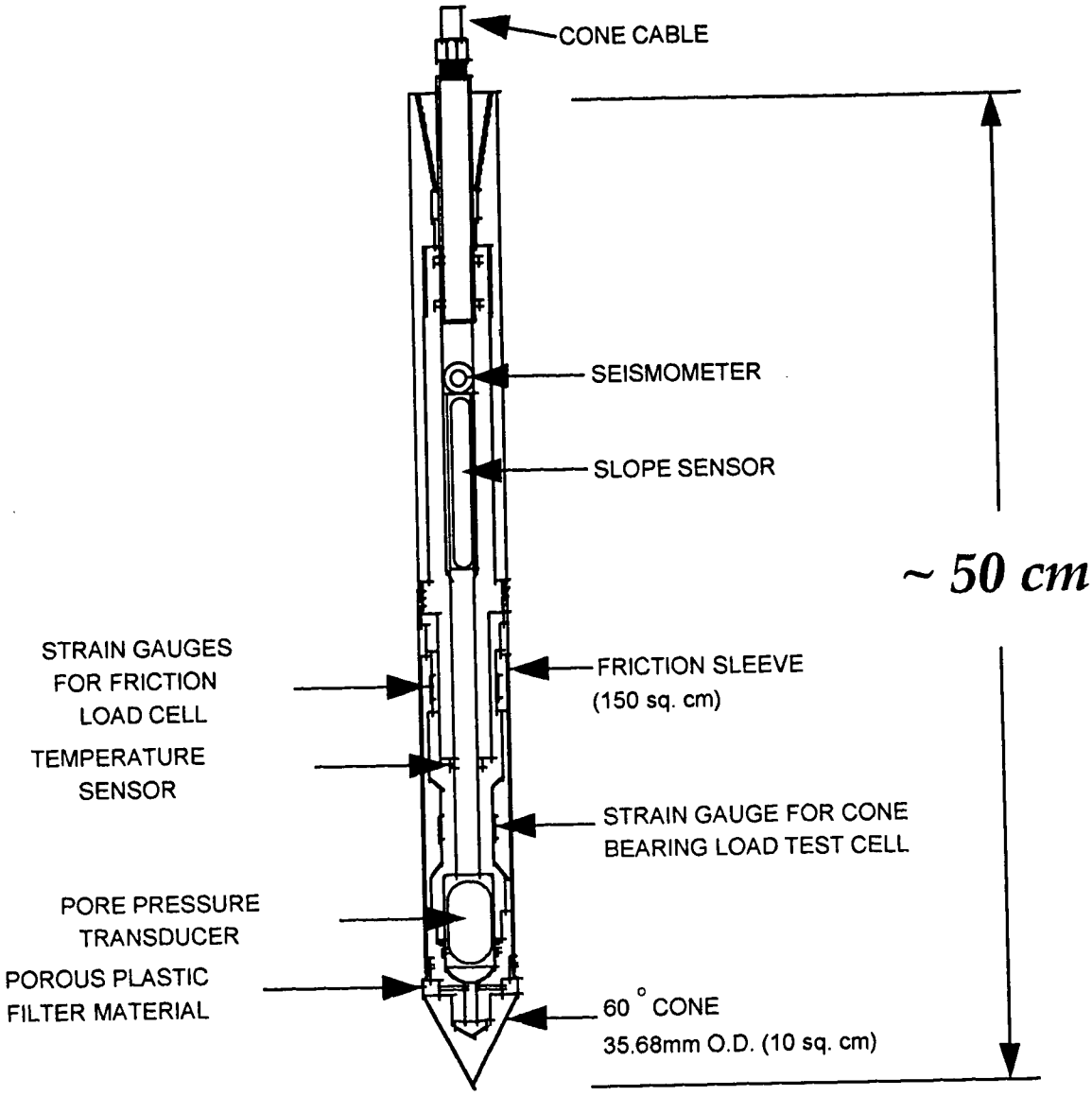


Figure 3.7: Schematic of Standard Piezocone

(f_s), and pore pressure response at up to three locations (typically referred to as U1, U2, and U3). U1 is located in front of the cone tip, U2 is located behind the cone tip and U3 is located behind the friction sleeve. U2 is the most common location for measurement of pore pressure response. All measurements are made by calibrated strain gauges and /or pore pressure

transducers that are highly linear and non-hysteretic. Temperature (t) and inclination (i) are also measured simultaneously as the CPTU is advanced into the ground. In addition, a cone capable of recording seismic wave velocities has been developed (Campanella and Robertson, 1984). From seismic wave velocities (V_s and V_P) low strain moduli can be computed directly.

The cone is pushed into the ground at a rate of about one metre every 50 seconds as per the ASTM Standard by a hydraulic pushing source. The specialty built UBC in-situ research vehicle was used for all field testing in this study. A detailed description of this vehicle and its capabilities is given by Campanella and Robertson (1981).

All cone channels are continuously monitored and are typically digitally reported at 25 mm intervals, thus providing essentially continuous in-situ data sampling. Data are acquired in clear format ASCII files which allow the user to carry out straightforward post-investigation analyses with any number of proprietary and commercial CPTU data evaluation software packages. Figure 3.8 is an example of a typical graphical data output, referred to as a cone plot, from a CPTU sounding carried out in sulphide bearing tailings. The first data column contains friction ratio (Rf), which can be used to estimate soil behaviour type. Rf is not directly measured, but rather is defined as $\frac{f_s}{q_t} * 100\%$, with f_s and q_t plotted in the second and third columns, respectively. q_t, is q_c corrected for the effects of in-situ water pressures on the mechanical design of the cone, which is only significant in soft cohesive soils (Robertson and Campanella, 1988). Column 4 contains the dynamic pore pressure response, and as denoted on the figure, the U2 pore pressure location was used for this sounding. Column 5 contains the bulk resistivity measurements recorded by the resistivity module. The interpteted stratigraphy for the sounding is shown in column 6.

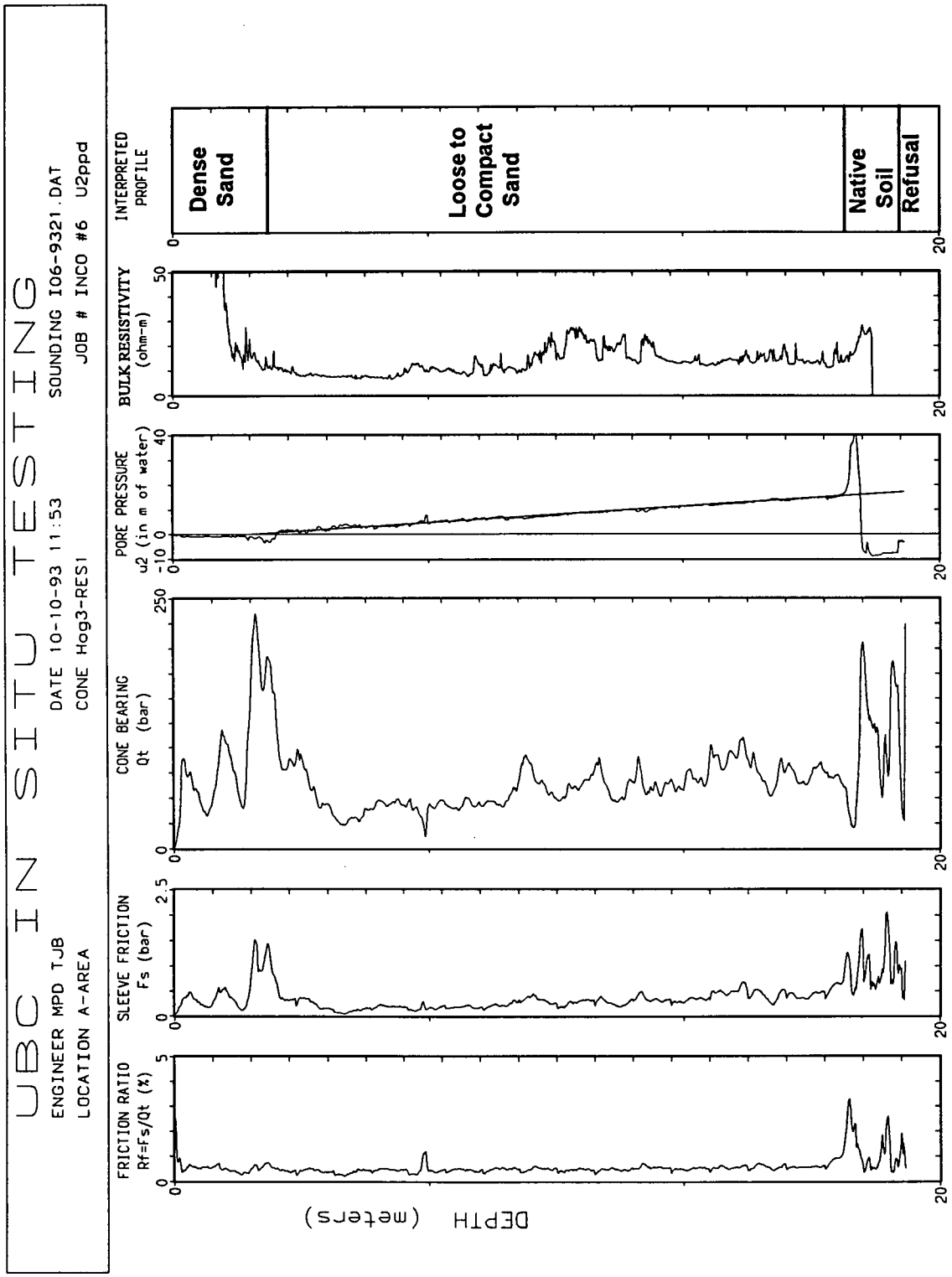
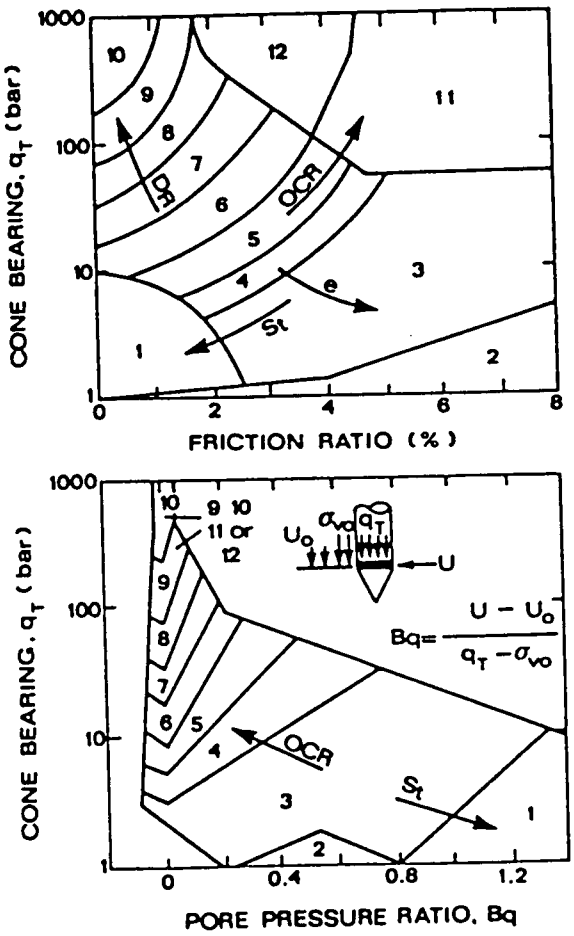


Figure 3.8: Typical RCPTU Profile in Sulphide Bearing Tailings

Extensive empirical correlations have been developed between the various CPTU channels, and combinations thereof, that provide soil behavior type (equivalent to stratigraphy) and geotechnical strength parameters (e.g. ϕ' ,D_r, SPT-N and S_u). These extensive correlations have been incorporated into the PC-based software program CPTINT (CPTINT 5.0, 1994). CPTINT was used to process data collected during field investigation programs for this study.

CPTINT utilizes soil interpretation charts developed by Robertson and Campanella (1988) for the estimation of soil behavior type. These charts are presented in Figure 3.9. The upper chart in Figure 3.9 estimates soil behavior type using the cone bearing (q_t) and the friction ratio (Rf) In general, as the proportion of fines and plastic characteristics increases, the bearing decreases and the friction ratio increases. In the case of a clean sand the cone bearing will be generally greater than 40 bar (where 1 bar = 100 kPa) and the friction ratio will be less than 0.75 %. Values of friction ratio greater than 2 % are generally representative of silty and/or clayey soils, whereas values greater than 5 % usually indicate high organic content. This is readily apparent on Figure 3.8, where the Rf in the sandy tailings was approximately 0.7% and was in excess of 2% in the clayey-silt native soil.

It is not always possible to accurately estimate soil behavior type using q_t and Rf, particularly in fine-grained materials (Campanella and Robertson, 1992). In these materials, the lower chart in Figure 3.9, which incorporates pore pressure measurements, provides more definitive interpretation. During penetration, pore pressures above or below equilibrium values (e.g. dependent upon a materials propensity to contract or dilate during shearing) are termed excess pore pressures. The excess pore pressure (Δu) measured during penetration provides an excellent means of detecting details in soil behavior type. For clean sandy soils excess pore pressures dissipate almost immediately (as seen in Figure 3.8 for the sandy tailings), while for finer-grained silts and clays significant excess pore pressures can be generated. Excess pore pressures can be either positive or negative depending upon pore pressure measurement



ZONE	Qc/N	SOIL BEHAVIOUR TYPE
1	2	SENSITIVE FINE GRAINED
2	1	ORGANIC MATERIAL
3	1	CLAY
4	1.5	SILTY CLAY TO CLAY
5	2	CLAYEY SILT TO SILTY CLAY
6	2.5	SANDY SILT TO CLAYEY SILT
7	3	SILTY SAND TO SANDY SILT
8	4	SAND TO SILTY SAND
9	5	SAND
10	6	GRAVELLY SAND TO SAND
11	1	VERY STIFF FINE GRAINED (*)
12	2	SAND TO CLAYEY SAND (*)

(*) Overconsolidated or cemented

Figure 3.9 Soil Behaviour Type Classification Chart (After Robertson and Campanella, 1988)

location and soil behavior (Gillespie, 1990). Normally consolidated silts and clays tend to develop positive excess pore pressures, whereas overconsolidated silts and clays tend to develop smaller positive or even negative excess pore pressures in the U2 measurement location. The negative pore pressure response observed in Figure 3.8 for the native soil would suggest that the clayey-silt soils are overconsolidated. The net effect of incorporating excess pore pressure measurements in the identification of soil behavior type is to improve the interpretation of fine-grained soils, while leaving the interpretation in sands unchanged. The lower chart in Figure 3.9 is based on the U2 location for pore pressure measurement.

Excess pore pressure measurements also provide valuable insight into the consolidation and hydraulic characteristics of the different soil strata. When penetration ceases, typically after each 1 m rod push, the excess pore pressures decay with time. Figure 3.10 is an example of a CPTU pore pressure dissipation from a sounding carried out in sulphide bearing tailings. The amount of time required for the pore pressure to decay to the equilibrium value (denoted as U_0 on Figure 3.10) depends on the coefficient of consolidation, which is a function of the compressibility and hydraulic conductivity of the soil. Conversely, the dissipation time can be used to estimate the coefficient of consolidation, C_v (or C_h) (where v and h are vertical and horizontal coefficients, respectively), through the use of cavity expansion theory. Robertson and Campanella (1988) provide a detailed discussion concerning the estimation of coefficient of consolidation from pore pressure dissipation data. Knowing $c_{v,h}$, the hydraulic conductivity (K) can be estimated using:

[3.6] $$K_{v,h} = c_{v,h} * m_{v,h} * \gamma_w$$

where $m_{v,h}$ is the coefficient of volume compressibility in either the vertical or horizontal plane, which can be estimated from CPTU data, and γ_w is the unit weight of water. In addition, in-

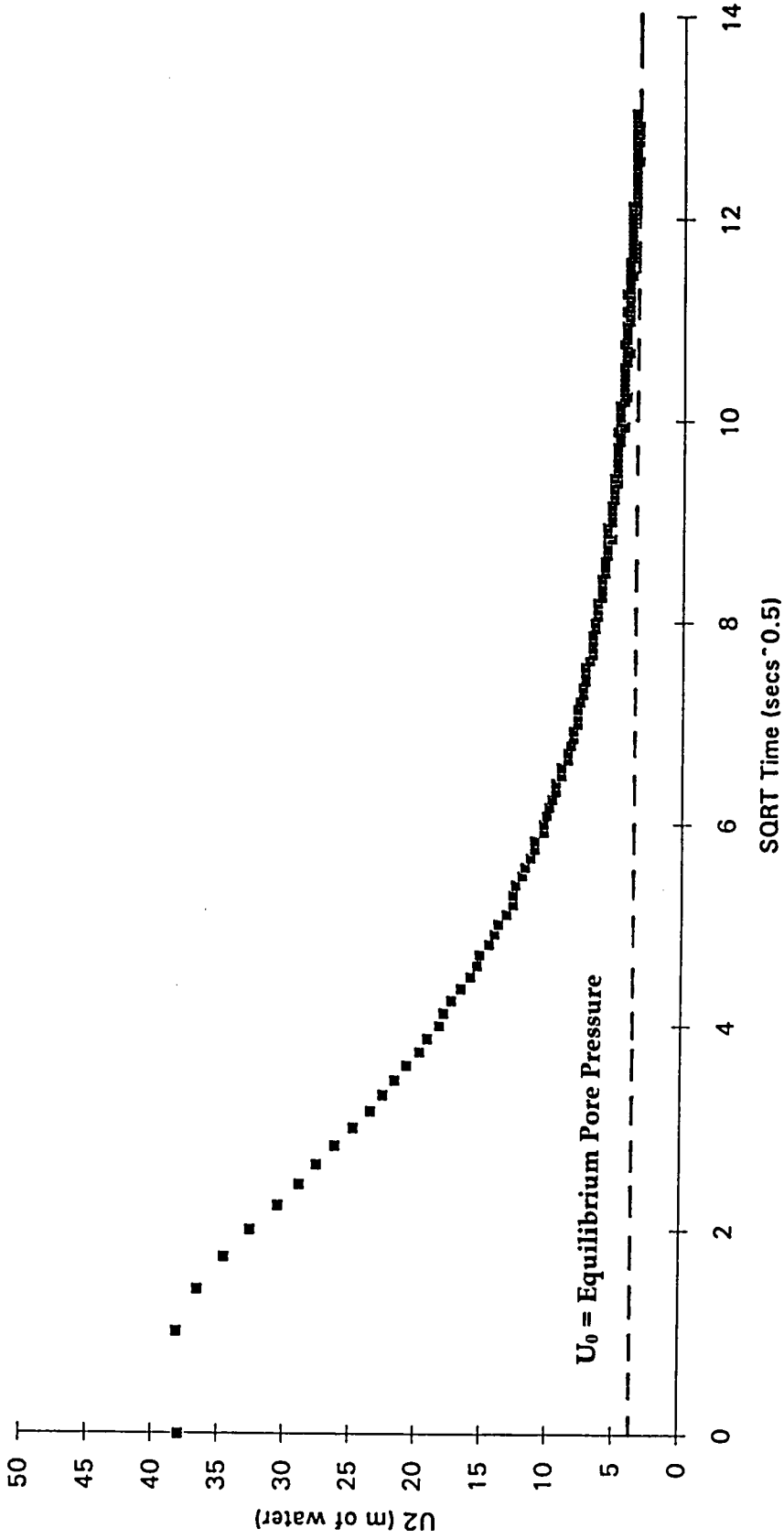


Figure 3.10: Typical Pore Pressure Dissipation in Fine-Grained Sulphide Bearing Tailings

situ equilibrium pressure head distribution and the identification of vertical gradients within the saturated zone can be determined based on the equilibrium pore pressure data for all soil types. Estimates of horizontal gradients can be made based on the depth of the water table at different CPTU locations.

3.3.1 APPLICATION OF CPTU FOR ASSESSMENT OF STATIC STABILITY

The CPTU offers an excellent method of delineating the information required for a static stability analysis of a tailings dam. Analysis of tailings dam stability, notwithstanding the form of the stability assessment being carried out, generally requires the following information:

- geometric configuration of the tailings dam;
- stratigraphic profiles within the dam and foundation materials;
- strength parameters for each stratigraphic unit within the dam and foundation materials and
- pore pressure distribution within the dam

The CPTU is unparalleled in its ability to identify soil stratigraphy (Campanella and Robertson, 1988). After distinct stratigraphic zones have been identified, the CPTU can give estimates of key geotechnical strength parameters for each stratigraphic zone. Established correlations exist for estimating ϕ', D_r, SPT-N and S_u (References for each correlation are included in the CPTINT 5.0 documentation contained in Appendix B). In addition, the CPTU can measure the in-situ equilibrium pressure head distribution and identify any gradients. Depending upon the scope of the project, more detailed geotechnical and hydrogeological information may be required. The CPTU data can be used to delineate critical zones for soil sampling and/or piezometer installation.

3.3.2 APPLICATION OF CPTU FOR ASSESSMENT OF FLOW LIQUEFACTION SUSCEPTIBILITY

Plewes et al. (1992) proposed a screening procedure for evaluating the susceptibility for flow liquefaction of soils using the CPTU. The screening procedure was developed on the basis of the state parameter (Ψ) and critical state theory. The state parameter, originally proposed by Been and Jefferies (1985), is defined as the difference between the current void ratio (e) and the critical void ratio (e_c) at the same stress level:

[3.7] $\Psi = e - e_c$

A positive Ψ value is representative of a SS (contractive) soil, whereas a negative Ψ value is representative of a SH (dilative) soil. The relative distribution of SS and SH soils can be used to assess the potential for flow liquefaction, given the SS soil is triggered to strain soften.

Plewes et al. (1992) applied the theoretical framework of critical state soil mechanics to laboratory and in-situ field data and derived a methodology for estimating the state parameter of a broad range of soils directly from the CPTU. Figure 3.11 presents the essence of this screening procedure. The parameters incorporated in Figure 3.11 are defined as follows:

Ψ = state parameter

Qp = normalized CPT resistance = $Qp(1-B_q)$

Qp = stress-normalized qt = $\frac{q_t - \sigma_{v0}}{\sigma_{v0}'}$

B_q = dynamic pore pressure ratio = $\dfrac{U2-U_0}{q_t-\sigma_{v0}}$

F = stress normalized friction ratio = $\dfrac{f_s}{q_t-\sigma_{v0}}(100\%)$

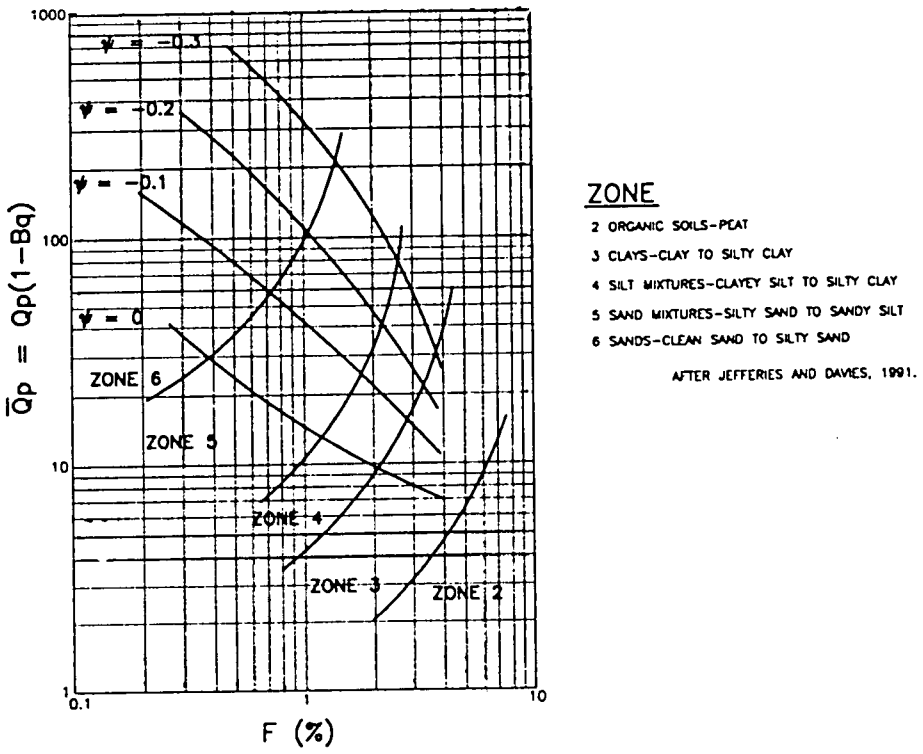


Figure 3.11: CPTU-Based Screening Chart For Estimating the State Parameter of Sands (After Plewes et al., 1992)

3.3.3 APPLICATION OF CPT FOR ASSESSMENT OF CYCLIC LIQUEFACTION SUSCEPTIBILITY

Currently, the most popular method for estimating liquefaction potential under dynamic loading conditions, referred to as cyclic liquefaction potential, makes use of the penetration

resistance (N value) from the Standard Penetration Test (SPT). Seed et al. (1985) proposed a methodology for evaluating liquefaction potential based upon a back analysis of historical records (referred to as the Berkeley records) at sites which were known to have liquefied or not liquefied under earthquake loading. Liquefaction was assumed to have occurred based on the presence of observable surface features such as sand boils and ground cracks. In the Seed methodology the soil conditions are defined by the normalized standard penetration resistance $(N_1)_{60}$ (normalized to one tsf and 60 % energy). Seed et al. (1985) give a comprehensive explanation of the methodology employed to relate $(N_1)_{60}$ values to cyclic liquefaction potential.

However, due to the poor repeatability associated with the SPT and the discrete nature of the test, CPTU-based methods of assessing cyclic liquefaction potential of soils are becoming increasingly popular. Robertson and Campanella (1985) proposed a chart, for estimating cyclic resistance ratio (CRR) for clean sands and silty sands using normalized CPT resistance. The normalized CPT resistance, q_{c1}, is defined as follows:

$$[3.8] \quad q_{c1} = q_c * \left(\frac{Pa}{\sigma_{v0}'}\right)^{0.5}$$

where,

q_c = cone penetration resistance

Pa = 101.3 kPa

σ_{v0}' = effective overburden stress (kPa)

The purpose of the normalization procedure is to remove the effect of stress level from the measured CPT tip resistance. It is recognized that q_{c1} does not represent true normalization, as q_{c1} is not unitless. Not withstanding this fact, q_{c1} can be effective in evaluating the cyclic

liquefaction susceptibility of soils. SPT-CPT conversions, as detailed by Robertson et al. (1983), were used to develop the CPT-based chart from the Seed SPT chart (Seed et al., 1985).

Recent comprehensive databases compiled by Stark and Olson (1995) and Suzuki et al. (1995) are in excellent agreement with the work of Robertson and Campanella (1985). Figure 3.12 compares the results of the recent CPT field performance data and the correlation developed by Robertson and Campanella (1985) for clean sands.

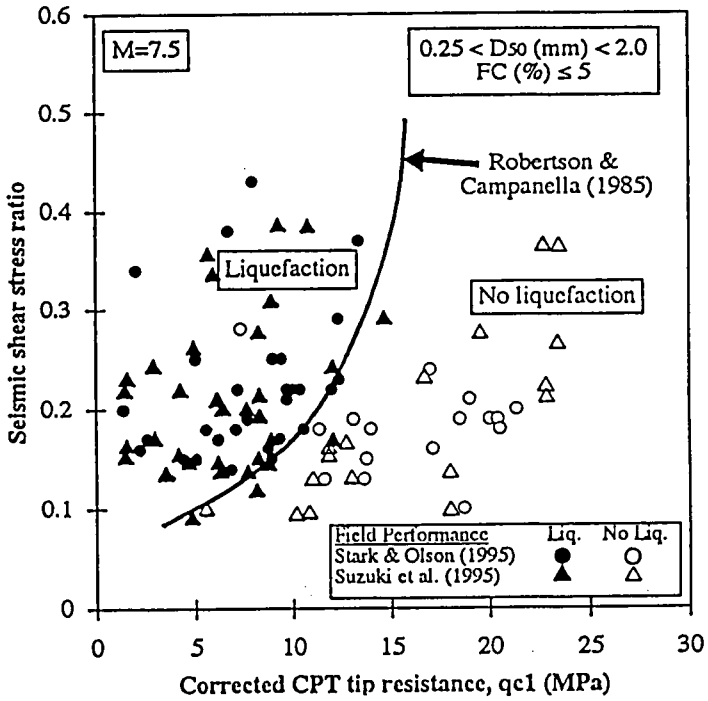


Figure 3.12: Comparison Between Robertson and Campanella (1985) CPT-Based Method For Estimating CRR of Clean Sands and Recent Field Performance Data (After Robertson and Fear, 1995)

Robertson and Fear (1995) proposed corrections to the normalized penetration resistance (q_{c1}) to obtain equivalent clean sand normalized penetration resistance $(q_{c1})_{ecs}$, based on fines

content and grain size. Fines Content (FC) is defined as soil particles having a mean diameter less than 68 μm. The proposed corrections are defined as follows:

[3.9] Δq_{c1} = 5 MPa if FC > 35%

Δq_{c1} = 0 if FC < 5%

Δq_{c1} = (FC-5)/6 MPa if 5% < FC < 35%

One shortcoming of using the CPTU instead of the SPT for cyclic liquefaction assessments is the inability to collect a soil sample and subsequently estimate fines content. However, over the past decade charts have been developed to estimate soil behaviour type from CPTU data (Robertson and Campanella, 1988; Robertson, 1990; Jefferies and Davies, 1993). A fundamental feature of each of the soil behaviour type charts is an increase in fines content with an increase in friction ratio (Rf), as demonstrated in Figure 3.13 by the recent work of Suzuki (1995). Also shown in Figure 3.13 are recent data collected by the UBC ISTG (Kokan, 1992). There is a fair degree of scatter about Figure 3.13, with fines content ranging approximately an order of magnitude when Rf is greater than 1%. This may be largely attributed to the fact that the CPT is not solely influenced by fines content in responding to soil behaviour, but is also influenced by factors such as soil plasticity and mineralogy. A fundamental difficulty with Figure 3.13 is that a loose clean sand falling in Zone 1 on Figure 3.9 could be confused with a denser sand containing fines. Caution should be exercised in using the relationship in Figure 3.13, and it is recommended that fines content be determined from soil sampling prior to its application to specific sites.

Robertson and Fear (1995) proposed a methodology for estimating fines content directly from CPT data by means of the soil behaviour type index, I_c, which they defined as:

[3.10] $$I_c = [(3.47 - \log Q)^2 + (\log F + 1.22)^2]^{0.5}$$

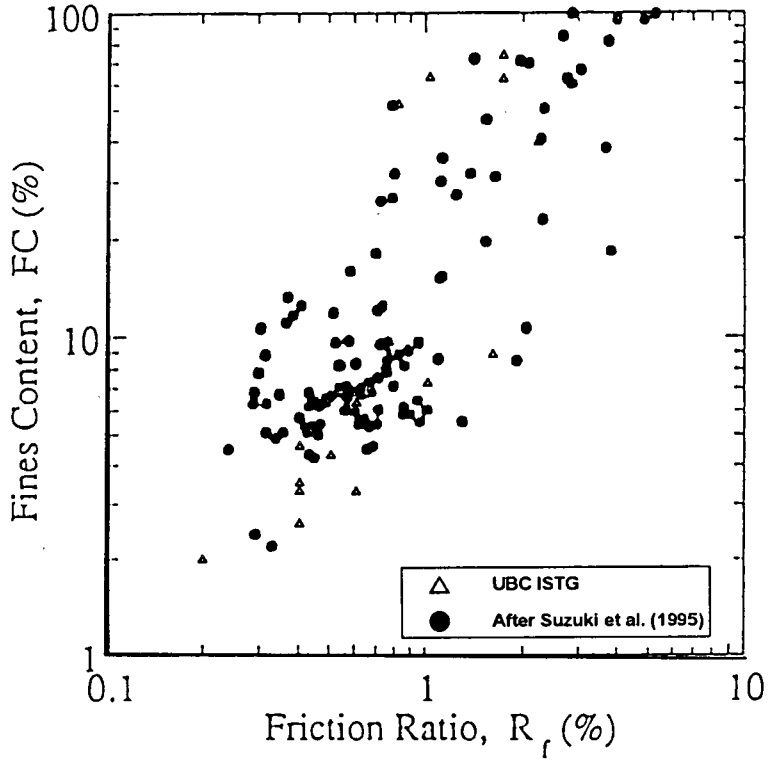


Figure 3.13: Variation of Fines Content With Friction Ratio (Adapted From Suzuki et al., 1995)

where,

Q	=	normalized penetration resistance, dimensionless
	=	$(q_c-\sigma_{v0})/\sigma_{v0}'$
F	=	normalized friction ratio, in %
	=	$[(f_s/(q_c-\sigma_{v0})]*100\%$
q_c	=	CPT penetration resistance
f_s	=	CPT sleeve friction
σ_{v0}	=	total overburden stress
σ_{v0}'	=	effective overburden stress

The premise of I_c, which was originally proposed by Jefferies and Davies (1993), is that soil behaviour type is a function of the radius of a concentric circle about a common point for a stress-normalized soil behaviour type chart. Jefferies and Davies (1993) provide a detailed explanation of the theoretical development of I_c.

Robertson and Fear (1995) proposed that the soil behaviour type index and the relationship between Rf and fines content proposed by Suzuki et al. (1995) could be used to directly estimate fines content from I_c according to the following relationship:

[3.11] Fines Content, FC (%) = $1.375\ I_c^3 - 3.5$

The above expression to determine fines content can be coupled with the corrections recommended in [3.9] to determine corrections to q_{c1} for fines content. Subsequently, this correction can be applied to q_{c1} to determine the equivalent normalized penetration resistance for clean sand, $(q_{c1})_{ecs}$, from which the CRR of the soil profile can be determined according to Figure 3.12. The CRR for the soil profile can then be compared to the cyclic stress ratio (CSR), which is computed similarly to the Seed method (Seed et al., 1985) to determine the cyclic liquefaction susceptibility of the soil.

Given that the methodology proposed by Robertson and Fear (1995) for estimating cyclic liquefaction susceptibility incorporates the relationship shown in Figure 3.13, it should be used with caution. As was previously stated there is a fair degree of scatter associated with Figure 3.13, and there is a danger of confusing loose sands with denser sands containing fines. In the absence of fines content determination from soil sampling at specific sites, the methodology proposed by Robertson and Fear (1995) should be treated as a preliminary assessment of cyclic liquefaction potential.

4.0 SITE DESCRIPTIONS AND TESTING PROGRAMS

4.1 INCO COPPER CLIFF TAILINGS AREA

4.1.1 SITE DESCRIPTION

INCO's Central Tailings Area is located near the town of Copper Cliff, Ontario, just west of the city of Sudbury. The Central Tailings Area consists of five inactive impoundments (designated as A, CD, M, P and Q) where tailings deposition occurred from 1937-1988, and the adjacent R area where tailings are actively being deposited. A schematic of INCO's Central Tailings Area is shown in Figure 4.1. In addition a smaller inactive tailings impoundment exists in the Upper Pond area to the north of the smelter complex.

Tailings dam construction at the Central Tailings Area has been and continues to be carried out using the upstream construction method. Martin and Tissington (1996) provide a detailed summary of the evolution of tailings dam design at the Central Tailings Area. The tailings occupy an area in excess of 20 km^2 and the depth of the tailings ranges from less than 1 m, where they lie directly on a bedrock ridge, to greater than 45 m overlying the Pleistocene sediment cover in the centre of the main tailings area (Coggans, 1991).

4.1.2 TAILINGS MINERALOGY

Tailings in INCO's Central Tailings Area were produced from processing of ore extracted from the Sudbury sublayer. The ore mineralogy of the sublayer is generally well understood but many minor phases are present (Hawley, 1962). The majority of the Sudbury ore consists of varying proportions of pyrrhotite, pentlandite and chalcopyrite. Other sulphide minerals of local importance include pyrite, cubanite and millerite (Pattison, 1979).

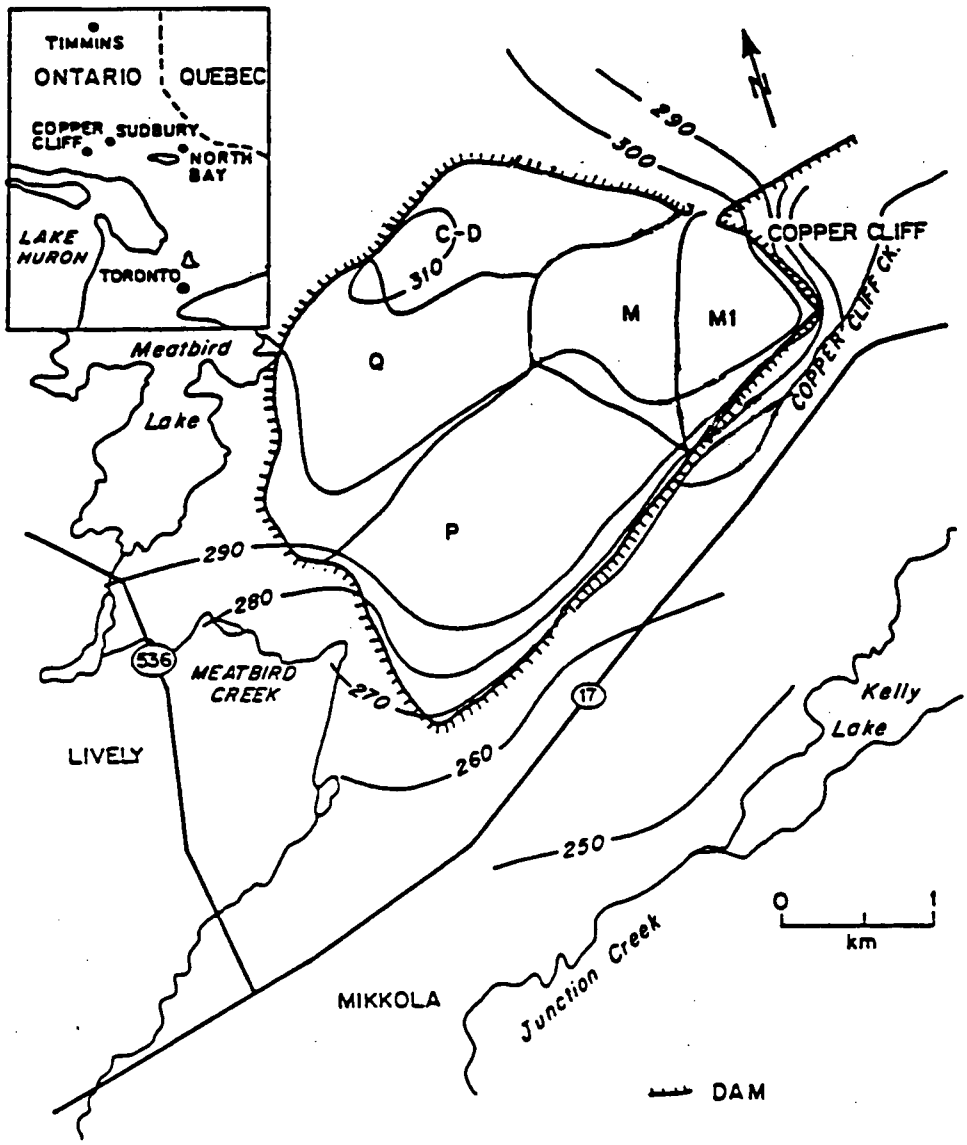


Figure 4.1: Schematic of INCO Copper Cliff Central Tailings Area (After Coggans, 1991)

It is difficult to give absolute values for the mineralogical constituents of the tailings due to variations in the host rocks, ore grades and extraction practices over time. However, an approximate estimate of tailings mineralogy is as follows (Peters, 1984):

Feldspar	50%	Magnetite	0.6%
Amphiboles	20%	Pentlandite	0.5%
Quartz	10%	Chalcopyrite	0.3%
Pyroxenes	7%	Biotite	7%
Pyrrhotite	5.6%		

From the above list it is apparent that pyrrhotite is the principle contributor to the overall sulphide content of the tailings. Oxidation of sulphide minerals and subsequent development of ARD is well-documented for the various impoundments contained in the INCO Central Tailings Area. W.D. Robertson et al. (1991), Coggans. (1991) and De Vos (1992) each give details concerning contamination of tailings pore water due to ARD processes.

4.1.3 TEST PROGRAM

A geoenvironmental field investigation was carried out by the UBC ISTG at INCO's Copper Cliff Central Tailings Area in October of 1993. In addition to acting as a test site for the purposes of this thesis, the site investigation program formed the basis of a demonstration project carried out for INCO and the Federal government MEND (Mine Environment Neutral Drainage) initiative for the purpose of evaluating the applicability of the RCPTU for the geoenvironmental characterization of sulphide bearing tailings. The findings of this demonstration project are included in Campanella et al., (1994).

A summary of the testing program is given in Table 4.1. All test work was carried out using the UBC In-Situ Research Vehicle, which was shipped by railway to Sudbury, Ontario and subsequently driven to the mine site. The field testing program was carried out over a span of approximately 2 weeks, and included 6 CPTU and 26 RCPTU tests at 11 different tailings impoundments within the Central Tailings Area.

TABLE 4.1: Summary: 1993 Field Investigation Program at INCO Central Tailings Area

Location of Sounding	File Name	Test Date (mon/day)	Test Performed	Sounding Depth (m)	Specific Comments
M-Area	I03-9301	10-1-93	RCPTU	9.62	BAT water samples were recovered at 5.60 and 6.00 m.
	I02-9304	10-3-93	RCPTU	42.30	
A-Area	I06-9302	10-2-93	RCPTU	18.30	
	I06-9303	10-2-93	RCPTU	18.20	
	I06-9321	10-10-93	RCPTU	19.12	BAT water samples were recovered at 4.0, 5.0, 6.0, 7.0, and 8.0 m.
C-D Area	I04-9305	10-3-93	CPTU	7.72	
Pistol Area - Pistol Dam	I11-9308	10-4-93	CPTU	13.78	Sounding was at crest of dam.
	I11-9309	10-5-93	RCPTU	40.20	Sounding was at crest of dam.
	I18-9322	10-11-93	RCPTU	36.40	Sounding was at first bench of dam (Sta. 386 on existing I.P. line)
	I19-9323	10-11-93	RCPTU	6.52	Sounding was at base of dam (4m equidistant from Waterloo piezometer nests IN82, IN21, and IN23).
	I20-9324	10-11-93	RCPTU	5.20	Sounding was at base of dam (10m North of Waterloo piezometer nest IN23).
	I21-9325	10-11-93	RCPTU	4.95	Sounding was at base of dam (adjacent to Waterloo piezometer nest IN23).
	I22-9326	10-12-93	RCPTU	3.88	Sounding was on service road at the base of dam (adjacent to Waterloo piezometer nest IN32).
	I23-9327	10-12-93	RCPTU	14.48	Sounding was on service road at base of dam (adjacent to Waterloo piezometer nest IN22).
	I24-9328	10-12-93	RCPTU	3.42	Sounding was on service road at base of dam (adjacent to Waterloo piezometer nest IN27).
	I11-9330	10-13-93	RCPTU	43.28	Sounding was at crest of dam
	I25-9331	10-14-93	RCPTU	3.85	Sounding was on service road at base of dam (adjacent to Waterloo piezometer nest IN33).
	I26-9332	10-14-93	RCPTU	10.08	Sounding was on service road at base of dam (adjacent to Waterloo piezometer nest IN34).
Whissel Dam	I12-9306	10-4-93	RCPTU	15.05	
	I12-9307	10-4-93	CPTU	28.43	
Cecchetto Dam	I10-9313	10-6-93	RCPTU	18.38	
	I10-9314	10-6-93	RCPTU	22.50	
Q-Area	I13-9310	10-5-93	RCPTU	7.75	
	I17-9311	10-6-93	RCPTU	13.70	
	I14-9312	10-6-93	RCPTU	8.48	
R3 - Dam 15	I09-9315	10-7-93	CPTU	10.58	
	I09-9316	10-7-93	CPTU	10.40	
R2 - Dam 14	I08-9317	10-7-93	RCPTU	2.08	Sounding was stopped due to extremely dense material.
	I08-9318	10-7-93	CPTU	8.45	
Upper Pond	I15-9319	10-8-93	RCPTU	19.68	
	I16-9320	10-9-93	RCPTU	19.25	BAT water samples were recovered at 4.0, 5.0, and 6.0 m.
Pyrrhotite Dam	I01-9329	10-13-93	RCPTU	41.62	

The locations of all tests were designated by INCO personnel, with the exception of test work at the base of Pistol Dam. In this area testing was carried out in close proximity to existing

University of Waterloo piezometer nests to optimize geochemical data. deVos (1992) gives details concerning University of Waterloo piezometer installations. All tests were carried out in sulphide-bearing tailings, with the exception of the test work in the native soils at the base of Pistol Dam.

4.2 FALCONBRIDGE FAULT LAKE TAILINGS IMPOUNDMENT

4.2.1 SITE DESCRIPTION

The Fault Lake tailings impoundment is located near the town of Falconbridge, Ontario, and approximately 0.5 km east of the Sudbury Airport. A schematic of the Fault Lake tailings impoundment is shown in Figure 4.2. The creation of the Fault Lake tailings impoundment consisted of filling in several glacial kettle lakes, between 1965 and 1978, whose remnant deposits form the basal layers for the tailings. The tailings are contained by dams to the northeast and southwest of the site. The tailings encompass an area of approximately 22 hectares, and the tailings have a maximum depth of approximately 30 m (St. Arnaud et al., 1994).

4.2.2 TAILINGS MINERALOGY

Similarly to the tailings at INCO, the Fault Lake tailings were produced from the milling of ores extracted from the Sudbury sublayer. The complete details of the mineralogical make-up of the Fault Lake Tailings site are not documented, but it is estimated that the tailings contain as much as 50 % pyrrhotite (St. Arnaud et al., 1994), which is approximately ten times the pyrrhotite content of the INCO Central Tailings Area. The very high pyrrhotite content of the tailings indicates the tailings are highly susceptible to ARD processes, and this was confirmed by previous site investigations at the site (St. Arnaud et al., 1994).

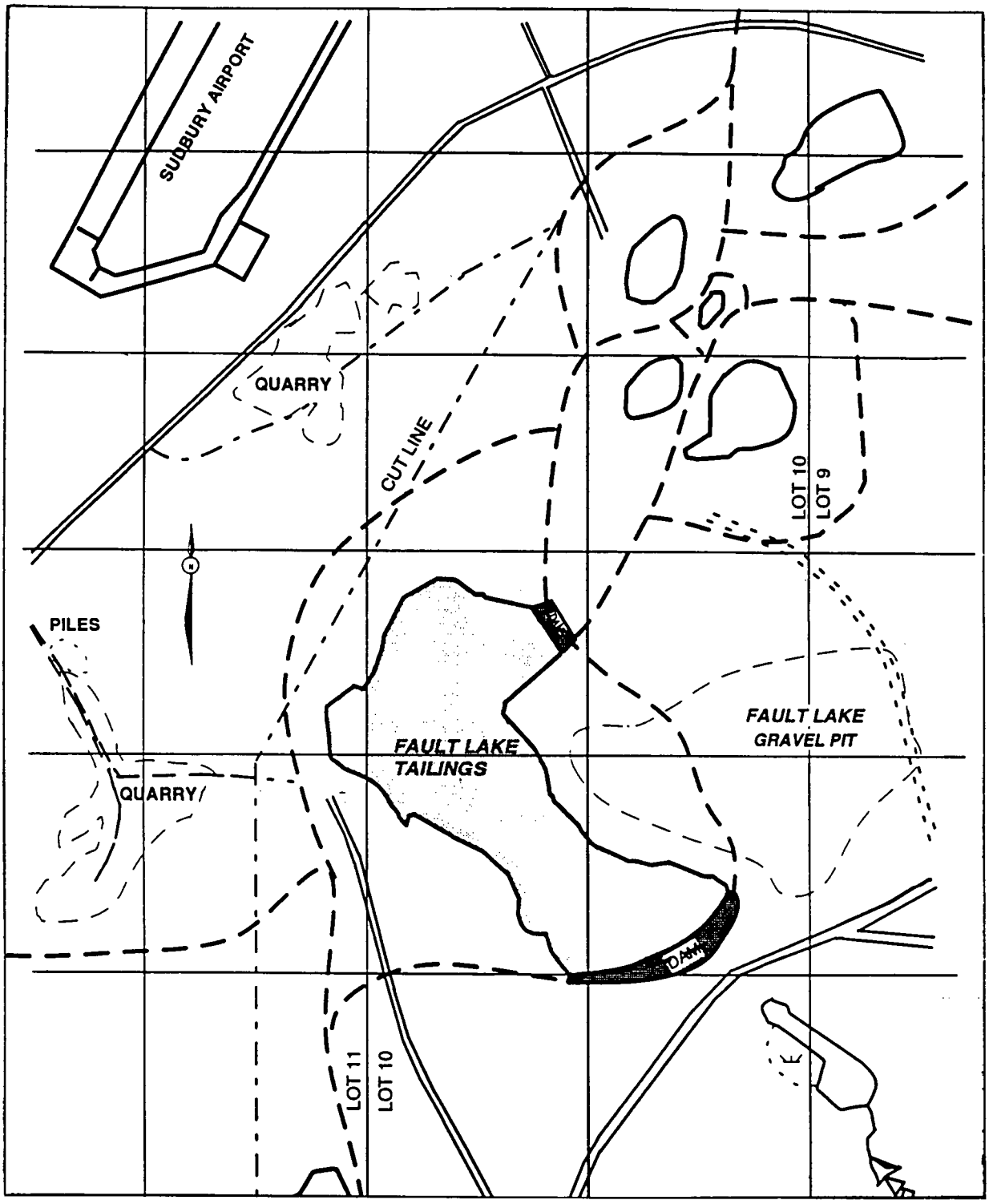


Figure 4.2: Schematic of Falconbridge Fault Lake Tailings Impoundment (After St. Arnaud et al., 1994)

4.2.3 TEST PROGRAM

Two RCPTU soundings were carried out near the centre of the impoundment at Falconbridge's Fault Lake Tailings site in October, 1993. The UBC In-Situ Research Vehicle was used for the test work, and was driven to the test site as it was in close proximity to the INCO Copper Cliff site (<30 km). In addition to acting as a research site for this thesis, Falconbridge personnel were interested in locating the phreatic surface in the tailings. The locations of the tests were designated by Falconbridge personnel. Details concerning the two tests are presented in Table 4.2.

TABLE 4.2: Summary: 1993 Field Investigation Program at Falconbridge Fault Lake Tailings Impoundment

Location of Sounding	File Name	Test Date (mon./day)	Test Performed	Sounding Depth (m)	Specific Comments
Fault Lake	F01-9333	10-14-93	RCPTU	41.10	Falconbridge Piezometers FS-15A and FS-15B installed adjacent to RCPTU location to depths of 35m and 24 m, respectively
	F02-9334	10-14-93	RCPTU	22.70	

4.3 GIBRALTAR MINES TAILINGS IMPOUNDMENT

4.3.1 SITE DESCRIPTION

The Gibraltar Mines tailings impoundment is located approximately 160 km south of Prince George, British Columbia, near McLeese Lake. A schematic of the Gibraltar Mines tailings impoundment is shown in Figure 4.3. The tailings impoundment is currently active and has been in operation since 1977. The impoundment area is a natural valley with a small saddle

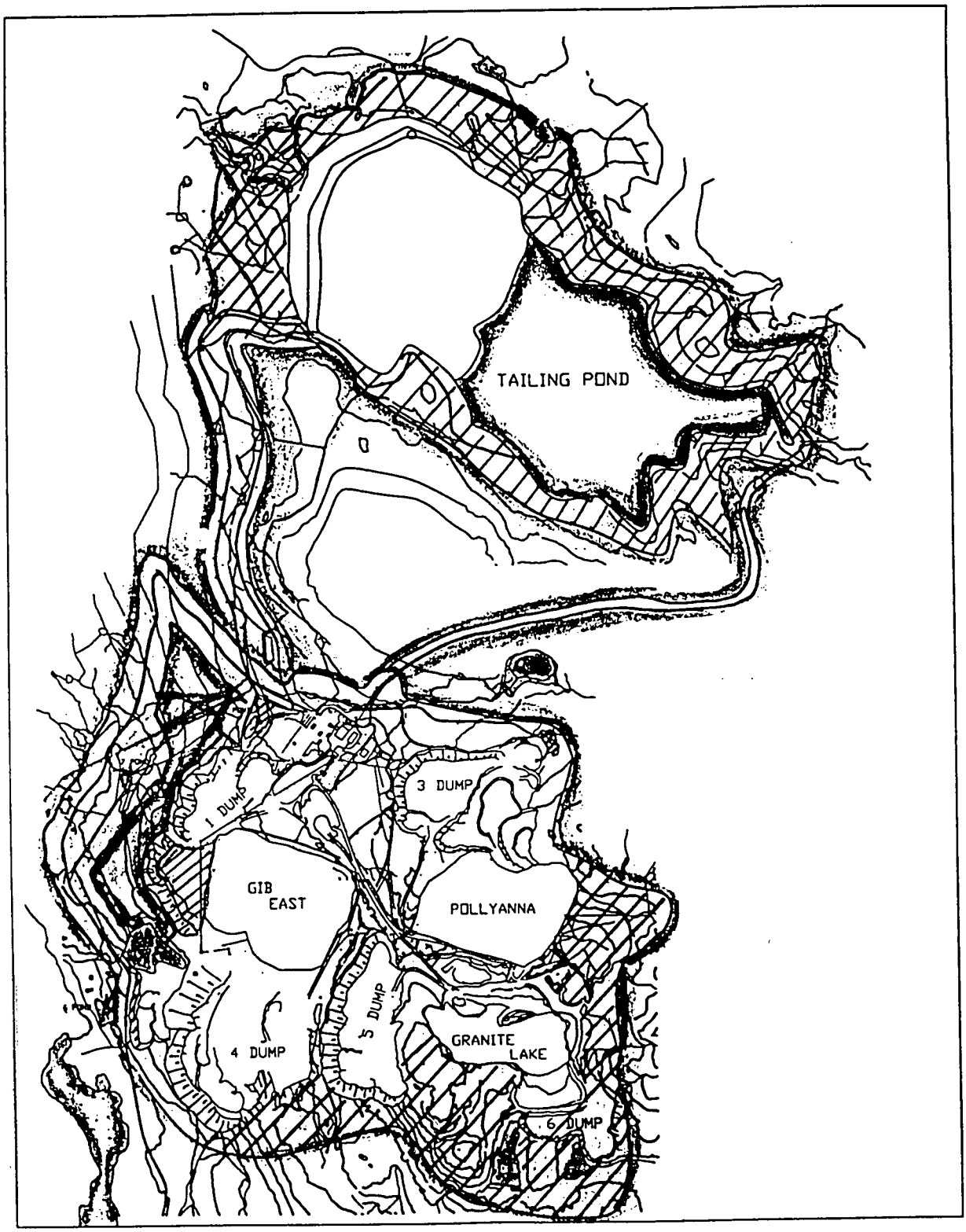


Figure 4.3: Schematic of Gibraltar Mines Tailings Impoundment (After Gibraltar Mines Ltd.)

dam located at the east end and a tailings dam under construction at the west end. Cycloning of the tailings produces a sand used in the centreline method of dam construction.

4.3.2 TAILINGS MINERALOGY

The Gibraltar Mines tailings were produced from processing of ore obtained from the quartz diorite of the Granite Mountain pluton (Gibraltar Mines Ltd., 1992). This rock is composed of quartz (25-30%), a mixture of albite-epidote-zoisite-muscovite (50-55%), chlorite (20%) and biotite (1%). The sulphide content of the tailings is estimated to be less than 1% pyrite, based on acid-based accounting tests of tailings samples (Gibraltar Mines Ltd., 1992). The sulphide mineral content is significantly less than that found in the tailings at the INCO and Falconbridge sites. This would indicate that ARD development in the Gibraltar tailings would be of a lesser extent than that experienced at the other sites.

4.3.3 TEST PROGRAM

A geoenvironmental field investigation program was carried out by the UBC ISTG at the Gibraltar Mines tailings impoundment in late summer 1994. The UBC In-Situ Research Vehicle, which was transported to the site by truck, was used for all test work. The location of all tests were designated by Gibraltar Mines Ltd. personnel. A summary of the field investigation program is presented in Table 4.3.

The purpose of the field work was to further evaluate the RCPTU for geoenvironmental assessment of sulphide bearing tailings, and more specifically to increase the database of bulk resistivity measurements and accompanying pore water chemistry for sites affected by ARD contamination. It was hoped that further data would permit more detailed comparisons

between the different sites, and provide better insight into the applicability of the RCPTU for evaluating ARD processes.

Table 4.3: Summary 1994 Field Investigation Program at Gibraltar Mines Tailings Impoundment

Location of Sounding	File Name	Test Date (mon/day)	Test Performed	Sounding Depth (m)	Specific Comments
Tailings	GB-T9403	8-30-94	RCPTU	10.20	
	GB-T9404	8-30-94	RCPTU	3.28	
	GB-T9405	8-31-94	RCPTU	3.92	
	GB-T9406	8-31-94	RCPTU	6.15	
	GB-T9407	8-31-94	RCPTU	12.02	
	GB-T9409	9-1-94	RCPTU	30.68	
	GB-T9410	9-3-94	RCPTU	12.65	
	GB-T9411	9-3-94	RCPTU	18.33	2 Bat samples at both 16.5 m and 17.1 m

5.0 DISCUSSION OF TEST RESULTS

The intention of Section 5.1 is to demonstrate the interpretation of RCPTU data for the range of materials encountered in the field investigation programs. Also, the RCPTU soundings presented in Section 5.1 will be discussed in greater detail with respect to characterization of tailings pore water chemistry, hydrogeological properties and geotechnical parameters in later sections of this chapter. Graphical and tabular data for all RCPTU soundings discussed in Chapter 5 are included in the appropriate appendices following the text of this thesis.

5.1 TYPICAL RCPTU TEST RESULTS

5.1.1 PISTOL TAILINGS IMPOUNDMENT (INCO)

A graphical representation, known as a coneplot, for an RCPTU sounding (I11-9330) carried out at the crest of Pistol Dam located in the INCO Central Tailings Area is shown in Figure 5.1. Briefly reviewing the stratigraphy, there is a very dense oxidized layer evident from the surface to a depth of approximately 3 m. Below this depth, a fine sandy tailings is present that shows a slight fining downward trend. Based upon the pore pressure and bulk resistivity response, the phreatic surface was determined to be located at 15 m. The pore pressure profile from 15 m to 37 m in the tailings shows interlayered positive and negative excess pore pressure response. This CPTU signature is consistent with beached tailings that periodically are allowed to establish a desiccated and oxidized layer during the period following deposition and prior to further dam construction. The sounding exited from the tailings at a depth of about 37 metres into a very stiff silty clay deposit. In this fine-grained native material, excess pore pressures of over 100 m of water pressure were measured during penetration, attesting to the stiff nature, low hydraulic conductivity and high stress levels present in this material.

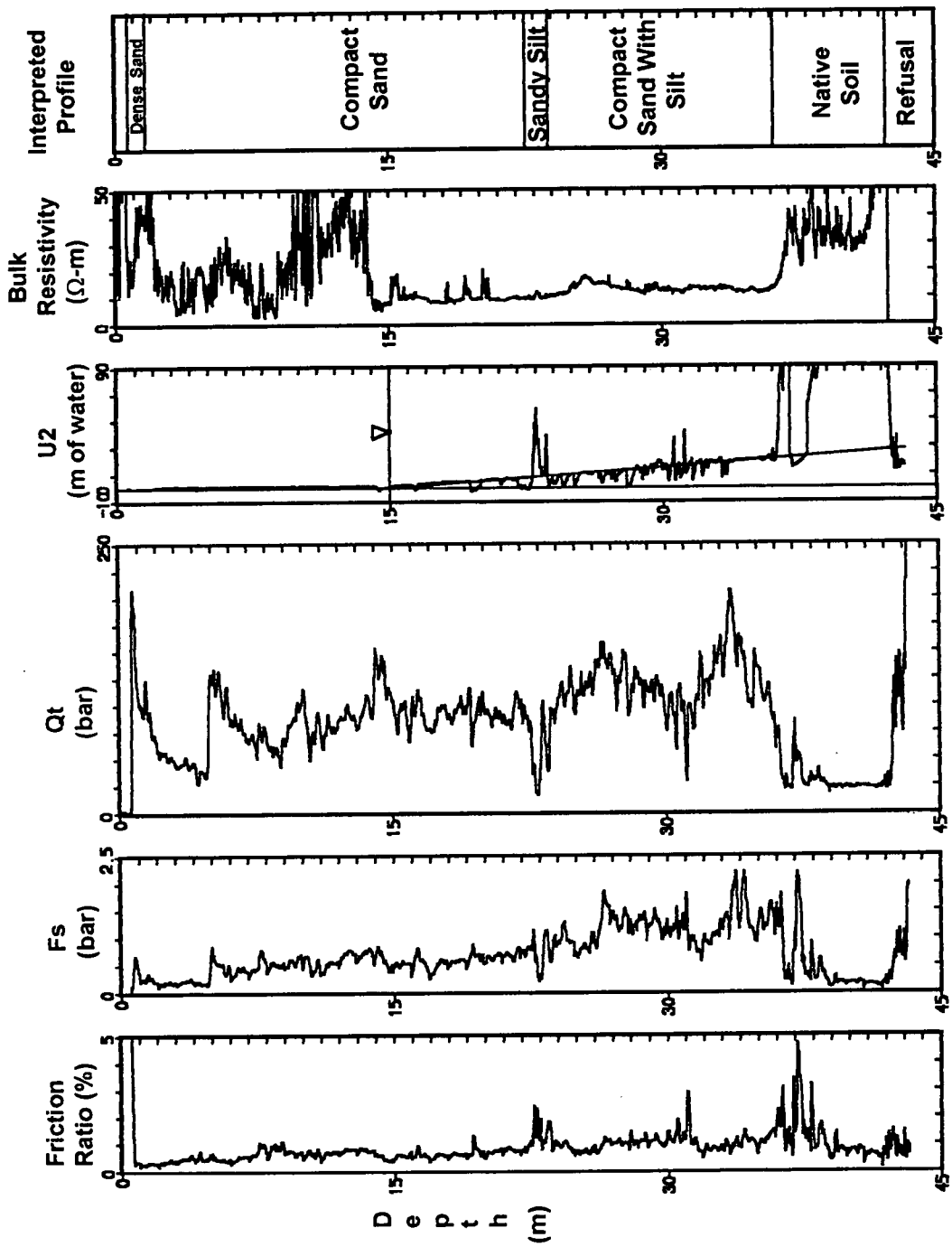


Figure 5.1: RCPTU Profile - Crest of Pistol Dam

It is interesting to note that some lower resistivity values (higher conductivity) do exist above the phreatic surface. The moisture retention capabilities of tailings are well-documented (Vick, 1983) and it is apparent that the unsaturated tailings in this area may have a high degree of saturation and that the pore water present has elevated levels of ionic constituents. Below the phreatic surface, the bulk resistivity values were quite constant at approximately 10 Ω-m, indicating that elevated levels of ionic loading are present in the pore water. The resistivity values in the native materials rose sharply to values of about 30 Ω-m which indicates a reduction in ionic loading of the pore water.

5.1.2 BASE OF PISTOL DAM (INCO)

Eight RCPTU soundings were carried out in native soils at the base of Pistol Dam and a typical RCPTU profile (I23-9327) is shown in Figure 5.2. A review of the coneplot indicates that the upper 1.3 m is a relatively firm silty clay soil, which is well demonstrated by the peak in friction ratio values above 3% to 5% and the negative response of the pore pressure. This upper layer is underlain by a fine silty sand to a depth of approximately 3.4 m, where the cone encountered a soft sensitive fine-grained soil to a depth of approximately 6 m. From 6 m to approximately 14.3 m is a compact sand with interbedded silt layers, below which is a large boulder or bedrock. The phreatic surface was estimated to be at the ground surface based on pore pressure dissipation data and bulk resistivity response.

The bulk resistivity measurements exhibited interesting variability in this sounding. The bulk resistivities generally ranged from 10 -20 Ω-m in the upper 3 m, increased to greater than 50 Ω - m from 5 - 10 m and then decreased to approximately 20 Ω-m from 11m - refusal. The lower bulk resistivity measurements in the upper and lower depths of the sounding indicated elevated levels of ionic loading of the pore water, whereas the higher bulk resistivity measurements in the middle portion of the sounding indicate significantly lower levels of pore

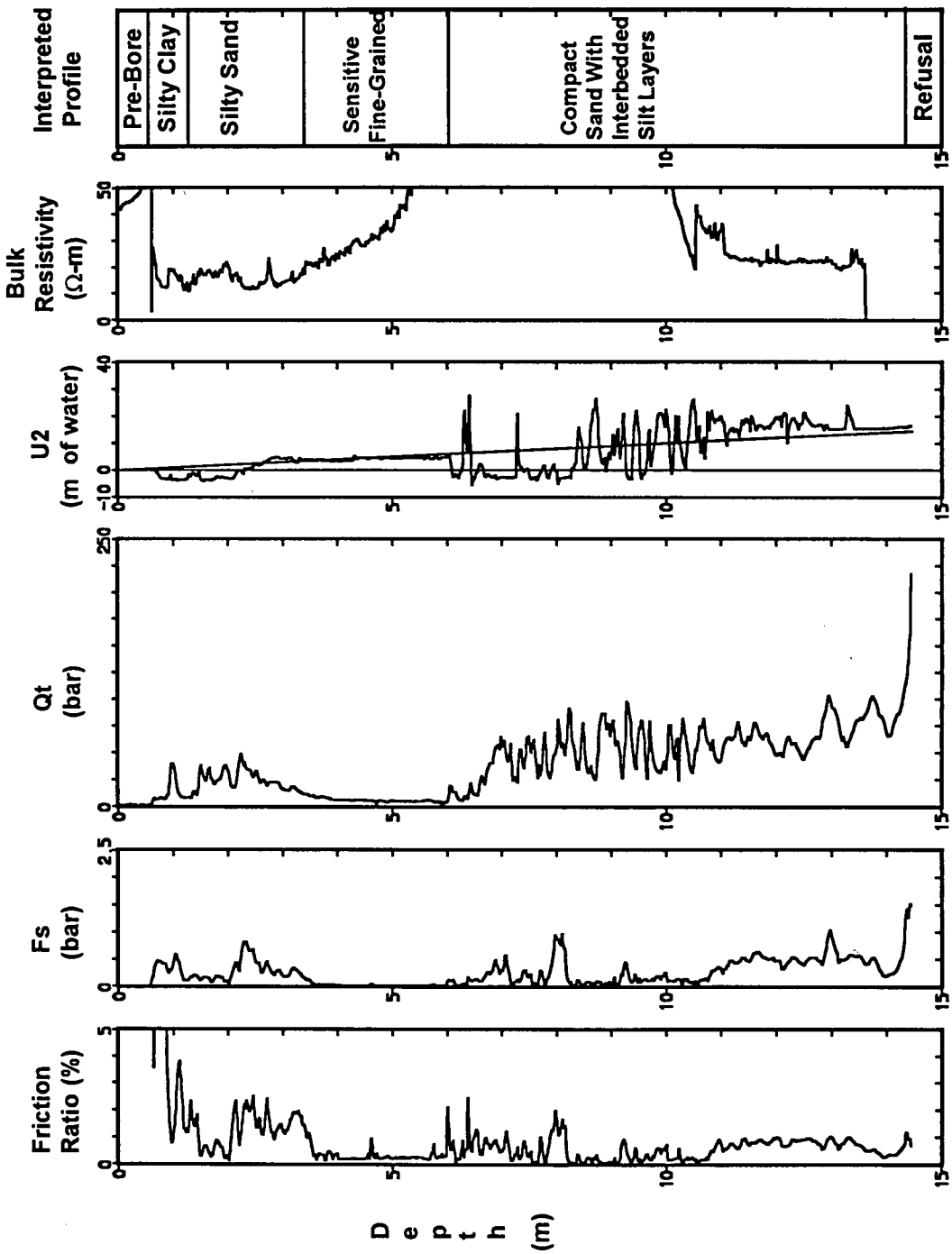


Figure 5.2: RCPTU Profile - Base of Pistol Dam

water ionic loading. The trends in bulk resistivity observed in this sounding are in agreement with the findings of de Vos (1992), who carried out chemical analyses of pore water samples from an adjacent University of Waterloo piezometer installation (IN22). Data from de Vos (1992) are included in Appendix D.

5.1.3 FAULT LAKE TAILINGS IMPOUNDMENT (FALCONBRIDGE)

A coneplot for an RCPTU sounding (F01-9333) carried out near the centre of the Fault Lake tailings impoundment is shown in Figure 5.3. The tailings to a depth of approximately 4.6 m consist of a compact silty sand, as indicated by the cone bearing and friction ratio. From 4.6 m to 28 m the tailings are interbedded layers of loose silty sand and clayey silt. The fine-grained nature of the tailings made it difficult to discern the boundary between the tailings and the underlying lacustrine native soil. The more uniform response of the cone channels below a depth of approximately 28 m is indicative of the relatively homogeneous native soil, rather than the highly layered tailings. The phreatic surface was estimated to be at a depth of approximately 10.5 m based upon the dynamic pore pressure response and this was confirmed from pore pressure dissipation data. There is no discernable decrease in the bulk resistivity at 10.5 m, which suggests a high degree of tension saturation and significant ionic loading of the pore water. The RCPTU met refusal at a depth of 41 m in what was considered to be a very dense gravely till material.

Similarly to the RCPTU bulk resistivity measurements at Pistol Dam, the Fault Lake tailings exhibited low bulk resistivity measurements above the phreatic surface, This indicates a high degree of saturation and significant ionic loading of the pore water. Very low bulk resistivity measurements of between 1 - 2 Ω-m were recorded in the upper 4 m, suggesting ionic loading of the pore water was most severe in the upper tailings. The bulk resistivity profile remained

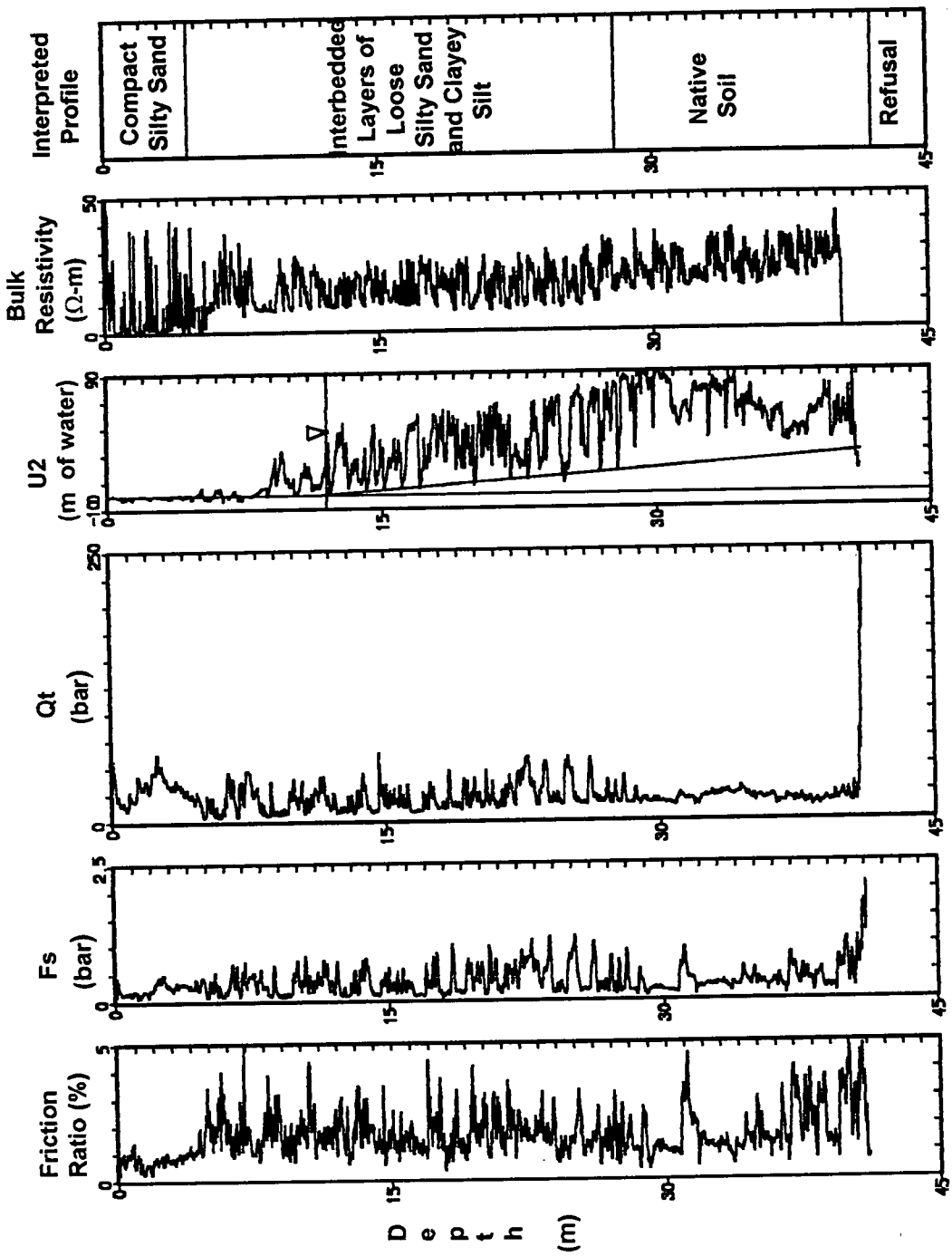


Figure 5.3: RCPTU Profile - Fault Lake Tailings Impoundment

relatively constant near 15 Ω-m in the saturated zone and showed an increasing trend in the native material.

5.1.4 GIBRALTAR TAILINGS IMPOUNDMENT (GIBRALTAR)

A coneplot for an RCPTU sounding (GB-T9411) carried out on the northern crest of the tailings impoundment is shown in Figure 5.4. The upper tailings consist of a dense sand to a depth of approximately 1.6 m. This upper crust is underlain by a compact sand to a depth of approximately 8.2 m. From 8.2 m to a depth of approximately 17.2 m the tailings ranged from a loose to compact sand. The phreatic surface was determined to be at a depth of 16.5 m, as evidenced by both pore pressure response and bulk resistivity measurements. The native soil, consisting of a clayey silt soil, is encountered at a depth of approximately 17.2 m, and the RCPTU met refusal at a depth of 18.3 m.

Bulk resistivity measurements in the unsaturated zone generally remained between 50 and 200 Ω-m. The much higher bulk resistivity measurements at this site in comparison with those observed at the crest of Pistol Dam at the INCO site and at the Falconbridge site, can be explained by lesser saturation of the tailings and/or lesser ionic loading of the tailings pore water. Given the lower sulphide mineral content of the Gibraltar tailings in comparison with the other sites, it is likely based upon this limited data that ARD processes are less developed. The lower values of bulk resistivity measured in the unsaturated zone (between 50 - 75 Ω-m) are likely due to higher levels of saturation of the tailings. Bulk resistivity measurements below the phreatic surface decreased to values of approximately 20 Ω-m, which indicates elevated levels of ionic loading of the pore water.

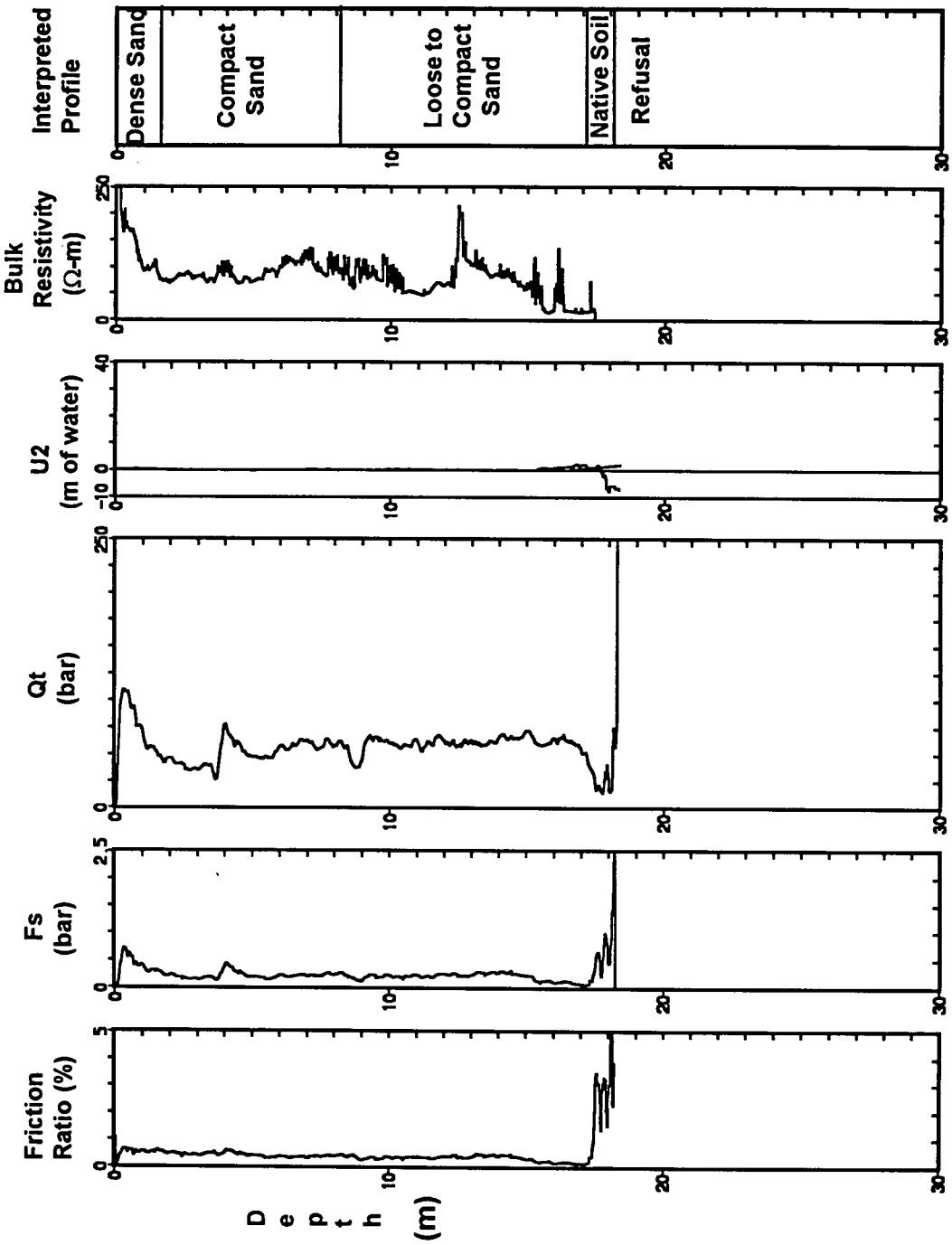


Figure 5.4: RCPTU Profile - Gibraltar Tailings Impoundment

5.2 REPEATABILITY OF RCPTU TEST RESULTS

One of the key concerns to the user of any characterization technology is the repeatability of the data produced. The repeatability of the CPTU is well-established (Gillespie, 1990). To demonstrate the full nature of the data repeatability, three soundings were carried out within a total distance of 5 metres in the A-Area of the INCO Central Tailings Area. Figure 5.5 shows the three soundings plotted with respect to their cone tip resistance, friction and pore pressure values. The repeatability of the CPTU data is excellent, and any differences can be attributed to stratigraphic variations in the tailings themselves.

As the purpose of this study was in part to demonstrate the ability of the RCPTU to delineate ARD contamination, it was essential to demonstrate the repeatability of the bulk resistivity measurements. Figure 5.6 shows comparisons between two sets of RCPTU soundings carried out in two different tailings impoundments at INCO. In each case, the RCPTU soundings were carried out within a distance of 5 metres. The repeatability of the RCPTU measurements is very good for both comparisons, particularly for measurements below the phreatic surface. Bulk resistivity measurements above the phreatic surface show similar trends, and differences can largely be attributed to the effects of variable saturated conditions.

5.3 CHARACTERIZATION OF PORE WATER CHEMISTRY

One of the main purposes of this thesis was to evaluate the ability of the RCPTU to assess the pore water chemistry of sulphide bearing tailings and adjacent native soils affected by ARD contamination. To evaluate relationships between bulk resistivity measurements and pore water chemistry in a straightforward manner, reference to Table 2.3 in Section 2.2.1.2 was used as the basis for evaluating ARD processes. From Table 2.3, increasing oxidation of sulphide minerals results in a corresponding increase in ionic loading of the tailings pore water. This

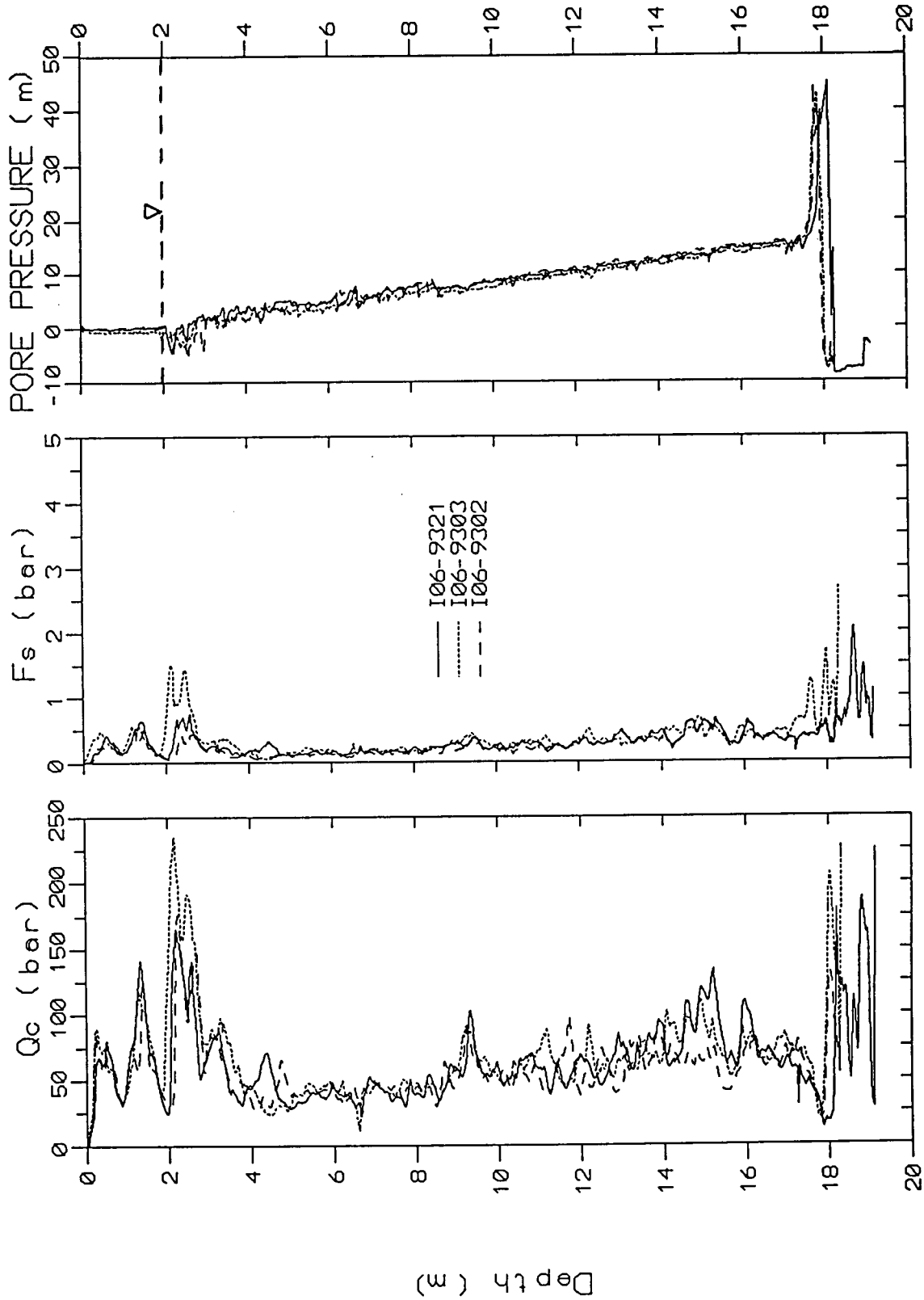


Figure 5.5: Repeatability of CPTU Measurements

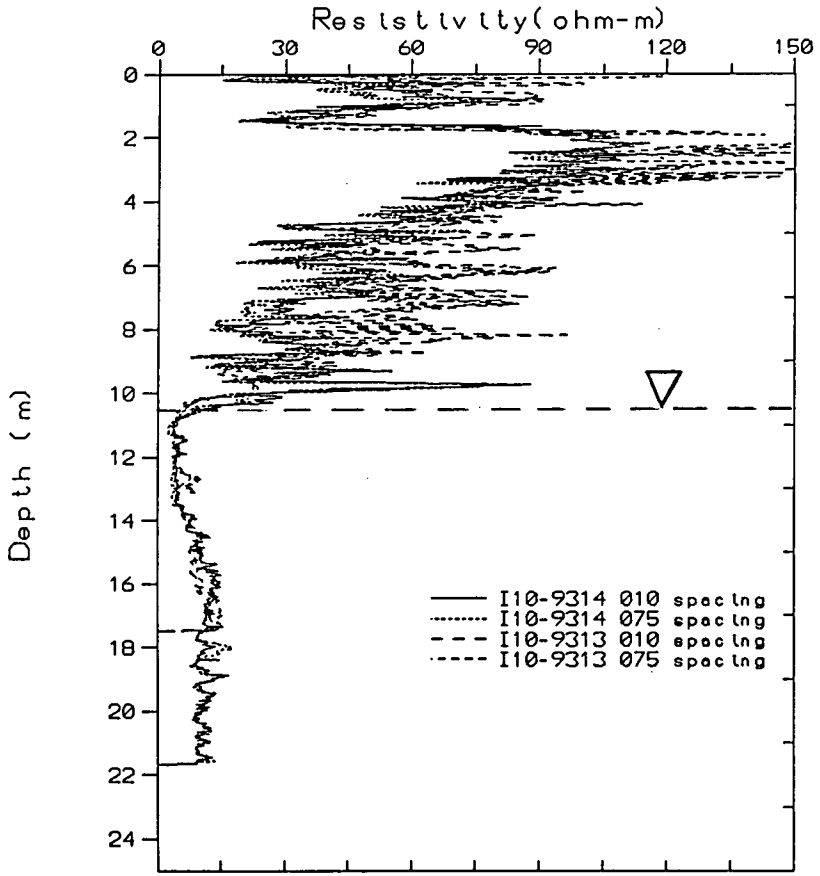


Figure 5.6a: Comparison of RCPTU Bulk Resistivity Measurements at Cecchetto Dam (INCO)

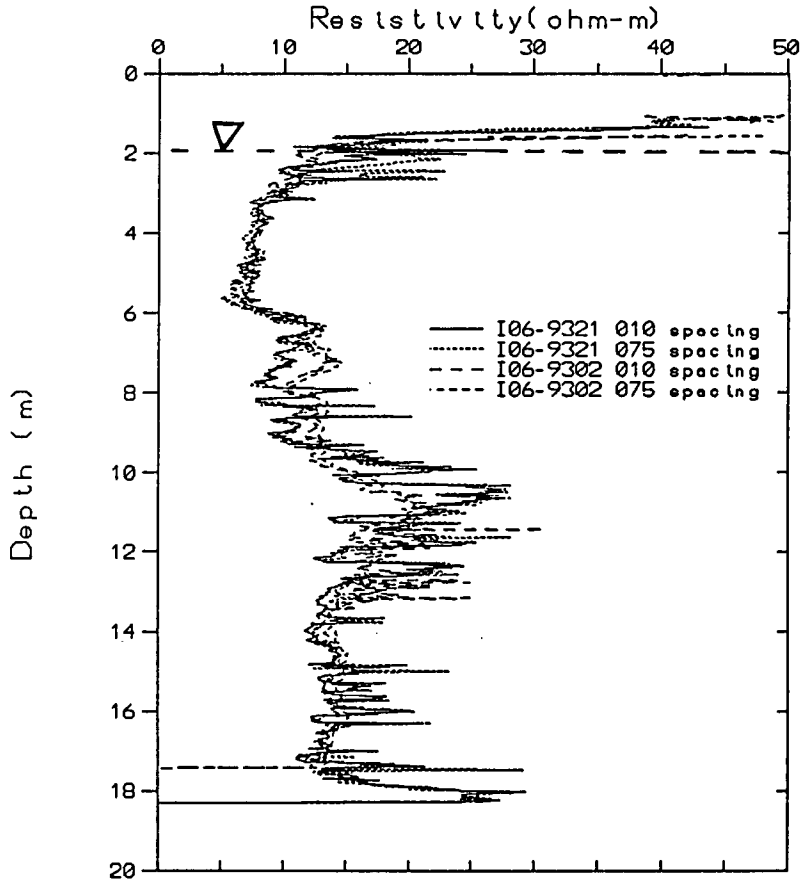


Figure 5.6b: Comparison of RCPTU Bulk Resistivity Measurements at A-Area (INCO)

increased ionic loading takes the form of increased sulphate levels, increased hydrogen ion concentration (resulting in a decrease in pH) and increased heavy metals concentrations. Correspondingly, increased ionic loading results in decreased pore water resistivity (or increased electrical conductivity) and subsequently decreased bulk resistivity measurements below background values.

It should be noted that all data collected for the respective sites represent relatively small samples of site conditions, and all discussions contained herein with respect to ARD processes and contamination are restricted to the specific locations where test work was carried out. Appendix D provides a summary of locations at which both RCPTU testing and chemical analyses of pore water samples were carried out. The large size of the sulphide bearing tailings impoundments at which test work were carried out precludes any overall assessments with respect to ARD development and contamination. Interpretations of test results with respect to ARD contamination in the native soils at the base of INCO's Pistol Dam may be more definitive due to the relatively small size of the site.

5.3.1 PORE WATER SAMPLING PRACTICES AND CHEMICAL ANALYSES

Pore water sampling and subsequent chemical analyses were carried out at all test sites to facilitate the interpretation of RCPTU bulk resistivity measurements. At INCO, pore water chemistry data were collected from three different sources: BAT pore water samples, pore water extractions from tailings samples and pore water samples from existing University of Waterloo piezometer nests. The BAT pore water sampling was carried out by the UBC ISTG and the pore water extractions from tailings samples were done by INCO using a modification of the immiscible displacement technique developed by Patterson et al. (1978). INCO conducted all chemical analyses for both the BAT samples and samples extracted from tailings solids, with the exception of the pH and conductivity of BAT samples which were carried out

in the field by the UBC ISTG using portable meters. Metals were analyzed by means of an Inductively Coupled Plasma - Atomic Emission Spectrophotometer (ICP-AES) and sulphate concentrations were determined through use of a High Performance Liquid Chromotograph (HPLC). The University of Waterloo carried out all sampling and chemical analyses for pore water samples collected from the University of Waterloo piezometer nests. de Vos (1992) provides details concerning piezometer specifications, sampling protocol and chemical analyses.

Pore water analyses and sampling at the Fault Lake tailings site were conducted by the Noranda Technology Centre under the direction of Falconbridge Ltd. Two piezometers, FS15A and FS15B, were installed immediately adjacent to RCPTU sounding F01-9333 to depths of 35 m and 24 m, respectively. The piezometers consist of a 1.9 cm ID, schedule 80 PVC pipe with a 0.30 m PVC screened tip. Continuous tailings samples were recovered from borehole FS15A with a 1.5 m split spoon sampler. Subsequently, pore water samples were collected by squeezing tailings using a pneumatic squeezing device (Noranda Technology Centre, 1994). Chemical analyses were carried out on the pore water samples extracted from tailings solids using an ICP - AES. In addition, pH and conductivity measurements were recorded for each pore water sample.

Limited pore water sampling, comprised of four BAT samples, was conducted at the Gibraltar Mines tailings impoundment. The BAT pore water samples were collected by the UBC ISTG, and conductivity measurements were recorded for each sample in the field using a portable meter (Omega model CDH-30). Gibraltar Mines Ltd. determined sulphate concentrations for each sample by HPLC.

Appendix D contains a summary of pore water chemistry data from all test sites.

5.3.2 RCPTU BULK RESISTIVITY MEASUREMENTS IN UNSATURATED SULPHIDE BEARING TAILINGS (INCO AND FALCONBRIDGE TAILINGS)

Bulk resistivity measurements above the phreatic surface were generally much higher and showed more variability than bulk resistivity measurements in fully-saturated conditions. This is readily apparent by examination of the bulk resistivity profiles shown in Figure 5.6.

The relatively uniform nature of many tailings deposits facilitates the interpretation of the factors affecting bulk resistivity response in tailings. Section 3.1.1 reviewed the various factors which can affect bulk resistivity response in soils. In a uniform tailings deposit the porosity, temperature, shape of pore size and cation exchange capacity of matrix materials are likely similar and their influence on changes in bulk resistivity response may be considered negligible. Therefore, the remaining two factors: (1) degree of saturation and (2) ionic composition of the pore water predominately control changes in bulk resistivity response. The moisture retention capabilities of tailings can result in variable saturated conditions above the phreatic surface and subsequent variability in bulk resistivity response. Variabilities in saturation make it difficult to discern the influence of the ionic composition of the pore water on bulk resistivity response.

There were two RCPTU soundings which exhibited very low bulk resistivity measurements above the phreatic surface. Coneplots of the RCPTU data for the soundings at INCO's Pistol Dam (Figure 5.1) and Falconbridge's Fault Lake Tailings impoundment (Figure 5.3) were provided in Section 5.1 and general interpretations were given for each test. Figure 5.7a and Figure 5.7b present bulk resistivity profiles for the unsaturated portion of each sounding and the location of the phreatic surface is noted for the respective soundings. Also shown on each figure are pore water sulphate concentrations which were derived from pore water sampling at the depths shown and subsequent chemical analyses. The purpose of the pore water

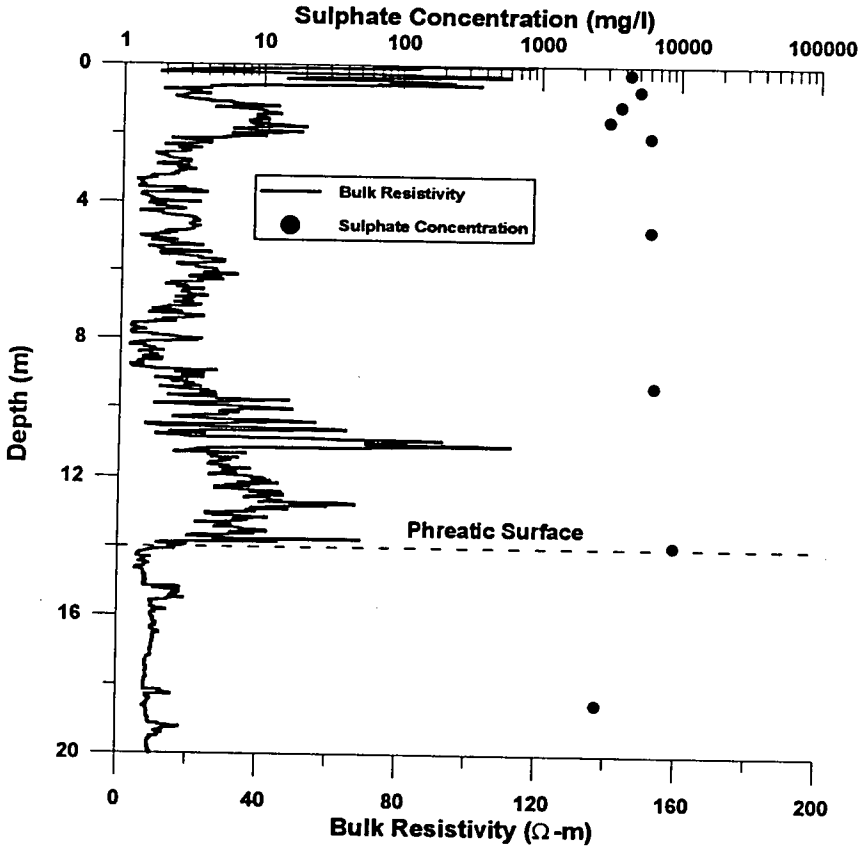


Figure 5.7a: RCPT Bulk Resistivity Measurements in Unsaturated Tailings at the Crest of Pistol Dam

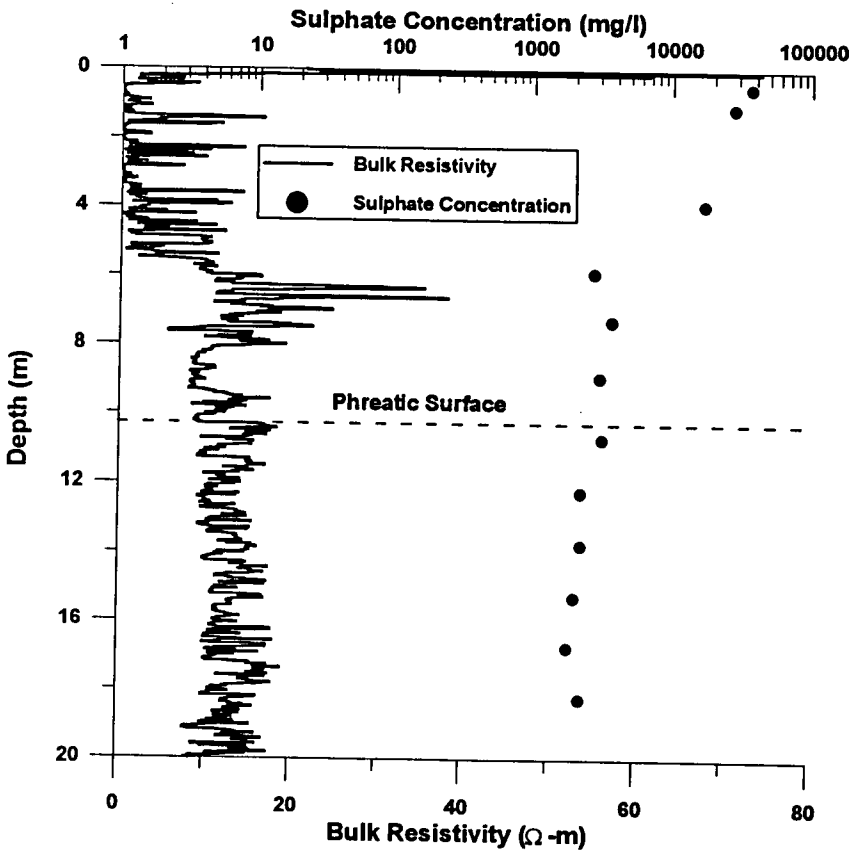


Figure 5.7b: RCPT Bulk Resistivity Measurements Unsaturated Tailings at the Fault Lake Tailings Impoundment

sampling was to evaluate the influence of pore water ionic composition on the low bulk resistivity measurements above the phreatic surface observed for each sounding. The elevated sulphate concentrations above the phreatic surface for the two soundings confirmed that the low bulk resistivity measurements in the unsaturated tailings are not only a function of variable saturated conditions, but are also affected by significant ionic loading of the pore water. The elevated sulphate concentrations are consistent with pore water affected by ARD processes, as discussed in Section 2.2.1.

The elevated sulphate concentrations for the sounding at Pistol Dam are relatively uniform and vary from approximately 2000 - 5000 mg/L, indicating significant ionic loading of the tailings pore water. Based upon the relative uniformity of the pore water sulphate concentrations, the variability noted in the bulk resistivity measurements is likely more a function of variable saturated conditions. The spikes in the bulk resistivity measurements (such as near the surface and at a depth of approximately 11.5 m where bulk resistivity measurements exceeded 100 Ω-m) are indicative of poorly saturated conditions. The lower boundary of bulk resistivity measurements (values of approximately 10 Ω-m) are indicative of nearly-saturated tailings where the influence of the conductive pore water is readily apparent.

Sulphate concentrations of the tailings pore water in the unsaturated zone for the sounding at the Fault Lake tailings impoundment were more variable than those observed at INCO's Pistol Dam. Sulphate concentrations were very high in the upper 4 m (values > 10 000 mg/L) and were lower and more uniform below this depth (values of approximately 2000 mg/L). The much higher sulphate concentrations measured in the near surface tailings pore water at the Falconbridge site in comparison with those measured at INCO's Pistol Dam, suggests that sulphide oxidation processes are more severe in the upper 4 m of the unsaturated tailings at the Falconbridge site. This can largely be explained by the much higher sulphide mineral content contained in the Falconbridge tailings. Bulk resistivity measurements in the upper 4

m at the Falconbridge site varied from approximately 1 Ω-m - 20 Ω-m. The very low bulk resistivity measurements are reflective of very high ionic loading of the tailings pore water, whereas the upper boundary of these measurements indicate lesser saturation of the tailings. From a depth of approximately 4 m to the phreatic surface depth at 11.5 m the bulk resistivity measurements were generally higher than those found in the upper 4 m, which corresponds with the reduction in tailings pore water sulphate concentration. The higher spikes of bulk resistivity measurements recorded between approximately 6 m and 8 m are most likely due to a lower degree of tailings saturation.

More detailed pore water chemistry data were available from pore water sampling carried out adjacent to the RCPTU sounding (F01-9333) at the Fault Lake tailings impoundment. Figures 5.8a - 5.8d present pore water pH, iron (Fe) concentrations, magnesium (Mg) concentrations and nickel (Ni) concentrations respectively for the upper 20 m of tailings. The increased acidity (pH less than 4) and elevated heavy metals concentrations in the upper 4 m of tailings are consistent with Stage 3 ARD processes, as discussed in Section 2.2.1. The extremely high sulphate concentrations, shown in Figure 5.6, also support this finding. Below the depth of 4 m, the pH is relatively neutral due to alkalinity in the tailings which acts as a buffering agent. The heavy metals concentrations of the tailings pore water below 4 m depth are significantly lower, with the exception of Mg which showed a smaller decrease. The pore water chemistry below the depth of 4 m indicates that ARD processes are less severe than that experienced in the upper 4 m of tailings, and are consistent with Stage 2 ARD processes.

The evolution of ARD development at the Fault Lake tailings impoundment can be explained in terms of the one-dimensional model presented in Section 2.2.1.2. The upper 10.5 m of the tailings are not fully-saturated (denoted as Z1 in Figure 2.2). The zone of oxidation (Z3) comprises the upper 4 m of the tailings and the zone of neutralization (Z4) extends below a

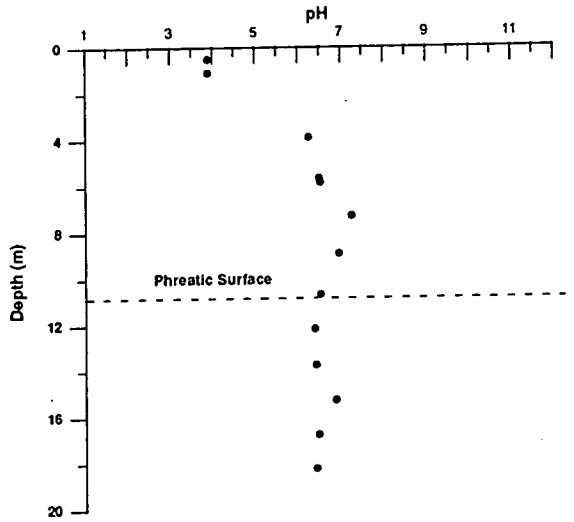


Figure 5.8a: Comparison Between RCPTU Bulk Resistivity Measurements and Pore Water pH in Unsaturated Sulphide Bearing Tailings

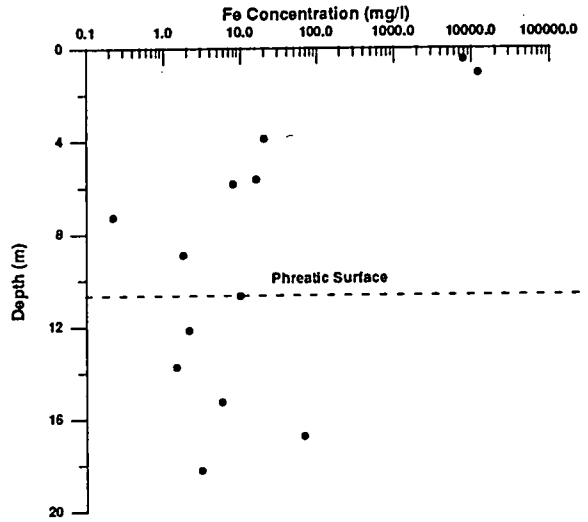


Figure 5.8b: Comparison Between RCPTU Bulk Resistivity Measurements and Pore Water Fe Concentration in Unsaturated Sulphide Bearing Tailings

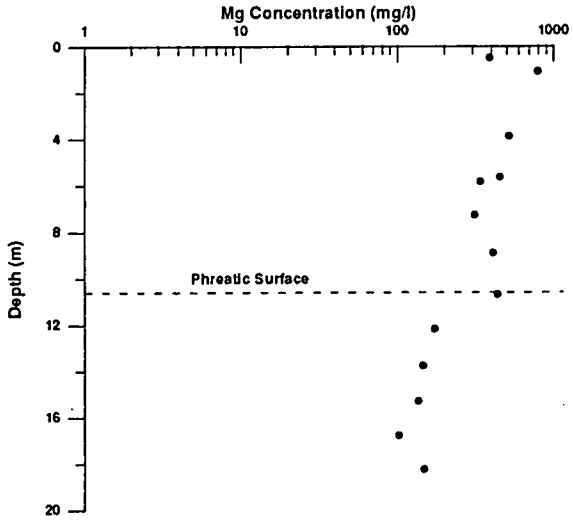


Figure 5.8c: Comparison Between RCPTU Bulk Resistivity Measurements and Pore Water Mg Concentration in Unsaturated Sulphide Bearing Tailings

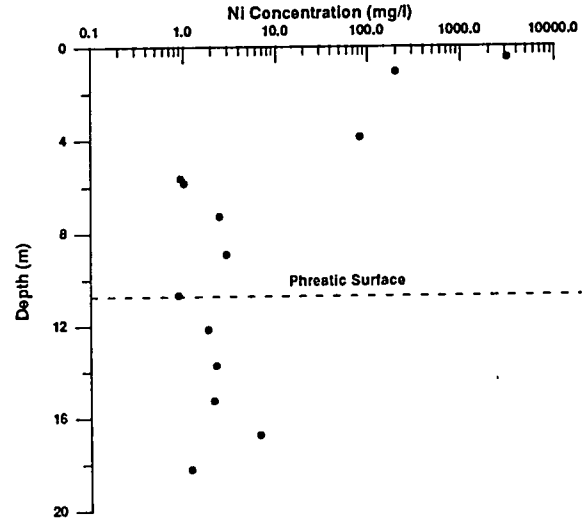


Figure 5.8d: Comparison Between RCPTU Bulk Resistivity Measurements and Pore Water Ni Concentration in Unsaturated Sulphide Bearing Tailings

depth of 4 m. The interface between the zone of neutralization and the original tailings process water (Z2) could not be determined from the available data.

Based upon the data presented in this section, the RCPTU can be used to qualitatively assess ARD contamination in the unsaturated zone. Interpretation of the countering effects of variable saturated conditions and changing pore water chemistry on bulk resistivity measurements are enhanced if tailings pore water chemistry data are available. A measure which would further enhance interpretation of bulk resistivity measurements in the unsaturated zone would be the collection of tailings samples, and subsequent measurement of tailings saturation. The measurement of tailings saturation would permit better interpretation of the relative influence of tailings saturation and pore water chemistry on bulk resistivity measurements.

5.3.3 COMPARISONS BETWEEN RCPTU BULK RESISTIVITY MEASUREMENTS AND PORE WATER CHEMISTRY IN SATURATED SULPHIDE BEARING TAILINGS AND SURROUNDING SATURATED NATIVE SOILS (ALL TEST SITES)

The data presented in this section were collected in saturated sulphide bearing tailings, with the exception of some INCO data from the saturated native soils at the base of Pistol Dam. With the influence of variable saturation removed, the bulk resistivity response is largely governed by the ionic composition of the pore water. The ability of the RCPTU to assess ARD contamination of pore water is evaluated through comparisons between bulk resistivity (and bulk conductivity) measurements and specific properties and dissolved ionic constituents of pore water samples.

5.3.3.1 Comparison of RCPTU Bulk Resistivity and Pore Water Resistivity

Plots of RCPTU bulk resistivity in relation to pore water resistivity for saturated INCO tailings, Falconbridge tailings, Gibraltar tailings and INCO native soils are shown in Figures 5.9a through 5.9d, respectively. Estimates of average apparent formation factor (F) ($F = \frac{\rho_b}{\rho_f} = n^{-m}$) are shown on each plot. By defining F for a given site, estimates of pore water resistivity can be made directly from the RCPTU bulk resistivity measurements, which reduces the need for more expensive pore water sampling practices. While recognizing that there is a fair degree of scatter about the linear trends of the respective plots and the relatively small data sets (particularly for the Gibraltar data), the average F is approximately 3.6 for the INCO tailings, 5.4 for the Falconbridge tailings and 3.6 for the Gibraltar tailings. Estimates of F in the INCO native soils (shown in Figure 5.9d) demonstrated a bilinear realtionship. The average F for pore water resistivities below 20 Ω-m was approximately 4.0, and the average F was approximately 1.75 for pore water resistivities above 20 Ω-m. Considering that the data were collected in similar sandy soils at the base of INCO's Pistol dam, differences in soil type and porosity are likely not responsible for the variations in F. The differences in F for the higher pore water resistivities can be explained by the fact that Archie's Equation may not be valid for the less conductive pore water due to the influence of the soil matrix on the bulk resistivity measurements.

The average F was the same for the INCO and Gibraltar tailings from which the data were collected, indicating similarities in soil behaviour types for the two sites. This is in agreement with the generally sandy nature of the tailings previously noted for the INCO and Gibraltar tailings in Section 5.1. However, the small size of the data sets precludes any definitive comparisons between the two sites.

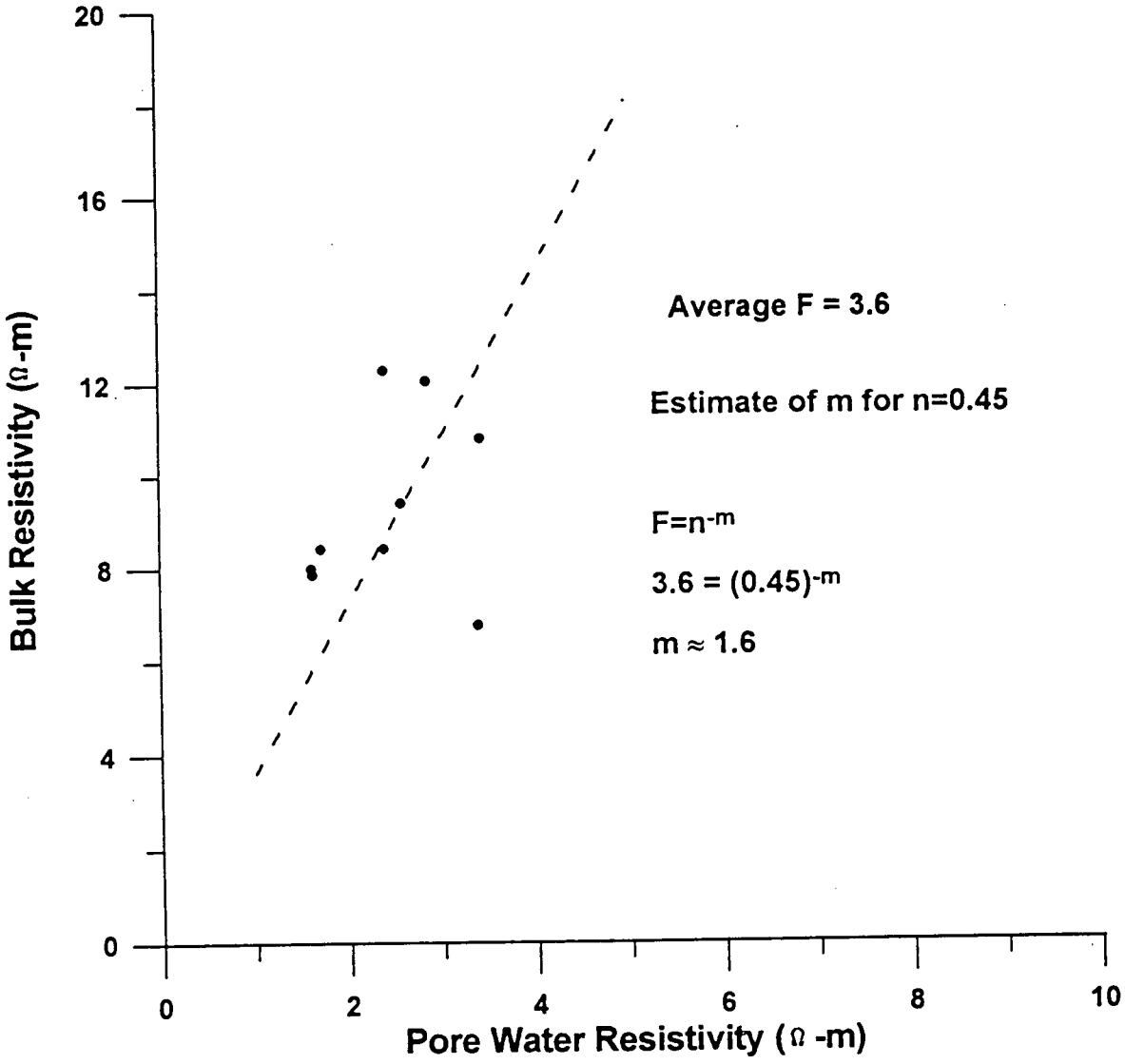


Figure5.9a: Comparison of RCPTU Bulk Resistivity and Pore Water Resistivity - Saturated INCO Tailings

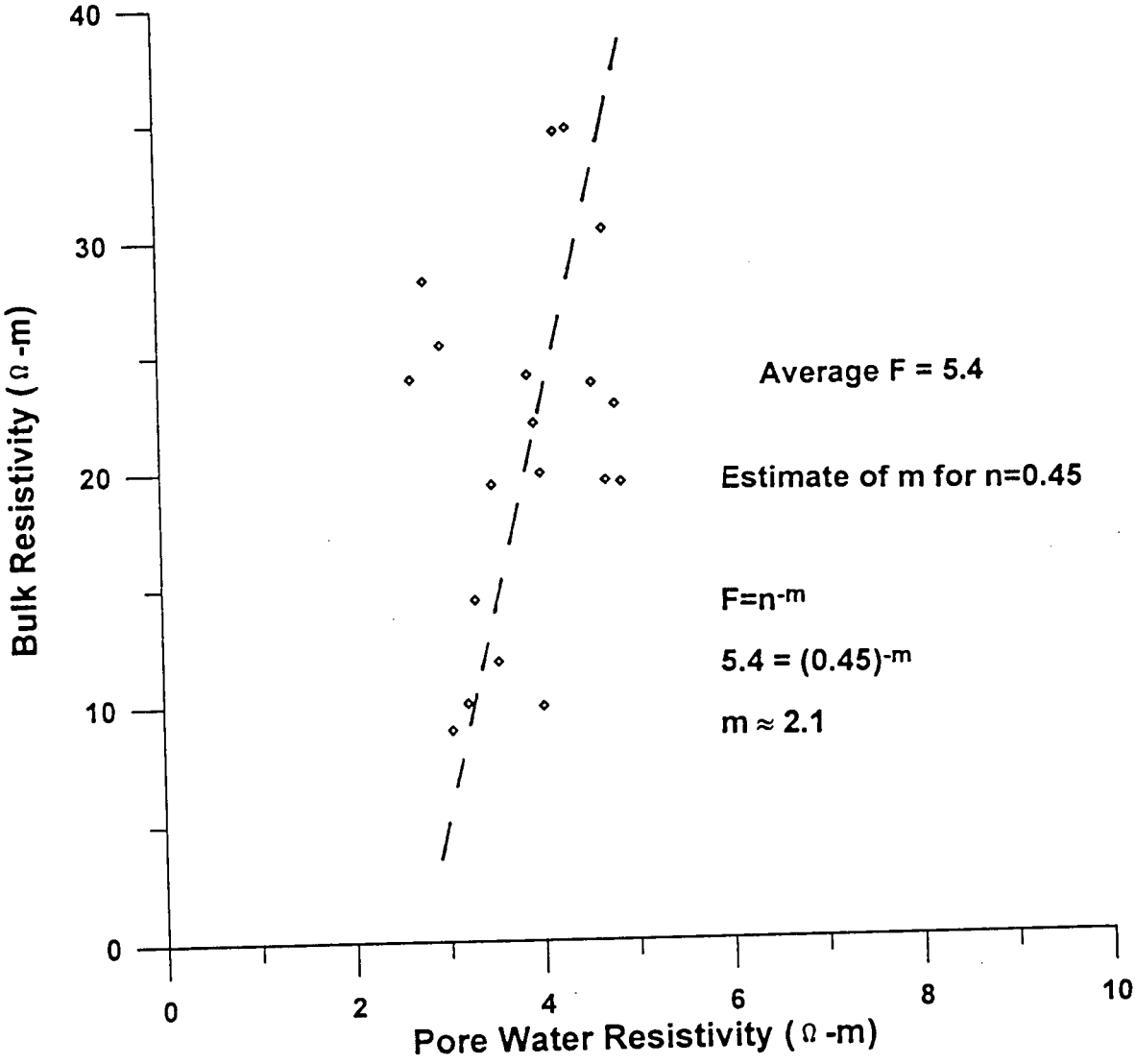


Figure 5.9b: Comparison Between RCPTU Bulk Resistivity and Pore Water Resistivity - Saturated Falconbridge Tailings

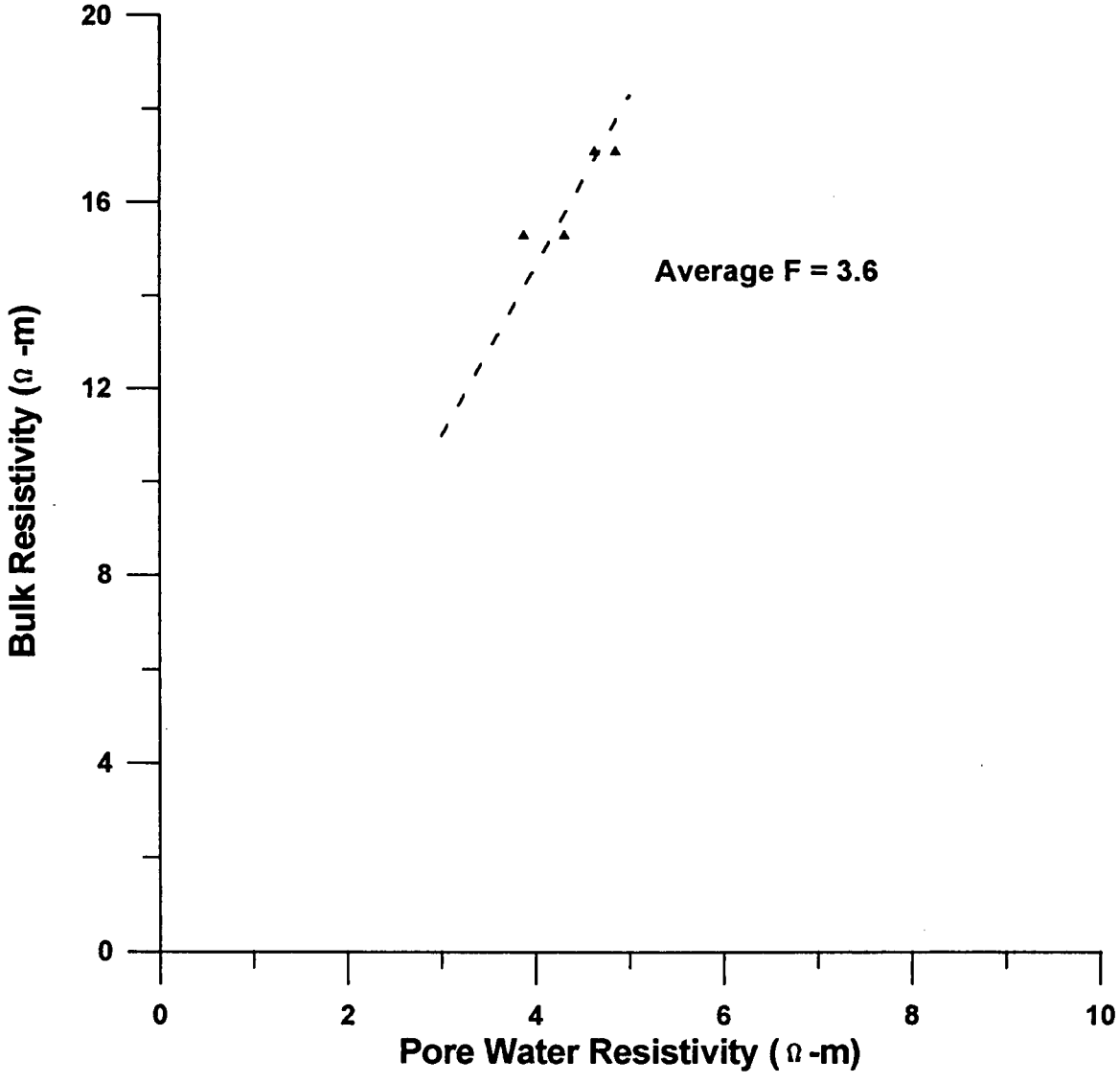


Figure 5.9c: Comparison Between RCPTU Bulk Resistivity and Pore Water Resistivity - Saturated Gibraltar Tailings

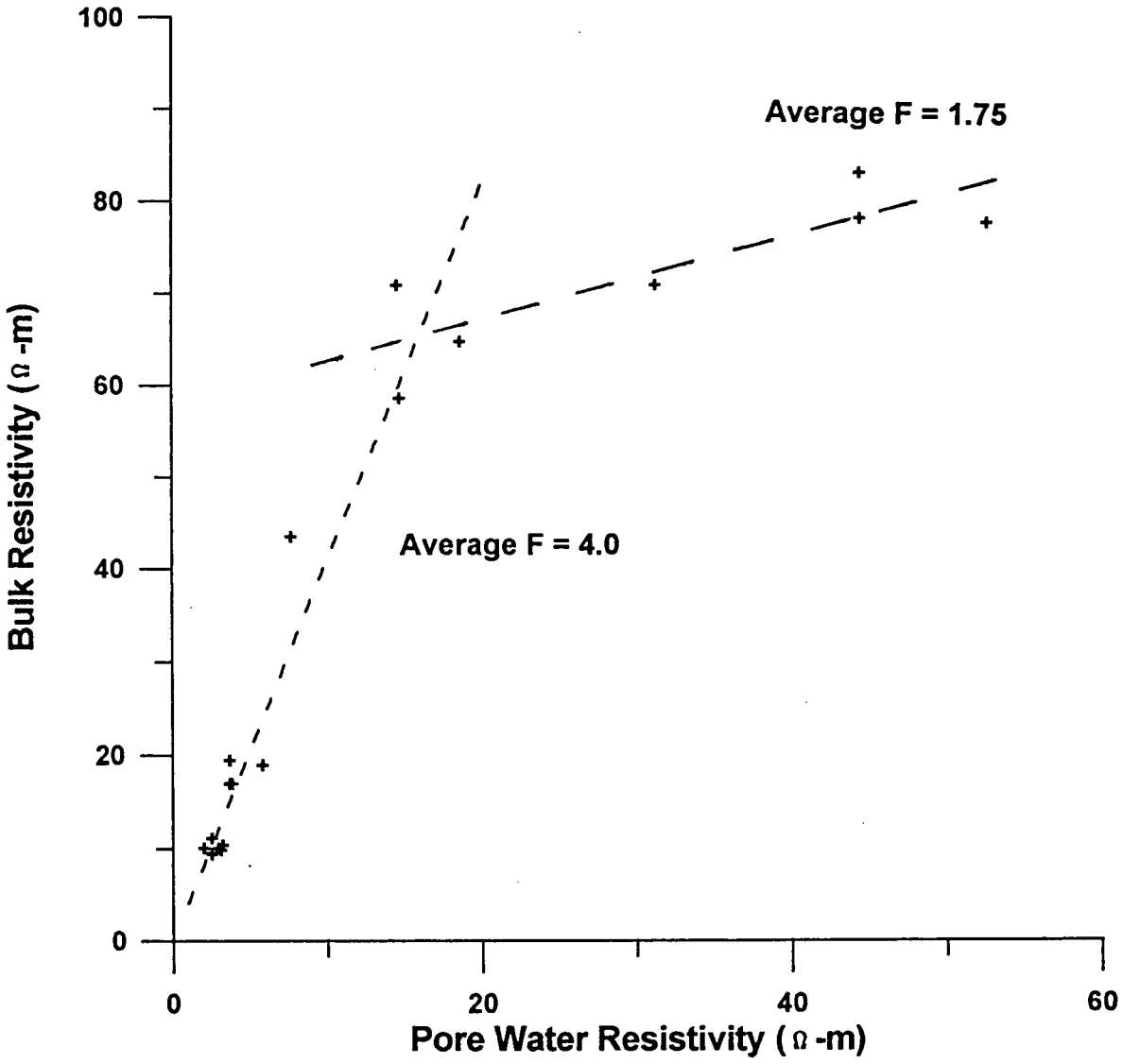


Figure 5.9d: Comparison Between RCPTU Bulk Resistivity and Pore Water Resistivity - Saturated INCO Native Soils

The differences in F observed between the different sites can largely be explained by differences in soil behaviour type, as F is an intrinsic property of the soil. The relative influence of soil behaviour type on F is reflected in the soil behaviour type constant, m. Estimates of m are shown in Figures 5.9a and 5.9b for the INCO and Falconbridge tailings, respectively. An average porosity (n) of 0.45 was used in these estimates for both sites, which was based on literature values from previous investigations at each site (Coggans, 1991 and St. Arnaud et al., 1994). The estimate of m for the INCO tailings was approximately 1.6, and for the Falconbridge tailings was approximately 2.1. The estimates of m for each site are consistent with literature values (Jackson et al., 1978) for the soil behaviour types exhibited by the INCO and Falconbridge tailings. The Falconbridge tailings were much finer-grained and more cohesive than the INCO tailings, and this is reflected in the higher m value for the Falconbridge tailings. Estimates of m were not made for the Gibraltar tailings and the INCO native soils due to the absence of estimates of porosity, but given the generally sandy nature of the soils at both sites from which the data were collected, it is likely that m values would be similar to the estimate for the INCO tailings.

5.3.3.2 Comparison of Pore Water Sulphate Concentration and RCPTU Bulk Conductivity

The observed relationships between pore water sulphate concentrations and bulk conductivity measurements are shown for the saturated INCO tailings, Falconbridge tailings, Gibraltar tailings and INCO native soils in Figures 5.10a through 5.10d, respectively. Bulk conductivity is used instead of bulk resistivity, due to the accepted use of bulk conductivity in the environmental sciences. The relationship between pore water sulphate concentration and bulk conductivity is especially important due to the fact that sulphate concentration is an excellent indicator of ARD development. Elevated sulphate concentrations generally occur in tailings pore water prior to increased heavy metals concentrations and increased acidity. Identification of elevated sulphate concentrations during Stage 1 ARD can enable the

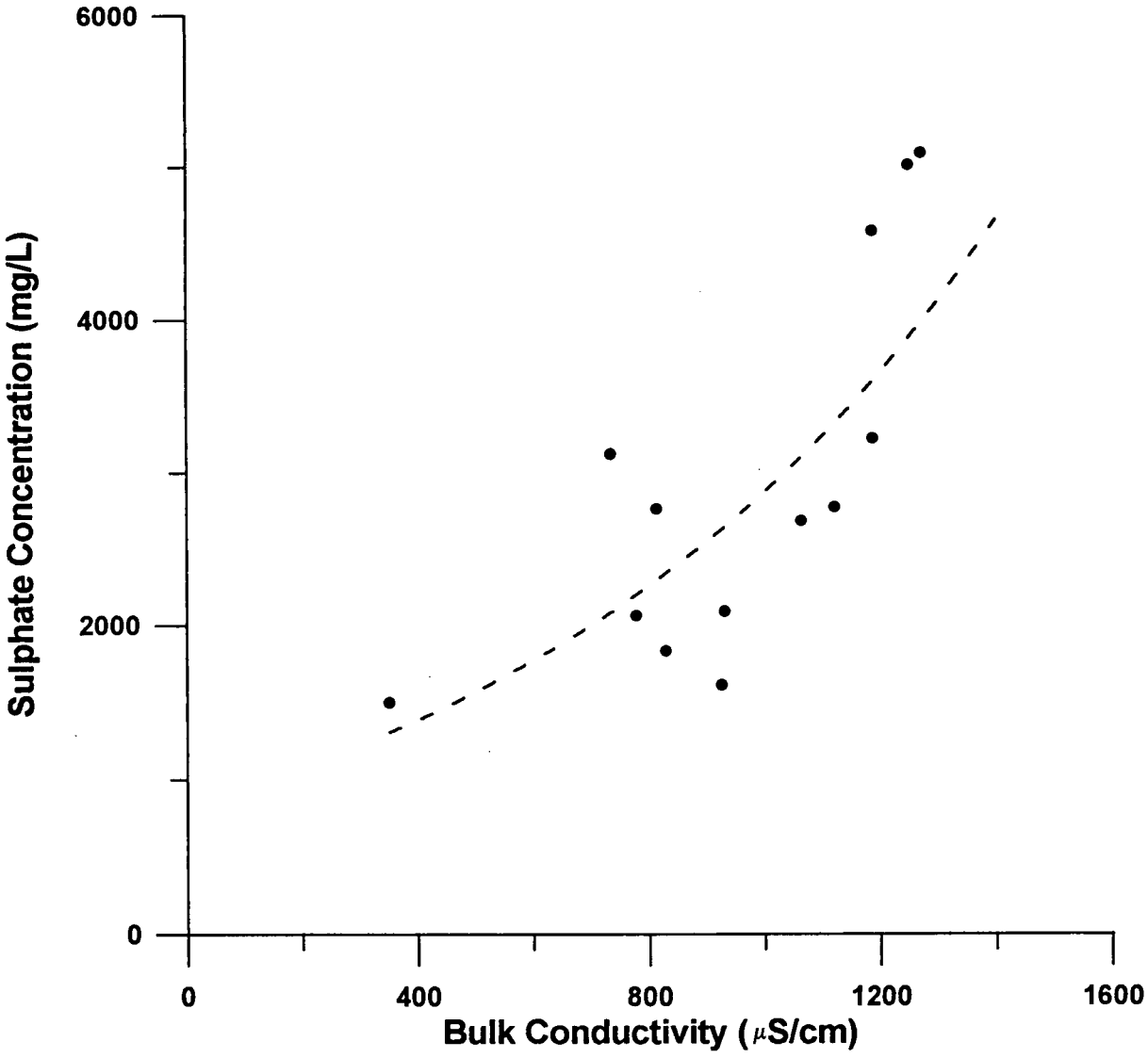


Figure 5.10a: Comparison Between Pore Water Sulphate Concentration and RCPTU Bulk Conductivity - Saturated INCO Tailings

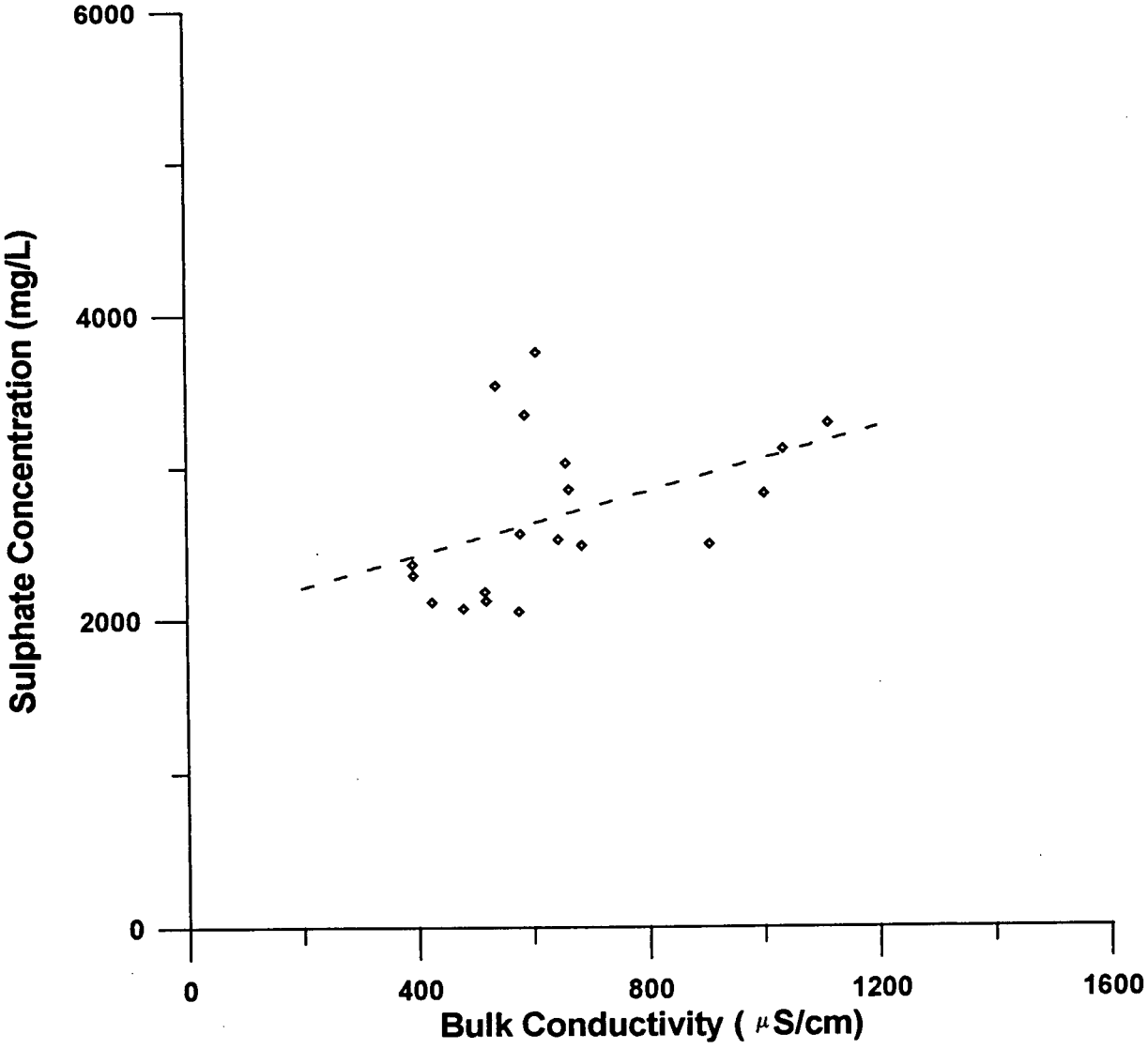


Figure 5.10b: Comparison Between Pore Water Sulphate Concentration and RCPTU Bulk Conductivity - Saturated Falconbridge Tailings

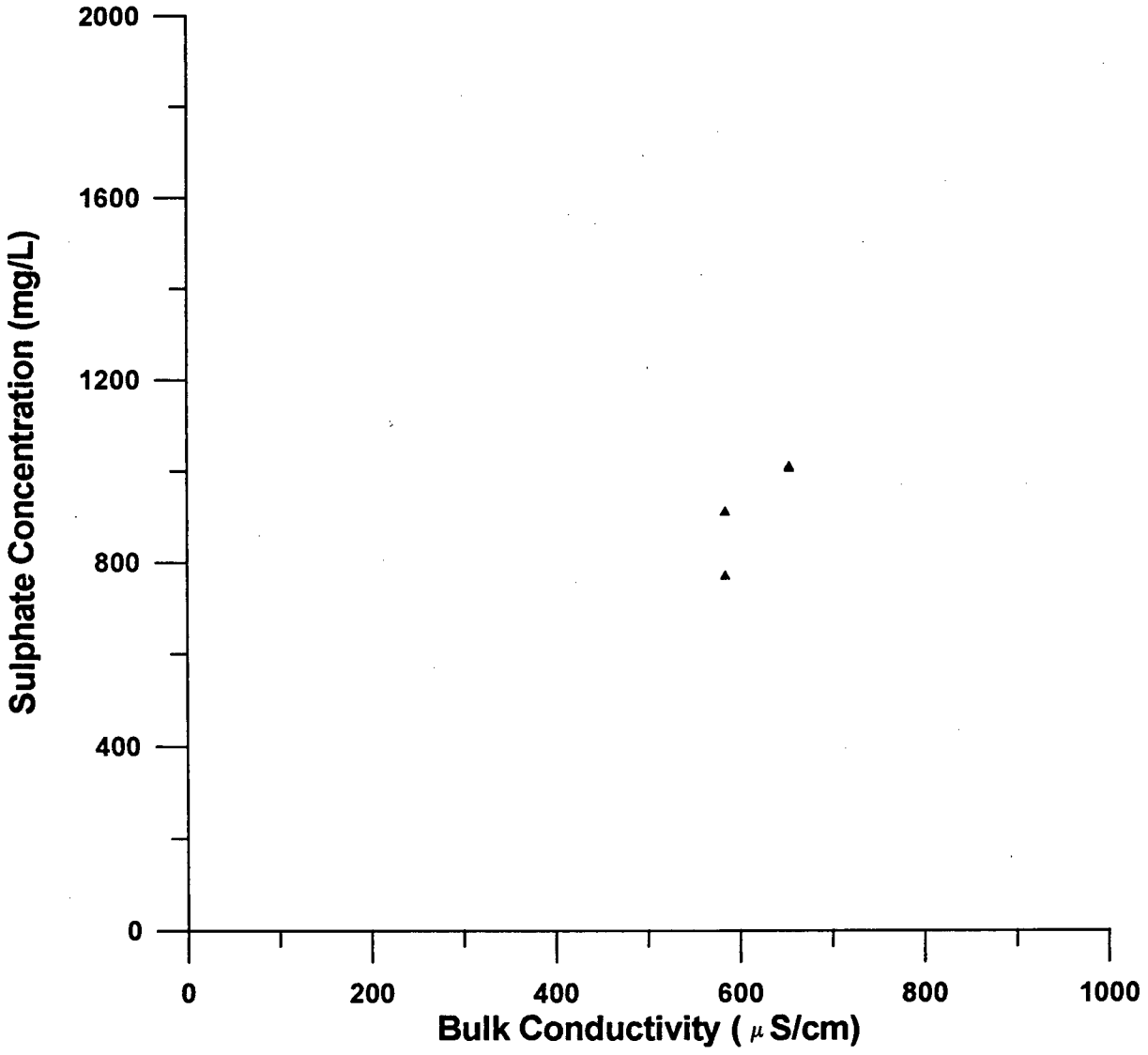


Figure 5.10c: Comparison Between Pore Water Sulphate Concentration and RCPTU Bulk Conductivity - Saturated Gibraltar Tailings

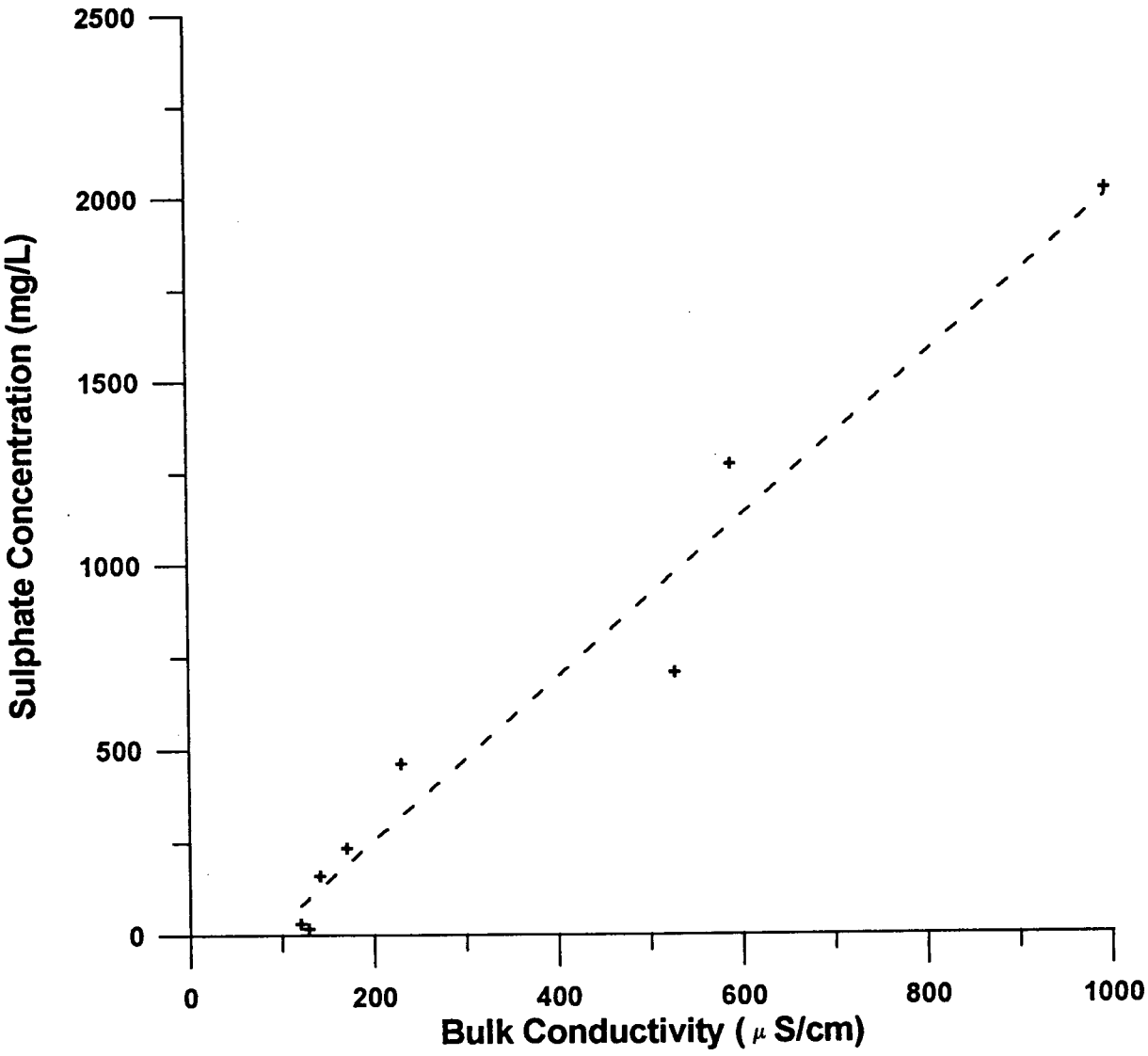


Figure 5.10d: Comparison Between Pore Water Sulphate Concentration and RCPTU Bulk Conductivity - Saturated INCO Native Soils

enactment of appropriate mitigation and abatement strategies prior to the development of more contaminated Stage 2 and Stage 3 ARD.

For the INCO tailings, sulphate concentrations generally increased with bulk conductivity, and an approximate curvilinear relationship is shown in Figure 5.10a. The pore water sulphate concentrations ranged from approximately 1500 - 5100 mg/L and the corresponding bulk conductivity measurements ranged from approximately 380 - 1250 μS/cm. Sulphate concentrations in the Falconbridge tailings generally increased with bulk conductivity (Figure 5.10b) and demonstrated a more linear trend than that for the INCO tailings. Pore water sulphate concentrations ranged from approximately 1400 - 3600 mg/L and bulk conductivity measurements ranged from approximately 400 - 1100 μS/cm. The data set for the Gibraltar tailings consisted of only three data points (Figure 5.10c), with sulphate concentrations of approximately 800 - 1100 mg/L and corresponding bulk conductivity measurements of approximately 600 - 700 μS/cm. Pore water sulphate concentrations in the INCO native soils demonstrated a linear relationship with bulk conductivity measurements (Figure 5.10d). Pore water sulphate concentrations and corresponding bulk conductivity measurements varied significantly for the INCO native soils. Pore water sulphate concentrations varied from very low values of approximately 20 mg/L to a peak of approximately 2000 mg/L, and bulk conductivities similarly ranged from approximately 100 - 1000 μS/cm. The lower values of pore water sulphate concentrations and bulk conductivity measurements are likely reflective of baseline values (i.e. not affected by ARD contamination) for the site, whereas elevated pore water sulphate concentrations and bulk conductivity measurements indicate the influence of ARD contamination. de Vos (1992) gives details concerning the transport of ARD contamination from the adjacent INCO sulphide bearing tailings, and also gives a detailed assessment of the extent of ARD contamination at the site.

The much higher sulphate concentrations and higher bulk conductivities in the saturated INCO and Falconbridge tailings indicate that ARD processes are more pronounced than for the saturated Gibraltar tailings and INCO native soils. Correspondingly, the greater linearity observed between pore water sulphate concentrations and bulk conductivities for the INCO native soils in comparison with the INCO and Falconbridge tailings is likely due to a lesser degree of ARD contamination at the site. The generally low pore water sulphate concentrations measured in the INCO native soils are indicative of Stage 1 ARD processes, and therefore the pore water likely contains low heavy metals and acidity. With the absence of significant heavy metals and acidity contained in the pore water, bulk conductivity measurements are largely influenced by pore water sulphate concentrations. It is interesting to note that the data collected in the Gibraltar tailings plots very close to the relationship derived between pore water sulphate concentrations and bulk conductivity for the INCO native soils.

Figure 5.11 shows a plot of pore water sulphate concentration and bulk conductivity for all test sites, and also shown are data from Merkel (1972). Merkel carried out surface resistivity testing in combination with discrete pore water sampling in native soils adjacent to sulphide bearing mine waste. As can be seen in Figure 5.11, the data from this study were in reasonably good agreement with the findings of Merkel. High bulk conductivity measurements correspond with elevated pore water concentrations, which are indicative of ARD contamination. The linear trend shown in Figure 5.11 is very valuable for the characterization of ARD processes in saturated sulphide bearing tailings and adjacent native soils, as it enables a direct estimate of pore water sulphate concentration from RCPTU bulk conductivity measurements. Given that the data set from which Figure 5.11 was developed is relatively small, its application is likely limited to the sites studied in this thesis. The agreement between the data from this study and the data of Merkel suggests that Figure 5.11

may have more global applications to other sites, but this requires corroboration from further field studies at different sites.

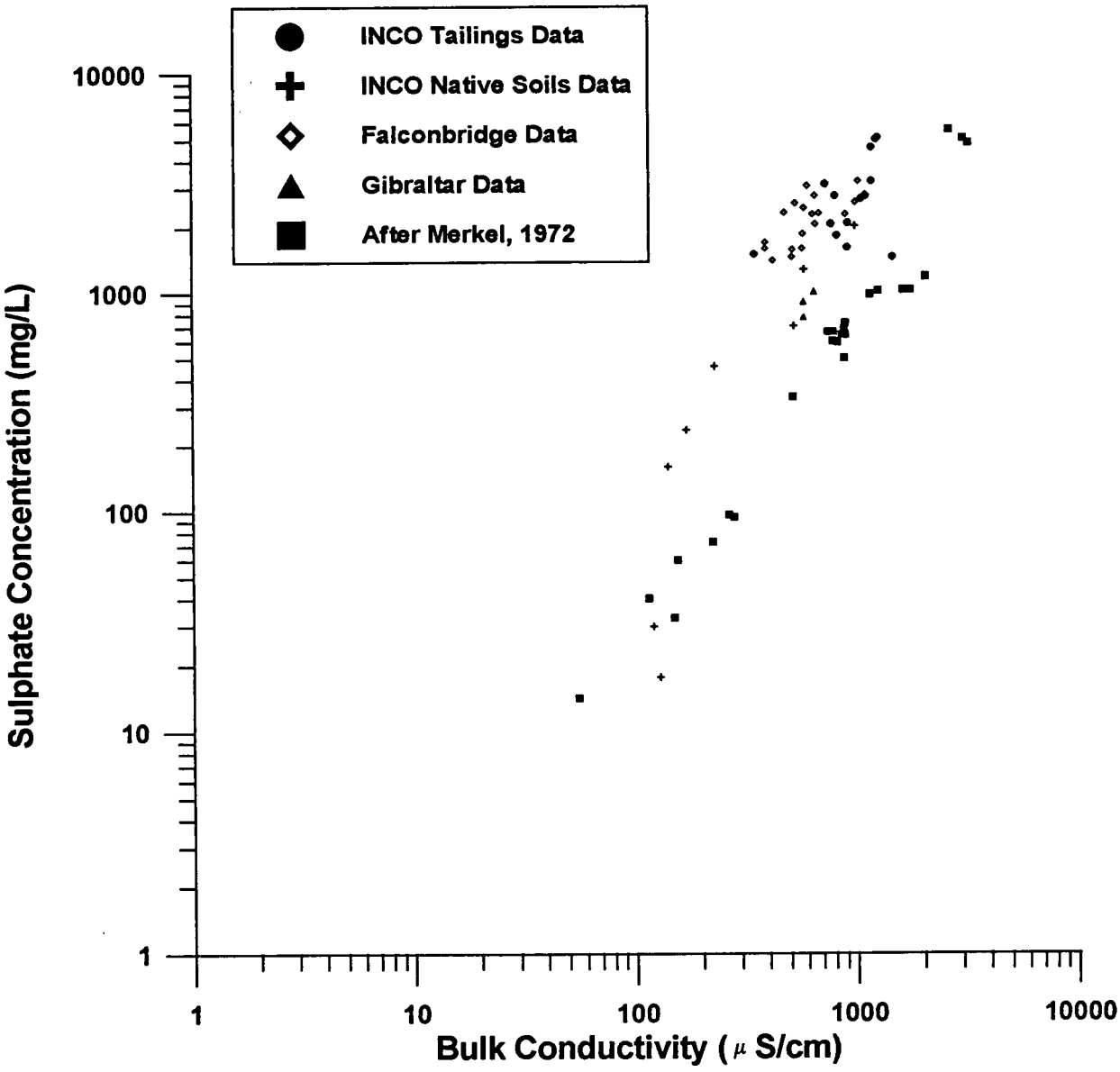


Figure 5.11: Comparison Between Pore Water Sulphate Concentration and Bulk Conductivity in Saturated Sulphide Bearing Tailings and Native Soils

5.3.3.3 Comparison of Pore Water pH and RCPTU Bulk Conductivity

Pore water pH is an important indicator of the progression of ARD development. Decreases in pH (or increases in acidity) are associated with more developed Stage 2 and Stage 3 ARD processes. Subsequently, it would be expected that decreases in pH would be accompanied by increases in bulk conductivity. Plots of pore water pH and bulk conductivity measurements for the saturated INCO tailings, Falconbridge tailings and INCO native soils are shown in Figures 5.12a through 5.12c, respectively. No pore water pH data were measured for the saturated Gibraltar tailings.

Pore water pH showed no discernable trend with respect to bulk conductivity for the INCO tailings, as shown in Figure 5.12a. However, pH measurements were slightly acidic and ranged from approximately 5 - 6. Corresponding bulk conductivity measurements in the INCO tailings ranged from approximately 800 - 1400 μS/cm. For the Falconbridge tailings, pore water pH followed the expected trend and decreased with increased bulk conductivity (Figure 5.12b). pH measurements were essentially neutral and ranged from approximately 6.4 - 7.6 and bulk conductivities ranged from 400 - 1000 μS/cm. Pore water pH measurements in the INCO native soils showed a decreasing trend with bulk conductivity (Figure 5.12c), similar to that observed in the Falconbridge tailings. pH values were neutral and generally higher than at the other sites and ranged from approximately 6.5 - 8.3, although a pH low of approximately 6 and a pH high of 10 were measured. Correseponding bulk conductivities ranged from approximately 100 - 1000 μS/cm in the INCO native soils.

The slightly acidic pH measurements in the saturated INCO tailings pore water suggests that alkaline materials in the tailings are not sufficient to neutralize acid generated from oxidation of sulphide minerals. The small number of samples precludes any definitive conclusions, but it appears that acidic conditions (later Stage 2 ARD processes) are developing for the tailings

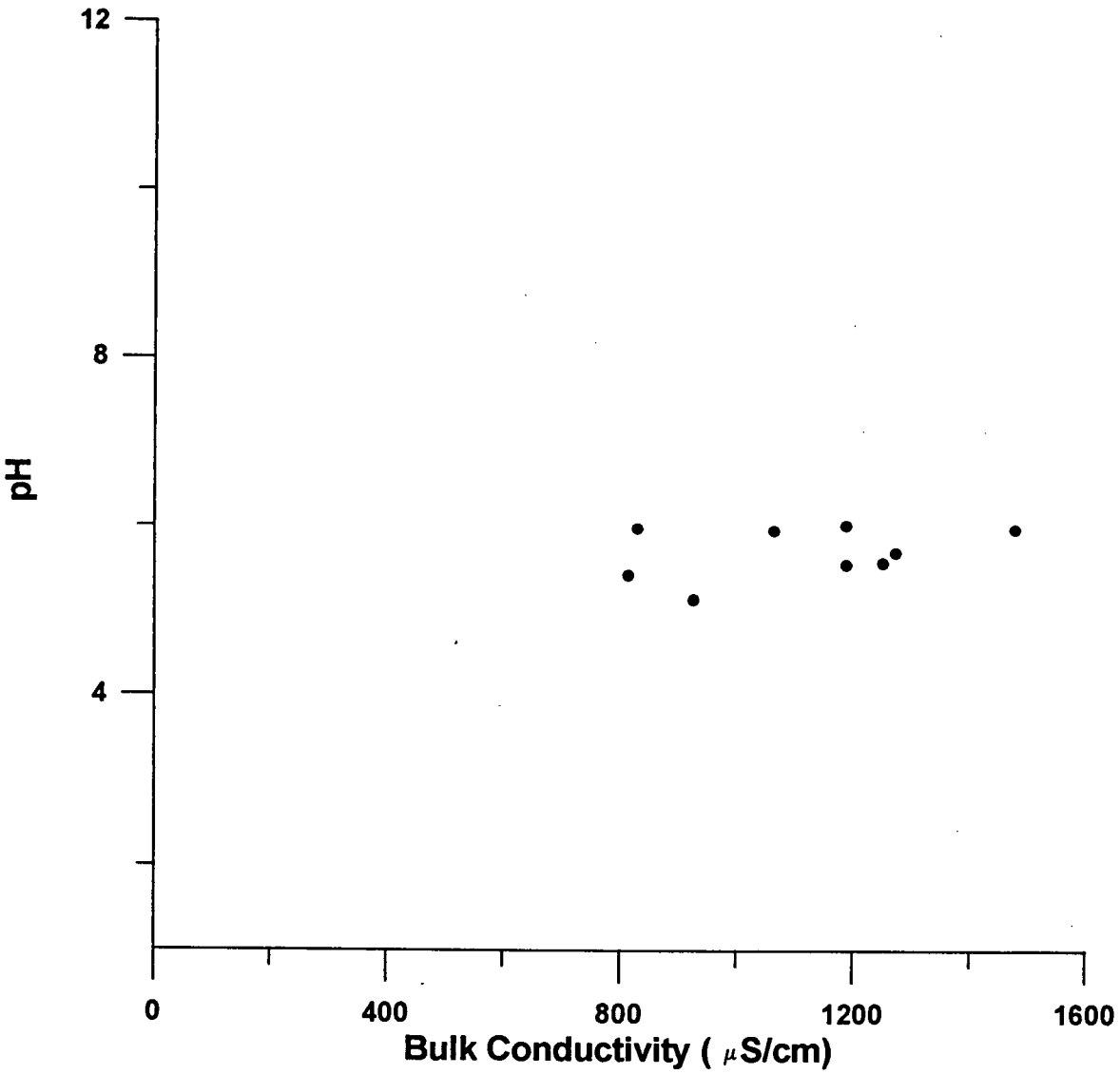


Figure 5.12a: Comparison Between Pore Water pH and RCPTU Bulk Conductivity - Saturated INCO Tailings

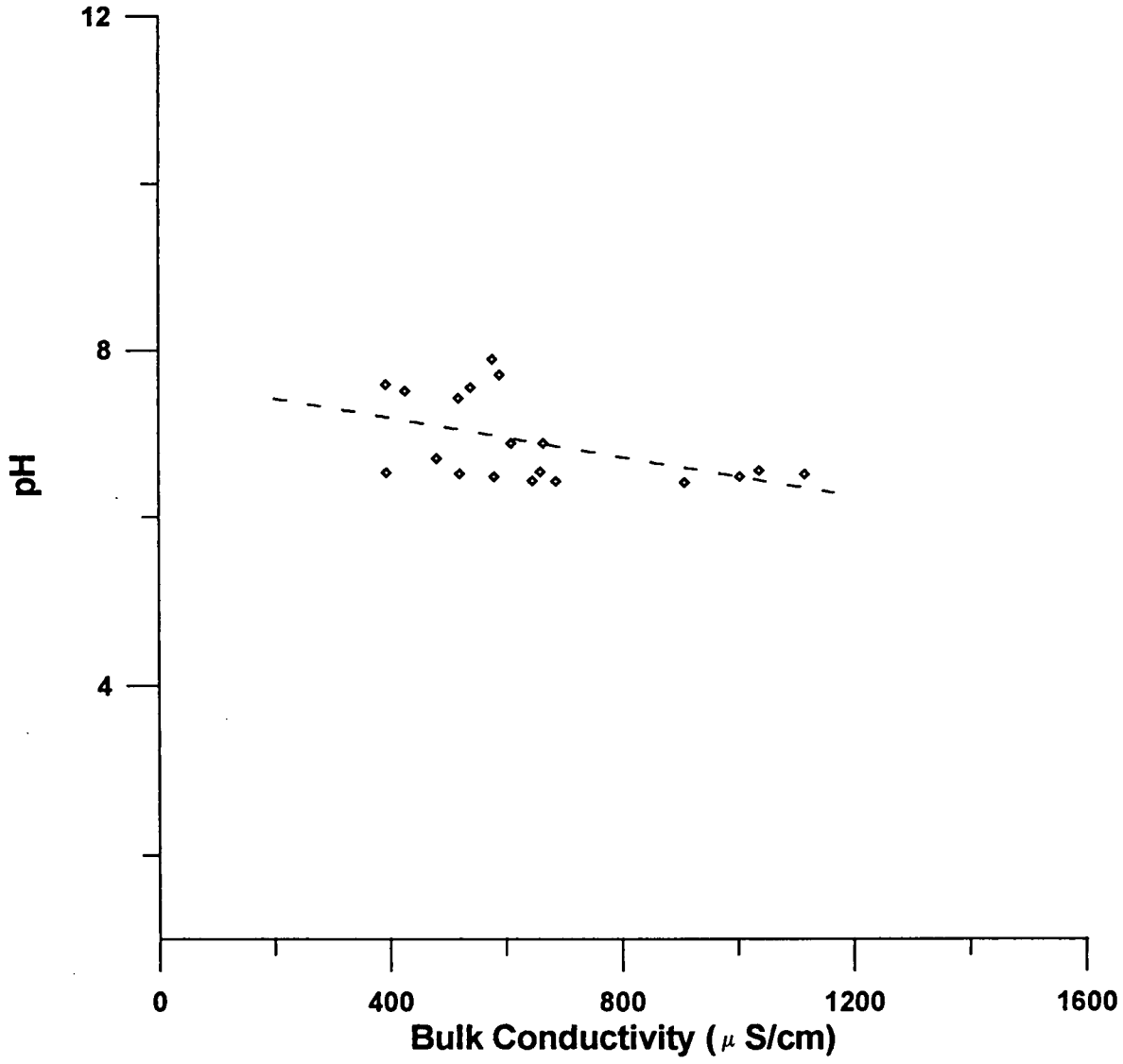


Figure 5.12b: Comparison Between Pore Water pH and RCPTU Bulk Conductivity - Saturated Falconbridge Tailings

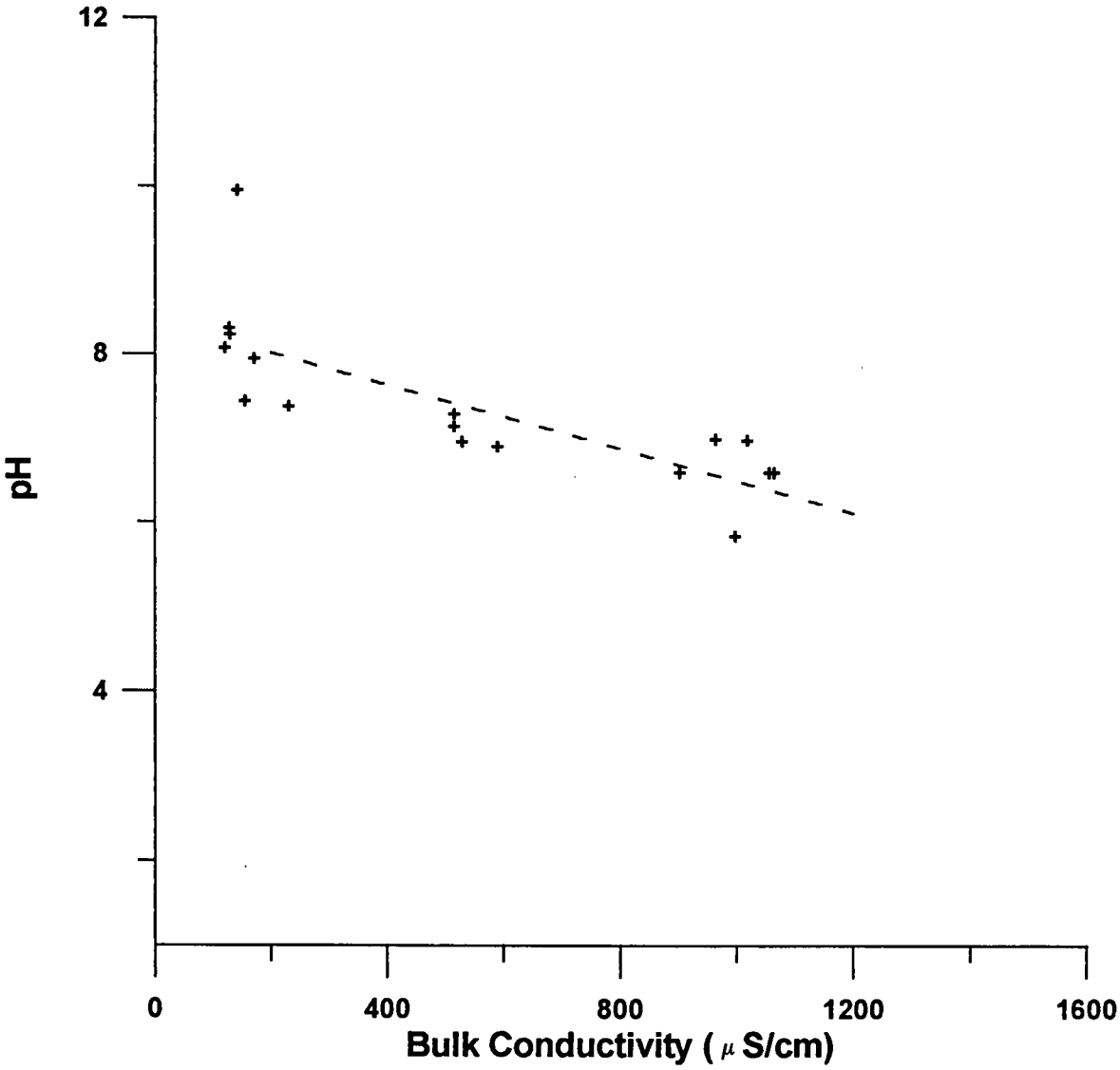


Figure 5.12c: Comparison Between Pore Water pH and RCPTU Bulk Conductivity - Saturated INCO Native Soils

from which the samples were collected. The neutral pH values for the saturated Falconbridge tailings and INCO native soils indicate that alkaline materials are sufficient at both sites to neutralize any acidity associated with ARD processes.

5.3.3.4 Comparison of Pore Water Heavy Metals Concentrations and RCPTU Bulk Conductivity

Pore water heavy metals concentrations are commonly the most harmful contaminants contained in ARD contamination to the receiving environments. This is reflected in the Federal restrictions on effluent quality from mine sites (shown in Table 2.1 in Section 2.1), which largely contains restrictions on pore water heavy metals concentrations. Elevated pore water heavy metals concentrations are symptomatic of more developed Stage 2 and Stage 3 ARD processes. Acidity generated in the sulphide bearing tailings causes the dissolution of heavy metals contained in the tailings. The type and concentrations of heavy metals contained in ARD contamination from sulphide bearing tailings impoundments are dependent upon the mineralogy of the tailings and the surrounding native soils. It would be expected that increased heavy metals concentrations in the tailings pore water would correspond with increased bulk conductivity of the tailings, due to the overall increase in concentration of ionic constituents. However, due to the variability in the mineralogy of the tailings and the surrounding native soils for a large impoundment structure, it is reasonable to expect that relationships between specific heavy metals concentrations and bulk conductivity measurements would be highly site-specific and show a high degree of scatter.

Figures 5.13a through 5.13c present comparisons between pore water iron (Fe) concentration, nickel (Ni) concentration and magnesium (Mg) concentration and bulk conductivity measurements for the saturated INCO tailings, Falconbridge tailings and INCO native soils. No pore water heavy metals concentrations were measured for the Gibraltar tailings. The

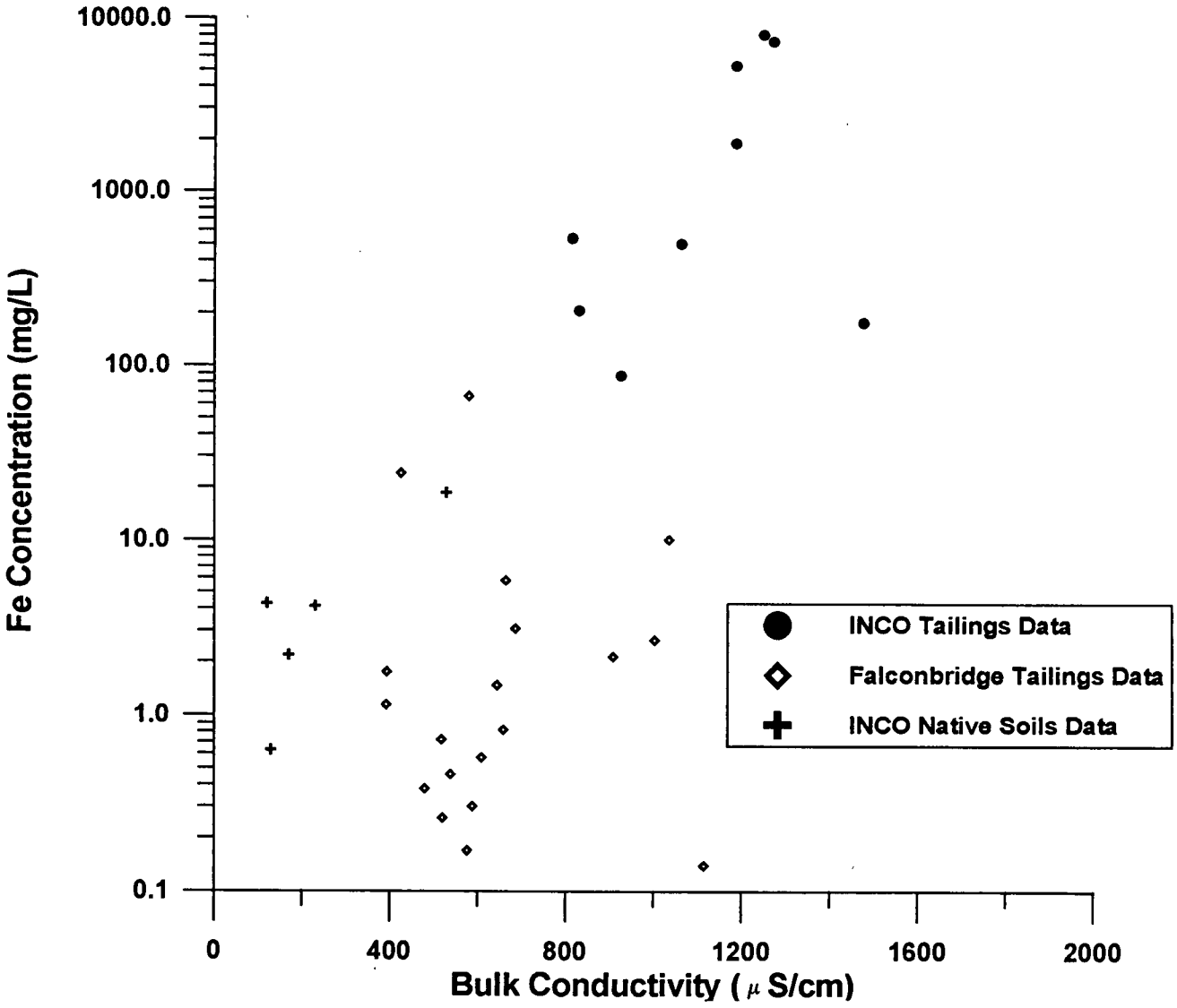


Figure 5.13a: Comparison Between Pore Water Fe Concentration and RCPTU Bulk Conductivity in Saturated Sulphide Bearing Tailings and Native Soils

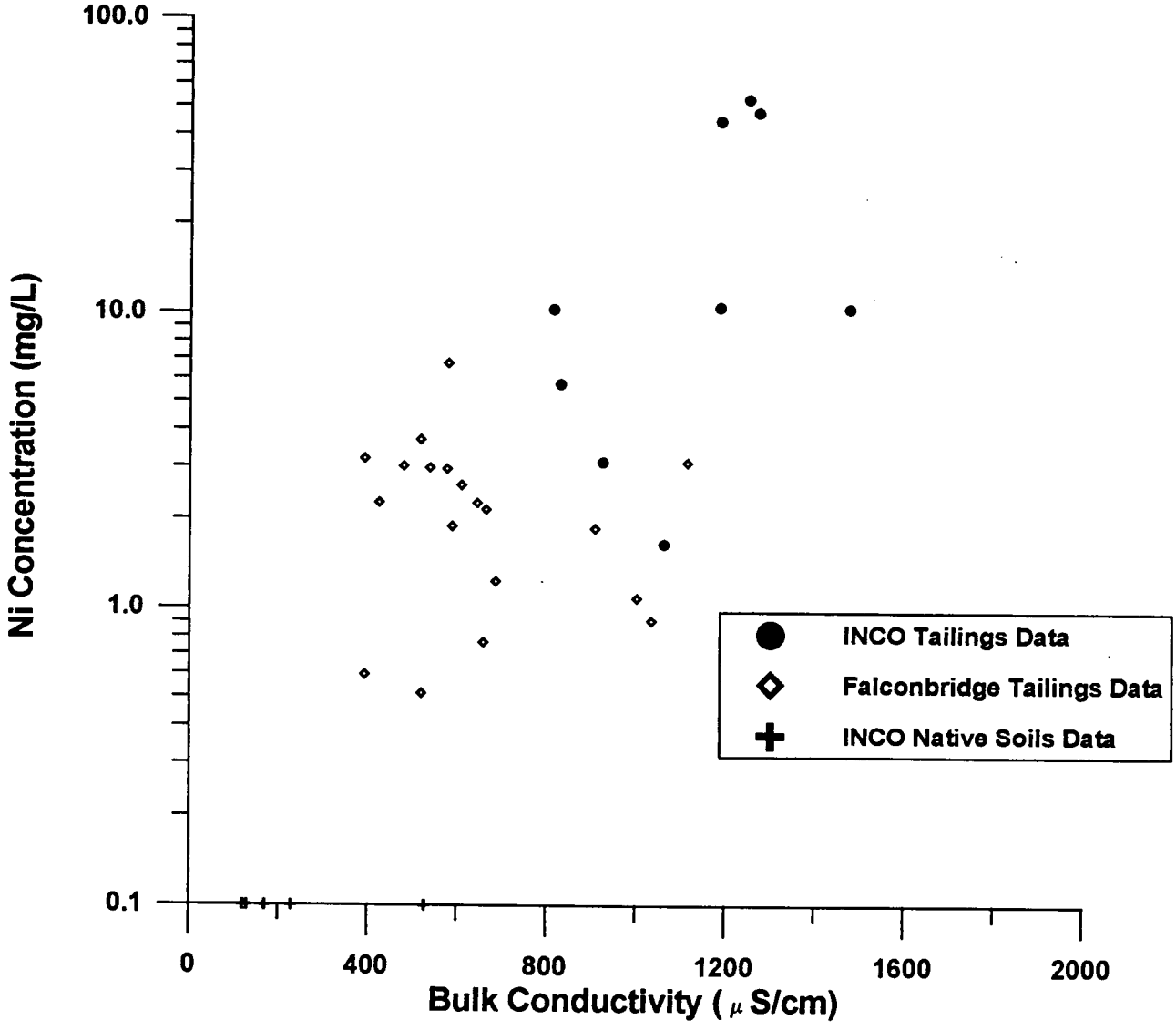


Figure 5.13b: Comparison Between Pore Water Ni Concentration and RCPTU Bulk Conductivity in Saturated Sulphide Bearing Tailings and Native Soils

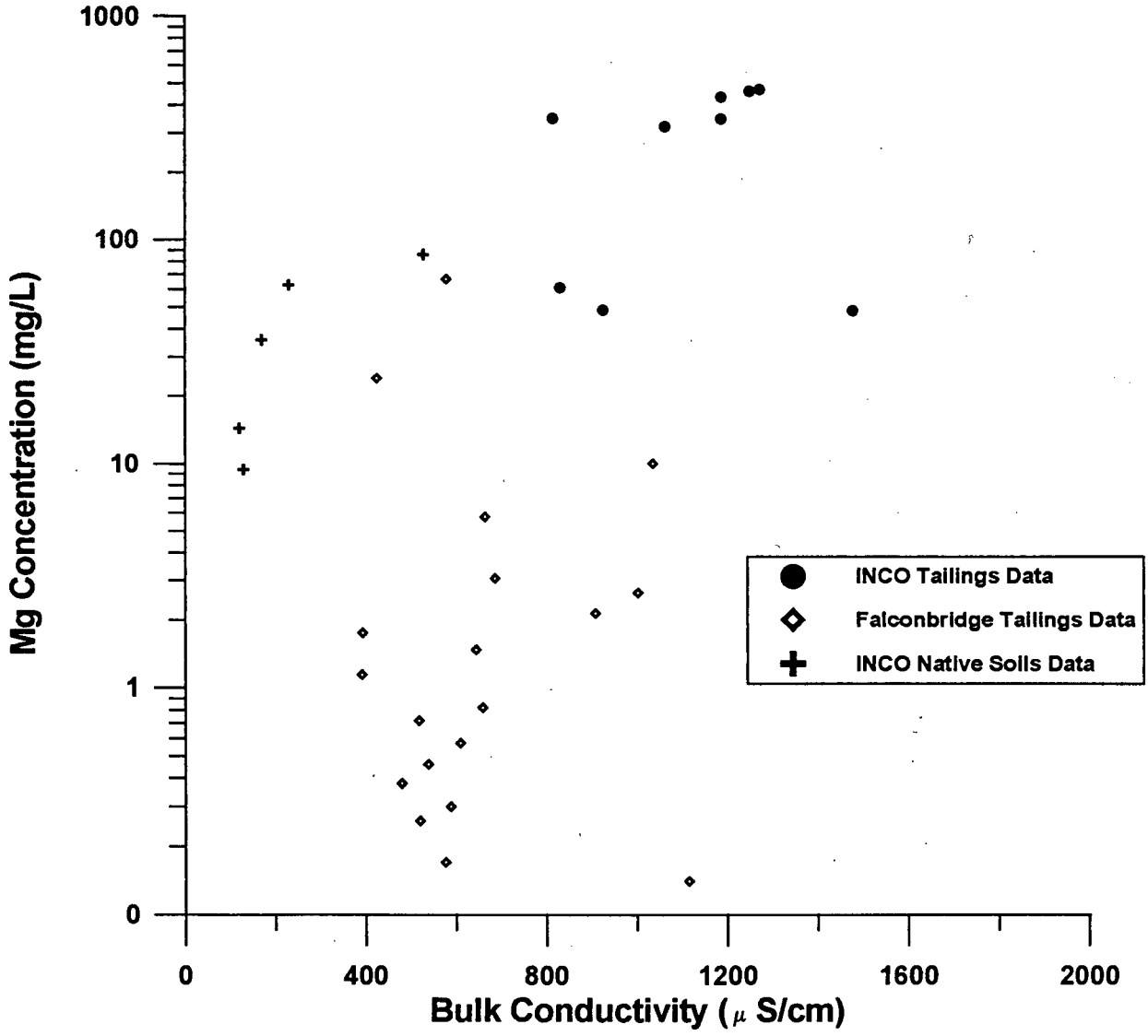


Figure 5.13c: Comparison Between Pore Water Mg Concentration and RCPTU Bulk Conductivity in Saturated Sulphide Bearing Tailings and Native Soils

selection of Fe, Ni and Mg pore water concentrations for these comparisons was based on careful consideration of multi-element chemical analyses on pore water samples from the different sites. Fe, Ni, and Mg generally had higher concentrations than other dissolved heavy metals and had a wider range of magnitudes which facilitated comparisons with bulk conductivity data.

Figure 5.13a shows a plot of iron (Fe) concentration versus bulk conductivity measurements for the saturated INCO tailings, Falconbridge tailings and INCO native soils. Data from each site showed a trend of increased pore water Fe concentration with bulk conductivity, and this trend was more pronounced for the INCO data. Pore water Fe concentrations ranged from approximately 100 - 1000 mg/L for the INCO tailings, from approximately 0.1 - 70 mg/L for the Falconbridge tailings and from approximately 0.5 - 20 mg/L for the INCO native soils. The corresponding bulk conductivity measurements ranged from approximately 800 - 1500 μS/cm for the INCO tailings, 400 - 1100 μS/cm for the Falconbridge tailings and 100 - 500 μS/cm for the INCO tailings. The same data set of bulk conductivity measurements is used in comparisons with Fe, Ni and Mg concentrations, as heavy metals concentrations were determined from multi-element analyses of a constant set of pore water samples. The much higher pore water Fe concentrations and higher bulk conductivities measured in the INCO tailings are indicative of more severe ARD contamination at the site in comparison with the Falconbridge tailings and INCO native soils.

Figure 5.13b shows a plot of pore water Ni concentrations with respect to measured bulk conductivities for the saturated soils at the different test sites. Ni pore water concentrations generally increased with bulk conductivity measurements for the INCO tailings and Falconbridge tailings, while pore water Ni concentrations in the INCO native soils were below testing limits (< 0.05 mg/L). Similarly for pore water Fe concentrations, pore water Ni concentrations were much higher for the INCO tailings and ranged from approximately 1.5 -

60 mg/L. The upper bound of 60 mg/L is significantly greater than the maximum "grab sample" Ni concentration of 1 mg/L, as specified in the Federal restrictions governing effluent from mine sites (Table 2.1). Ni concentrations in the Falconbridge tailings pore water ranged from approximately 2 - 7 mg/L, which are also higher than the Federal restrictions. The much higher Ni concentrations measured in the INCO tailings pore water samples further supports the premise that ARD processes are more developed in the saturated INCO tailings than for the saturated Falconbridge tailings and INCO native soils.

Pore water Mg concentrations are plotted in relation to bulk conductivity measurements for the saturated soils of the different test sites in Figure 5.13c. Mg concentrations measured in the pore water of INCO tailings were generally much greater than pore water Mg concentrations in Falconbridge tailings and INCO native soils. In the INCO tailings pore water Mg concentrations generally increased with bulk conductivity and ranged from approximately 50 - 500 mg/L. Similarly, Mg pore water concentrations in the INCO native soils tended to increase with bulk conductivity and ranged from approximately 10 - 100 mg/L. Mg pore water concentrations in the Falconbridge tailings showed no discernable trend with bulk conductivity and ranged from a low concentration of 0.5 mg/L to a peak concentration of 60 mg/L. The generally much higher Mg concentrations in the pore water of the saturated INCO tailings in comparison with data from the other sites are consistent with the findings for pore water Fe and Ni concentrations. Moreover, it provides further evidence of more significant ARD contamination affecting the saturated INCO tailings than at the other sites.

Copper (Cu), arsenic (As), lead (Pb) and zinc (Zn) concentrations for INCO and Falconbridge pore water samples were below federal restrictions, as specified in Table 2.1 in Section 2.2, and in many cases were below the detection limits of the testing equipment.

5.3.3.5 Summary

Of the relationships presented in Section 5.3.3 between RCPTU bulk resistivity (or bulk conductivity) measurements and pore water chemistry, those between bulk resistivity and pore water resistivity and bulk conductivity and pore water sulphate concentration appear strongest. The strength of the relationship between RCPTU bulk resistivity and pore water resistivity lies in the fact that a fundamental characteristic of ARD development is increased ionic loading of the pore water with ARD development. Increased ionic loading of the pore water results in a corresponding increase in pore water conductivity, which largely governs the bulk resistivity response of the soil. Similarly, the strength of the relationship between RCPTU bulk conductivity and pore water sulphate concentration can be attributed to the fact that increased pore water sulphate concentration with ARD progression is a principle contributor to overall increased ionic loading of the pore water. The relationships between RCPTU bulk conductivity measurements and pore water pH and heavy metals concentrations are clouded by the influences of soil mineralogy. The pH of the pore water is a function of acid generated by sulphide oxidation and alkalinity contained in the tailings and native soils. The net effect is that pore water samples of similar pH can have widely varying pore water ionic concentrations (which directly influence bulk conductivity measurements), due to the effects of alkalinity. Thus, it is difficult to infer pore water pH directly from RCPTU bulk conductivity measurements. Similarly, pore water heavy metals concentrations are dependent upon soil mineralogy. For a large tailings impoundment it is reasonable to expect significant variations in tailings mineralogy, which results in a fair degree of scatter between RCPTU bulk conductivity measurements and pore water concentrations of specific heavy metals.

The data presented in Section 5.3.3 gives insight into the relative stage of ARD development for the test locations from which test data were collected. It must be stressed that

interpretation of the data should be restricted to the specific testing locations for the respective sites.

The results of testing indicate that ARD contamination is more severe for the saturated INCO tailings than for the saturated Falconbridge tailings and INCO native soils. In general higher RCPTU bulk conductivity (or lower bulk resistivity) measurements and higher pore water concentrations of acidity and heavy metals were measured for the INCO saturated tailings in comparison with the other test sites. In the saturated INCO tailings, high pore water sulphate concentrations in combination with the slightly acidic pore water pH and elevated heavy metals concentrations of the pore water indicates later Stage 2 development. In the saturated Falconbridge tailings, the fact that elevated heavy metals are contained in the pore water is indicative of Stage 2 ARD development. However, the significantly lower pore water heavy metals concentrations and generally lower sulphate concentrations and bulk conductivity measurements in comparison with the saturated INCO tailings data indicates that ARD processes are less developed for the saturated Falconbridge tailings. Further evidence of this fact, was the neutral pH of the Falconbridge tailings pore water in comparison with the slightly acidic INCO tailings pore water. In the saturated INCO native soils, lower pore water sulphate concentrations and bulk conductivity measurements were measured in comparison with the saturated INCO and Falconbridge tailings. Significantly lower pore water heavy metals concentrations and higher pH were measured in the saturated native INCO soils in comparison with the saturated INCO tailings, while these values were approximately similar to those measured in the saturated Falconbridge tailings (with the exception of pore water Ni concentration, which was much lower). ARD contamination is significantly lower for the INCO native soils than for the INCO tailings, and based upon pore water sulphate concentrations and bulk conductivity measurements is less severe than that in the Falconbridge tailings. However, based upon the peaks in pore water sulphate concentrations and heavy metals concentrations and peaks in bulk conductivity measurements at specific

locations at the base of INCO's Pistol dam it is apparent that ARD contamination is impacting the site from the adjacent INCO tailings. This is in agreement with the findings of de Vos (1992) who provides more definitive information with respect to the impact of ARD contamination at the site. The small quantity of data from the saturated Gibraltar tailings prevents any meaningful comparisons with the site, although based on limited bulk conductivity and pore water sulphate concentration data it appears ARD processes are less developed than those for the saturated INCO and Falconbridge tailings.

It is important to note that the findings with respect to ARD development in the saturated INCO tailings and Falconbridge tailings is the opposite of the findings for the unsaturated tailings at each site. In the unsaturated Falconbridge tailings higher pore water sulphate concentrations and higher bulk conductivity measurements were measured in comparison with the unsaturated INCO tailings, which indicates that ARD processes are more developed in the unsaturated Falconbridge tailings. By contrast, based upon the data presented in Section 5.3.3, it appears that ARD processes are more developed for the saturated INCO tailings in comparison with the saturated Falconbridge tailings. This can likely be explained by the fact that the INCO tailings are much older than the Falconbridge tailings. Deposition of tailings in the INCO Central Tailings Area occurred from 1937-1988, whereas deposition of tailings at the Falconbridge Fault Lake site took place from 1964-1978. ARD is a time-dependent process, as discussed in Section 2.2.1, and the pore water of the saturated INCO tailings has had a longer time to accumulate ionic constituents from acid generation in the unsaturated zone (as shown in Figure 2.2) in comparison with the saturated Falconbridge tailings. Based upon the much higher sulphide mineral content and the more severe ARD development in the unsaturated Falconbridge tailings, it is reasonable to project that ARD development in the saturated Falconbridge tailings could exceed that found in the saturated INCO tailings with the progression of time.

5.4 CHARACTERIZATION OF HYDROGEOLOGICAL CHARACTERISTICS

5.4.1 BASE OF PISTOL DAM (INCO)

A summary of estimated hydrogeological characteristics for the base of Pistol Dam is presented in Table 5.1. Pore pressure dissipations carried out during CPTU soundings were used to measure equilibrium pore pressures and estimate hydraulic conductivity for each depth shown. The CPTU data are in excellent agreement with data obtained from University of Waterloo piezometer installations, which are also shown in Table 5.1. Of particular interest was sounding I23-9327, which confirmed the existence of an upward gradient, i, (characteristic of an Artesian condition) by University of Waterloo piezometer installation IN22. Figure 5.14 shows the measured equilibrium pore pressures versus theoretical hydrostatic pore pressures for both the CPTU and the University of Waterloo piezometer. The agreement between the two data sets is excellent, and the magnitude of the upward gradient is approximately 0.10 - 0.15. As shown in Figure 5.14, hydraulic gradient is defined as the ratio between the excess pore pressure (Δu), which is the difference between the measured equilibrium pore pressure and the estimated hydrostatic pore pressure, and the vertical depth (Δl) over which the excess pore pressure was recorded. As both Δu and Δl have units of metres, hydraulic gradient measurements are dimensionless.

The CPTU estimates of hydraulic conductivity show good consistency and range from 10^{-6} - 10^{-7} cm/s. This is consistent with University of Waterloo piezometer data and with the literature (Freeze and Cherry, 1979) for the observed soil stratigraphy (clay - fine sand).

W.D. Robertson et al. (1991), on the basis of sulphate measurements from University of Waterloo piezometer nests, estimated an upward migration (v) of seepage from Pistol Dam of

Table 5.1: Summary of Estimated Hydrogeological Characteristics at the Base of Pistol Dam

CPTU Sounding	Depth (m)	Equilibrium Pore Pressure (m of H_20)	Hydraulic Conductivity (cm/sec)	U. of W. Piezometer Installation	Depth (m)	Equilibrium Pore Pressure (m of H_20)	Hydraulic Conductivity (cm/sec)
I19-9323	1.2	1.5	4.1×10^{-7}				
	2.2	2.5	8.8×10^{-6}				
	3.2	3.4	3.4×10^{-6}				
	4.2	4.2					
I20-934	2.2	2.0	7.3×10^{-7}				
	3.2	3.1	3.5×10^{-7}				
	4.2	4.2	1.6×10^{-6}				
I21-9325	2.2	0.9	4.7×10^{-7}				
	4.2	2.7	3.4×10^{-7}				
	4.9	3.4	8.1×10^{-7}				
I22-9326	3.9	4.1	6.7×10^{-7}	IN32	2.1	2.1	
					4.1	4.3	
I23-9327	4.3	4.2		IN22	2.2	2.0	2.0×10^{-7}
	9.3	10.6	8.1×10^{-7}		6.9		4.0×10^{-8}
	10.3	11.6	1.4×10^{-6}		7.0	8.5	
	12.3	13.6	4.0×10^{-6}		8.8	10.4	
	13.3	14.8			10.0	11.6	
	14.3	15.7			14.4	15.9	9.0×10^{-5}
	14.5	15.9					
I26-9332	6.2	6.2	2.7×10^{-6}	IN34	5.5	5.5	
	8.2	8.2	2.8×10^{-6}		9.5	9.6	
	9.2	9.2			12.5	12.6	
	10.2	10.2					

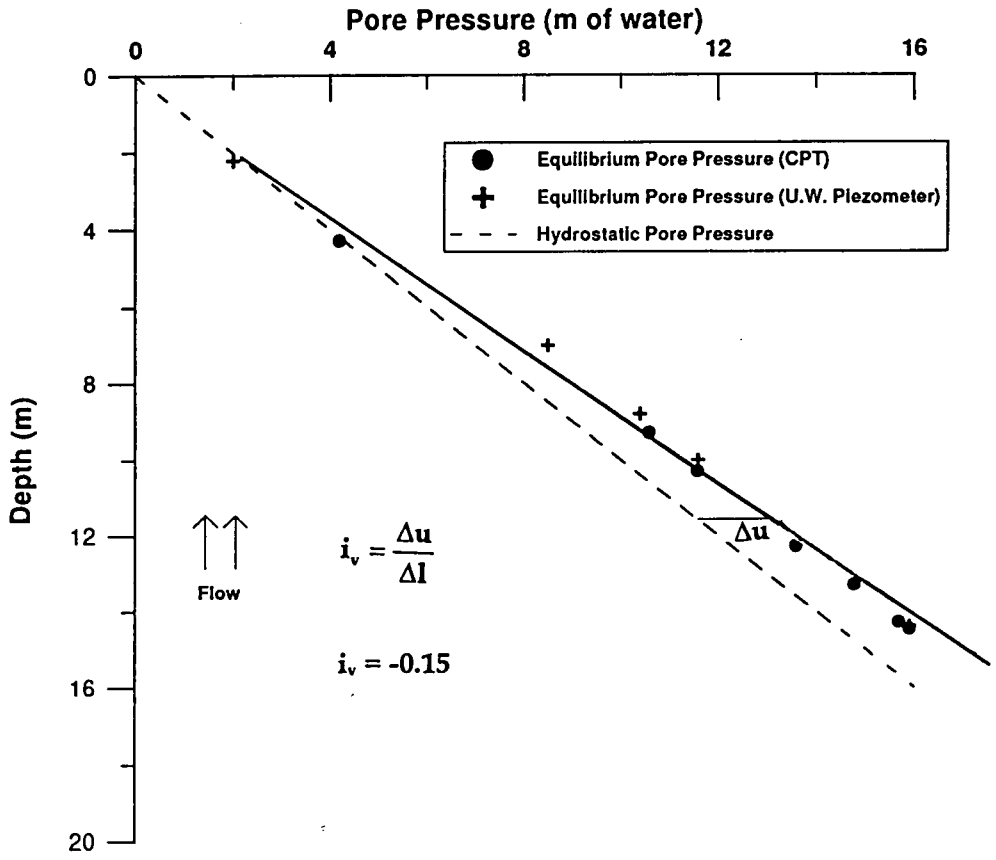


Figure 5.14: Estimate of Hydraulic Gradient in Native Soils at the Base of Pistol Dam

approximately 20 cm/year in the vicinity of piezometer IN22. The rate of upward migration is equivalent to the groundwater velocity and is defined as follows:

[5.1] v=K*i

The rate of upward migration of seepage from Pistol Dam in the native soils in the vicinity of piezometer IN22 can be calculated from [5.1] using the estimates of upward gradient and hydraulic conductivity derived from the CPTU data. Assuming an average gradient magnitude of 0.125 and an average hydraulic conductivity of 2.5 x 10^{-6} cm/sec for the native soils, the upward rate of migration of the seepage is estimated to be 10 cm/yr. Considering

the strong dependence of equation [5.1] on hydraulic conductivity, which can show a broad range of values, the agreement between the W.D. Robertson et al. (1991) estimate for upward migration and that derived from CPTU data is considered excellent.

5.4.2 FAULT LAKE TAILINGS IMPOUNDMENT (FALCONBRIDGE)

Hydrogeological parameters for this site were based on extensive pore pressure dissipation tests carried out during sounding F01-9333. Determination of the depth of the phreatic surface was a primary concern of Falconbridge personnel. The location of the phreatic surface was found by measurement of the equilibrium pore pressure for each dissipation test depth, and this indicated a significant downward gradient in the tailings. Figure 5.15 shows a comparison between the equilibrium pore pressures measured in the tailings and the hydrostatic pore pressures based on the estimated location of the phreatic surface. The difference between the measured pore pressures in the tailings and the hydrostatic pore pressures translates to a downward gradient of magnitude 0.4, as shown in 5.15. It should be noted that the magnitude of the gradient has been estimated based on only one day of testing and that the magnitude of the gradient may be subject to seasonal variation.

The existence of the downward gradient is due to the difference in pore water pressures between the tailings impoundment and the regional groundwater system. During active deposition of the tailings into the impoundment the tailings were kept saturated. The process water discharged with the tailings and infiltration from precipitation maintained the local groundwater table at the surface of the impoundment. After deposition of tailings into the impoundment ceased in 1978, the position of the phreatic surface gradually started to decline. Currently, the phreatic surface is estimated to be at a depth of 10.5 m. The downward gradient is acting to lower the phreatic surface in the tailings until it coincides with the

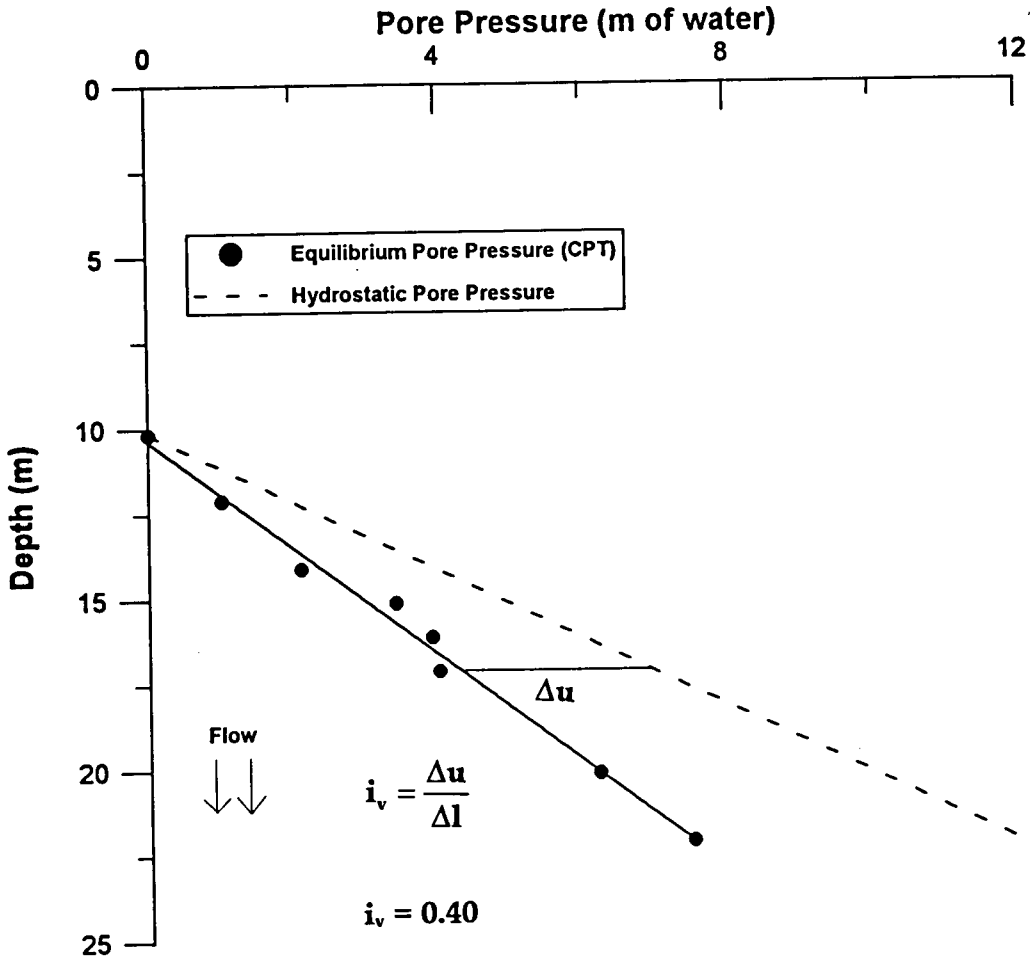


Figure 5.15: Estimate of Hydraulic Gradient in Sulphide Bearing Tailings at the Fault Lake Tailings Impoundment

elevation of the regional groundwater table. The rate at which this decline is occurring is very slow, and this can be attributed to the low hydraulic conductivity of the tailings.

Estimates of hydraulic conductivity were also made based on pore pressure dissipations at different depths. Estimates of hydraulic conductivity in the tailings ranged from 10^{-5}-10^{-6}

cm/s which are representative of the fine-grained nature of the tailings and in agreement with previous studies (Noranda Technology Centre, 1994). The hydraulic conductivity in the lacustrine foundation material were in the same range as the tailings, which is typical of the clayey-silt soil.

Based upon the estimates of average gradient magnitude of 0.4 and average hydraulic conductivity of the tailings of 5.0×10^{-6} cm/s, the average downward migration of tailings pore water is estimated to be 60 cm/year from equation [5.1]. This estimate of pore water migration should be considered preliminary as it is dependent upon the magnitude of the gradient estimated from CPTU data, which was not corroborated due to a lack of other field data.

5.5 PHYSICAL CHARACTERIZATION

5.5.1 GENERAL

Figure 5.16 presents estimates of geotechnical strength parameters and interpreted stratigraphy for an RCPT sounding carried out at the crest of Pistol Dam (I11-9330). Relative Density (D_r) and peak friction angle (ϕ') are drained strength parameters, and therefore estimates of these parameters were restricted to sandy tailings and native soils. Contrastingly, estimates of undrained strength (S_u) were restricted to the silty clay native soils. Estimates of SPT $(N_1)_{60}$ were made for all soil types. Details concerning the empirical correlations used in the estimation of each parameter are included in the references for CPTINT 5.0, which are included in Appendix B.

Relative Density (D_r) is an index parameter that can be used to provide an indication of the stress-strain behaviour of a cohesionless soil. D_r is a ratio used to express the relationship

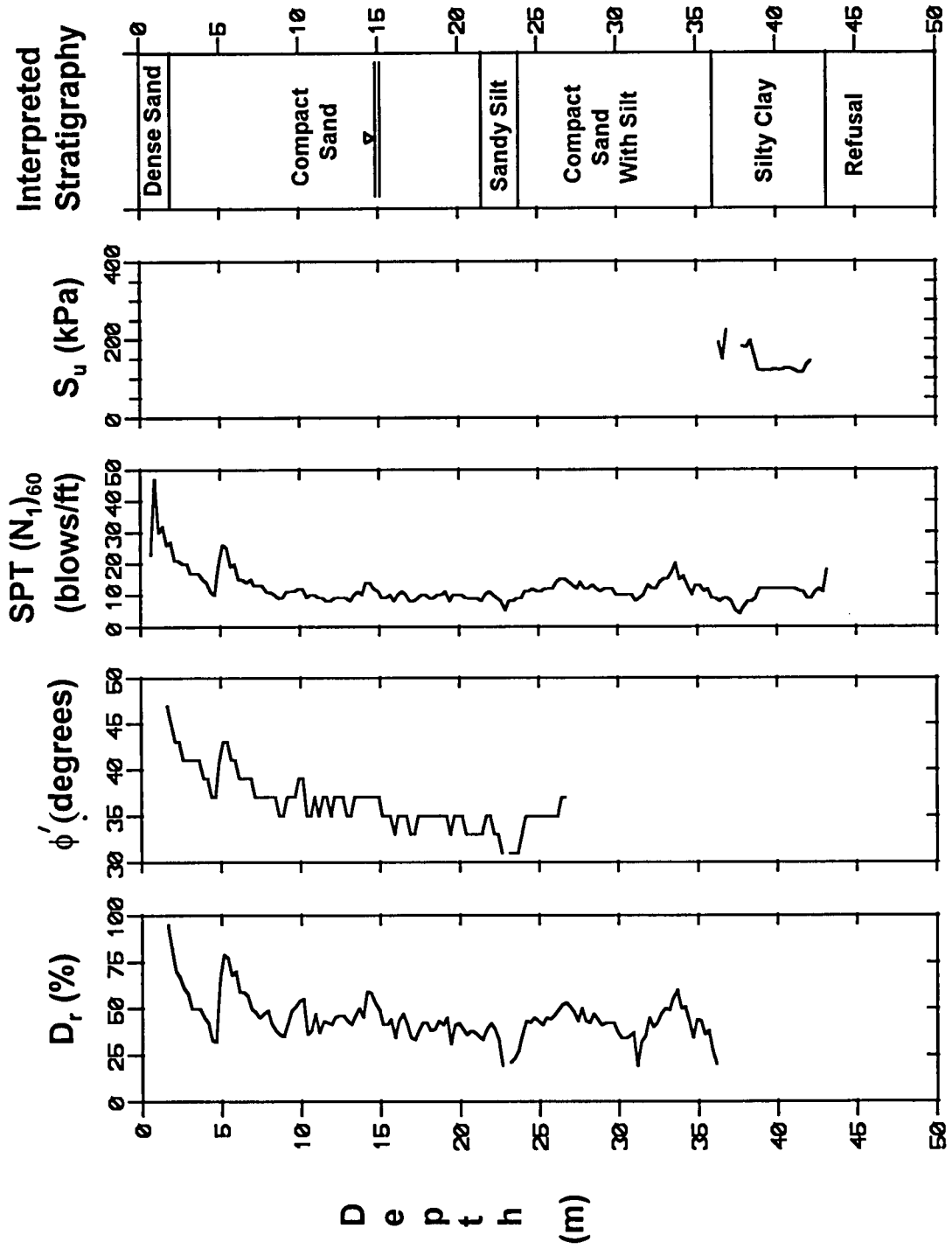


Figure 5.16: Estimates of Geotechnical Strength Parameters For RCPTU Sounding at the Crest of Pistol Dam

between the actual void ratio and the minimum and maximum void ratios of a soil. D_r in the upper tailings crust (above 1.6 m depth) was above 90 % indicating a very dense soil. Below the upper crust of tailings, D_r of the tailings generally ranged from 35 - 60 %, with occasional looser and denser layers falling outside this range.

Peak friction angle (ϕ') is essentially the stress-dependent component of the shear strength for the soil. It is not an inherent value but depends on many things, most predominately the density and distribution and angularity of grain size. ϕ' was estimated to be greater than 45° in the dense upper crust of tailings. Below this layer, ϕ' showed a decreasing trend and ranged from approximately 31 - 41° in the tailings. The correlation used to estimate ϕ', proposed by Robertson and Campanella (1983), was developed for incompressible sands. The stratigraphic profile shown in Figure 5.16, which was inferred from the CPTU data, indicates a higher silt content of the tailings below a depth of approximately 22 m. This increase in silt content results in a corresponding increase in soil compressibility. For more compressible soils, the correlation typically results in lower (and conservative) estimates of ϕ'. Below a depth of approximately 27 m, estimates of ϕ' were not made as the more compressible nature of the tailings was beyond the scope of the correlation.

SPT $(N_1)_{60}$ values are considered an index of soil density. Predicted $(N_1)_{60}$ values were very high (> 45 blows/ft.) in the dense upper crust of the tailings, ranged from approximately 15 - 20 blows/ft. in the tailings from 1.6 m - 6.4 m and ranged from approximately 8 - 15 blows/ft. for the remaining depth of tailings. Estimates of $(N_1)_{60}$ values in the native silty clay soil ranged from 4 - 12.

Undrained shear strength is the shear strength of the soil measured during shearing under undrained loading conditions. S_u is not a unique parameter and depends significantly on the type of test used, rate of strain and the orientation of the failure planes. Estimates of S_u in the

native silty clay soil ranged from approximately 110 - 200 kPa. This corresponds to a $\frac{S_u}{\sigma_{v0}'} \approx$ 0.2 - 0.4, which is indicative of a lightly overconsolidated fine-grained soil.

5.5.2 PRELIMINARY ASSESSMENT OF FLOW LIQUEFACTION SUSCEPTIBILITY

CPTU data from a RCPTU sounding at the crest of INCO's Pistol Dam (I11-9330) is plotted in Figure 5.17 with respect to state parameter (ψ), in accordance with the framework of Plewes et al. (1992) presented in Section 3.3.2. Negative values of ψ are representative of essentially dilative (SH) soils, whereas positive values of ψ are representative of essentially contractive (SS) soils. Figure 5.17a is a plot of all CPTU data points for the sounding (collected every 0.025 m) with respect to ψ. Most of the data points for the sounding plot as a negative ψ value, but a significant portion of the data has a ψ value between 0 - -0.05. Considering the screening nature of this methodology, soils with ψ values between 0 - -0.05 can be conservatively viewed as potentially contractive. Figure 5.17b is a plot of ψ versus depth, which facilitates the interpretation of the data presented in Figure 5.17a with respect to specific depths. The phreatic surface for this sounding was located at a depth of 15 m, and the discussion of soil behaviour and the susceptibility for flow liquefaction is focused on saturated soils. Upon review of Figure 5.17b, it is apparent that there is potential for contractive behaviour of the tailings. If the boundary of contractive/dilative soil behaviour is conservatively assumed to be ψ = -0.05, then the saturated tailings are potentially contractive from 15 m - 27 m and from 31 m - 32.5 m. Saturated zones that show stronger tendencies for contractive behaviour include the tailings between 15 - 17.5 m, 22.5 m - 24 m and 31m - 32 m. The interface between the tailings and the native soils is approximately located at a depth of 37 m. The native silty clay soil is interpreted to be strongly contractive, with ψ values generally greater than 0.10. However, the relatively stiff nature of the silty clay soil (as evidenced by $\frac{S_u}{\sigma_{v0}'} \approx$ 0.2 - 0.4)

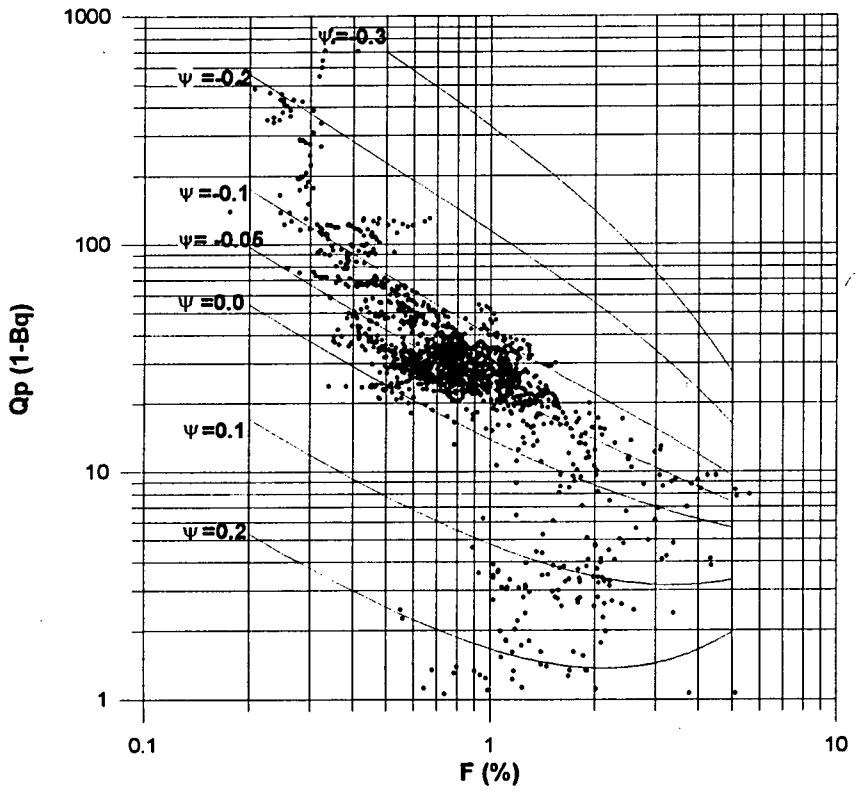


Figure 5.17a CPTU-Based Method of Estimating State Parameter (ψ) For RCPTU Sounding at the Crest of Pistol Dam

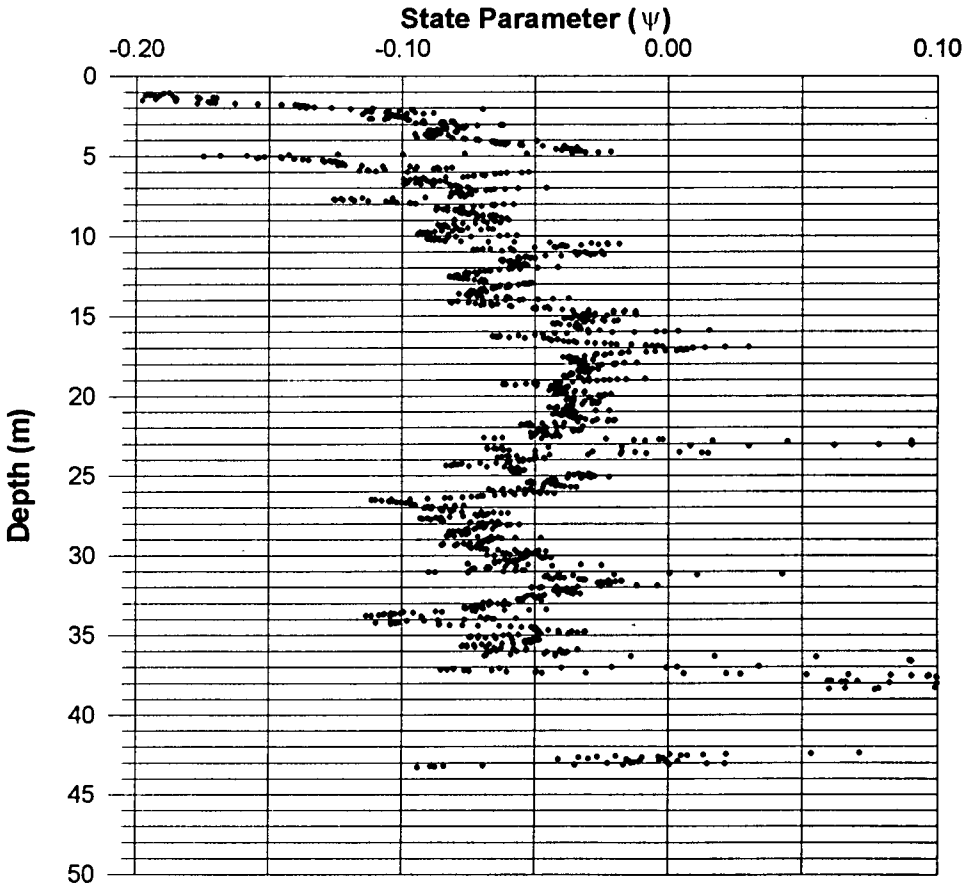


Figure 5.17b State Parameter (ψ) Versus Depth For RCPTU Sounding at the Crest of Pistol Dam

indicates that the native soils may not exhibit a strain softening response and subsequently may not be susceptible to flow liquefaction.

5.5.3 PRELIMINARY ASSESSMENT OF CYCLIC LIQUEFACTION SUSCEPTIBILITY

An assessment of the susceptibility for cyclic liquefaction of soils requires consideration of site seismicity. The maximum credible earthquake (MCE) represents the most severe earthquake that could be reasonably expected to occur at a given site, and is generally considered the appropriate design event for closure of tailings impoundments. The INCO Central Tailings Area lies in a zone of low seismicity that includes northeast and southeast Ontario, Southern Quebec and northeast Newfoundland. There are no known events larger than M = 4.3 since records were initially compiled in the 1930's (Basham et al., 1982). For the INCO Central Tailings Area, a peak ground acceleration (amax) of 0.1g is estimated for a MCE of M=5.0, occurring at a distance of 20 km for the site (Martin and Tissington, 1996).

Section 3.3.3 described a methodology proposed by Robertson and Fear (1995) for evaluating the cyclic liquefaction susceptibility of soils from CPT data. Figure 5.18 through Figure 5.20 provide a summary of this procedure for a RCPTU sounding at the crest of INCO's Pistol Dam (I11-9330). The CPT tip resistance (q_c) is normalized with respect to effective overburden stress according to equation [3.8]. The effect of the normalization procedure is readily apparent, as shown in Figure 5.18. The plot of non-normalized q_c (Figure 5.18a) shows an increasing trend with depth, whereas the plot of normalized q_{c1} (Figure 5.18b) shows a slight decreasing trend with depth. The differences between q_c and q_{c1} can be attributed to stress-level effects. By elimination of these effects, q_{c1} gives a more meaningful measure of soil behaviour.

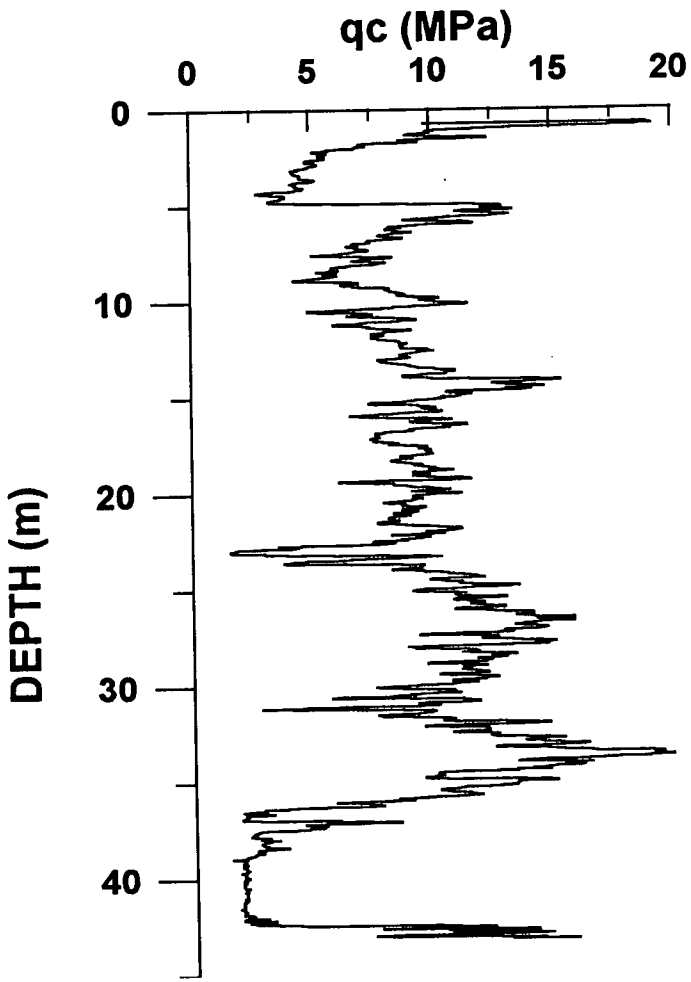


Figure 5.18a: q_c Versus Depth For RCPTU Sounding at the Crest of Pistol Dam

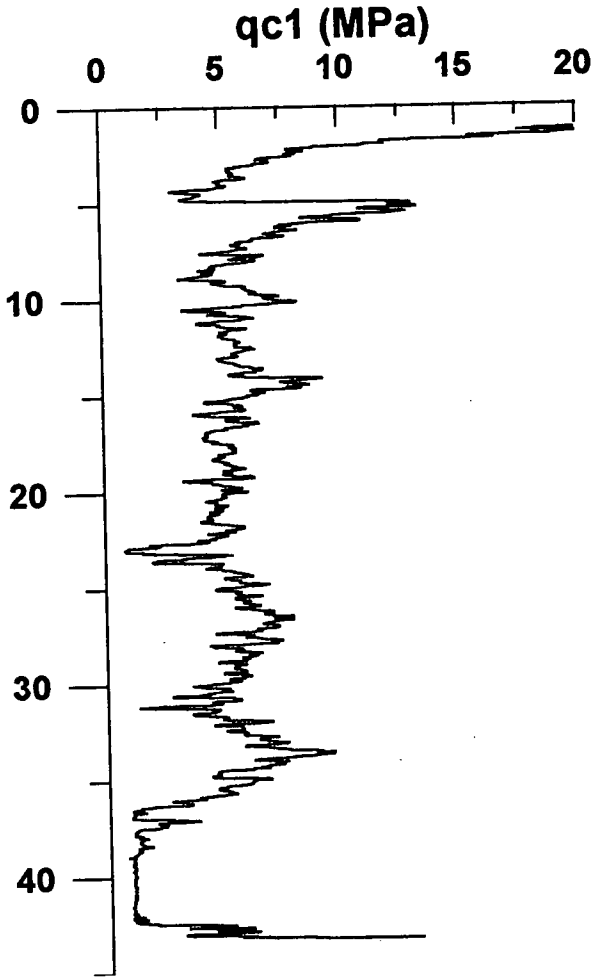


Figure 5.18b: q_{c1} Versus Depth For RCPTU Sounding at the Crest of Pistol Dam

Figure 5.19 details the steps followed in correcting q_{c1} for the effects of the fines content (FC) in the tailings and native soils. The fines content was estimated according to equation [3.11], and was found to increase with depth (Figure 5.19a). The increase in FC with depth is consistent with the previous observations noted for this sounding, as discussed in Section 5.1.1. Of particular interest were the estimated FC for the tailings from a depth of approximately 22.5 m - 24 m. The large increase in FC in this zone ($25 < FC < 50$) is in agreement with the previously denoted sandy silt soil behaviour type. The interface of the tailings and the fine-grained native soils at a depth of approximately 37 m is readily apparent by the large increase in FC.

Corrections to q_{c1} for FC, referred to as Δq_{c1} were made according to equation [3.9], and are shown with respect to depth in Figure 5.19b. The Δq_{c1} values mirror the changes in FC, with increases in FC resulting in increases to Δq_{c1} values.

Figure 5.19c is a plot of normalized CPT tip resistance (q_{c1}) corrected for fines content to an equivalent clean sand, referred to as $(q_{c1})_{ecs}$, with respect to depth. The $(q_{c1})_{ecs}$ values are simply the sum of q_{c1} and Δq_{c1} values. The net effect of correcting q_{c1} for FC is to reduce the susceptibility for cyclic liquefaction of finer-grained soils, which is similar to the recommendations of Seed et al. (1985) for the SPT. It should be noted that the estimates for FC shown in Figure 5.19b were not compared with FC determined from soil samples due to a lack of available data. Given the discussion in Section 3.3.3 concerning the correlation from which the FC estimates were derived, and the fact that FC acts to reduce cyclic liquefaction susceptibility, this procedure for estimating cyclic liquefaction susceptibility should be considered preliminary.

Figure 5.20 presents the results of a preliminary assessment of cyclic liquefaction susceptibility for the tailings and native soils at the crest of INCO's Pistol Dam. The cyclic resistance ratio (CRR) of the soils were estimated from $(q_{c1})_{ecs}$ values using the chart shown in Figure 3.12.

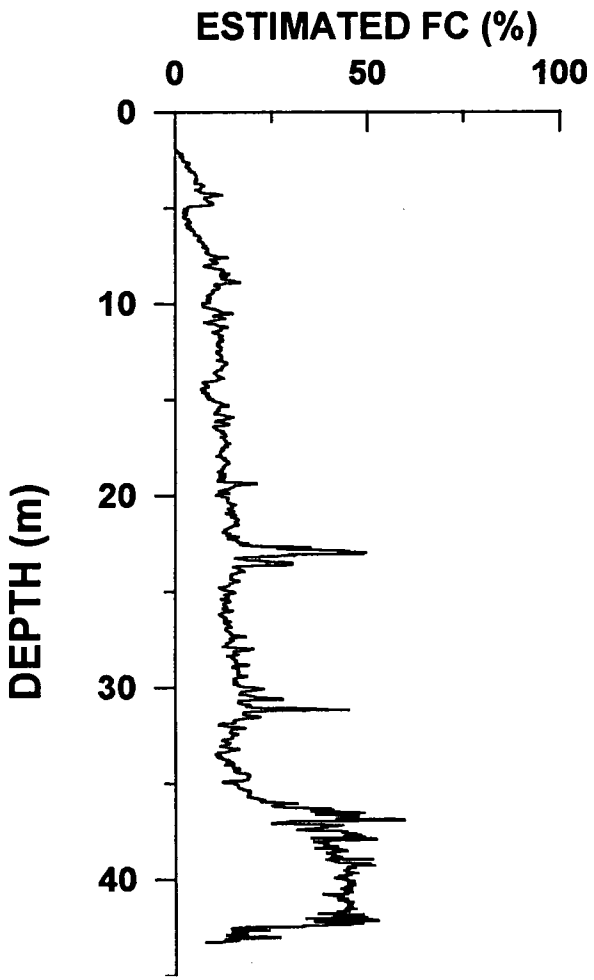


Figure 5.19a: Estimated Fines Content (FC) Versus Depth For RCPTU Sounding at the Crest of Pistol Dam

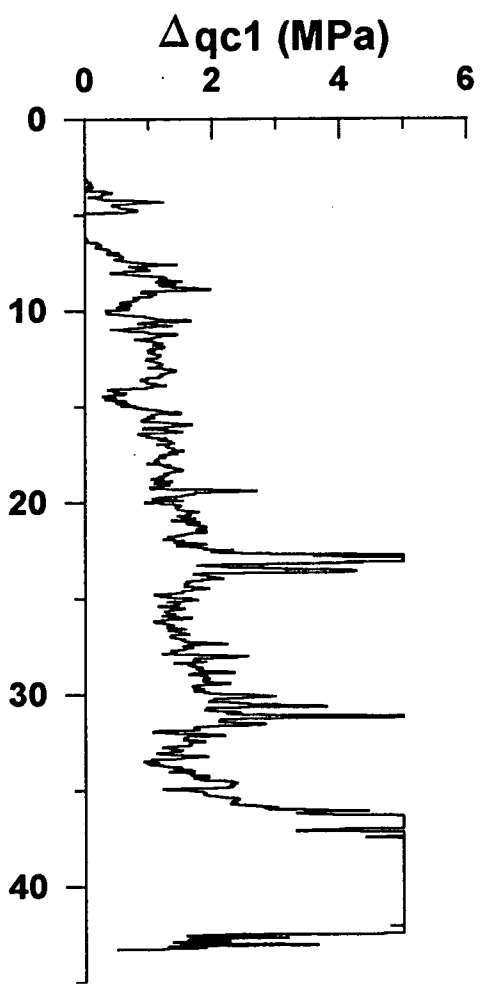


Figure 5.19b: Δq_{c1} Versus Depth For RCPTU Sounding at the Crest of Pistol Dam

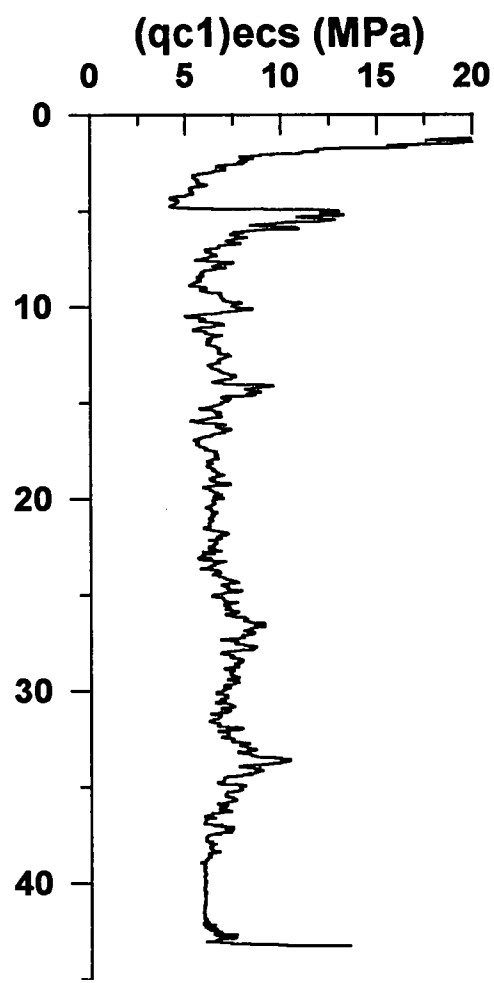


Figure 5.19c: $(q_{c1})_{ecs}$ Versus Depth For RCPTU Sounding at the Crest of Pistol Dam

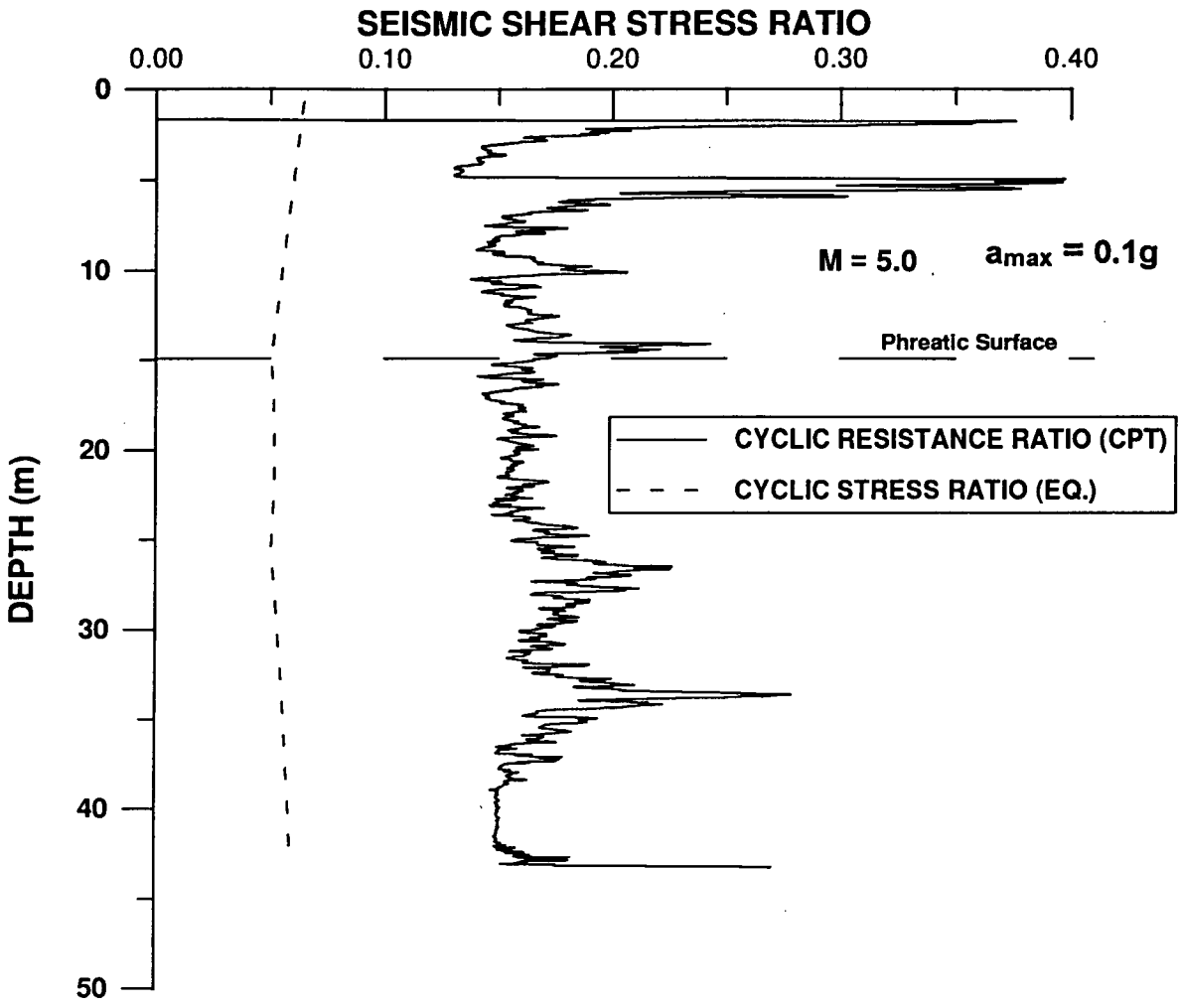


Figure 5.20: Seismic Shear Stress Ratio Versus Depth For RCPTU Sounding at the Crest of Pistol Dam

The cyclic stress ratio (CSR) induced by the MCE was calculated using the relationship proposed by Seed at al. (1985). A scaling factor of 1.5 was used to account for the earthquake M=5.0, in accordance with the recommendations of Seed et al. (1985). As shown in Figure 5.20, the CRR of the penetrated soils are substantially greater than the CSR induced by the MCE for both unsaturated and saturated conditions. Thus, cyclic liquefaction of the saturated tailings and native soils does not appear to be a possibility based on this preliminary assessment. This finding is not surprising considering the low seismicity of the site.

6.0 COMPARISON OF THE RCPTU AND CONVENTIONAL TESTING METHODS

Table 6.1 presents a summary comparison of the RCPTU and conventional testing methods with respect to data procurement and cost for geoenvironmental characterization of sulphide bearing tailings. The quality of data procurement for each test is rated from A - C for the various geoenvironmental criterion shown in Table 6.1, with A being the highest rating. Factors considered in rating quality of data procurement include data continuity (e.g. continuous data collection versus discrete sampling) and the overall preference of test data for engineering design. N/A indicates that a test method is not applicable for evaluating a particular geoenvironmental criteria. The costs shown for each test method are approximate and exclusive of mobilization/demobilization costs, which are likely similar for all test methods.

Based on the comparison shown in Table 6.1, the RCPTU can provide a technically sound cost-effective alternative to conventional testing methods. To match the data accumulated by the RCPTU, conventional technology would require a combination of (2) to (5) inclusive from Table 6.1. The likely per-metre costs for a combination of these methods would exceed $100/m, although not all sites require such a comprehensive characterization and consequently costs would be lower for less detailed characterizations. However, even the cost of carrying out drilling with just SPT testing is still more costly than the RCPTU, which provides (2) to (5) inclusive. The economic benefit gained by expanded use of RCPTU in comparison with conventional methods can be used to strengthen site investigation programs. For a given site, the cost savings realized through application of RCPTU testing could be used to carry out a larger number of RCPTU tests in comparison with standard drilling methods, which would result in a more detailed characterization of subsurface conditions. The cost savings from using RCPTU testing could also be used for collection of pore water samples by means of BAT technology, which would significantly enhance interpretation of bulk resistivity

measurements. The comparison presented in Table 6.1 underscores the ability of the RCPTU to provide comprehensive geoenvironmental site characterization at reasonable cost in sulphide bearing tailings impoundments.

Table 6.1: RCPTU Testing Versus Conventional Testing Methods With Respect to Data Procurement and Cost

	Stratigraphy	Bulk Resistivity	Geotechnical Parameters	Hydrogeological Characteristics	Cost ($/m)
(1). RCPTU	A	A	B	B	25-30 (Woeller, 1994)
(2).Drilling with 5' SPT	B	N/A	C	N/A	50 (Diggle, 1994)
(3).Drilling with continuous sampling	A	N/A	A (with lab testing)	N/A	100 + lab costs (Diggle, 1994)
(4).Drilling with resistivity well logging	C	A	N/A	N/A	45 (King, 1994)
(5).Drilling with nested piezometers	C	N/A	N/A	A	100 (Diggle, 1994)

7.0 RECOMMENDED PROCEDURES FOR USING IN-SITU TESTING METHODS FOR THE GEOENVIRONMENTAL CHARACTERIZATION OF SULPHIDE BEARING TAILINGS IMPOUNDMENTS

Based on the experience and results from the field work carried out for this thesis, Figure 7.1 provides a framework for the application of in-situ testing methods for the geoenvironmental characterization of sulphide bearing tailings impoundments. The RCPTU and CPTU can rapidly provide a comprehensive and economical assessment of environmental and geotechnical site conditions. The RCPTU provides a direct measure of the bulk resistivity of the soil and pore water, which can be used to infer pore water contamination due to oxidation of sulphide minerals and subsequent ARD processes. In addition, discrete pore water sampling (i.e. BAT sampling) and subsequent chemical analyses can be used to augment RCPTU testing by assisting the interpretation of the effects of pore water chemistry on bulk resistivity measurement.

The CPTU provides valuable insight into the geotechnical and hydrogeological properties of tailings. The CPTU effectively delineates stratigraphic variations in tailings, gives estimates of key geotechnical strength parameters and can measure pore pressure distribution within the tailings. This information is, at a minimum, required for any stability analysis of a tailings impoundment. Additionally, the CPTU data can be used to carry out preliminary assessments of liquefaction susceptibility, considering both static and dynamic loading conditions. The ability to examine liquefaction susceptibility directly from CPTU data is a significant attraction of the technology, considering the preponderance of historical tailings dam failures which have been attributed to liquefaction of the tailings. Finally, estimates of hydraulic conductivity of tailings and the identification of hydraulic gradients in the tailings can be used to assess transport of ARD contamination in sulphide bearing tailings.

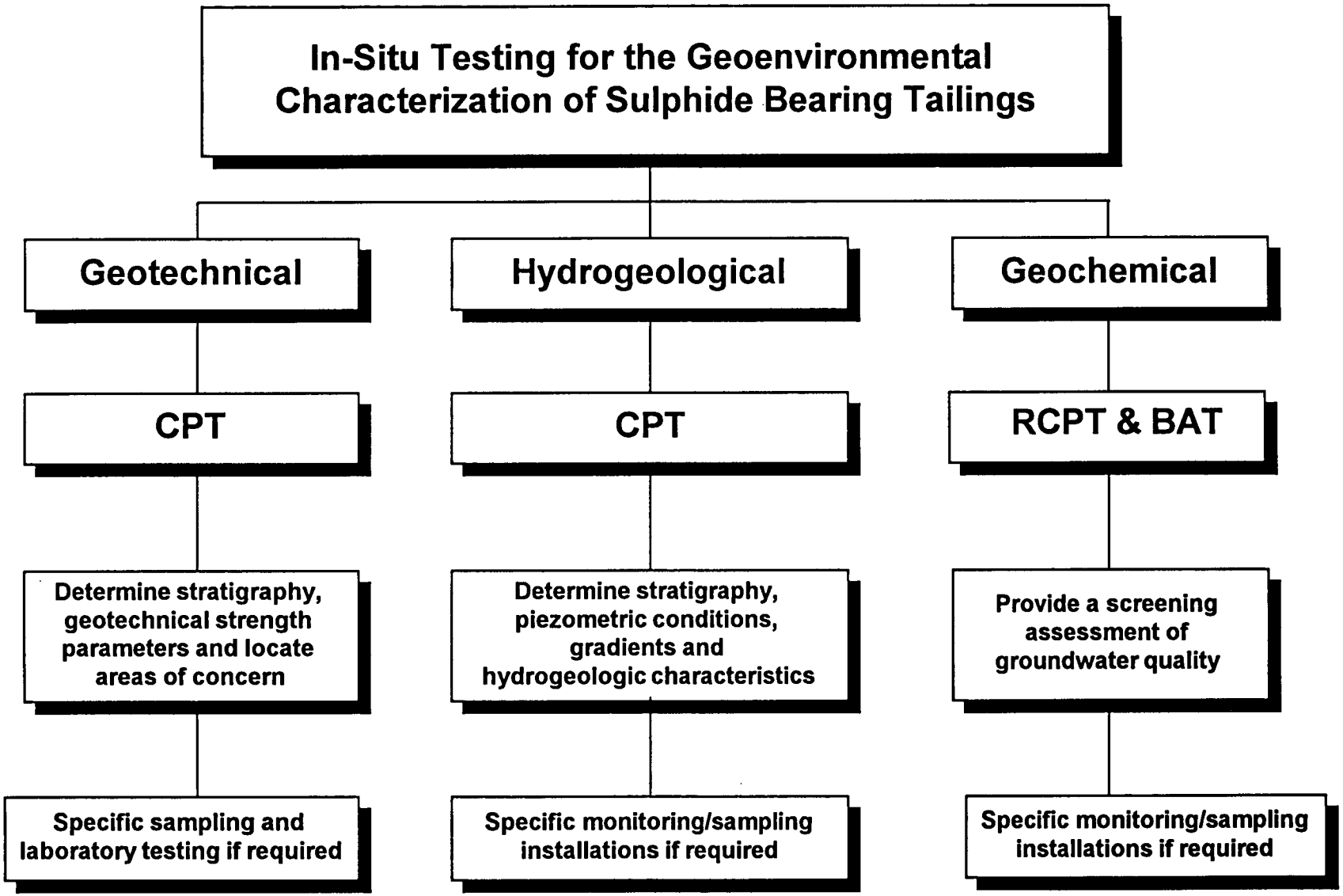


Figure 7.1: Proposed Methodology For the Application of In-Situ Testing Methods for the Geoenvironmental Characterization of Sulphide Bearing Tailings

Depending upon the complexity of the site being investigated, the in-situ testing data may be sufficient. However, the in-situ testing results may indicate environmental and geotechnical conditions which require further assessment. In general, it would be expected that the results of an in-situ field testing program at a sulphide bearing tailings impoundment would be supplemented by some form of conventional drilling program. The results of the in-situ testing program could be used to direct additional site investigation activity, which may include discrete soil sampling and lab testing, installation of monitoring/sampling stations and discrete pore water sampling and chemical analyses. An initial site investigation program may include a wide variety of conventional testing methods to supplement the in-situ testing program. However, if strong correlations can be developed between the results of the RCPTU data and the results of the conventional drilling-based testing methods then future geoenvironmental characterizations at the site can be focused on the more cost-effective in-situ testing technology.

8.0 SUMMARY AND CONCLUSIONS

The results from site investigations carried out at three Canadian mine sites demonstrate that in situ testing, and more specifically the resistivity piezocone (RCPTU), can provide a technically sound and cost-effective technique for the geoenvironmental characterization of sulphide bearing tailings impoundments. Based on the results from the in situ field testing program the following can be concluded:

(1). RCPTU bulk resistivity measurements in the unsaturated zone of sulphide bearing tailings and native soils affected by acid rock drainage (ARD) processes can provide a qualitative measure of pore water chemistry. Bulk resistivity measurements are influenced by the countering effects of changing saturation and pore water chemistry which causes measured bulk resistivities to be highly variable. However, the assessment of ARD processes in sulphide bearing tailings by the RCPTU is aided by the moisture retention capabilities of tailings and the highly conductive pore water symptomatic of ARD contamination. As evidenced by RCPTU soundings at INCO and Falconbridge mine sites, very low bulk resistivity measurements (< 10 Ω-m) can be measured in the unsaturated tailings. These low bulk resistivity measurements are a function of high saturation and high pore water conductivity. The low bulk resistivity measurements corresponded with high pore water sulphate concentrations, obtained from chemical analyses of discrete pore water samples, which are indicative of ARD contamination. Discrete pore water sampling in combination with RCPTU testing enhances the qualitative interpretation of the relative influence of saturation and pore water chemistry on bulk resistivity measurements in the unsaturated zone of sulphide bearing tailings and native soils.

Based on the results of RCPTU testing and chemical analyses of discrete pore water samples, ARD processes were more severe in the unsaturated Falconbridge tailings than in the

unsaturated INCO tailings, for the specific test locations. Lower bulk resistivity measurements (indicative of higher pore water conductivity and corresponding ionic loading) and significantly higher pore water sulphate concentrations were measured in the Falconbridge unsaturated tailings in comparison with the INCO unsaturated tailings.

(2). RCPTU bulk resistivity measurements in the saturated zone of sulphide bearing tailings and native soils provide a more definitive measure of pore water chemistry than measurements in the unsaturated zone, due to the removal of the influence of variable saturation on bulk resistivity measurements. RCPTU bulk resistivity measurements corresponded with pore water chemistry of discrete pore water samples, demonstrating the ability of the tool to map low resistivity pore water. Of particular interest were relationships developed between pore water resistivity and RCPTU bulk resistivity and pore water sulphate concentration and RCPTU bulk conductivity for all test sites. Estimates of apparent formation factor (F) based on the relationship between bulk resistivity and pore water resistivity were made for all test sites. The estimates of F enable estimation of pore water resistivity directly from RCPTU bulk resistivity measurements, from which increases in ionic loading of the pore water due to ARD contamination can be inferred. RCPTU bulk conductivity measurements showed good agreement with pore water sulphate concentrations for all test sites. Pore water sulphate concentration is a key indicator of ARD processes, as elevated sulphate concentrations occur prior to the development of more developed ARD processes (i.e. increased acidity and heavy metals concentrations). The results from this study indicate that the detection of elevated pore water sulphate concentrations in sulphide bearing tailings and native soils is feasible with the RCPTU. Therefore, the RCPTU appears to be well-suited for the long-term monitoring of sulphide bearing tailings impoundments, where contamination can take place over tens of years.

The data presented in this study for saturated sulphide bearing tailings and saturated native soils give insight into the relative stage of ARD development for the test locations from which test data were collected. It must be stressed that interpretation of the data should be restricted to the specific testing locations for the respective sites.

The results of testing indicate that ARD contamination is more severe for the saturated INCO tailings than for the saturated Falconbridge tailings and INCO native soils. In general higher RCPTU bulk conductivity (or lower bulk resistivity) measurements and higher pore water concentrations of acidity and heavy metals were measured for the INCO saturated tailings in comparison with the other test sites. In the saturated INCO tailings, high pore water sulphate concentrations in combination with the slightly acidic pore water pH and elevated heavy metals concentrations of the pore water indicates later Stage 2 development. In the saturated Falconbridge tailings, the fact that elevated metals are contained in the pore water is indicative of Stage 2 ARD development. However, the significantly lower pore water heavy metals concentrations and generally lower sulphate concentrations and bulk conductivity measurements in comparison with the saturated INCO tailings data indicates that ARD processes are less developed for the saturated Falconbridge tailings. Further evidence of this fact, was the neutral pH of the Falconbridge tailings pore water in comparison with the slightly acidic INCO tailings pore water. In the saturated INCO native soils, lower pore water sulphate concentrations and bulk conductivity measurements were measured in comparison with the saturated INCO and Falconbridge tailings. Significantly lower pore water heavy metals concentrations and higher pH were measured in the saturated native INCO soils in comparison with the saturated INCO tailings, while these values were approximately similar to those measured in the saturated Falconbridge tailings (with the exception of pore water Ni concentration, which was much lower). ARD contamination is significantly lower for the INCO native soils than for the INCO tailings, and based upon pore water sulphate concentrations and bulk conductivity measurements is less severe than that in the

Falconbridge tailings. However, based upon the peaks in pore water sulphate concentrations and heavy metals concentrations and peaks in bulk conductivity measurements at specific locations at the base of INCO's Pistol dam it is apparent that ARD contamination is impacting the site from the adjacent INCO tailings. The small quantity of data from the saturated Gibraltar tailings prevents any meaningful comparisons with the site, although based on limited bulk conductivity and pore water sulphate concentration data it appears ARD processes are less developed than those for the saturated INCO and Falconbridge tailings.

(3). CPTU pore pressure dissipation data can provide reasonable estimates of hydrogeological characteristics which can be used for modeling transport of ARD contamination. An estimate of the migration of ARD contamination at the base of Pistol Dam was in reasonable agreement with an estimate based on pore water sulphate concentration.

(4). CPTU-based methods can provide an initial assessment of the potential for liquefaction of tailings, under both static and dynamic loading conditions. Methodologies proposed by Plewes et al. (1992) and Robertson and Fear (1995) were used to assess flow liquefaction and cyclic liquefaction susceptibility, respectively, of tailings at the crest of INCO's Pistol Dam. Results indicate that zones of tailings are potentially contractive, and therefore could be susceptible to flow liquefaction if a viable triggering mechanism exists. Results of the preliminary assessment of cyclic liquefaction susceptibility indicate that the tailings would not liquefy under the design earthquake event.

9.0 RECOMMENDATIONS FOR FUTURE RESEARCH

In order to improve the application of the RCPT and discrete pore water sampling technologies for the geoenvironmental characterization of sulphide bearing tailings the following recommendations are proposed:

(1). Improved Physical Design of the Resistivity Module:

The length (350 mm) and the diameter (15 cm^2) of the resistivity module can inhibit penetration in dense soils due to excessive friction on the resistivity module. Although this occurred seldomly during the course of the field investigation program, it is recognized that the size of the resistivity module could be problematic at other sites. The UBC ISTG has recently reduced the diameter of the resistivity module from 15 cm^2 to 10.5 cm^2. The smaller diameter of the new module should significantly reduce potential problems with pushing in dense soils.

(2). Improved BAT Water Sampling Technology:

The hypodermic needle system employed by the BAT system used in this study became blocked several times by rubber after it punctured the septum. Notwithstanding the problems experienced with blocking of the hypodermic needle, the hypodermic needle system often requires a long period of time for sample recovery. Methods based on BAT-type technology, but not employing a hypodermic needle should be investigated. Campanella et al. (1995) modified the BAT system by replacing the hypodermic needle and septum system with a 9.5 mm swagelock fitting in a study of in situ measurement of hydraulic conductivity in sands. This system permits much higher flow rates than the hypodermic needle, which reduces the length of sampling time. The use of the swagelock fitting may be appropriate for

environmental sampling, but issues of sample integrity and cross-contamination require further research.

(3). More Comparisons of RCPTU Bulk Resistivity Measurements and Pore Water Chemistry in Sulphide Bearing Tailings:

It would be beneficial to conduct further studies at the INCO Central Tailings Area, Falconbridge Fault Lake tailings impoundment and Gibraltar tailings impoundment to strengthen the relationships developed between RCPTU bulk resistivity measurements and pore water chemistry for these sites. Also, more site investigations at other sulphide bearing tailings impoundments would provide data for evaluation of potential global relationships between bulk resistivity measurements and pore water chemistry, particularly for the relationship between bulk resistivity and pore water sulphate concentration.

(4). Development of a Resistivity Module Capable of Measuring the Induced Polarization Response of Sulphide Bearing Tailings:

Induced polarization (IP) is a current stimulated electrical phenomena observed as a delayed voltage response in earth materials (Sumner, 1976). Surface resistivity methods have been used in mineral exploration for identifying disseminated sulphide minerals, which exhibit a characteristic IP response (Sumner, 1976). Research is currently being carried out by the UBC ISTG for modification of the resistivity module to enable measurement of the IP response of penetrated soils. The ability to measure IP response with the resistivity module would enable estimation of sulphide content in sulphide bearing tailings. Thus, the RCPTU would be capable of assessing the current state of ARD processes through bulk resistivity measurements, and also give insight into the future potential for sulphide oxidation by estimating the sulphide content of the tailings.

(5). Use of a pH Module in Combination With the Resistivity Module For Geoenvironmental Characterization of Sulphide Bearing Tailings:

A pH module, capable of measuring pore water pH, could be used in combination with the resistivity module for assessing ARD contamination in sulphide bearing tailings. As the pore water acidity is indicative of the stage of ARD development, the pH module would provide valuable insight into ARD contamination of sulphide bearing tailings. Currently, pH modules configured for CPT technology are commercially available (Jolly, 1996).

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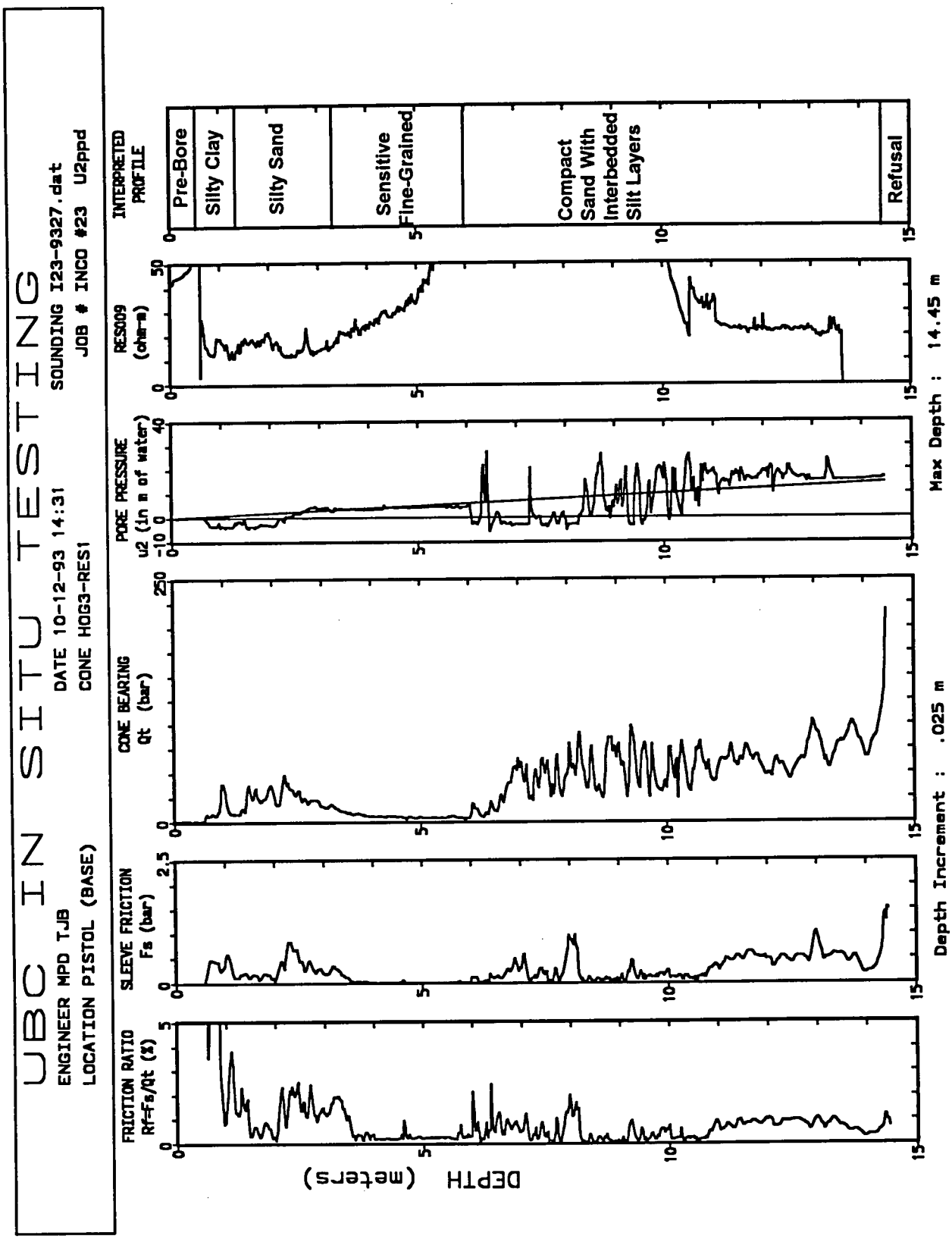
APPENDIX A - RCPT CONEPLOTS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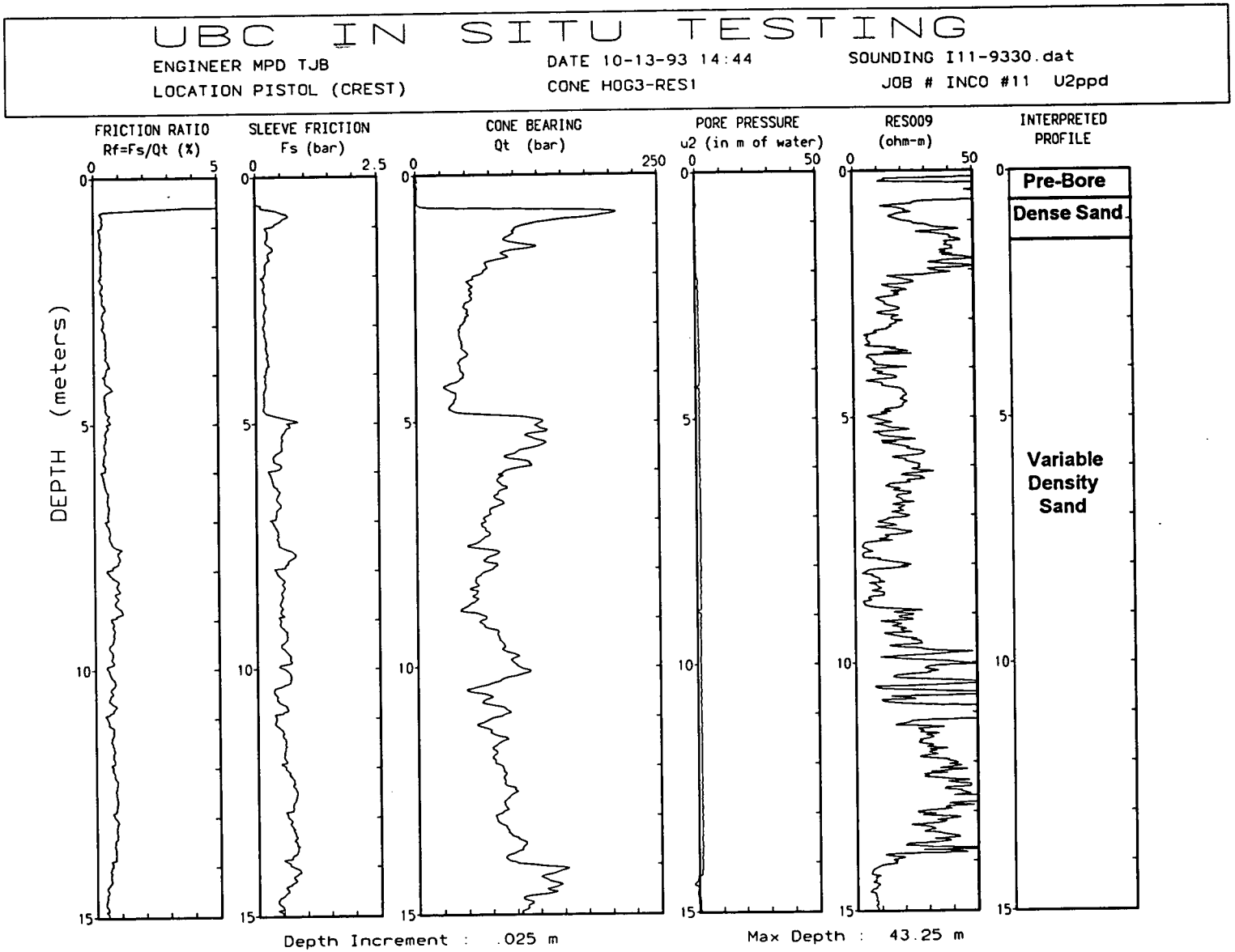
ENGINEER MPD TJB
DATE 10-12-93 14:31
SOUNDING I23-9327.dat
LOCATION PISTOL (BASE)
CONE HOG3-RES1
JOB # INCO #23 U2ppd
INTERPRETED PROFILE
Pre-Bore
Silty Clay
Silty Sand
Sensitive Fine-Grained
Compact Sand With Interbedded Silt Layers
Refusal
RES009 (ohm-m)
PORE PRESSURE u2 (in m of water)
CONE BEARING Qt (bar)
SLEEVE FRICTION Fs (bar)
FRICTION RATIO Rf=Fs/Qt (%)
DEPTH (meters)
Max Depth : 14.45 m
Depth Increment : .025 m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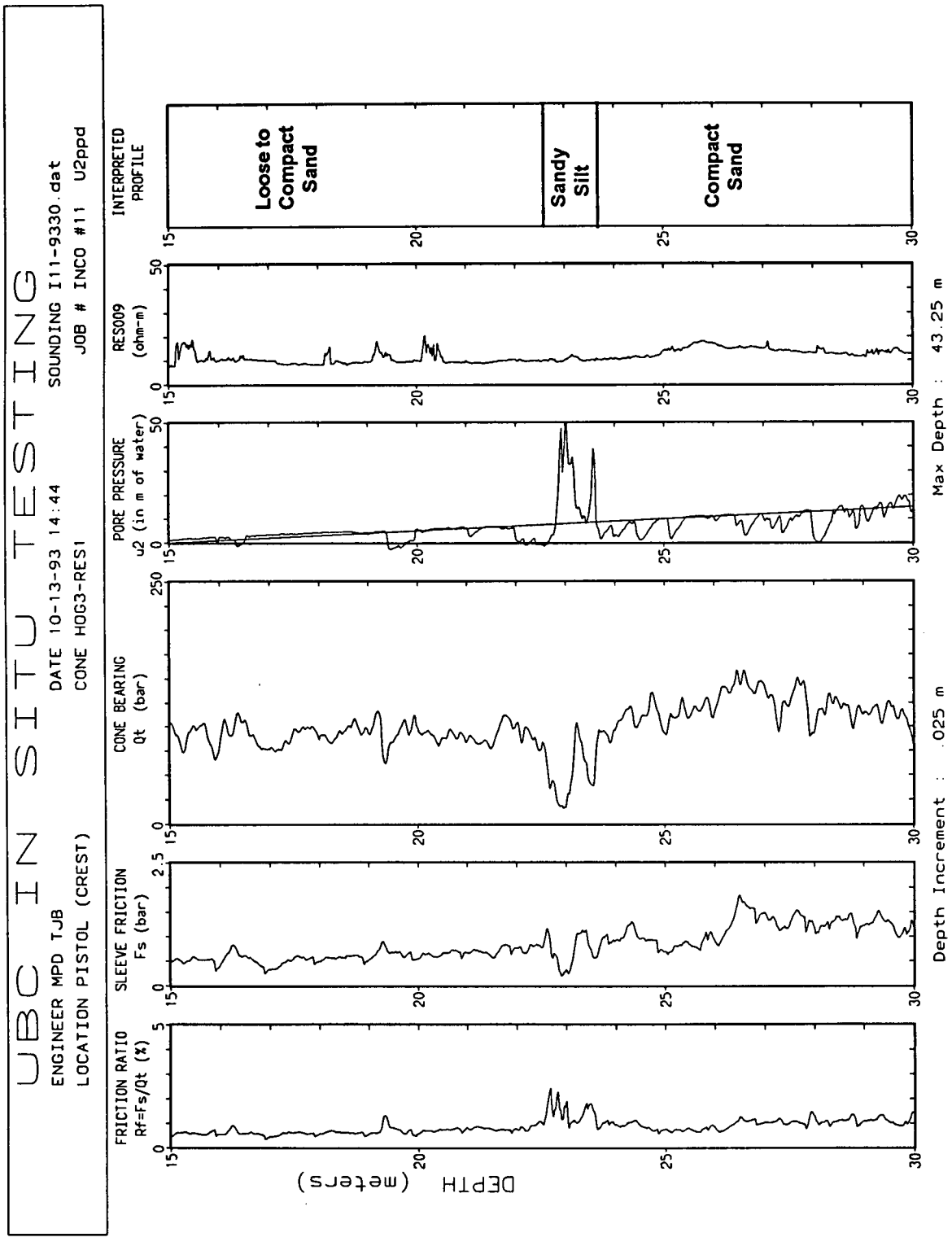
ENGINEER MPD TJB
LOCATION PISTOL (CREST)
DATE 10-13-93 14:44
CONE HOG3-RES1
SOUNDING I11-9330.dat
JOB # INCO #11 U2ppd
FRICTION RATIO
Rf=Fs/Qt (%)
SLEEVE FRICTION
Fs (bar)
CONE BEARING
Qt (bar)
PORE PRESSURE
u2 (in m of water)
RES009
(ohm-m)
INTERPRETED
PROFILE
DEPTH (meters)
Pre-Bore
Dense Sand
Variable
Density
Sand
Depth Increment : .025 m
Max Depth : 43.25 m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ENGINEER MPD TJB
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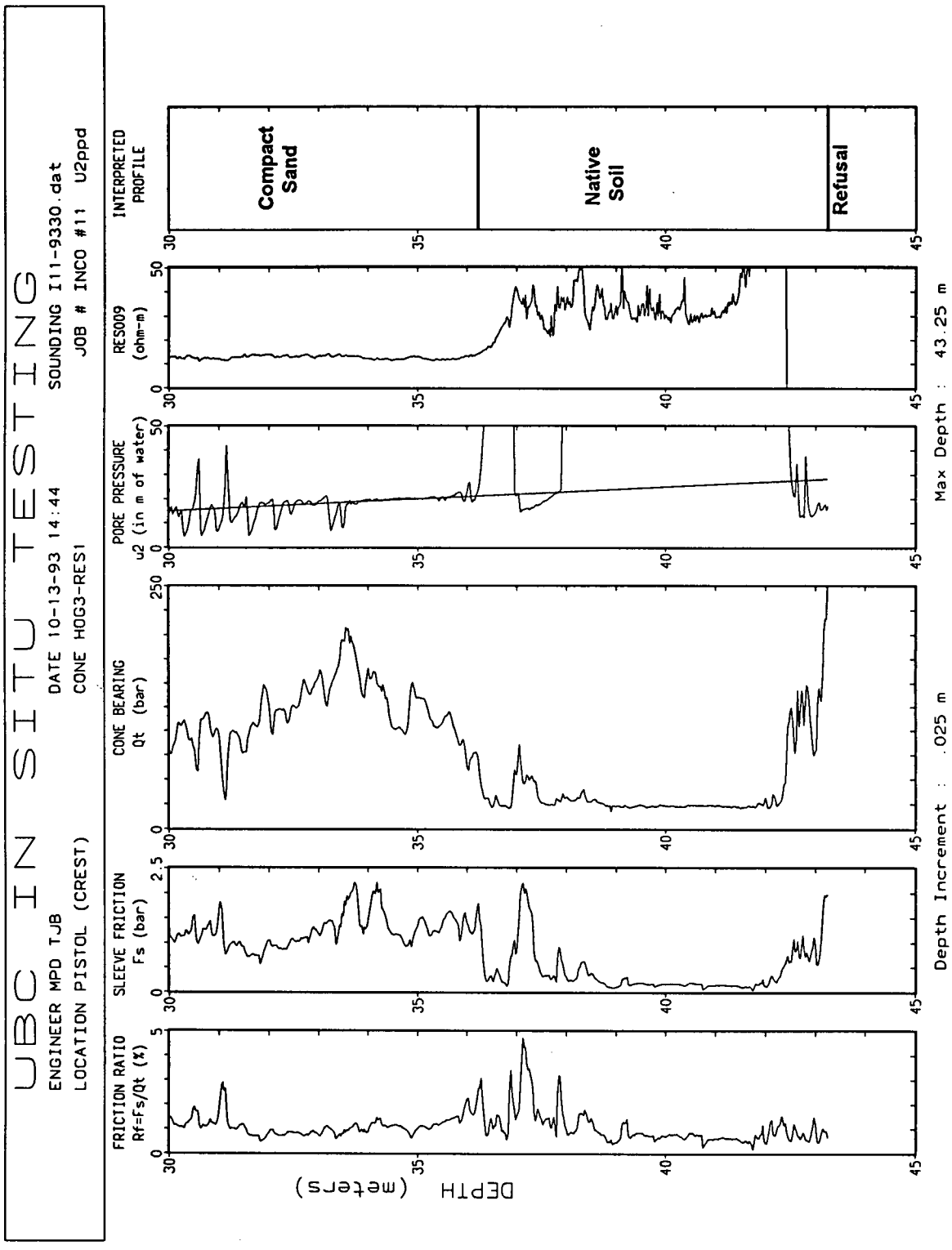
SOUNDING I11-9330.dat
LOCATION PISTOL (CREST)
CONE HOG3-RES1
JOB # INCO #11 U2ppd
FRICTION RATIO Rf=Fs/Qt (%)
SLEEVE FRICTION Fs (bar)
CONE BEARING Qt (bar)
PORE PRESSURE u2 (in m of water)
RES009 (ohm-m)
INTERPRETED PROFILE
Loose to Compact Sand
Sandy Silt
Compact Sand
DEPTH (meters)
Depth Increment : .025 m
Max Depth : 43.25 m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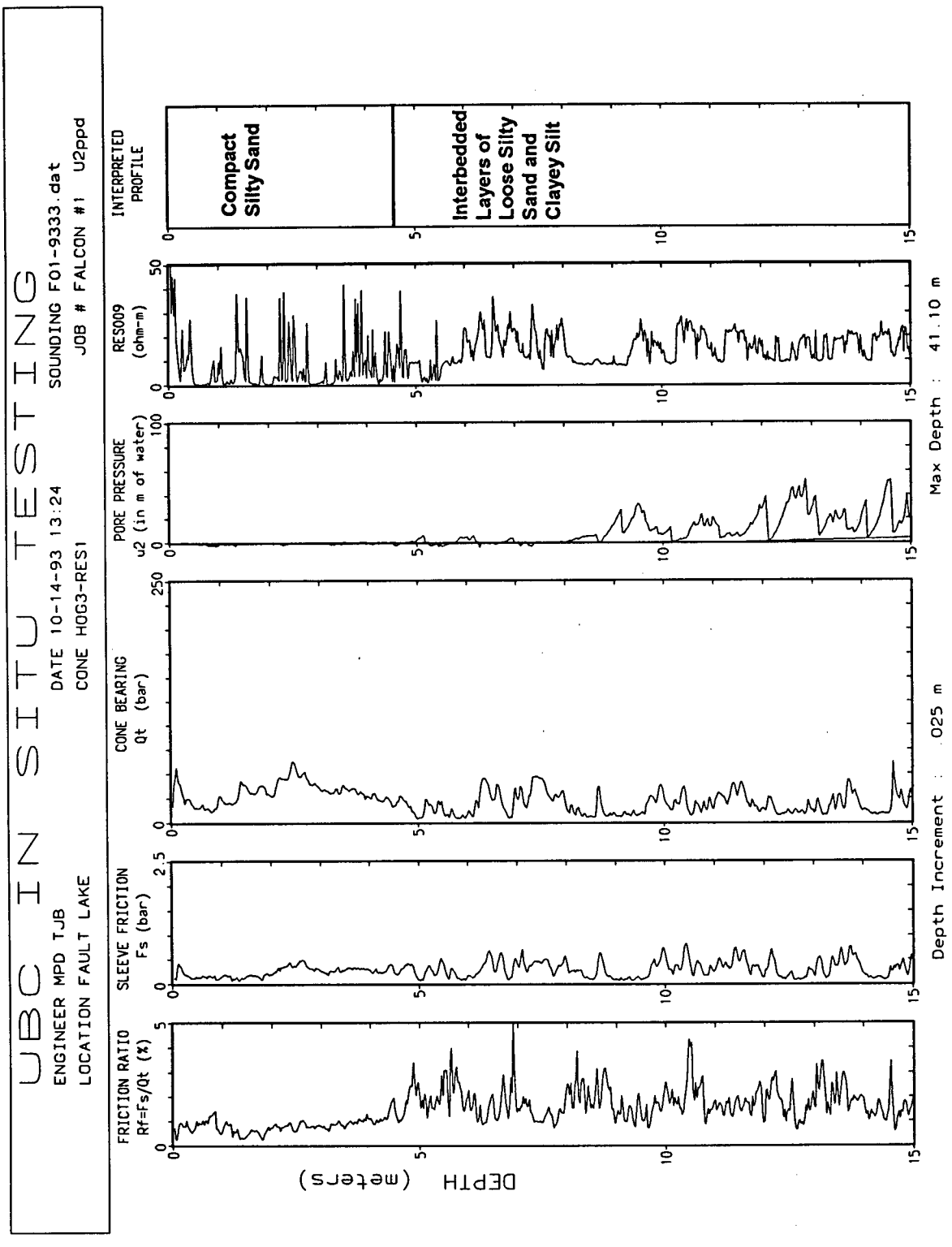
ENGINEER MPD TJB
DATE 10-13-93 14:44
SOUNDING I11-9330.dat
LOCATION PISTOL (CREST)
CONE HOG3-RES1
JOB # INCO #11 U2ppd
FRICTION RATIO Rf=Fs/Qt (%)
SLEEVE FRICTION Fs (bar)
CONE BEARING Qt (bar)
PORE PRESSURE u2 (in m of water)
RES009 (ohm-m)
INTERPRETED PROFILE
Compact Sand
Native Soil
Refusal
DEPTH (meters)
Depth Increment : .025 m
Max Depth : 43.25 m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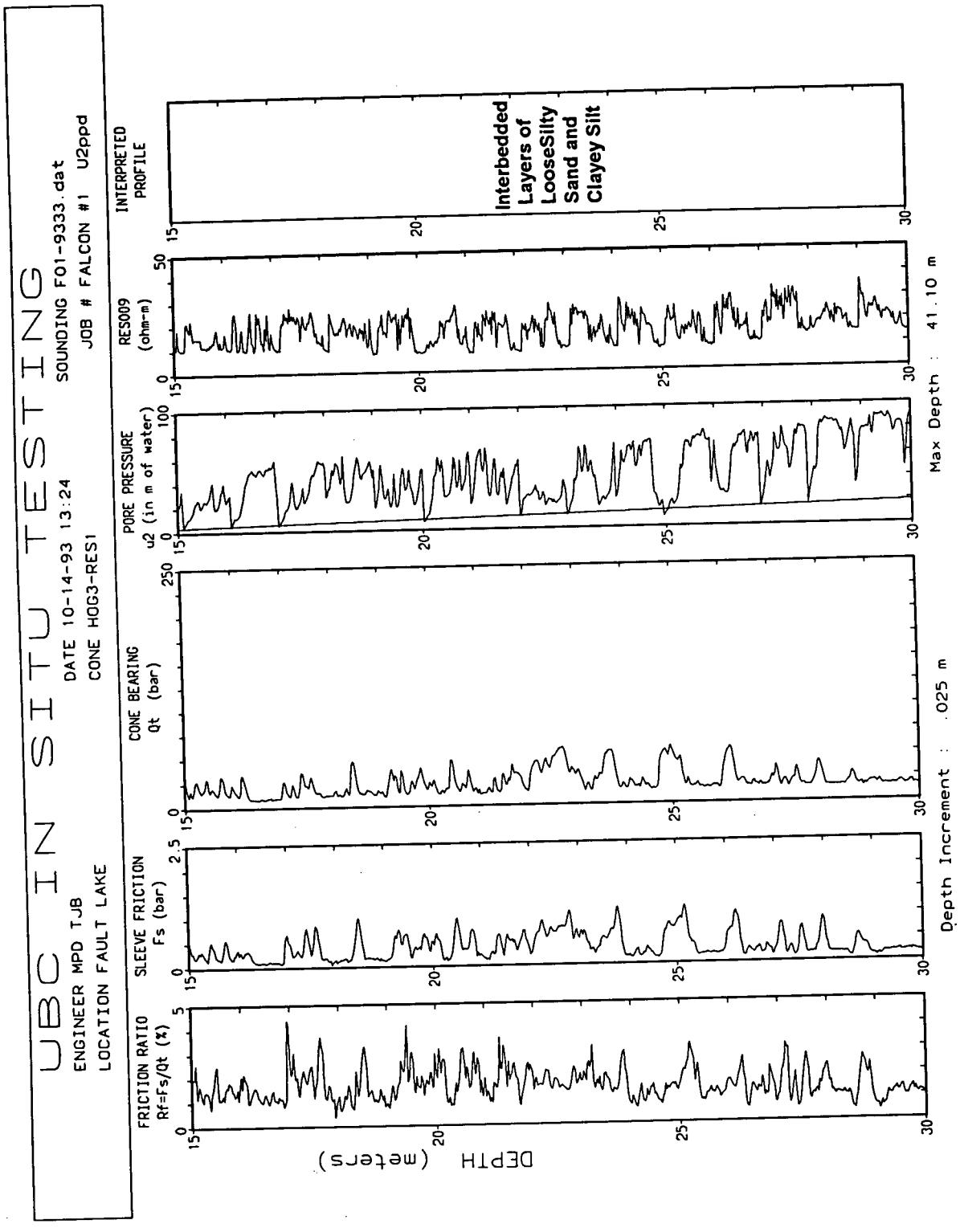
ENGINEER MPD TJB
LOCATION FAULT LAKE
DATE 10-14-93 13:24
CONE HOG3-RES1
SOUNDING FO1-9333.dat
JOB # FALCON #1 U2ppd
FRICTION RATIO Rf=Fs/Qt (%)
SLEEVE FRICTION Fs (bar)
CONE BEARING Qt (bar)
PORE PRESSURE u2 (in m of water)
RES009 (ohm-m)
INTERPRETED PROFILE
Compact Silty Sand
Interbedded Layers of Loose Silty Sand and Clayey Silt
DEPTH (meters)
Depth Increment : .025 m
Max Depth : 41.10 m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SOUNDING F01-9333.dat
DATE 10-14-93 13:24
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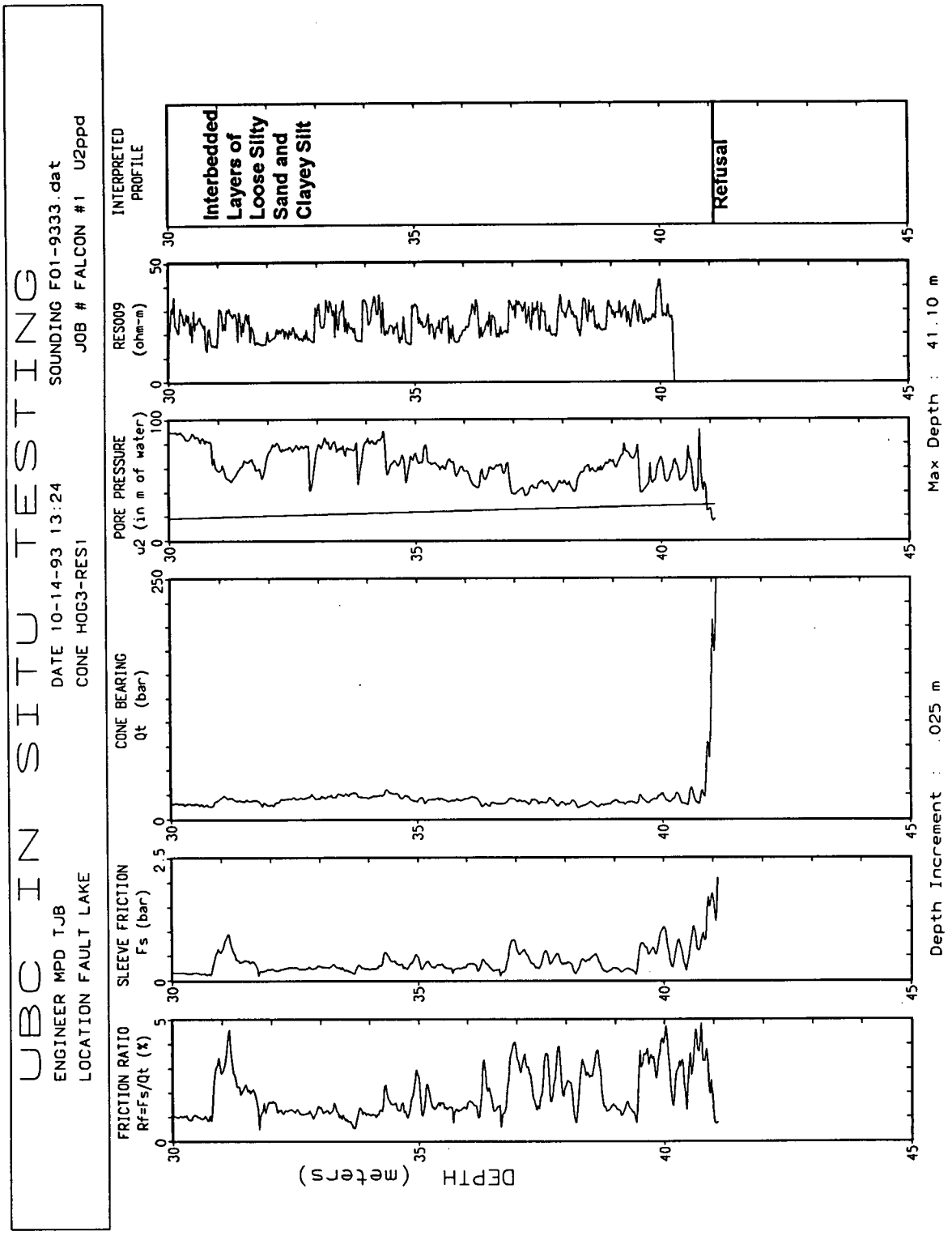
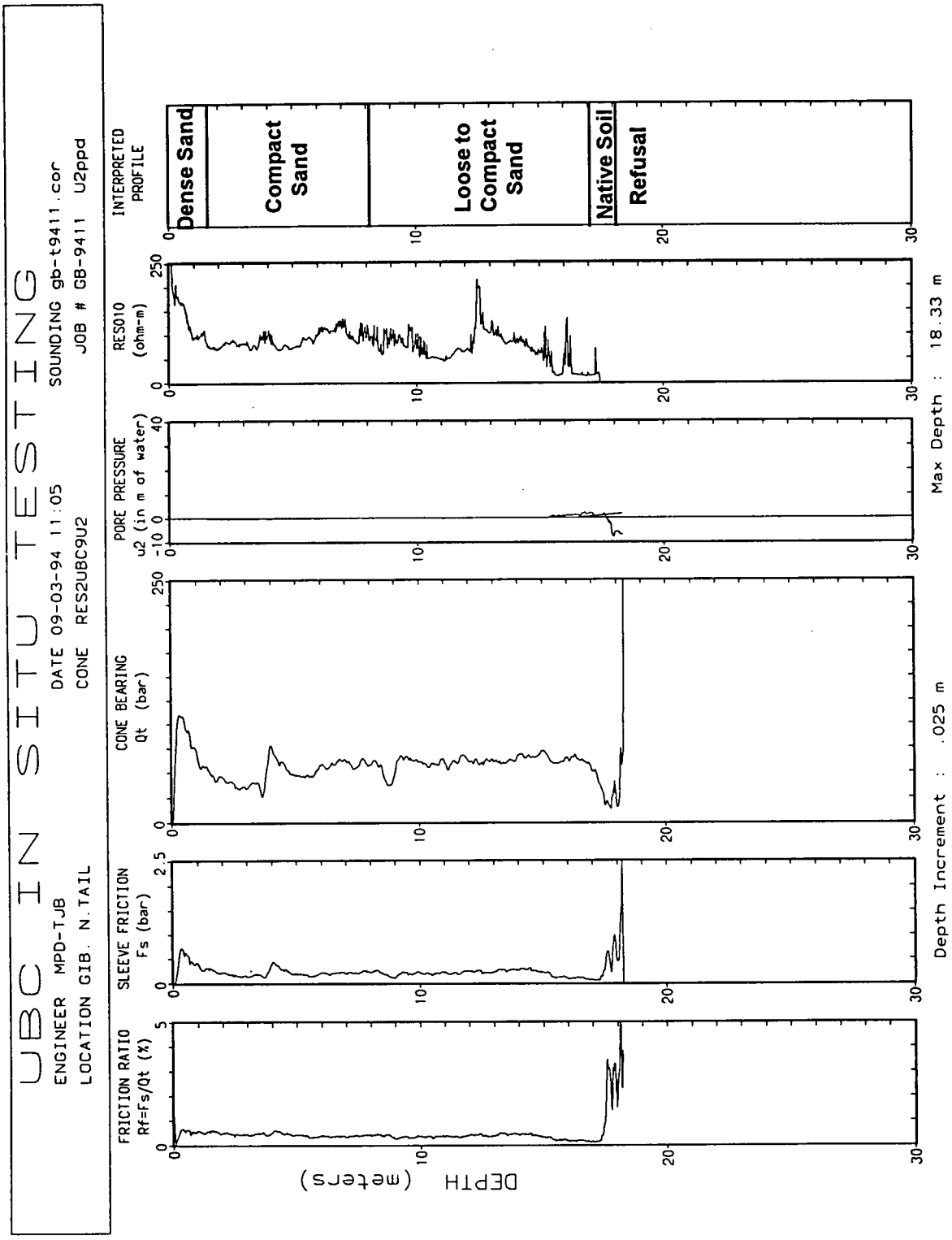
ENGINEER MPD TJB
CONE HOG3-RES1
LOCATION FAULT LAKE
FRICTION RATIO Rf=Fs/Qt (%)
SLEEVE FRICTION Fs (bar)
CONE BEARING Qt (bar)
PORE PRESSURE u2 (in m of water)
RES009 (ohm-m)
INTERPRETED PROFILE
Interbedded Layers of LooseSilty Sand and Clayey Silt
DEPTH (meters)
Depth Increment : .025 m
Max Depth : 41.10 m


UBC IN SITU TESTING
ENGINEER MPD TJB
DATE 10-14-93 13:24
SOUNDING FO1-9333.dat
LOCATION FAULT LAKE
CONE HOG3-RES1
JOB # FALCON #1 U2ppd
FRICTION RATIO Rf=Fs/Qt (%)
SLEEVE FRICTION Fs (bar)
CONE BEARING Qt (bar)
PORE PRESSURE u2 (in m of water)
RES009 (ohm-m)
INTERPRETED PROFILE
Interbedded Layers of Loose Silty Sand and Clayey Silt
Refusal
DEPTH (meters)
Depth Increment : .025 m
Max Depth : 41.10 m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LOCATION GIB. N.TAIL
DATE 09-03-94 11:05
CONE RES2UBC9U2
SOUNDING gb-t9411.cor
JOB # GB-9411 U2ppd
FRICTION RATIO Rf=Fs/Qt (%)
SLEEVE FRICTION Fs (bar)
CONE BEARING Qt (bar)
PORE PRESSURE u2 (in m of water)
RES010 (ohm-m)
INTERPRETED PROFILE
Dense Sand
Compact Sand
Loose to Compact Sand
Native Soil
Refusal
DEPTH (meters)
Depth Increment : .025 m
Max Depth : 18.33 m

APPENDIX B - RCPT INTERPRETATIONS

CPTINT 5.0 - List of reference sources

Originally from the Reference section of the file INTRT2.TXT for the program CPTINTR1 version 3.05, written by JAMES GREIG.
This section was extracted, revised and new information was added for the program:

Program: CPTINT - CPT Cone Interpretation Program
Version: 5.0
Written by: Thomas Wong and R. G. Campanella
University of British Columbia
Department of Civil Engineering

REFERENCES

1) Bellotti, R., Crippa, V., Pedroni, S., Baldi, G., Fretti, C., Ostricati, D., Ghionna, V., Jamiolkowski, M., Pasqalini, E., 1985, "Laboratory Validation Of In-Situ Tests", Italian Geotechnical Society Jubilee Volume for the XI ICSMFE, San Francisco, Cal.
2) Durgunoglu, H.T. and Mitchell, J.K., 1975, "Static Penetration Resistance of Soils: I-Analysis", Proceedings of the ASCE Specialty Conference on In-Situ Measurement of Soil Properties, Raleigh, North Carolina, Vol. I.
3) "Earthquake Design in the Fraser Delta - Geotechnical Aspects" Task Force Report, May 1991 - Co-chair: Dr. P. M. Byrne, Univ. of British Columbia, Dept. of Civil Engineering, Vancouver, B.C., V6T 1Z4.
4) Janbu, N. and Senneset, K., 1974,. "Effective Stress Interpretation of In Situ Static Penetratuion Tests", Proceedings of the European Symposium on Penetration Testing, Stockholm Sweden, Vol. 2.2.
5) Jamiolkowski, M., Ladd, C.C., Germaine, J.T., Lancellotta, R., 1985, "New Developments in Field and Laboratory Testing of Soils", State of the Art Address for XIth ICSMFE, San Francisco.
6) Robertson, P.K. and Campanella, R.G., 1983, "Interpretation of Cone Penetration Tests - PART I (SAND) and PART II (CLAY)", Canadian Geotechnical Journal, Vol. 20, No. 4.
7) Robertson, P.K., Campanella, R.G., and Wightman, A., 1983, "SPT - CPT Correlations", Journal of the Geotechnical Division, ASCE, Vol. 109, Nov.
8) Robertson, P.K. and Campanella, R.G., 1989 "Guidelines for Geotechnical Design using CPT and CPTU", Soil Mechanics Series NO. 120, Civil Eng. Dept., Univ. of B.C., Vancouver, B.C., V6T 1Z4, Sept 1989.
9) Robertson, P.K., 1990, Soil Classification using the CPT, Canadian Geotechnical Journal, Vol. 27, No.1, Feb, 151-158.
10) Schmertmann, J.H., 1976, "An updated Correlation between Relative Density, Dr and Fugro-type Electric Cone Bearing, qc" Department of Civil Engineering Report, University of Florida, July.
11) Seed, H.B., Idriss, I.M. and Arango, I., 1983, "Evaluation of Liquefaction Potential Using Field Performance Data", Journal of Geotechnical Engineering Division, ASCE, Vol. 109, No. 3, March 1983, pp. 458-482.
12) Seed, H.B. and Idriss, I.M., 1971, "Simplified procedure for Evaluation Soil Liquefaction Potential", Journal of Soil Mechanics and Foundations, ASCE, SM9, Vol. 97, Sept.

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"File Number:                 Date:  10-12-93 14:31
"Operator:   UBC ISTG          On Site Location: PISTOL BASE
"Cone Type: HOG3RES1           Comment:   123-9327
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"SUMMARY SHEET
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"'a' for calculating Qt:                  0.800
"Value for Water Table (in m):            0.000
"Valid Zone Classification based on:      Bq
"Missing unit weight to start depth:      19.000
"Method for calculating Su:               Nkt
"Value of the constant Nkt:               12.500
"Define Zone 6 for Sand Parameters?       NO
"Sand Compressibility for calc Dr:        Moderate
"Method for Friction Angle:               Robertson & Campanella
"
"Soil Behavior Type Zone Numbers
"For Rf Zone & Bq Zone Classification
"-----------------------------------
"Zone #1=Sensitive fine grained     Zone #7 =Silty sand
"Zone #2=Organic material           Zone #8 =Fine sand
"Zone #3=Clay                       Zone #9 =Sand
"Zone #4=Silty clay                 Zone #10=Gravelly sand
"Zone #5=Clayey silt                Zone #11=Very stiff fine grained *
"Zone #6=Sandy silt                 Zone #12=Sand to clayey sand *
"   * Overconsolidated and/or cemented
"
"NOTE:
"-----
"For soil classification, Rf values > 8 are assumed to be 8.
"
"( Note: 9E9 means Out Of Range )
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" Depth (meter)	Qt(avg) (bars)	Rf (%)	U2 (meter)	RES075 (ohm-m)	Gamma (kN/m^3)	EOS(avg) (kPa)	Rf Zone (zone #)	Bq Zone (zone #)	Dr (%)	Phi (degree)	Spt N (blow/ft)	Spt N1 (blow/ft)	Su (kPa)
0.150	0.760	0.000	-0.020	89.011	9E9	9E9	1	9E9	9E9	9E9	9E9	9E9	9E9
0.400	0.640	0.000	0.000	89.306	9E9	9E9	1	9E9	9E9	9E9	9E9	9E9	9E9
0.650	4.438	5.633	-0.600	54.413	18.860	9E9	3	4	9E9	9E9	3	2	35.317
0.900	18.506	1.999	-3.260	16.118	18.860	9E9	6	6	9E9	9E9	7	4	147.483
1.150	12.568	2.355	-3.670	16.282	18.860	0.506	5	6	9E9	9E9	5	8	99.601
1.400	16.316	0.993	-1.740	15.599	18.860	2.769	6	6	9E9	9E9	7	11	129.207
1.650	26.817	0.507	-3.730	20.728	18.860	5.031	7	7	81	47	9	14	9E9
1.900	30.094	0.462	-2.840	20.288	18.860	7.293	7	7	78	47	10	15	9E9
2.150	29.007	1.289	-1.680	17.545	18.860	9.556	7	7	71	45	10	15	9E9
2.400	33.173	2.083	0.680	13.053	19.650	11.917	6	8	71	45	8	12	9E9
2.650	23.290	1.589	2.550	14.925	18.860	14.279	6	7	53	43	8	12	9E9
2.900	20.515	1.219	4.310	14.639	18.860	16.541	6	7	45	41	7	11	9E9
3.150	16.025	1.629	3.820	14.905	18.860	18.803	6	6	9E9	9E9	6	9	124.223
3.400	11.482	1.420	3.680	19.304	18.860	21.066	5	6	9E9	9E9	5	8	87.504
3.650	8.482	0.318	3.690	23.115	18.860	23.328	1	6	9E9	9E9	3	5	63.128
3.900	6.407	0.312	3.400	24.915	18.860	25.591	1	5	9E9	9E9	3	5	46.146
4.150	5.478	0.183	3.470	27.052	18.860	27.853	1	5	9E9	9E9	3	5	38.339
4.400	5.506	0.182	4.380	30.983	18.860	30.116	1	5	9E9	9E9	3	5	38.185
4.650	4.584	0.371	4.300	32.931	18.860	32.378	1	4	9E9	9E9	3	5	30.435
4.900	4.465	0.224	4.340	36.866	18.860	34.641	1	4	9E9	9E9	3	5	29.104
5.150	4.408	0.227	4.460	43.642	18.860	36.903	1	4	9E9	9E9	3	5	28.266
5.400	4.129	0.242	4.560	57.008	18.860	39.166	1	4	9E9	9E9	3	5	25.665
5.650	4.988	0.281	4.500	69.310	18.860	41.428	1	4	9E9	9E9	3	5	32.158
5.900	3.758	0.506	4.510	70.146	18.860	43.691	1	4	9E9	9E9	3	5	21.942
6.150	11.334	0.512	-0.330	75.479	18.860	45.953	6	6	9E9	9E9	5	8	82.165
6.400	11.370	0.774	8.160	76.987	18.860	48.216	6	6	9E9	9E9	5	8	82.081
6.650	22.460	0.721	-0.490	79.729	18.860	50.478	7	7	25	37	7	11	9E9
6.900	50.655	0.651	-2.810	81.541	19.650	52.840	8	8	55	41	13	20	9E9
7.150	42.702	0.569	-2.950	81.423	19.650	55.300	8	8	48	39	11	17	9E9
7.400	47.578	0.414	2.440	81.608	19.650	57.760	8	8	51	41	12	18	9E9
7.650	43.956	0.268	-2.260	81.781	19.650	60.220	8	8	47	39	11	16	9E9
7.900	43.612	0.970	-0.390	81.068	19.650	62.680	7	8	46	39	11	15	9E9
8.150	68.157	0.779	-3.190	80.766	19.650	65.140	8	8	62	41	17	23	9E9
8.400	52.652	0.080	5.700	81.927	19.650	67.600	8	8	51	39	13	17	9E9
8.650	34.001	0.191	14.320	19.714	18.860	69.961	8	7	34	37	11	14	9E9
8.900	77.547	0.063	4.440	13.101	19.650	72.322	9	9	65	41	16	20	9E9
9.150	52.815	0.328	10.970	12.212	19.650	74.782	8	8	49	39	13	16	9E9
9.400	66.874	0.251	6.810	12.933	19.650	77.242	8	8	58	41	17	20	9E9
9.650	59.897	0.187	2.930	11.278	19.650	79.702	8	8	53	39	15	17	9E9
9.900	35.640	0.522	17.340	10.780	18.860	82.063	7	7	32	37	12	14	9E9
10.150	56.719	0.196	10.660	9.908	19.650	84.425	8	8	50	39	14	15	9E9
10.400	53.576	0.157	12.550	8.600	19.650	86.885	8	8	47	39	13	14	9E9
10.650	66.769	0.153	12.680	36.028	19.650	89.345	8	8	55	39	17	18	9E9
10.900	48.870	0.622	18.880	33.292	19.650	91.805	8	8	42	37	12	12	9E9
11.150	61.745	0.651	14.530	26.357	19.650	94.265	8	8	50	39	15	15	9E9
11.400	65.367	0.751	16.670	23.765	19.650	96.725	8	8	52	39	16	16	9E9
11.650	69.147	0.845	16.670	23.097	19.650	99.185	8	8	54	39	17	17	9E9
11.900	59.054	0.862	17.040	23.171	19.650	101.645	8	8	47	39	15	14	9E9
12.150	54.401	0.768	17.900	22.557	19.650	104.105	8	8	43	37	14	13	9E9
12.400	52.646	0.904	18.140	23.068	19.650	106.565	7	8	42	37	13	12	9E9
12.650	57.707	0.886	17.700	22.072	19.650	109.025	8	8	45	37	14	13	9E9
12.900	85.145	0.817	16.050	22.725	19.650	111.485	8	9	59	39	17	15	9E9
13.150	76.539	0.766	15.240	21.077	19.650	113.945	8	9	55	39	15	13	9E9
13.400	68.537	0.833	18.220	24.026	19.650	116.405	8	8	50	39	17	15	9E9
13.650	89.351	0.541	15.340	10.804	19.650	118.865	8	9	60	39	18	15	9E9
13.900	85.852	0.377	15.370	0.000	19.650	121.325	8	9	58	39	17	14	9E9
14.150	76.420	0.391	15.790	0.000	19.650	123.785	8	9	53	39	15	12	9E9
14.400	131.816	0.863	16.112	0.000	19.650	126.245	9	9	74	41	26	21	9E9

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"SUMMARY SHEET
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"'a' for calculating Qt:                0.800
"Value for Water Table (in m):          15.000
"Valid Zone Classification based on:    Bq
"Missing unit weight to start depth:    19.000
"Method for calculating Su:             Nkt
"Value of the constant Nkt:             12.500
"Define Zone 6 for Sand Parameters?     NO
"Sand Compressibility for calc Dr:      Moderate
"Method for Friction Angle:             Robertson & Campanella
"
"Soil Behavior Type Zone Numbers
"For Rf Zone & Bq Zone Classification
"-----------------------------------
"Zone #1=Sensitive fine grained     Zone #7 =Silty sand
"Zone #2=Organic material           Zone #8 =Fine sand
"Zone #3=Clay                       Zone #9 =Sand
"Zone #4=Silty clay                 Zone #10=Gravelly sand
"Zone #5=Clayey silt                Zone #11=Very stiff fine grained *
"Zone #6=Sandy silt                 Zone #12=Sand to clayey sand *
"   * Overconsolidated and/or cemented
"
"NOTE:
"-----
"For soil classification, Rf values > 8 are assumed to be 8.
"
"( Note: 9E9 means Out Of Range )
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Depth (meter)	Qt(avg) (bars)	Rf (%)	U2 (meter)	RES075 (ohm-m)	Gamma (kN/m^3)	EOS(avg) (kPa)	Rf Zone (zone #)	Bq Zone (zone #)	Dr (%)	Phi (degree)	Spt N (blow/ft)	Spt N1 (blow/ft)	Su (kPa)
0.150	0.990	0.000	-0.020	89.730	9E9	9E9	1	9E9	9E9	9E9	9E9	9E9	9E9
0.400	0.938	0.000	-0.080	87.539	9E9	9E9	1	9E9	9E9	9E9	9E9	9E9	9E9
0.650	72.751	0.362	0.030	58.946	19.650	2.456	8	9	136	9E9	15	23	9E9
0.900	153.647	0.331	-0.140	14.668	19.650	7.369	9	9	141	9E9	31	47	9E9
1.150	99.619	0.238	-0.040	27.700	19.650	12.281	9	9	113	9E9	20	30	9E9
1.400	105.722	0.263	0.100	34.221	19.650	17.194	9	9	108	9E9	21	32	9E9
1.650	87.372	0.294	0.100	34.781	19.650	22.106	9	9	95	47	17	26	9E9
1.900	70.254	0.280	0.200	41.007	19.650	27.019	8	8	82	45	18	27	9E9
2.150	55.923	0.284	0.660	26.380	19.650	31.931	8	8	70	43	14	21	9E9
2.400	55.468	0.312	0.900	20.410	19.650	36.844	8	8	67	43	14	21	9E9
2.650	50.930	0.387	1.000	13.410	19.650	41.756	8	8	61	41	13	20	9E9
2.900	50.280	0.352	1.000	17.629	19.650	46.669	8	8	58	41	13	20	9E9
3.150	43.903	0.392	1.170	17.114	19.650	51.581	8	8	50	41	11	17	9E9
3.400	45.405	0.465	1.250	6.861	19.650	56.494	8	8	50	41	11	17	9E9
3.650	48.516	0.484	1.310	13.130	19.650	61.406	8	8	50	41	12	17	9E9
3.900	43.987	0.518	1.390	7.886	19.650	66.319	8	8	45	39	11	15	9E9
4.150	42.218	0.464	1.420	17.388	19.650	71.231	8	8	42	39	11	14	9E9
4.400	34.591	0.489	1.080	13.067	19.650	76.144	7	8	33	37	9	11	9E9
4.650	35.726	0.445	1.340	20.448	19.650	81.056	7	8	32	37	9	10	9E9
4.900	87.925	0.571	1.280	11.748	19.650	85.969	8	9	66	41	18	20	9E9
5.150	125.416	0.479	1.310	10.393	19.650	90.881	9	9	79	43	25	26	9E9
5.400	123.465	0.416	1.270	12.439	19.650	95.794	9	9	77	43	25	25	9E9
5.650	101.133	0.406	1.190	17.780	19.650	100.706	9	9	68	41	20	19	9E9
5.900	107.634	0.378	1.220	19.704	19.650	105.619	9	9	70	41	22	20	9E9
6.150	84.396	0.363	1.330	22.948	19.650	110.531	8	9	59	39	17	15	9E9
6.400	85.567	0.494	1.380	15.103	19.650	115.444	8	9	59	39	17	15	9E9
6.650	82.959	0.540	1.500	14.686	19.650	120.356	8	9	57	39	17	14	9E9
6.900	71.719	0.527	1.480	13.855	19.650	125.269	8	8	50	39	18	15	9E9
7.150	68.541	0.572	1.560	12.328	19.650	130.181	8	8	48	37	17	13	9E9
7.400	66.391	0.654	1.560	14.971	19.650	135.094	8	8	45	37	17	13	9E9
7.650	71.239	0.974	1.500	4.453	19.650	140.006	8	8	47	37	18	13	9E9
7.900	74.787	0.765	1.390	7.224	19.650	144.919	8	9	49	37	15	11	9E9
8.150	63.818	0.752	1.450	11.855	19.650	149.831	8	8	42	37	16	11	9E9
8.400	58.678	0.895	1.420	7.179	19.650	154.744	8	8	38	37	15	10	9E9
8.650	56.637	0.874	1.360	7.350	19.650	159.656	8	8	36	35	14	9	9E9
8.900	56.282	0.865	1.110	10.907	19.650	164.569	8	8	35	35	14	9	9E9
9.150	68.835	0.738	1.250	16.904	19.650	169.481	8	8	42	37	17	11	9E9
9.400	83.032	0.699	1.140	15.188	19.650	174.394	8	9	49	37	17	11	9E9
9.650	90.715	0.638	1.250	22.755	19.650	179.306	8	9	51	37	18	11	9E9
9.900	99.321	0.596	1.060	25.640	19.650	184.219	8	9	54	39	20	12	9E9
10.150	102.553	0.641	1.160	32.808	19.650	189.131	8	9	55	39	21	12	9E9
10.400	64.092	0.691	1.140	30.338	19.650	194.044	8	8	36	35	16	9	9E9
10.650	68.842	0.635	1.110	32.445	19.650	198.956	8	8	38	35	17	10	9E9
10.900	87.693	0.558	1.160	45.855	19.650	203.869	8	9	47	37	18	10	9E9
11.150	67.466	0.596	1.310	58.961	19.650	208.781	8	8	37	35	17	9	9E9
11.400	81.016	0.655	1.310	28.846	19.650	213.694	8	9	43	37	16	9	9E9
11.650	78.736	0.700	1.310	32.640	19.650	218.606	8	9	42	37	16	8	9E9
11.900	78.096	0.694	1.310	28.299	19.650	223.519	8	9	41	35	16	8	9E9
12.150	87.197	0.739	1.370	33.472	19.650	228.431	8	9	45	37	17	9	9E9
12.400	91.617	0.808	1.390	29.343	19.650	233.344	8	9	46	37	18	9	9E9
12.650	92.396	0.814	1.330	36.406	19.650	238.256	8	9	46	37	18	9	9E9
12.900	86.337	0.744	1.390	36.377	19.650	243.169	8	9	43	35	17	9	9E9
13.150	82.449	0.814	1.480	26.661	19.650	248.081	8	9	41	35	16	8	9E9
13.400	95.387	0.779	1.390	21.454	19.650	252.994	8	9	46	37	19	10	9E9
13.650	106.208	0.738	1.430	21.995	19.650	257.906	8	9	50	37	21	11	9E9
13.900	95.196	0.666	1.330	18.414	19.650	262.819	8	9	45	37	19	10	9E9
14.150	138.874	0.557	1.200	8.586	19.650	267.731	9	9	59	37	28	14	9E9
14.400	136.892	0.469	-0.900	8.306	19.650	272.644	9	9	58	37	27	14	9E9

"---| INPUT FILE: c:\cptint\I11-9330.DAT |----------

" Depth (meter)	Qt(avg) (bars)	Rf (%)	U2 (meter)	RES075 (ohm-m)	Gamma (kN/m^3)	EOS(avg) (kPa)	Rf Zone (zone #)	Bq Zone (zone #)	Dr (%)	Phi (degree)	Spt N (blow/ft)	Spt N1 (blow/ft)	Su (kPa)
14.650	120.952	0.381	-0.420	7.035	19.650	277.556	9	9	53	37	24	12	9E9
14.900	109.520	0.424	0.500	7.749	19.650	282.469	9	9	49	37	22	11	9E9
15.150	90.457	0.568	1.390	11.751	19.650	285.910	8	9	41	35	18	9	9E9
15.400	90.986	0.584	1.860	16.475	19.650	288.370	8	9	41	35	18	9	9E9
15.650	99.329	0.533	1.970	10.958	19.650	290.830	9	9	44	35	20	10	9E9
15.900	75.688	0.593	1.960	10.523	19.650	293.290	8	9	34	33	15	8	9E9
16.150	96.921	0.664	2.100	10.538	19.650	295.750	8	9	43	35	19	10	9E9
16.400	106.697	0.623	-0.140	10.388	19.650	298.210	9	9	47	35	21	11	9E9
16.650	92.693	0.579	2.720	10.930	19.650	300.670	8	9	41	35	19	10	9E9
16.900	77.413	0.455	3.200	10.209	19.650	303.130	8	9	34	33	15	8	9E9
17.150	76.289	0.492	3.530	10.225	19.650	305.590	8	9	33	33	15	8	9E9
17.400	86.314	0.600	3.780	8.297	19.650	308.050	8	9	38	35	17	9	9E9
17.650	97.036	0.594	3.860	8.697	19.650	310.510	8	9	42	35	19	10	9E9
17.900	96.381	0.540	4.140	8.420	19.650	312.970	8	9	42	35	19	10	9E9
18.150	88.425	0.625	4.340	12.249	19.650	315.430	8	9	38	35	18	9	9E9
18.400	90.618	0.628	4.480	10.247	19.650	317.889	8	9	39	35	18	9	9E9
18.650	101.400	0.598	4.600	9.026	19.650	320.349	9	9	43	35	20	10	9E9
18.900	95.980	0.562	4.070	9.698	19.650	322.809	8	9	41	35	19	10	9E9
19.150	105.808	0.627	4.460	14.667	19.650	325.269	9	9	45	35	21	11	9E9
19.400	74.901	0.996	1.560	12.628	19.650	327.729	8	9	31	33	15	8	9E9
19.650	96.920	0.668	-1.550	9.973	19.650	330.189	8	9	41	35	19	10	9E9
19.900	100.552	0.586	1.650	10.035	19.650	332.649	9	9	42	35	20	10	9E9
20.150	93.779	0.675	5.060	15.091	19.650	335.109	8	9	39	35	19	10	9E9
20.400	86.567	0.699	5.940	15.118	19.650	337.569	8	9	36	33	17	9	9E9
20.650	91.909	0.752	6.060	10.496	19.650	340.029	8	9	38	33	18	9	9E9
20.900	88.973	0.743	6.250	10.121	19.650	342.489	8	9	37	33	18	9	9E9
21.150	85.941	0.817	4.120	9.997	19.650	344.949	8	9	35	33	17	9	9E9
21.400	82.279	0.789	6.560	9.383	19.650	347.409	8	9	33	33	16	8	9E9
21.650	96.799	0.730	6.570	10.138	19.650	349.869	8	9	39	35	19	10	9E9
21.900	104.859	0.729	5.560	10.973	19.650	352.329	8	9	42	35	21	11	9E9
22.150	95.076	0.760	0.290	10.395	19.650	354.789	8	9	39	33	19	10	9E9
22.400	83.535	0.974	0.280	9.899	19.650	357.249	8	9	33	33	17	9	9E9
22.650	58.099	1.501	0.450	9.652	19.650	359.709	7	8	19	31	15	8	9E9
22.900	21.742	1.693	26.120	10.235	19.650	362.169	6	6	9E9	9E9	9	5	138.766
23.150	61.604	1.049	31.300	10.979	19.650	364.629	8	8	21	31	15	8	9E9
23.400	65.127	1.522	11.580	9.658	19.650	367.089	7	8	23	31	16	8	9E9
23.650	73.034	0.983	14.960	9.807	19.650	369.549	8	8	27	31	18	9	9E9
23.900	91.044	1.019	4.800	10.838	19.650	372.009	8	9	36	33	18	9	9E9
24.150	109.449	0.931	4.550	11.192	19.650	374.469	8	9	43	35	22	11	9E9
24.400	108.848	1.032	6.520	11.298	19.650	376.929	8	9	42	35	22	11	9E9
24.650	117.721	0.791	3.630	11.851	19.650	379.389	9	9	45	35	24	12	9E9
24.900	110.543	0.695	9.310	12.850	19.650	381.849	9	9	43	35	22	11	9E9
25.150	105.636	0.691	5.380	15.624	19.650	384.309	8	9	41	35	21	11	9E9
25.400	116.843	0.730	8.820	15.789	19.650	386.769	9	9	45	35	23	12	9E9
25.650	116.866	0.677	11.000	18.210	19.650	389.229	9	9	44	35	23	12	9E9
25.900	120.449	0.832	10.670	18.500	19.650	391.689	9	9	46	35	24	12	9E9
26.150	133.408	0.712	10.590	17.882	19.650	394.149	9	9	49	35	27	14	9E9
26.400	143.953	1.011	10.360	15.809	19.650	396.609	9	9	52	37	29	15	9E9
26.650	146.596	1.123	5.890	15.774	19.650	399.069	8	9	53	37	29	15	9E9
26.900	141.550	1.014	10.210	15.842	19.650	401.529	9	9	51	9E9	28	14	9E9
27.150	129.020	1.047	8.180	15.843	19.650	403.989	8	9	48	9E9	26	13	9E9
27.400	114.654	1.020	7.360	14.040	19.650	406.449	8	9	43	9E9	23	12	9E9
27.650	139.145	1.035	10.460	14.383	19.650	408.909	9	9	50	9E9	28	14	9E9
27.900	115.578	1.095	11.600	13.299	19.650	411.369	8	9	43	9E9	23	12	9E9
28.150	112.584	1.033	1.220	13.996	19.650	413.829	8	9	42	9E9	23	12	9E9
28.400	128.191	1.025	10.220	12.812	19.650	416.289	8	9	47	9E9	26	13	9E9
28.650	119.384	1.151	13.460	12.632	19.650	418.749	8	9	44	9E9	24	12	9E9
28.900	111.595	1.048	10.950	11.564	19.650	421.208	8	9	41	9E9	22	11	9E9

"---| INPUT FILE: c:\cptint\I11-9330.DAT |----------

Depth (meter)	Qt(avg) (bars)	Rf (%)	U2 (meter)	RES075 (ohm-m)	Gamma (kN/m^3)	EOS(avg) (kPa)	Rf Zone (zone #)	Bq Zone (zone #)	Dr (%)	Phi (degree)	Spt N (blow/ft)	Spt N1 (blow/ft)	Su (kPa)
29.150	116.100	1.109	11.710	12.714	19.650	423.668	8	9	42	9E9	23	12	9E9
29.400	114.665	1.204	14.030	12.769	19.650	426.128	8	9	42	9E9	23	12	9E9
29.650	116.083	0.952	16.960	13.615	19.650	428.588	8	9	42	9E9	23	12	9E9
29.900	102.270	1.132	16.820	12.686	19.650	431.048	8	9	37	9E9	20	10	9E9
30.150	93.725	1.172	15.040	12.488	19.650	433.508	8	9	34	9E9	19	10	9E9
30.400	96.102	1.322	10.810	12.615	19.650	435.968	8	9	34	9E9	19	10	9E9
30.650	96.544	1.207	16.020	11.748	19.650	438.428	8	9	35	9E9	19	10	9E9
30.900	102.269	1.289	12.690	11.870	19.650	440.888	8	9	37	9E9	20	10	9E9
31.150	64.777	1.709	19.220	11.515	19.650	443.348	7	8	19	9E9	16	8	9E9
31.400	91.120	1.063	14.780	12.270	19.650	445.808	8	9	32	9E9	18	9	9E9
31.650	97.753	0.767	11.370	13.372	19.650	448.268	8	9	35	9E9	20	10	9E9
31.900	129.778	0.629	17.760	13.918	19.650	450.728	9	9	45	9E9	26	13	9E9
32.150	114.259	0.813	13.730	13.532	19.650	453.188	8	9	40	9E9	23	12	9E9
32.400	118.432	0.806	16.910	13.294	19.650	455.648	9	9	42	9E9	24	12	9E9
32.650	136.675	0.777	18.600	14.039	19.650	458.108	9	9	47	9E9	27	14	9E9
32.900	146.199	0.817	18.300	14.038	19.650	460.568	9	9	50	9E9	29	15	9E9
33.150	143.643	0.937	17.470	14.812	19.650	463.028	9	9	49	9E9	29	15	9E9
33.400	170.817	0.766	12.610	15.037	19.650	465.488	9	9	55	9E9	34	17	9E9
33.650	194.408	1.020	17.210	14.528	19.650	467.948	9	9	60	9E9	39	20	9E9
33.900	151.463	0.945	19.030	13.639	19.650	470.408	9	9	50	9E9	30	15	9E9
34.150	153.752	1.282	19.480	13.305	19.650	472.868	8	9	51	9E9	31	16	9E9
34.400	125.896	1.119	19.700	12.643	19.650	475.328	8	9	43	9E9	25	13	9E9
34.650	100.856	1.096	20.200	12.483	19.650	477.788	8	9	34	9E9	20	10	9E9
34.900	131.067	0.833	20.240	13.753	19.650	480.248	9	9	44	9E9	26	13	9E9
35.150	128.327	1.071	20.250	13.567	19.650	482.708	8	9	43	9E9	26	13	9E9
35.400	106.140	1.170	20.370	12.141	19.650	485.168	8	9	36	9E9	21	11	9E9
35.650	112.637	1.385	20.750	12.190	19.650	487.628	8	9	38	9E9	23	12	9E9
35.900	84.663	1.615	21.560	12.061	19.650	490.088	7	9	27	9E9	17	9	9E9
36.150	70.373	1.981	22.600	13.744	19.650	492.548	7	8	20	9E9	18	9	9E9
36.400	30.930	1.594	70.330	15.446	19.650	495.008	6	5	9E9	9E9	15	8	191.043
36.650	25.749	1.200	91.170	22.532	19.650	497.468	6	4	9E9	9E9	17	9	149.201
36.900	35.102	1.724	80.130	32.808	19.650	499.928	6	5	9E9	9E9	18	9	223.635
37.150	58.338	3.217	16.700	35.371	19.650	502.388	6	8	9E9	9E9	15	8	9E9
37.400	40.887	2.101	17.190	33.772	19.650	504.848	6	8	9E9	9E9	10	5	9E9
37.650	24.605	1.309	20.150	25.055	18.860	507.209	6	7	9E9	9E9	8	4	9E9
37.900	29.991	1.784	39.300	34.343	19.650	509.570	6	6	9E9	9E9	12	6	181.191
38.150	29.743	0.955	76.610	39.906	19.650	512.030	7	5	9E9	9E9	15	8	178.814
38.400	31.943	1.553	85.260	36.097	19.650	514.490	6	5	9E9	9E9	16	8	196.018
38.650	27.477	0.943	100.250	37.248	19.650	516.950	7	4	9E9	9E9	18	9	159.898
38.900	22.687	0.498	131.360	32.085	19.650	519.410	7	3	9E9	9E9	23	12	121.188
39.150	22.558	0.931	138.030	37.319	19.650	521.870	6	3	9E9	9E9	23	12	119.762
39.400	22.766	0.773	141.490	33.362	19.650	524.330	7	3	9E9	9E9	23	12	121.032
39.650	22.670	0.745	150.860	36.865	19.650	526.790	7	3	9E9	9E9	23	12	119.870
39.900	23.286	0.640	158.810	34.017	19.650	529.250	7	3	9E9	9E9	23	12	124.405
40.150	22.802	0.772	163.200	33.010	19.650	531.710	7	3	9E9	9E9	23	12	120.141
40.400	23.043	0.703	159.700	35.810	19.650	534.170	7	3	9E9	9E9	23	12	121.678
40.650	23.732	0.725	168.280	32.061	19.650	536.630	7	3	9E9	9E9	24	12	126.792
40.900	23.548	0.535	165.030	33.660	19.650	539.090	7	3	9E9	9E9	24	12	124.929
41.150	23.020	0.634	168.180	34.481	19.650	541.550	7	3	9E9	9E9	23	12	120.310
41.400	22.245	0.598	161.850	40.540	19.650	544.010	7	3	9E9	9E9	22	11	113.724
41.650	22.419	0.433	153.350	54.238	19.650	546.470	7	3	9E9	9E9	22	11	114.717
41.900	24.970	0.673	131.510	70.195	19.650	548.930	7	4	9E9	9E9	17	9	134.736
42.150	26.348	0.877	108.440	70.201	19.650	551.390	7	4	9E9	9E9	18	9	145.362
42.400	61.738	0.868	90.120	44.329	18.860	553.751	8	7	9E9	9E9	21	11	9E9
42.650	113.549	0.784	20.870	0.000	19.650	556.112	8	9	9E9	9E9	23	12	9E9
42.900	110.966	0.749	18.150	0.000	19.650	558.572	8	9	9E9	9E9	22	11	9E9
43.150	172.749	0.758	16.760	0.000	19.650	561.032	9	9	9E9	9E9	35	18	9E9

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"Output file from CPTINT - Version 5.0ppd
"=======================================
"INPUT FILE: c:\cptint\F01-9333.DAT
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"
"Licensed to:  UBC Course - For teaching only
"    Address:
"       City:
"
"Interpreter Name: TIM J. BOYD
"
"File Number:                Date:  10-14-93 13:24
"Operator:   UBC ISTG        On Site Location: Falcon No. 1
"Cone Type:  HOG3RES1        Comment:    F01-9333
"
"SUMMARY SHEET
"-------------
"'a' for calculating Qt:                0.800
"Value for Water Table (in m):          10.500
"Valid Zone Classification based on:     Bq
"Missing unit weight to start depth:     19.000
"Method for calculating Su:              Nkt
"Value of the constant Nkt:              12.500
"Define Zone 6 for Sand Parameters?      NO
"Sand Compressibility for calc Dr:       Moderate
"Method for Friction Angle:              Robertson & Campanella
"
"Soil Behavior Type Zone Numbers
"For Rf Zone & Bq Zone Classification
"-----------------------------------
"Zone #1=Sensitive fine grained     Zone #7 =Silty sand
"Zone #2=Organic material           Zone #8 =Fine sand
"Zone #3=Clay                       Zone #9 =Sand
"Zone #4=Silty clay                 Zone #10=Gravelly sand
"Zone #5=Clayey silt                Zone #11=Very stiff fine grained *
"Zone #6=Sandy silt                 Zone #12=Sand to clayey sand *
"   * Overconsolidated and/or cemented
"
"NOTE:
"-----
"For soil classification, Rf values > 8 are assumed to be 8.
"
"( Note: 9E9 means Out Of Range )
"
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Depth (meter)	Qt(avg) (bars)	Rf (%)	U2 (meter)	RES075 (ohm-m)	Gamma (kN/m^3)	EOS(avg) (kPa)	Rf Zone (zone #)	Bq Zone (zone #)	Dr (%)	Phi (degree)	Spt N (blow/ft)	Spt N1 (blow/ft)	Su (kPa)
0.150	37.230	0.682	-0.020	57.751	19.650	2.931	7	8	106	9E9	9	14	9E9
0.400	20.232	0.717	0.080	2.379	18.860	7.745	6	7	61	45	7	11	9E9
0.650	15.486	0.988	-0.690	1.610	18.860	12.460	6	6	9E9	9E9	6	9	122.895
0.900	17.340	0.779	-2.060	1.180	18.860	17.175	6	6	9E9	9E9	7	11	137.343
1.150	20.347	0.762	-0.640	1.928	18.860	21.890	6	7	39	41	7	11	9E9
1.400	32.464	0.367	-0.800	8.833	19.650	26.704	7	8	53	41	8	12	9E9
1.650	31.699	0.555	-0.060	12.295	19.650	31.616	7	8	48	41	8	12	9E9
1.900	33.669	0.514	-0.050	5.057	19.650	36.529	7	8	47	41	8	12	9E9
2.150	37.624	0.757	-0.310	4.730	19.650	41.441	7	8	49	41	9	14	9E9
2.400	51.869	0.727	-0.560	12.961	19.650	46.354	8	8	59	41	13	20	9E9
2.650	48.968	0.870	-0.110	12.048	19.650	51.266	7	8	55	41	12	18	9E9
2.900	38.615	0.777	-0.240	6.532	19.650	56.179	7	8	43	39	10	15	9E9
3.150	32.101	0.751	-0.440	5.532	19.650	61.091	7	8	34	37	8	11	9E9
3.400	33.056	0.853	-0.710	8.963	19.650	66.004	7	8	34	37	8	11	9E9
3.650	33.673	0.944	0.130	23.708	19.650	70.916	7	8	33	37	8	10	9E9
3.900	28.242	1.076	0.110	17.187	18.860	75.730	7	7	25	37	9	11	9E9
4.150	25.425	0.983	-0.270	11.830	18.860	80.445	7	7	19	35	8	9	9E9
4.400	21.999	1.427	-0.040	6.508	18.860	85.160	6	7	13	33	7	8	9E9
4.650	22.563	1.263	-0.870	7.971	18.860	89.875	6	7	12	33	8	8	9E9
4.900	11.616	2.453	0.820	6.250	18.860	94.590	5	6	9E9	9E9	5	5	85.361
5.150	14.051	1.630	2.600	7.029	18.860	99.305	5	6	9E9	9E9	6	6	104.464
5.400	16.171	2.041	-1.970	6.101	18.860	104.020	5	6	9E9	9E9	6	6	121.049
5.650	8.774	2.622	-1.350	9.594	18.860	108.735	4	6	9E9	9E9	4	4	61.489
5.900	5.742	1.986	3.140	11.477	18.860	113.450	4	4	9E9	9E9	4	4	36.857
6.150	14.706	1.319	2.870	17.134	18.860	118.165	6	6	9E9	9E9	6	5	108.197
6.400	37.758	1.330	-0.590	23.958	19.650	122.979	7	8	26	35	9	7	9E9
6.650	26.432	1.604	-0.390	21.710	18.860	127.792	6	7	11	31	9	7	9E9
6.900	14.885	1.841	1.790	20.762	18.860	132.507	5	6	9E9	9E9	6	5	108.480
7.150	24.400	1.668	-0.510	16.775	18.860	137.222	6	7	6	31	8	6	9E9
7.400	43.001	1.007	-1.460	23.297	19.650	142.036	7	8	28	35	11	8	9E9
7.650	31.230	1.214	-0.490	19.696	18.860	146.850	7	7	14	33	10	7	9E9
7.900	27.198	1.471	-0.090	21.497	18.860	151.565	6	7	8	31	9	6	9E9
8.150	12.683	2.137	1.700	11.888	18.860	156.280	5	6	9E9	9E9	5	3	88.964
8.400	7.566	2.101	4.390	8.263	18.860	160.995	4	5	9E9	9E9	4	3	47.649
8.650	16.817	2.111	3.440	9.158	18.860	165.710	5	6	9E9	9E9	7	5	121.283
8.900	7.846	1.899	8.480	7.837	18.860	170.425	5	4	9E9	9E9	5	3	49.137
9.150	7.435	1.318	16.560	8.204	18.860	175.140	5	4	9E9	9E9	5	3	45.468
9.400	8.178	1.333	21.320	13.700	18.860	179.855	5	3	9E9	9E9	8	5	51.038
9.650	17.645	1.173	20.150	18.646	18.860	184.570	6	5	9E9	9E9	9	5	126.397
9.900	28.744	1.833	8.880	15.402	18.860	189.285	6	7	6	31	10	6	9E9
10.150	17.245	1.914	5.880	9.596	18.860	194.000	6	6	9E9	9E9	7	4	122.443
10.400	23.904	2.221	2.750	21.000	18.860	198.715	6	7	-1	9E9	8	5	9E9
10.650	13.292	2.460	13.860	20.864	18.860	201.958	5	5	9E9	9E9	7	4	90.061
10.900	17.511	1.376	16.880	18.892	18.860	204.221	6	5	9E9	9E9	9	5	123.438
11.150	26.092	1.552	9.810	10.510	18.860	206.483	6	7	0	9E9	9	5	9E9
11.400	30.592	1.605	6.240	21.956	18.860	208.746	6	7	6	31	10	5	9E9
11.650	28.211	1.631	7.680	18.833	18.860	211.008	6	7	3	9E9	9	5	9E9
11.900	15.607	1.807	21.770	15.276	18.860	213.271	5	5	9E9	9E9	8	4	106.697
12.150	18.194	2.451	14.490	11.448	18.860	215.533	5	6	9E9	9E9	7	4	127.017
12.400	9.051	1.492	19.400	11.756	18.860	217.796	5	4	9E9	9E9	6	3	53.490
12.650	10.440	1.236	40.270	11.617	19.650	220.157	5	3	9E9	9E9	10	5	64.221
12.900	13.514	1.532	35.360	16.870	18.860	222.518	5	4	9E9	9E9	9	5	88.425
13.150	13.270	2.562	18.850	11.002	18.860	224.781	5	5	9E9	9E9	7	4	86.096
13.400	18.087	1.924	19.710	15.856	18.860	227.043	6	5	9E9	9E9	9	5	124.254
13.650	28.293	2.036	18.500	18.524	19.650	229.405	6	6	9E9	9E9	11	6	205.519
13.900	24.131	1.902	11.780	20.049	19.650	231.865	6	6	9E9	9E9	10	5	171.831
14.150	10.666	1.266	15.590	11.528	18.860	234.226	5	5	9E9	9E9	5	3	63.724
14.400	8.643	1.354	25.110	20.231	18.860	236.488	5	3	9E9	9E9	9	5	47.161

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" Depth (meter)	Qt(avg) (bars)	Rf (%)	U2 (meter)	RES075 (ohm-m)	Gamma (kN/m^3)	EOS(avg) (kPa)	Rf Zone (zone #)	Bq Zone (zone #)	Dr (%)	Phi (degree)	Spt N (blow/ft)	Spt N1 (blow/ft)	Su (kPa)
14.650	27.560	1.136	28.530	16.293	19.650	238.850	7	6	9E9	9E9	11	6	198.113
14.900	23.941	1.612	22.480	17.403	19.650	241.310	6	6	9E9	9E9	10	5	168.770
15.150	18.699	1.481	14.210	13.540	18.860	243.671	6	6	9E9	9E9	7	4	126.447
15.400	20.594	1.534	21.630	15.973	19.650	246.032	6	6	9E9	9E9	8	4	141.227
15.650	20.007	1.429	28.390	11.530	19.650	248.492	6	5	9E9	9E9	10	5	136.135
15.900	18.183	1.540	27.700	13.078	18.860	250.853	6	5	9E9	9E9	9	5	121.161
16.150	20.520	1.379	13.770	15.025	19.650	253.215	6	6	9E9	9E9	8	4	139.470
16.400	8.941	1.275	37.240	11.805	18.860	255.576	5	3	9E9	9E9	9	5	46.449
16.650	8.804	1.125	49.630	18.512	18.860	257.838	5	3	9E9	9E9	9	5	44.976
16.900	11.040	2.074	51.970	15.194	19.650	260.200	5	3	9E9	9E9	11	6	62.478
17.150	17.600	1.983	13.760	15.175	18.860	262.561	6	6	9E9	9E9	7	4	114.576
17.400	22.784	2.023	26.720	22.392	19.650	264.922	6	6	9E9	9E9	9	5	155.665
17.650	20.201	2.376	33.710	20.935	19.650	267.382	5	5	9E9	9E9	10	5	134.609
17.900	11.545	1.135	54.300	16.839	19.650	269.842	6	3	9E9	9E9	12	6	64.968
18.150	12.897	1.031	43.170	15.410	18.860	272.203	6	4	9E9	9E9	9	5	75.396
18.400	28.409	1.792	38.190	19.052	19.650	274.565	6	6	9E9	9E9	11	6	199.109
18.650	15.086	1.790	45.660	17.609	18.860	276.926	5	4	9E9	9E9	10	5	92.136
18.900	13.891	1.065	51.040	16.180	18.860	279.188	6	4	9E9	9E9	9	5	82.204
19.150	21.216	1.400	32.940	13.329	19.650	281.550	6	5	9E9	9E9	11	6	140.418
19.400	24.427	2.501	26.880	19.506	19.650	284.010	6	6	9E9	9E9	10	5	165.713
19.650	19.011	1.689	40.300	19.912	18.860	286.371	6	5	9E9	9E9	10	5	121.995
19.900	26.579	1.911	33.610	14.656	19.650	288.732	6	6	9E9	9E9	11	6	182.160
20.150	18.202	2.236	18.960	9.448	18.860	291.093	5	6	9E9	9E9	7	4	114.755
20.400	25.941	1.588	44.880	14.260	19.650	293.455	6	5	9E9	9E9	13	7	176.278
20.650	19.404	2.329	40.480	21.784	18.860	295.816	5	5	9E9	9E9	10	5	123.603
20.900	20.671	2.119	44.420	14.561	19.650	298.177	6	5	9E9	9E9	10	5	133.356
21.150	13.610	1.315	49.430	12.081	18.860	300.538	6	4	9E9	9E9	9	5	76.477
21.400	18.415	2.422	46.650	19.838	18.860	302.801	5	5	9E9	9E9	9	5	114.544
21.650	28.586	1.630	34.450	18.979	19.650	305.162	6	6	9E9	9E9	11	6	195.524
21.900	24.736	1.993	40.580	13.047	19.650	307.622	6	6	9E9	9E9	10	5	164.333
22.150	34.861	1.764	24.530	13.768	18.860	309.983	6	7	3	9E9	12	6	9E9
22.400	38.646	1.736	28.860	18.583	18.860	312.246	7	7	6	9E9	13	7	9E9
22.650	53.100	1.446	21.920	19.884	19.650	314.607	7	8	19	31	13	7	9E9
22.900	38.785	1.921	25.210	13.159	18.860	316.968	6	7	6	9E9	13	7	9E9
23.150	24.198	2.137	38.650	16.915	19.650	319.330	6	6	9E9	9E9	10	5	158.112
23.400	21.796	1.693	52.820	20.020	19.650	321.790	6	5	9E9	9E9	11	6	138.503
23.650	45.716	1.428	27.330	16.069	18.860	324.151	7	7	12	9E9	15	8	9E9
23.900	26.358	2.045	36.620	13.784	19.650	326.512	6	6	9E9	9E9	11	6	174.230
24.150	18.850	0.966	54.540	16.766	18.860	328.873	6	4	9E9	9E9	13	7	113.778
24.400	19.286	1.193	60.940	22.093	18.860	331.136	6	4	9E9	9E9	13	7	116.885
24.650	21.246	1.158	64.010	18.680	19.650	333.497	6	4	9E9	9E9	14	7	132.182
24.900	52.235	1.457	17.610	11.793	19.650	335.957	7	8	16	31	13	7	9E9
25.150	37.889	2.396	19.310	18.679	19.650	338.417	6	8	4	9E9	9	5	9E9
25.400	18.338	1.527	59.010	14.490	18.860	340.778	6	4	9E9	9E9	12	6	107.746
25.650	15.412	1.194	72.460	17.794	19.650	343.140	6	3	9E9	9E9	15	8	83.952
25.900	16.760	1.295	64.730	11.306	18.860	345.501	6	4	9E9	9E9	11	6	94.354
26.150	47.126	1.676	31.930	19.202	18.860	347.763	7	7	12	9E9	16	8	9E9
26.400	21.626	1.350	57.410	23.669	19.650	350.125	6	5	9E9	9E9	11	6	132.523
26.650	17.276	1.326	71.140	17.290	18.860	352.486	6	4	9E9	9E9	12	6	97.332
26.900	17.937	1.327	51.860	11.453	18.860	354.748	6	4	9E9	9E9	12	6	102.249
27.150	24.163	1.999	50.620	20.411	19.650	357.110	6	5	9E9	9E9	12	6	151.669
27.400	21.020	1.128	66.240	28.176	19.650	359.570	6	4	9E9	9E9	14	7	126.128
27.650	20.133	1.793	66.390	28.678	19.650	362.029	6	4	9E9	9E9	13	7	118.639
27.900	25.937	1.812	54.410	15.837	19.650	364.489	6	5	9E9	9E9	13	7	164.685
28.150	18.999	1.363	69.250	17.534	18.860	366.851	6	4	9E9	9E9	13	7	108.789
28.400	15.214	1.032	85.300	21.508	19.650	369.212	6	3	9E9	9E9	15	8	78.123
28.650	21.847	1.419	72.230	22.180	19.650	371.672	6	4	9E9	9E9	15	8	130.799
28.900	16.433	1.534	64.880	15.261	18.860	374.033	6	4	9E9	9E9	11	6	87.100

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Depth (meter)	Qt(avg) (bars)	Rf (%)	U2 (meter)	RES075 (ohm-m)	Gamma (kN/m^3)	EOS(avg) (kPa)	Rf Zone (zone #)	Bq Zone (zone #)	Dr (%)	Phi (degree)	Spt N (blow/ft)	Spt N1 (blow/ft)	Su (kPa)
29.150	18.620	0.644	79.500	25.301	18.860	376.296	6	4	9E9	9E9	12	6	104.218
29.400	15.800	1.133	88.700	23.707	19.650	378.657	6	3	9E9	9E9	16	8	81.277
29.650	16.882	1.161	83.700	20.177	19.650	381.117	6	3	9E9	9E9	17	9	89.539
29.900	16.848	1.110	75.820	16.349	18.860	383.478	6	4	9E9	9E9	11	6	88.877
30.150	15.941	1.004	89.250	25.718	19.650	385.839	6	3	9E9	9E9	16	8	81.240
30.400	15.278	0.982	85.520	25.791	19.650	388.299	6	3	9E9	9E9	15	8	75.541
30.650	14.331	0.942	83.650	23.484	19.650	390.759	6	3	9E9	9E9	14	7	67.575
30.900	16.729	2.666	69.270	17.137	18.860	393.120	5	4	9E9	9E9	11	6	86.373
31.150	21.835	3.485	54.790	26.859	19.650	395.482	5	5	9E9	9E9	11	6	126.835
31.400	18.491	2.212	56.610	24.481	18.860	397.843	5	4	9E9	9E9	12	6	99.695
31.650	18.777	1.763	64.560	21.885	18.860	400.105	6	4	9E9	9E9	13	7	101.606
31.900	15.300	1.359	59.630	16.142	18.860	402.368	6	4	9E9	9E9	10	5	73.415
32.150	16.759	1.319	77.430	18.554	18.860	404.630	6	4	9E9	9E9	11	6	84.712
32.400	20.808	1.250	75.320	20.333	19.650	406.991	6	4	9E9	9E9	14	7	116.715
32.650	20.967	1.149	76.830	19.118	19.650	409.451	6	4	9E9	9E9	14	7	117.599
32.900	22.307	1.188	63.070	20.391	19.650	411.911	6	5	9E9	9E9	11	6	127.927
33.150	22.649	1.214	79.960	27.052	19.650	414.371	6	4	9E9	9E9	15	8	130.265
33.400	23.711	1.118	77.040	27.627	19.650	416.831	6	5	9E9	9E9	12	6	138.373
33.650	25.671	0.752	74.980	25.898	19.650	419.291	7	5	9E9	9E9	13	7	153.657
33.900	22.133	1.184	69.460	22.637	19.650	421.751	6	5	9E9	9E9	11	6	124.958
34.150	23.203	1.125	81.690	29.156	19.650	424.211	6	4	9E9	9E9	15	8	133.124
34.400	26.316	1.752	71.640	24.857	19.650	426.671	6	5	9E9	9E9	13	7	157.634
34.650	23.662	1.327	65.350	21.479	19.650	429.131	6	5	9E9	9E9	12	6	136.014
34.900	20.163	1.949	62.840	21.997	19.650	431.591	6	5	9E9	9E9	10	5	107.627
35.150	19.372	1.678	68.910	24.146	18.860	433.952	6	4	9E9	9E9	13	7	100.914
35.400	20.303	1.473	62.840	22.323	19.650	436.314	6	5	9E9	9E9	10	5	107.976
35.650	18.679	1.280	63.140	23.161	18.860	438.675	6	4	9E9	9E9	12	6	94.598
35.900	19.564	1.349	58.320	18.873	18.860	440.937	6	5	9E9	9E9	10	5	101.305
36.150	21.161	1.413	50.000	26.833	19.650	443.299	6	5	9E9	9E9	11	6	113.694
36.400	14.458	2.283	52.890	22.078	18.860	445.660	5	4	9E9	9E9	10	5	59.682
36.650	15.767	1.211	60.990	23.514	18.860	447.922	6	4	9E9	9E9	11	6	69.776
36.900	19.085	3.312	51.220	24.887	18.860	450.185	5	5	9E9	9E9	10	5	95.946
37.150	17.701	3.135	40.310	31.566	18.860	452.447	5	5	9E9	9E9	9	5	84.496
37.400	17.718	1.733	43.210	28.314	18.860	454.710	6	5	9E9	9E9	9	5	84.254
37.650	18.108	2.584	47.310	26.004	18.860	456.972	5	5	9E9	9E9	9	5	87.000
37.900	15.615	2.709	45.110	23.276	18.860	459.235	5	5	9E9	9E9	8	4	66.678
38.150	15.854	1.697	45.050	28.943	18.860	461.497	6	5	9E9	9E9	8	4	68.211
38.400	13.788	2.872	55.440	25.869	18.860	463.759	5	4	9E9	9E9	9	5	51.305
38.650	14.504	2.951	58.300	26.052	18.860	466.022	5	4	9E9	9E9	10	5	56.657
38.900	15.495	1.388	62.970	26.772	18.860	468.284	6	4	9E9	9E9	10	5	64.212
39.150	16.815	1.308	67.050	30.142	18.860	470.547	6	4	9E9	9E9	11	6	74.396
39.400	16.738	1.613	70.760	29.349	18.860	472.809	6	4	9E9	9E9	11	6	73.401
39.650	19.237	3.426	47.780	27.004	18.860	475.072	5	5	9E9	9E9	10	5	93.017
39.900	22.273	3.619	57.730	30.732	19.650	477.433	4	5	9E9	9E9	11	6	116.913
40.150	19.589	2.930	55.500	27.927	18.860	479.794	5	5	9E9	9E9	10	5	95.058
40.400	18.620	2.798	56.050	0.000	18.860	482.057	5	5	9E9	9E9	9	5	86.927
40.650	21.368	3.763	54.450	0.000	19.650	484.418	4	5	9E9	9E9	11	6	108.531
40.900	62.725	2.117	44.620	0.000	19.650	486.878	7	8	16	9E9	16	8	9E9
41.150	207.366	0.757	17.400	0.000	19.650	489.338	9	9	62	9E9	41	21	9E9

```
"
"Output file from CPTINT - Version 5.0ppd
"=======================================
"INPUT FILE: B:\GB-T9411.COR
"--------------------------
"
"Licensed to:  UBC Course - For teaching only
"    Address:
"       City:
"
"Interpreter Name: TIM J. BOYD
"
"File Number:      0          Date: 9-03-94 11:05
"Operator:  MPD-TJB            On Site Location: GIB. N.TAIL
"Cone Type:  RES2UBC9U2        Comment: GB-9411  U2ppd
"
"SUMMARY SHEET
"-------------
"'a' for calculating Qt:                0.800
"Value for Water Table (in m):          16.500
"Valid Zone Classification based on:    Bq
"Missing unit weight to start depth:    19.000
"Method for calculating Su:             Nkt
"Value of the constant Nkt:             12.500
"Define Zone 6 for Sand Parameters?     NO
"Sand Compressibility for calc Dr:      Moderate
"Method for Friction Angle:             Robertson & Campanella
"
"Soil Behavior Type Zone Numbers
"For Rf Zone & Bq Zone Classification
"-----------------------------------
"Zone #1=Sensitive fine grained     Zone #7 =Silty sand
"Zone #2=Organic material           Zone #8 =Fine sand
"Zone #3=Clay                       Zone #9 =Sand
"Zone #4=Silty clay                 Zone #10=Gravelly sand
"Zone #5=Clayey silt                Zone #11=Very stiff fine grained *
"Zone #6=Sandy silt                 Zone #12=Sand to clayey sand *
"   * Overconsolidated and/or cemented
"
"NOTE:
"-----
"For soil classification, Rf values > 8 are assumed to be 8.
"
"( Note: 9E9 means Out Of Range )
"
```

"---| INPUT FILE: B:\GB-T9411.COR |----------

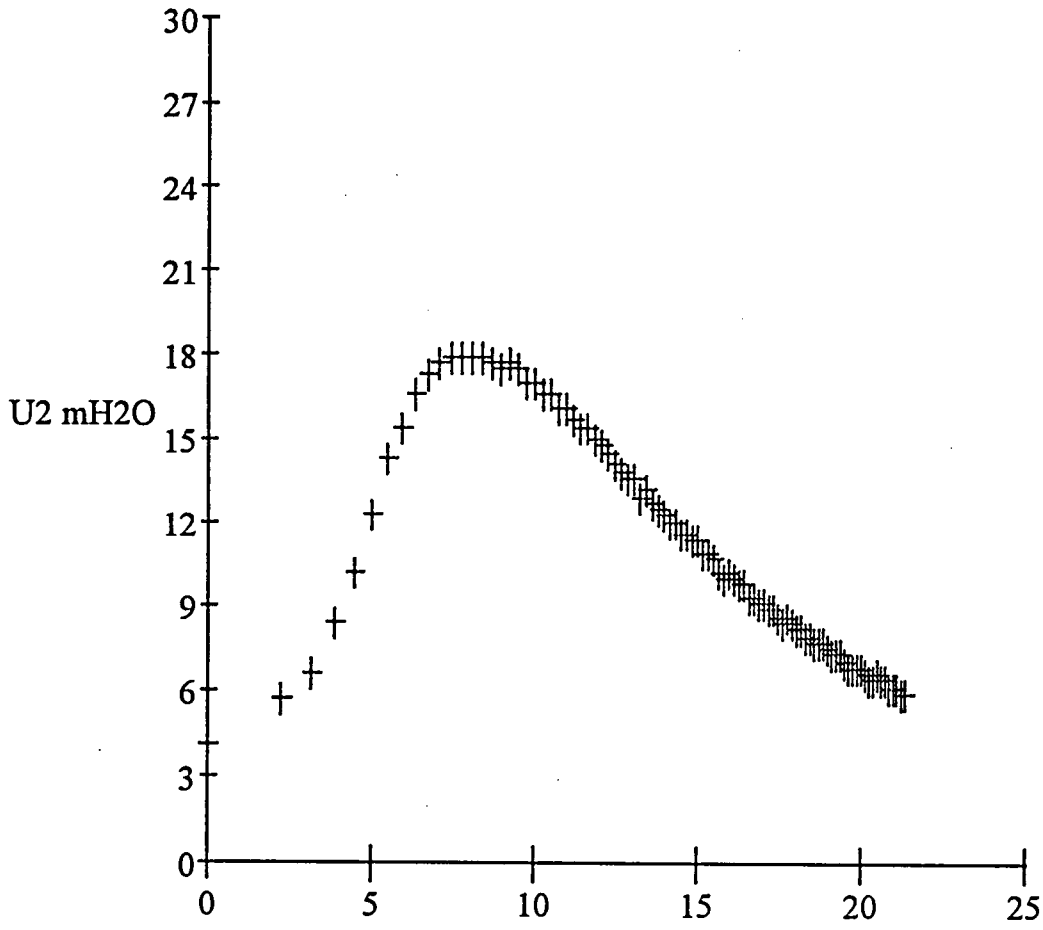
Depth (meter)	Qt(avg) (bars)	Rf (%)	U2 (meter)	RES075 (ohm-m)	Gamma (kN/m^3)	EOS(avg) (kPa)	Rf Zone (zone #)	Bq Zone (zone #)	Dr (%)	Phi (degree)	Spt N (blow/ft)	Spt N1 (blow/ft)	Su (kPa)
0.150	60.952	0.400	0.067	283.040	19.650	2.931	8	8	125	9E9	15	23	9E9
0.400	107.348	0.619	0.104	283.040	19.650	7.844	9	9	126	9E9	21	32	9E9
0.650	90.611	0.557	0.130	265.628	19.650	12.756	8	9	109	9E9	18	27	9E9
0.900	74.210	0.536	0.097	202.545	19.650	17.669	8	9	94	47	15	23	9E9
1.150	57.120	0.511	0.080	159.673	19.650	22.581	8	8	78	45	14	21	9E9
1.400	54.424	0.553	0.029	146.003	19.650	27.494	8	8	72	45	14	21	9E9
1.650	45.575	0.568	-0.133	127.856	19.650	32.406	8	8	62	43	11	17	9E9
1.900	44.902	0.476	-0.182	105.318	19.650	37.319	8	8	58	41	11	17	9E9
2.150	41.998	0.486	-0.217	106.091	19.650	42.231	8	8	53	41	10	15	9E9
2.400	40.142	0.428	-0.237	115.374	19.650	47.144	8	8	49	41	10	15	9E9
2.650	34.670	0.424	-0.258	125.450	19.650	52.056	7	8	41	39	9	14	9E9
2.900	35.260	0.428	-0.243	121.099	19.650	56.969	7	8	40	39	9	13	9E9
3.150	37.760	0.414	-0.231	111.571	19.650	61.881	7	8	40	39	9	13	9E9
3.400	39.162	0.470	-0.217	105.979	19.650	66.794	7	8	40	39	10	13	9E9
3.650	31.633	0.446	-0.187	108.695	18.860	71.607	7	7	30	37	11	14	9E9
3.900	66.211	0.467	-0.187	106.724	19.650	76.421	8	8	58	41	17	20	9E9
4.150	67.856	0.576	-0.167	104.848	19.650	81.334	8	8	57	41	17	19	9E9
4.400	59.697	0.472	-0.139	99.605	19.650	86.246	8	8	51	39	15	16	9E9
4.650	52.992	0.452	-0.105	101.330	19.650	91.159	8	8	45	39	13	14	9E9
4.900	47.800	0.397	-0.113	102.013	19.650	96.071	8	8	40	37	12	12	9E9
5.150	46.422	0.403	-0.115	106.402	19.650	100.984	8	8	38	37	12	12	9E9
5.400	46.510	0.355	-0.103	118.329	19.650	105.896	8	8	37	37	12	11	9E9
5.650	46.341	0.320	-0.081	130.154	19.650	110.809	8	8	36	37	12	11	9E9
5.900	54.164	0.362	-0.077	131.293	19.650	115.721	8	8	41	37	14	12	9E9
6.150	55.924	0.373	-0.056	133.855	19.650	120.634	8	8	41	37	14	12	9E9
6.400	56.917	0.340	-0.039	147.640	19.650	125.546	8	8	41	37	14	11	9E9
6.650	60.421	0.357	-0.023	152.535	19.650	130.459	8	8	43	37	15	12	9E9
6.900	62.505	0.351	-0.005	153.540	19.650	135.371	8	8	43	37	16	12	9E9
7.150	59.262	0.360	0.037	142.556	19.650	140.284	8	8	40	37	15	11	9E9
7.400	54.725	0.379	-0.004	131.939	19.650	145.196	8	8	36	37	14	10	9E9
7.650	61.410	0.395	0.032	112.895	19.650	150.109	8	8	40	37	15	11	9E9
7.900	58.329	0.405	-0.008	109.450	19.650	155.021	8	8	37	37	15	10	9E9
8.150	60.672	0.418	0.016	103.946	19.650	159.934	8	8	38	37	15	10	9E9
8.400	55.724	0.392	0.012	94.867	19.650	164.846	8	8	34	35	14	9	9E9
8.650	40.757	0.409	0.028	76.511	19.650	169.759	8	8	22	33	10	6	9E9
8.900	41.140	0.287	0.031	83.887	19.650	174.671	8	8	21	33	10	6	9E9
9.150	62.637	0.300	0.002	94.853	19.650	179.584	8	8	37	35	16	10	9E9
9.400	65.063	0.326	0.657	103.014	19.650	184.496	8	8	38	35	16	10	9E9
9.650	62.994	0.299	0.019	97.584	19.650	189.409	8	8	36	35	16	9	9E9
9.900	61.639	0.361	0.070	83.449	19.650	194.321	8	8	35	35	15	9	9E9
10.150	59.306	0.329	0.070	66.774	19.650	199.234	8	8	33	35	15	9	9E9
10.400	56.665	0.332	0.036	60.297	19.650	204.146	8	8	30	35	14	8	9E9
10.650	57.981	0.350	-0.003	60.598	19.650	209.059	8	8	31	35	14	8	9E9
10.900	61.925	0.360	0.018	60.878	19.650	213.971	8	8	33	35	15	8	9E9
11.150	55.648	0.354	-0.001	57.092	19.650	218.884	8	8	28	33	14	7	9E9
11.400	60.434	0.336	0.014	59.381	19.650	223.796	8	8	31	33	15	8	9E9
11.650	63.894	0.331	0.023	71.405	19.650	228.709	8	8	33	35	16	8	9E9
11.900	64.215	0.383	0.030	76.185	19.650	233.621	8	8	32	35	16	8	9E9
12.150	60.411	0.397	0.025	72.038	19.650	238.534	8	8	30	33	15	8	9E9
12.400	59.610	0.414	0.029	120.392	19.650	243.446	8	8	29	33	15	8	9E9
12.650	60.860	0.355	0.013	189.265	19.650	248.359	8	8	29	33	15	8	9E9
12.900	61.422	0.354	0.034	206.512	19.650	253.271	8	8	29	33	15	8	9E9
13.150	60.781	0.435	0.070	133.226	19.650	258.184	8	8	28	33	15	8	9E9
13.400	58.947	0.447	0.042	118.221	19.650	263.096	8	8	26	33	15	8	9E9
13.650	61.696	0.436	0.037	108.329	19.650	268.009	8	8	28	33	15	8	9E9
13.900	63.191	0.428	0.044	101.895	19.650	272.921	8	8	28	33	16	8	9E9
14.150	67.351	0.438	0.033	99.997	19.650	277.834	8	8	30	33	17	9	9E9
14.400	65.505	0.432	0.040	92.198	19.650	282.746	8	8	29	33	16	8	9E9

"---| INPUT FILE: B:\GB-T9411.COR |----------

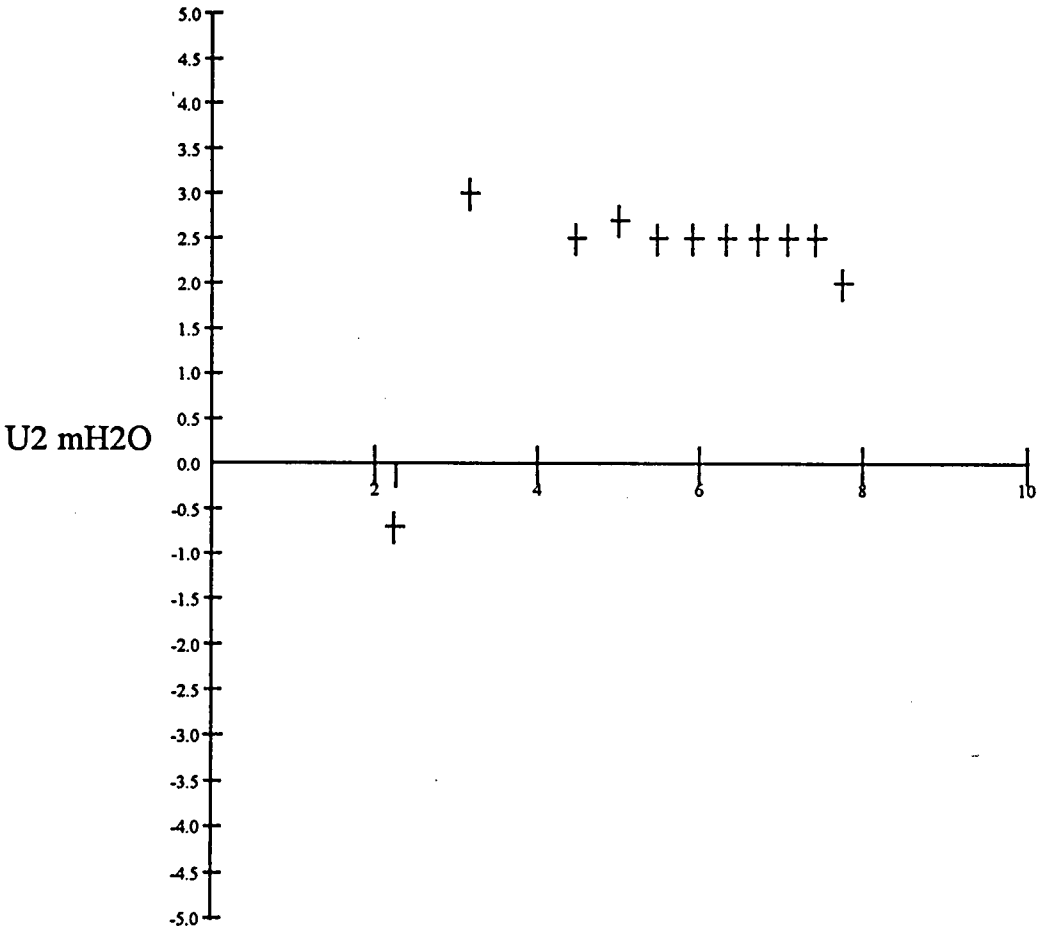
Depth (meter)	Qt(avg) (bars)	Rf (%)	U2 (meter)	RES075 (ohm-m)	Gamma (kN/m^3)	EOS(avg) (kPa)	Rf Zone (zone #)	Bq Zone (zone #)	Dr (%)	Phi (degree)	Spt N (blow/ft)	Spt N1 (blow/ft)	Su (kPa)
14.650	65.338	0.381	0.020	83.803	19.650	287.659	8	8	28	33	16	8	9E9
14.900	69.222	0.326	0.006	71.690	19.650	292.571	8	8	30	33	17	9	9E9
15.150	68.304	0.308	0.016	54.315	19.650	297.484	8	8	29	33	17	9	9E9
15.400	59.660	0.204	0.458	36.826	19.650	302.396	8	8	24	31	15	8	9E9
15.650	59.237	0.202	0.675	24.666	19.650	307.309	8	8	23	31	15	8	9E9
15.900	62.842	0.184	0.860	23.054	19.650	312.221	8	8	25	31	16	8	9E9
16.150	63.698	0.153	1.072	23.017	19.650	317.134	8	8	25	31	16	8	9E9
16.400	64.310	0.174	1.215	23.783	19.650	322.046	8	8	25	31	16	8	9E9
16.650	61.198	0.155	1.453	23.520	19.650	325.487	8	8	23	31	15	8	9E9
16.900	56.632	0.126	1.799	22.043	19.650	327.947	8	8	20	31	14	7	9E9
17.150	48.182	0.131	1.272	21.208	19.650	330.407	8	8	14	31	12	6	9E9
17.400	31.254	0.656	0.986	14.220	18.860	332.768	7	7	9E9	9E9	10	5	9E9
17.650	17.345	2.726	0.022	0.000	18.860	335.031	5	6	9E9	9E9	7	4	111.058
17.900	26.969	2.666	-5.575	0.000	18.860	337.293	6	7	9E9	9E9	9	5	9E9
18.150	46.882	2.308	-6.258	0.000	19.650	339.655	6	8	12	9E9	12	6	9E9
18.400	297.736	0.000	-7.080	0.000	20.440	342.213	10	10	84	41	50	25	9E9

APPENDIX C - RCPT PORE PRESSURE DISSIPATION PROFILES

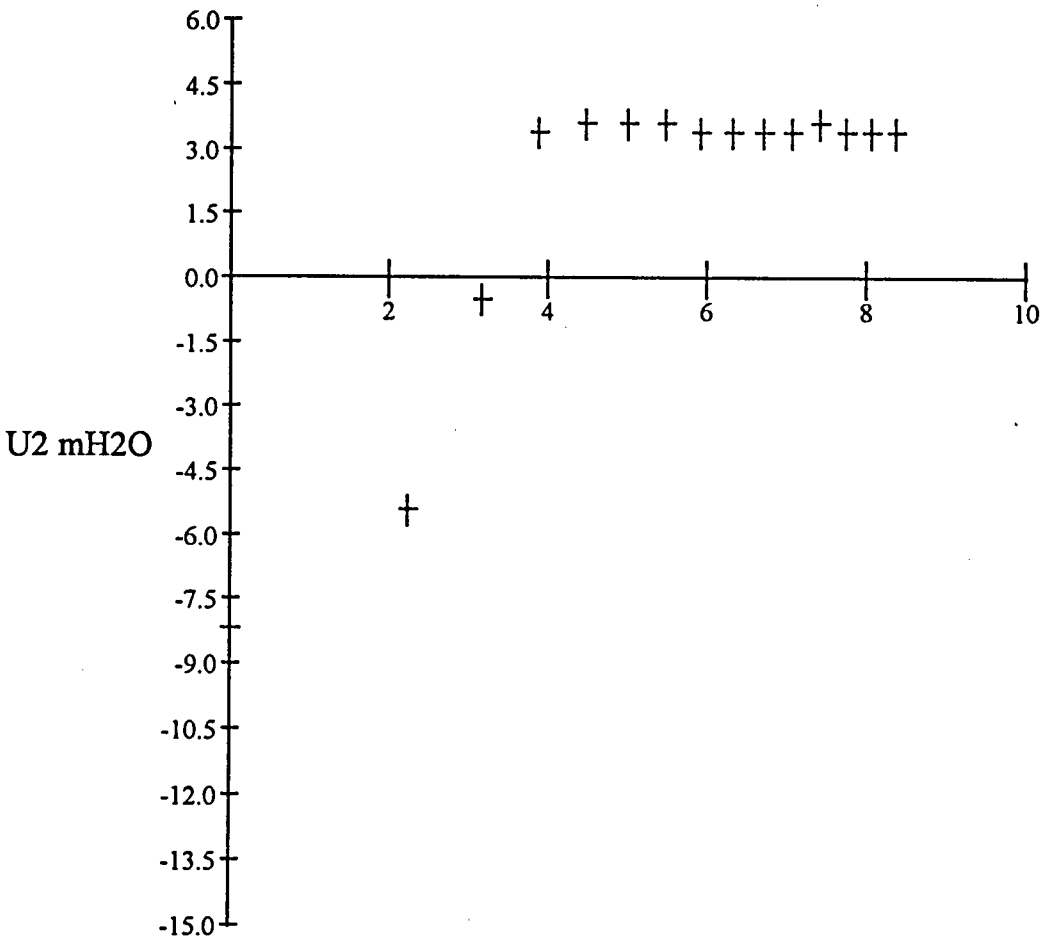
FILE: I19-9323 DISSIPATION AT DEPTH : 1.2 m



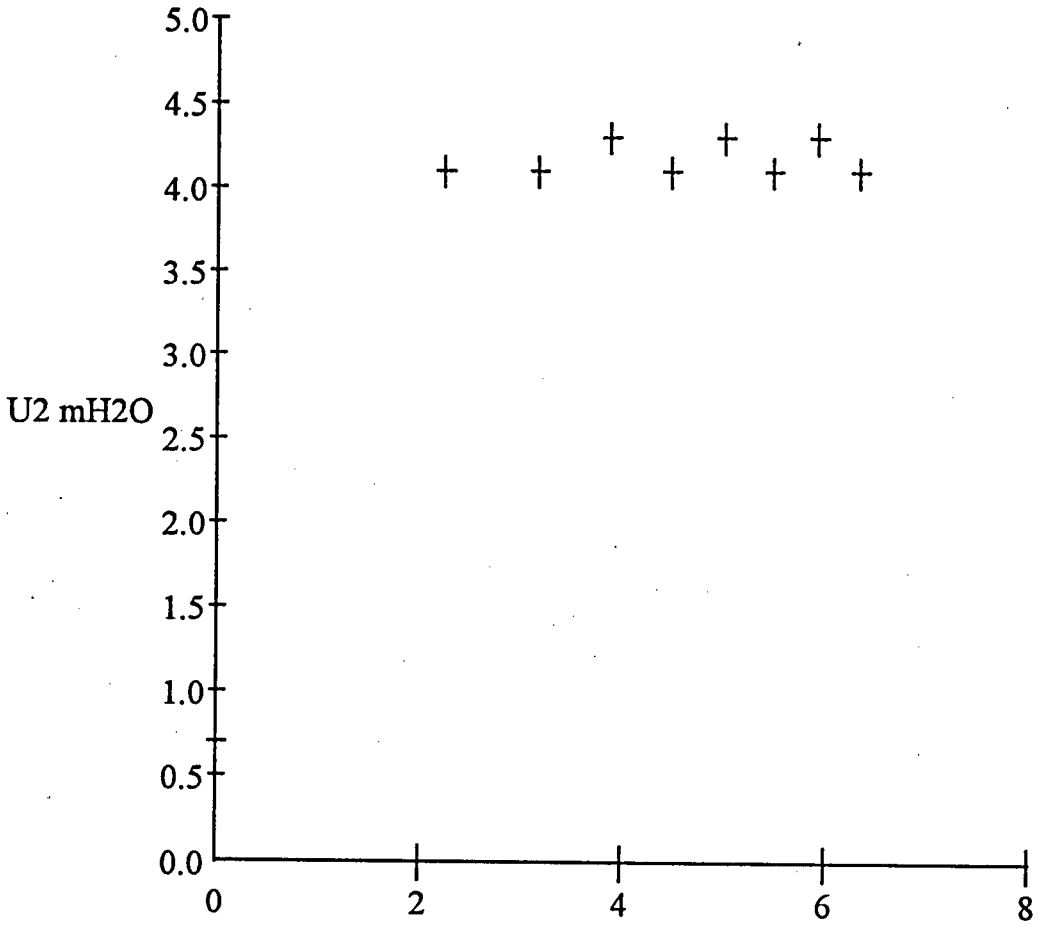
FILE: I19-9323.DIS DISSIPATION AT DEPTH : 2.2 m



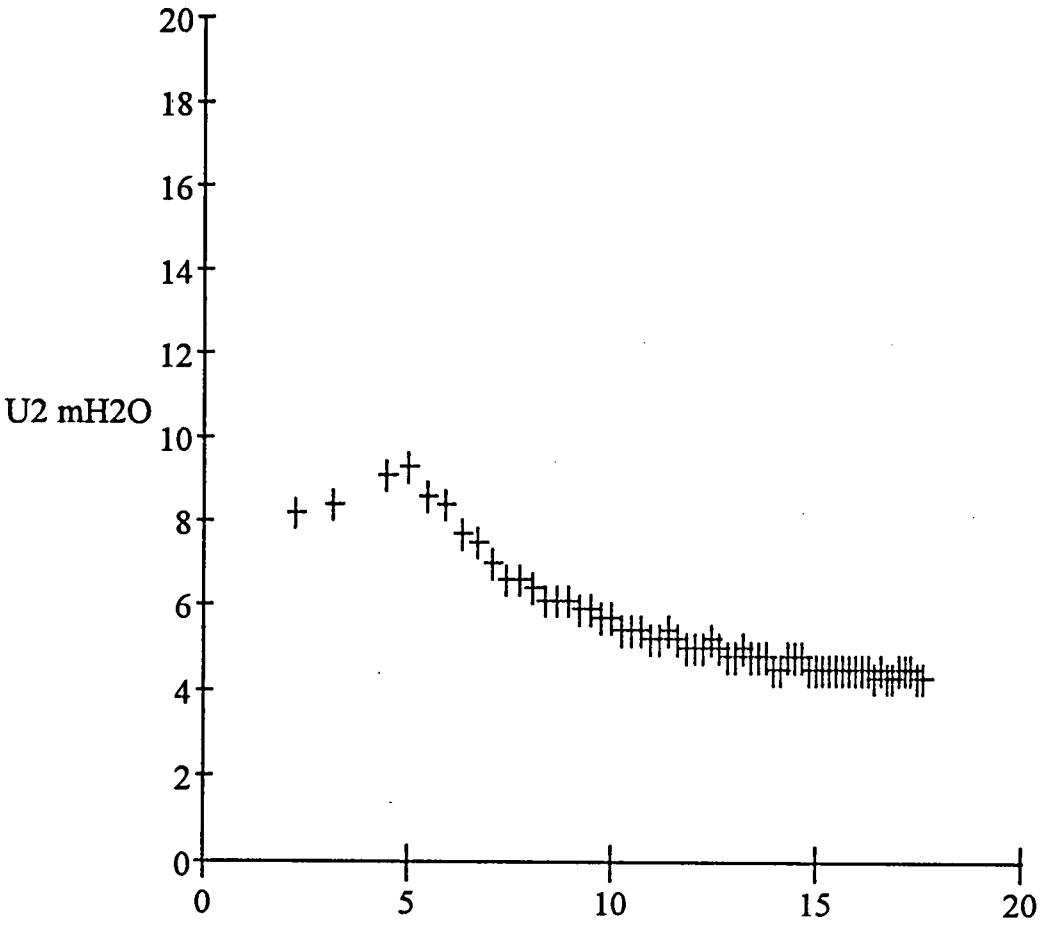
FILE: I19-9323.DIS DISSIPATION AT DEPTH = 3.2 m



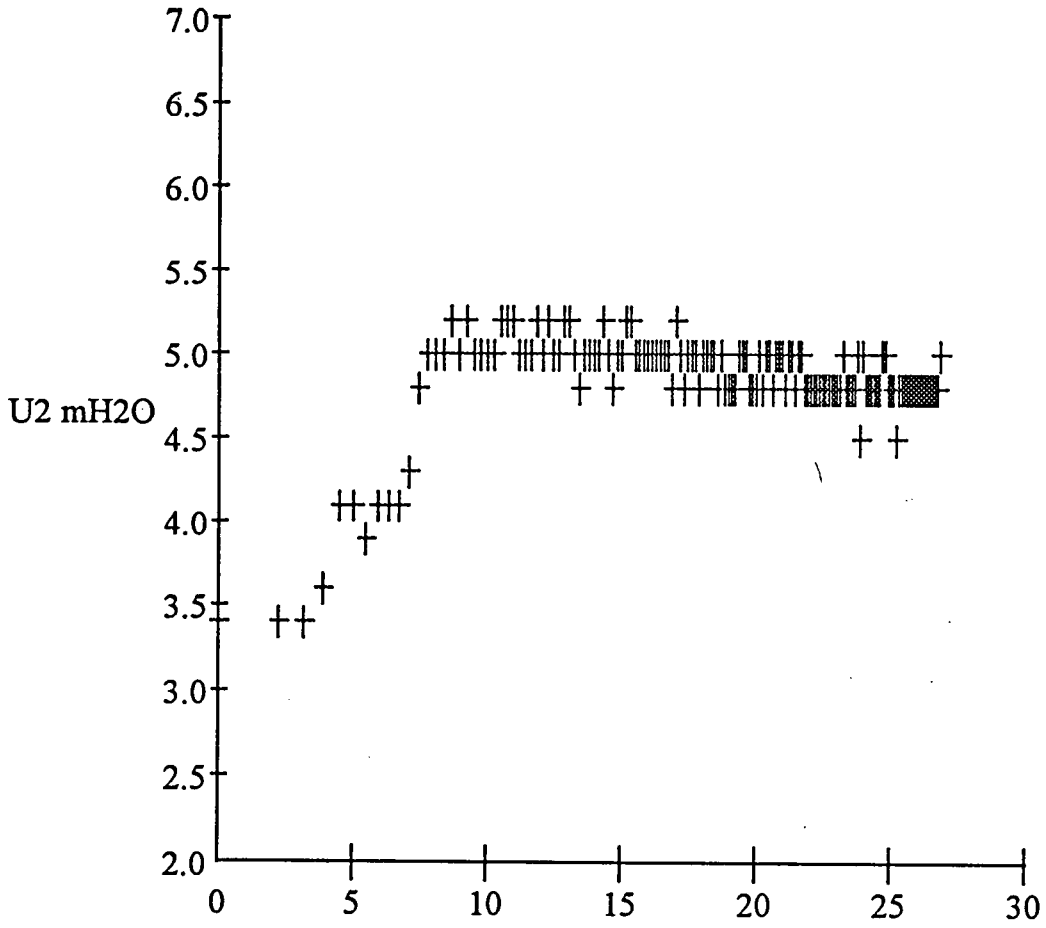
FILE: I19-9323.DIS DISSIPATION AT DEPTH = 4.2m



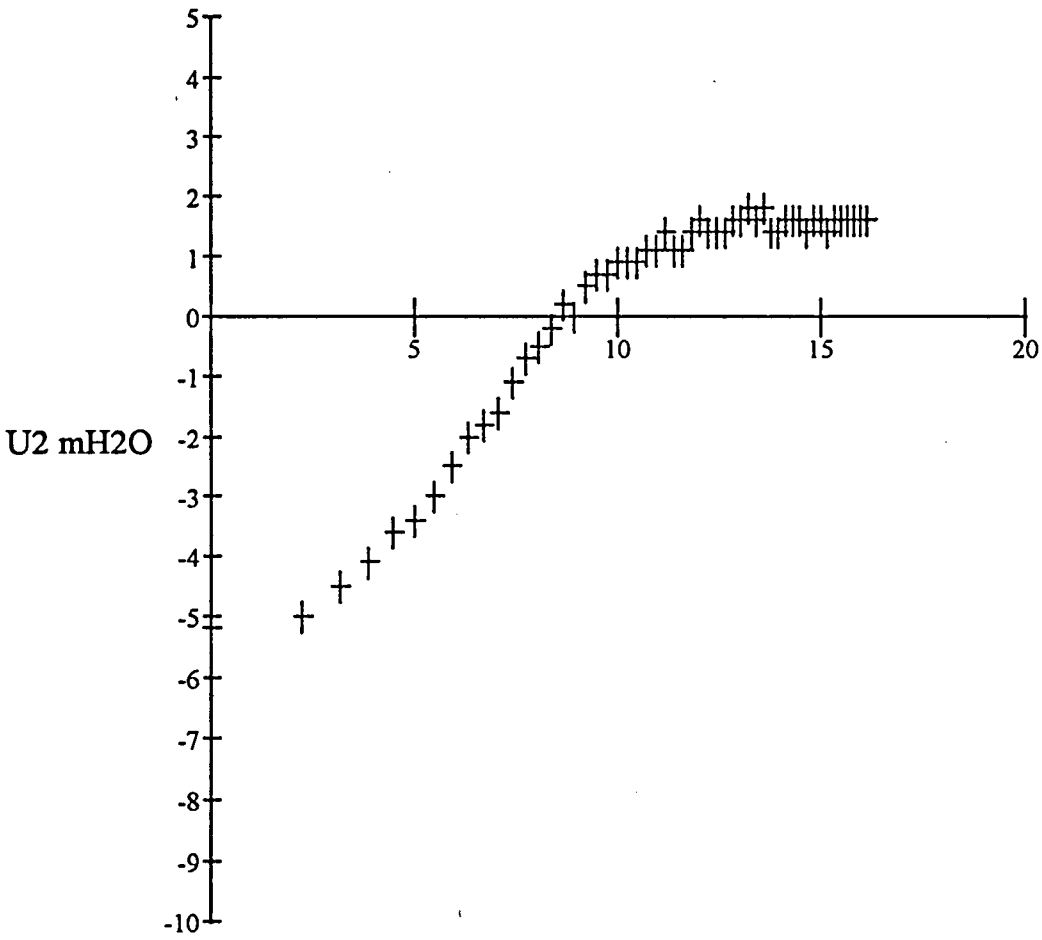
FILE: I19-9323.DIS DISSIPATION AT DEPTH = 5.2 m



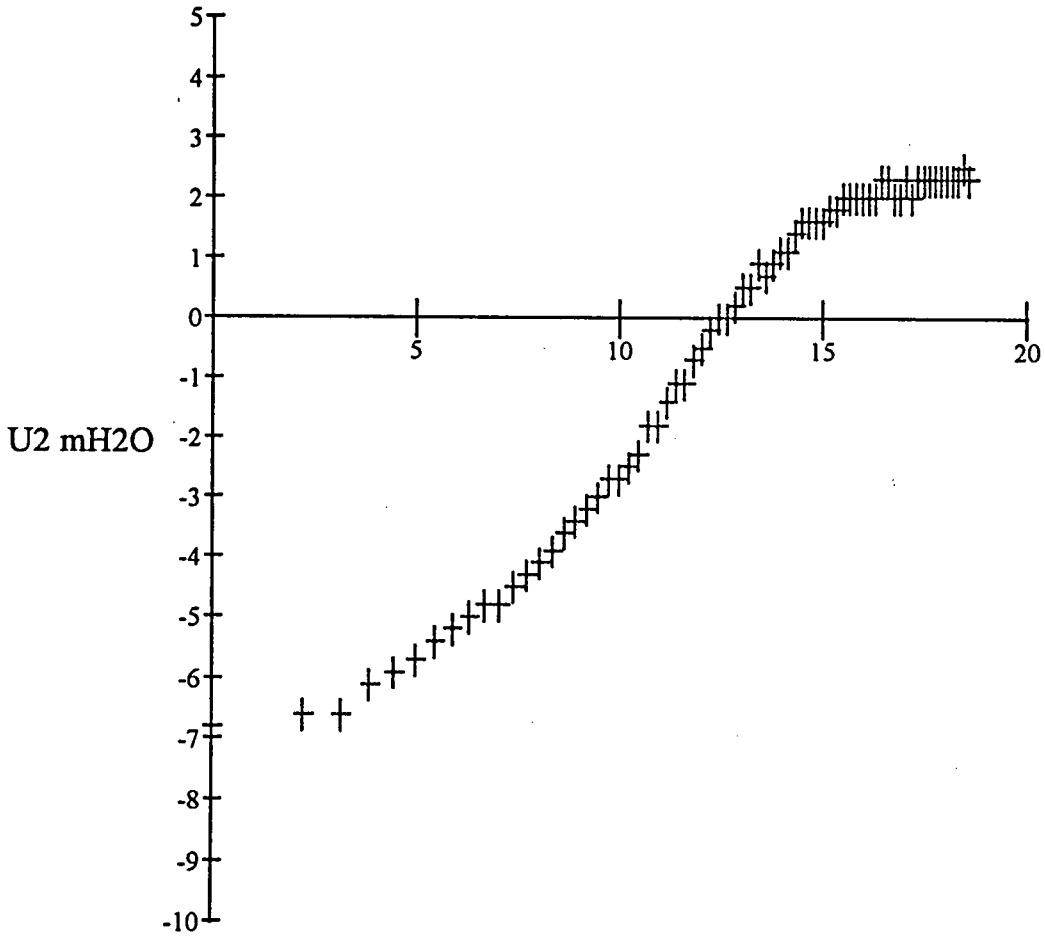
FILE: I19-9323.DIS DISSIPATION AT DEPTH = 6.5 m



FILE: I20-9324.DIS DISSIPATION AT DEPTH = 2.2 m



FILE : I20-9324.DIS DISSIPATION AT DEPTH = 3.2 m



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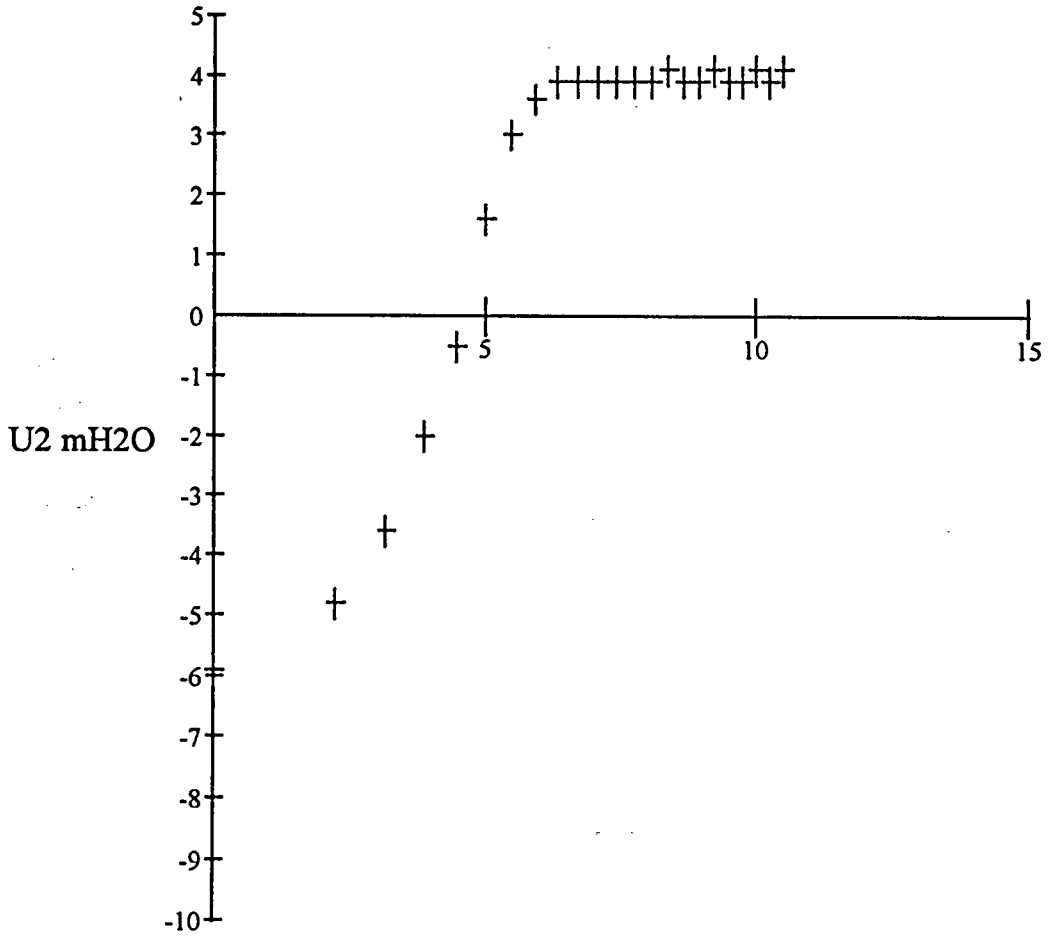
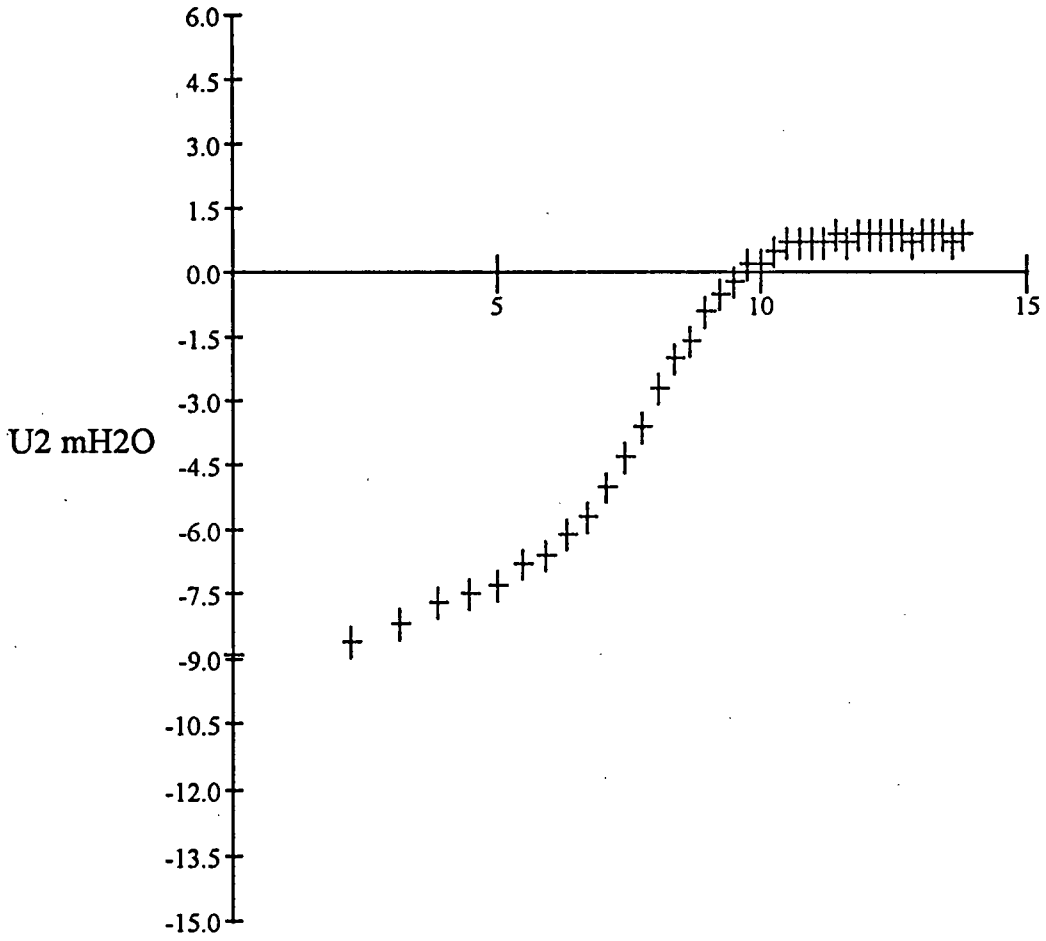
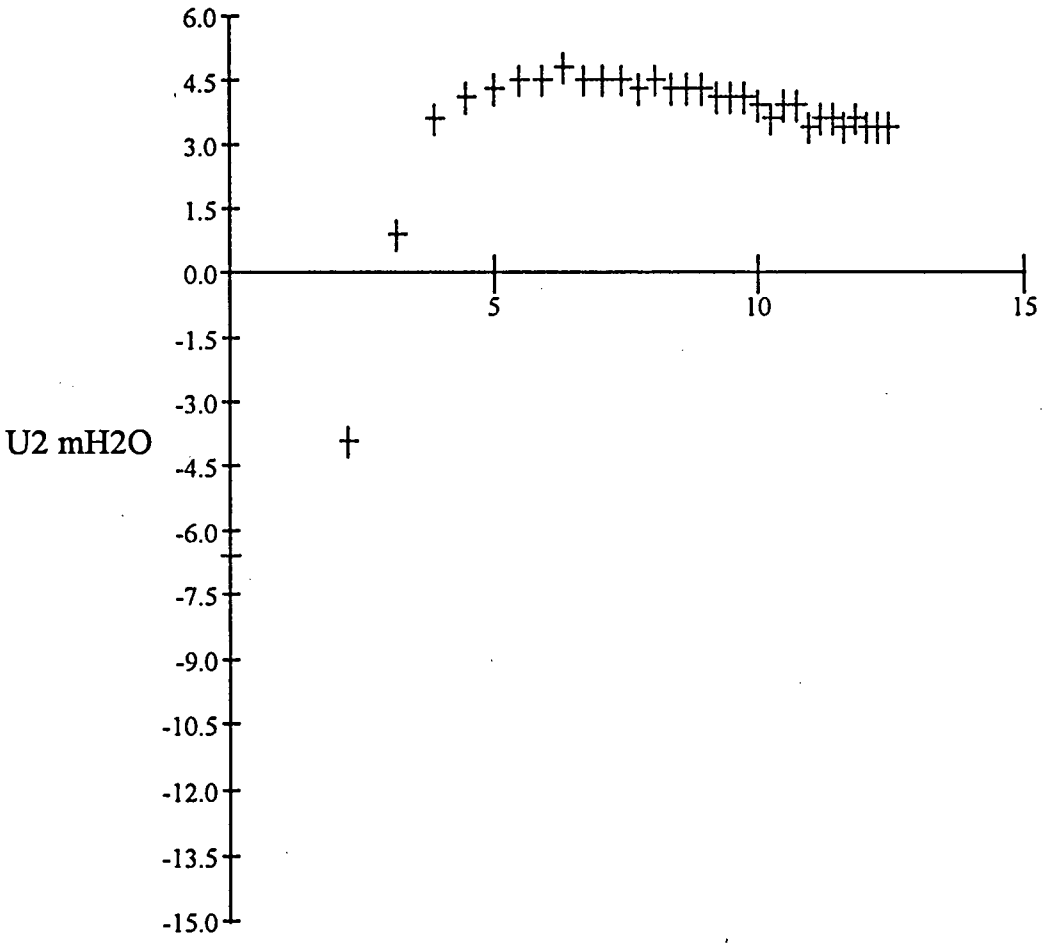


SQUARE ROOT OF TIME (sec.)

FILE: I21-9325.DIS DISSIPATION AT DEPTH = 2.2 m



FILE: I21-9325.DIS DISSIPATION AT DEPTH = 4.2 m



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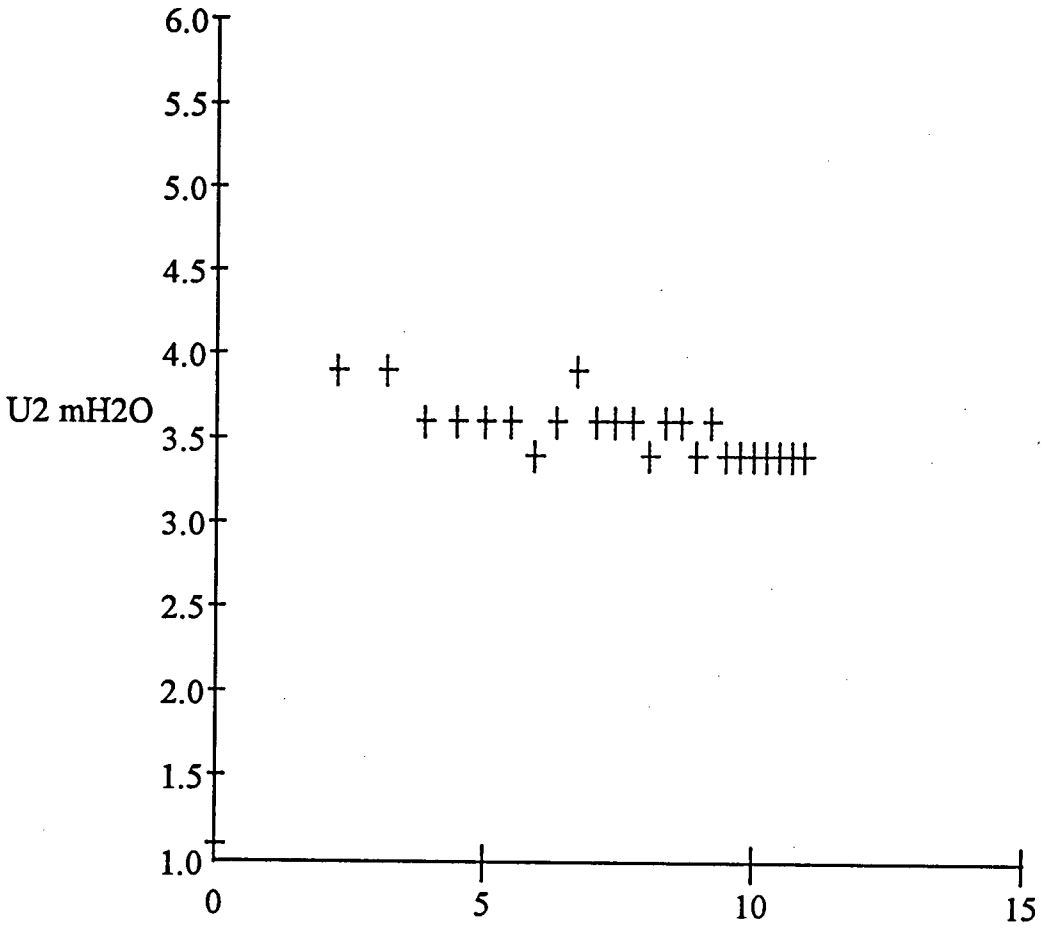

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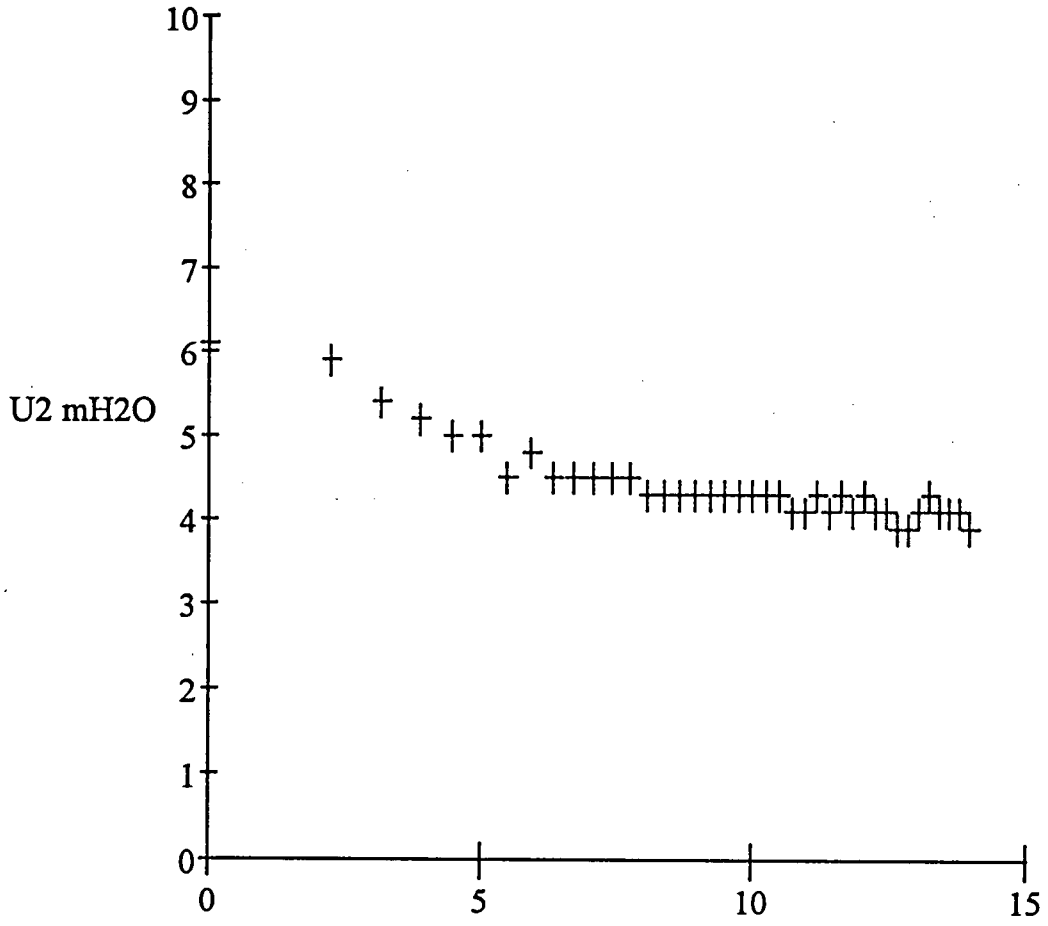
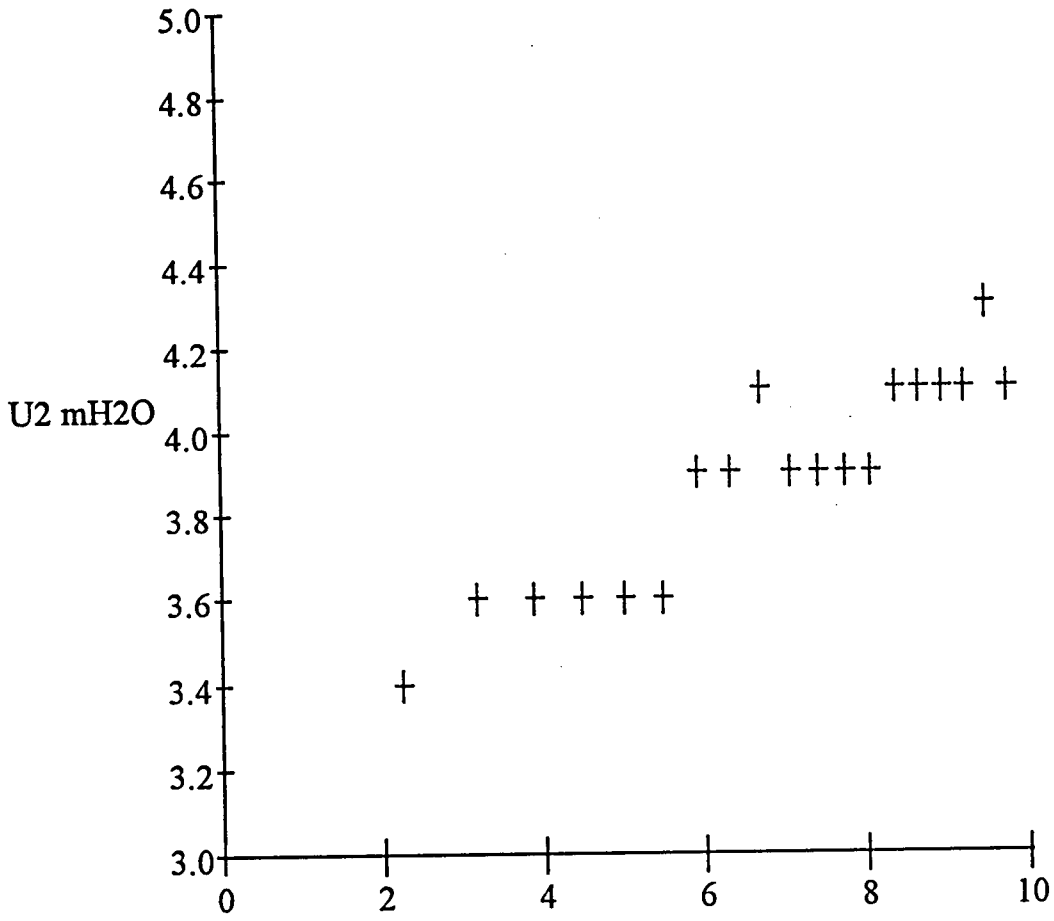


FILE: I23-9327.DIS DISSIPATION AT DEPTH = 4.3 m



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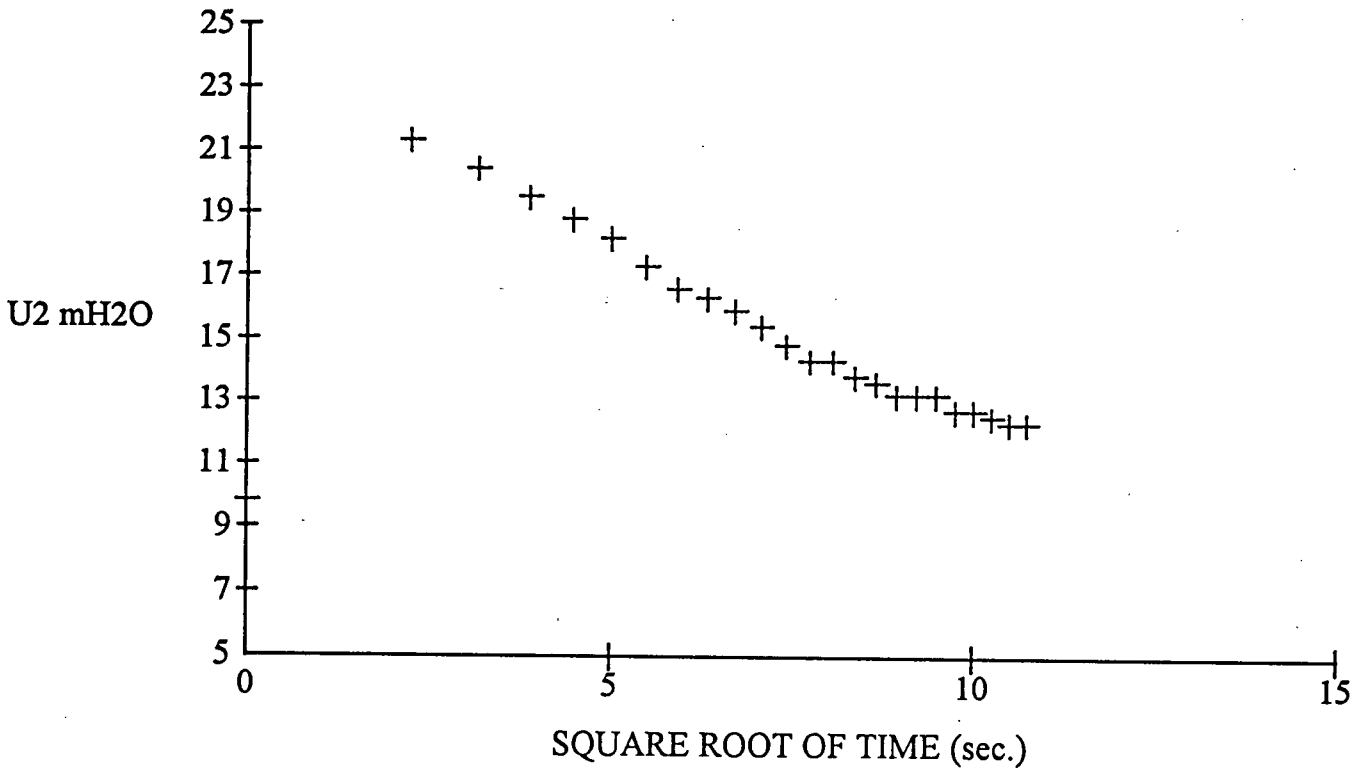

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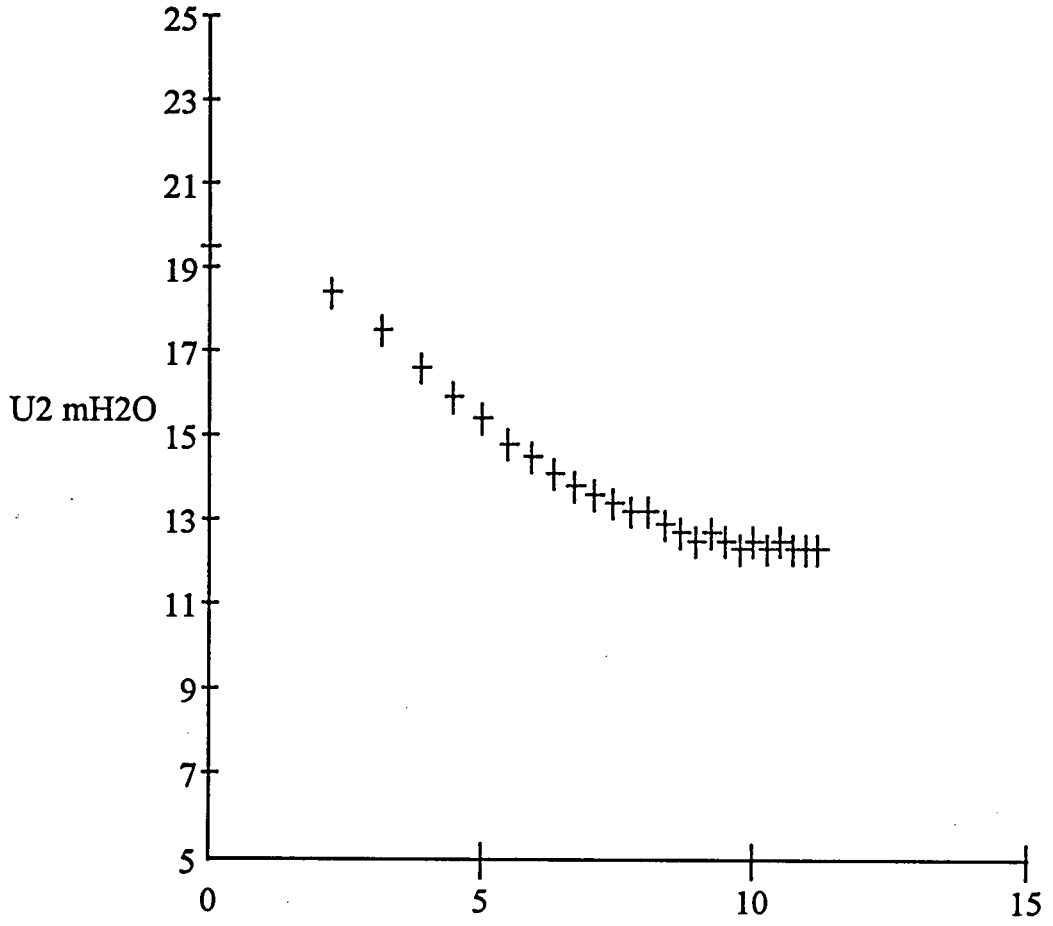
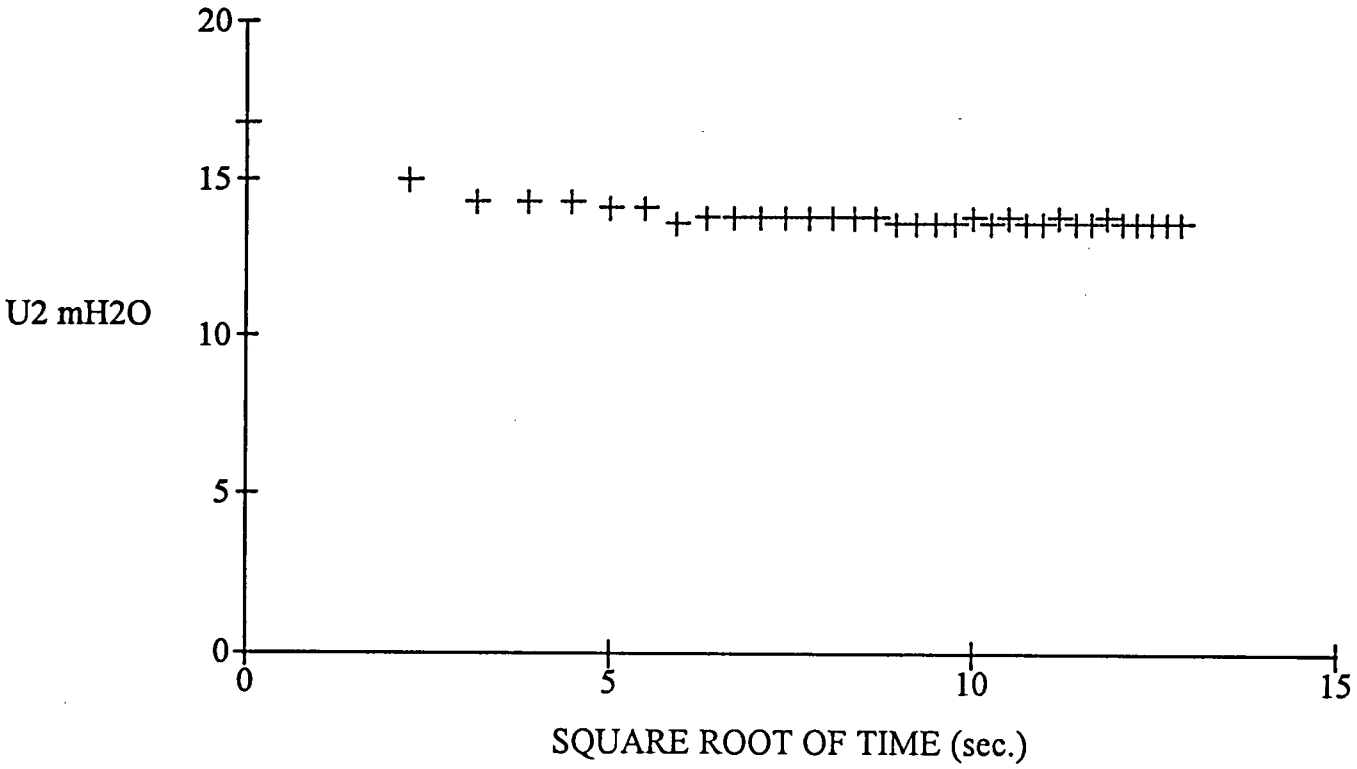


FILE: I23-9327.dis DISSIPATION AT 12.3 m



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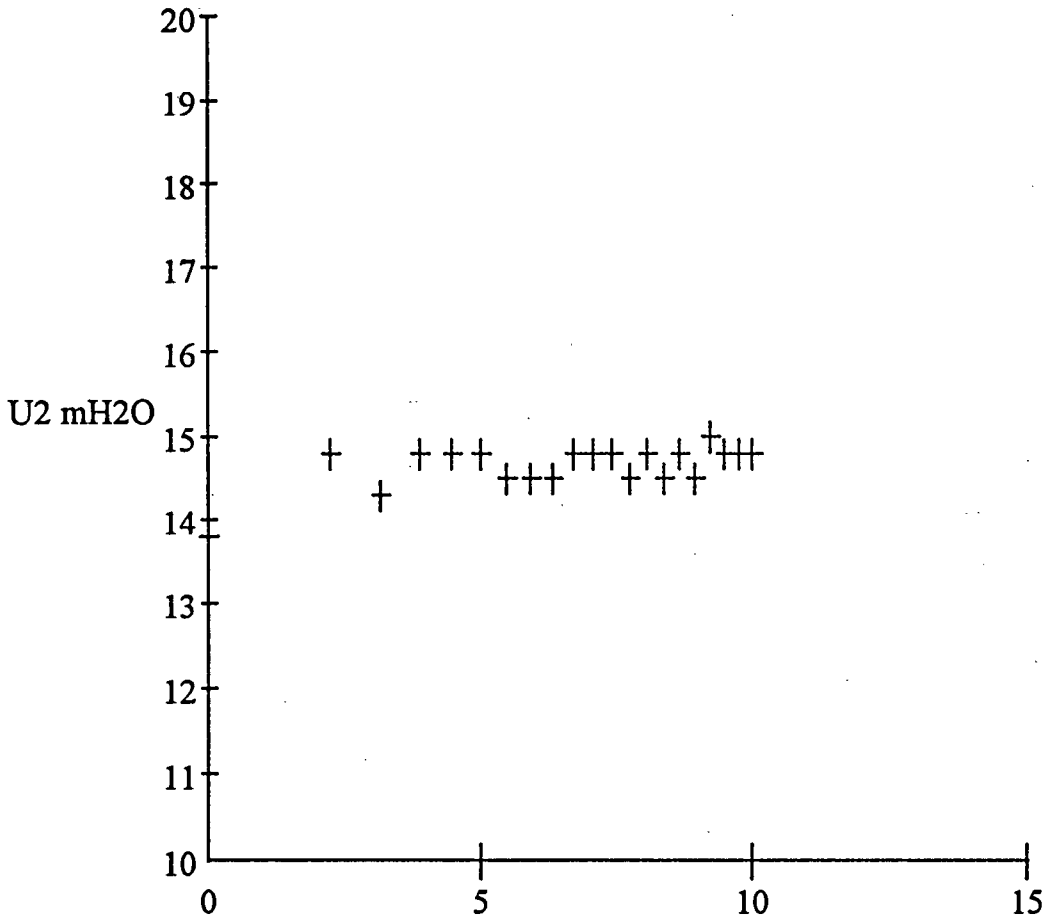
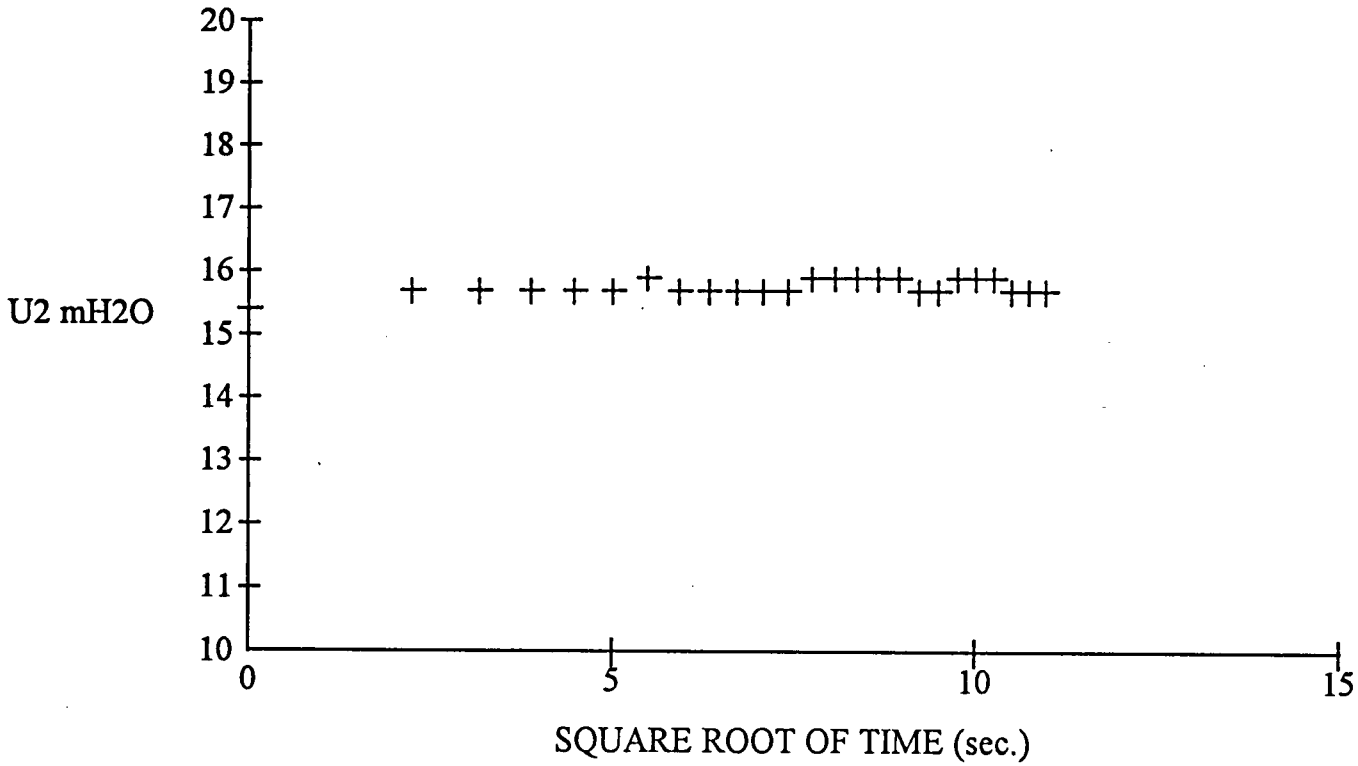
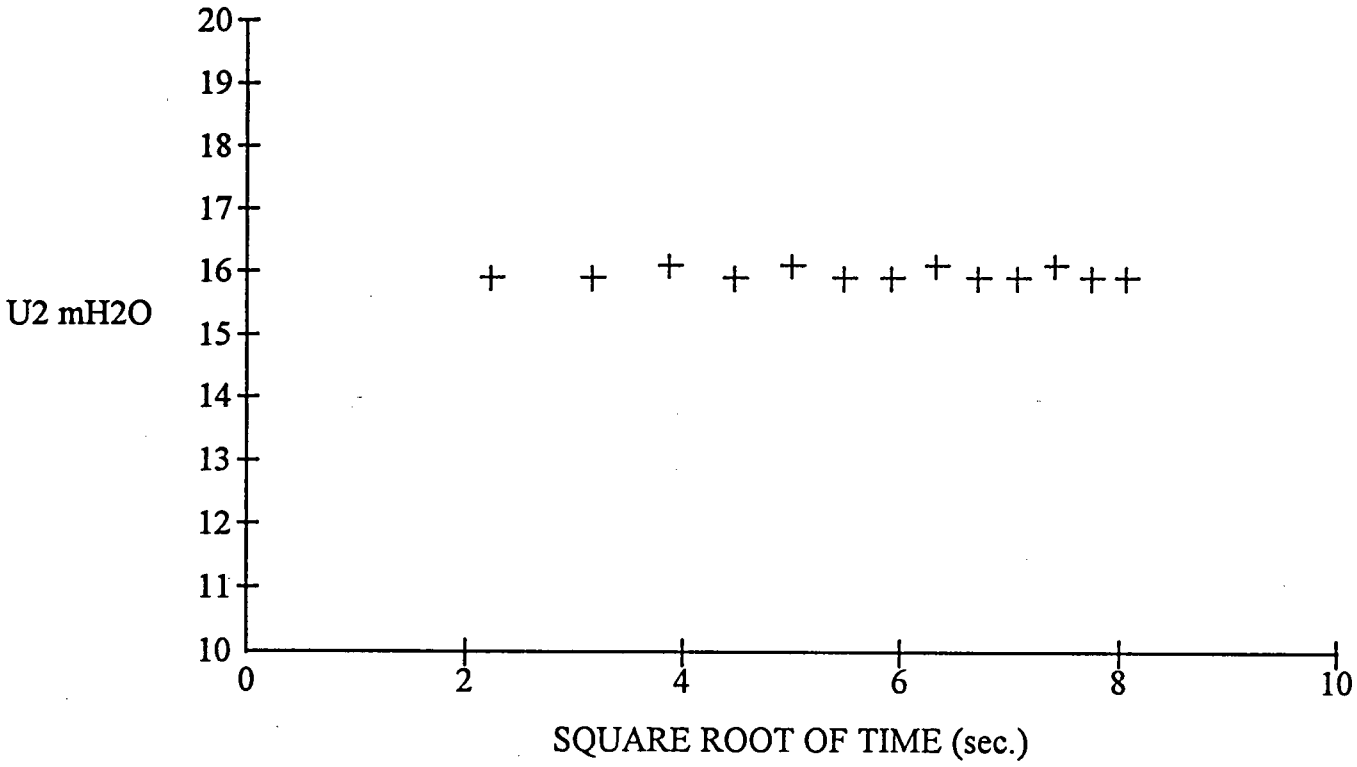


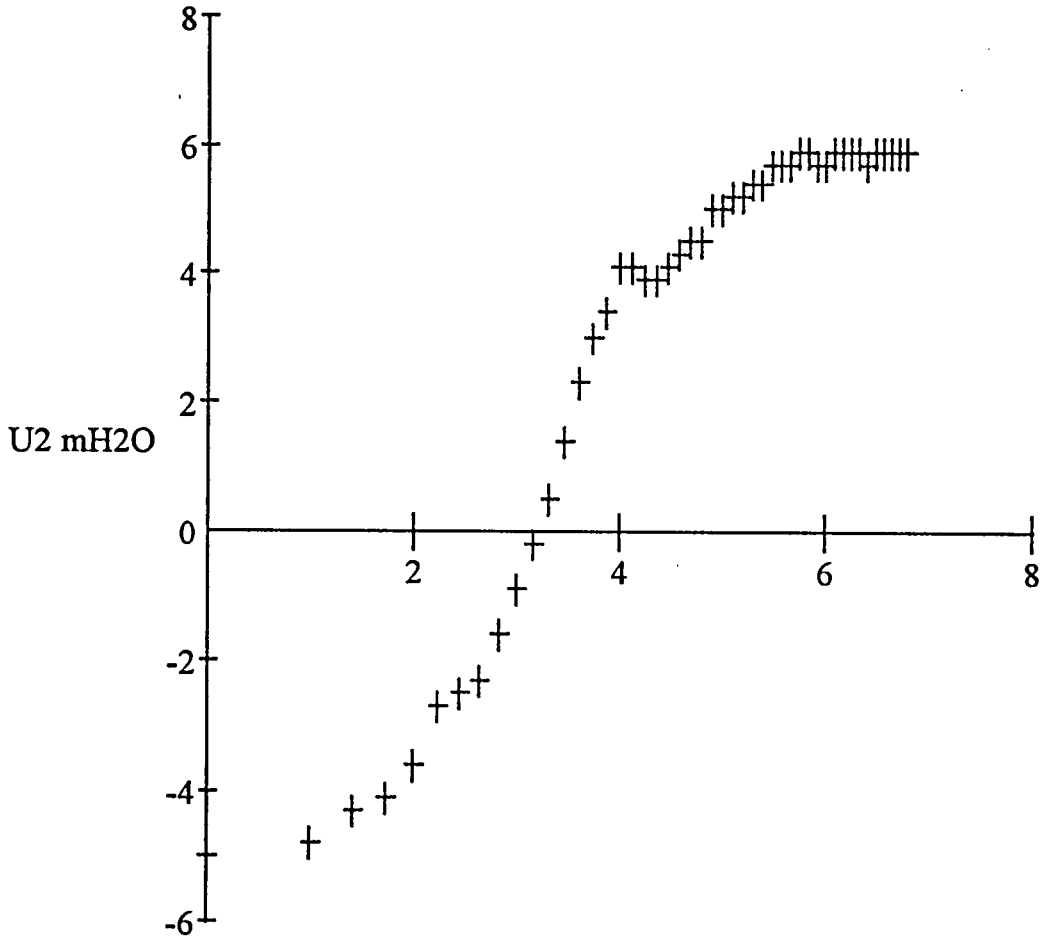
FILE: I23-9327.dis DISSIPATION AT 14.3 m



FILE: I23-9327.dis DISSIPATION AT 14.5 m



FILE: I26-9332.dis DISSIPATION AT 6.2 m



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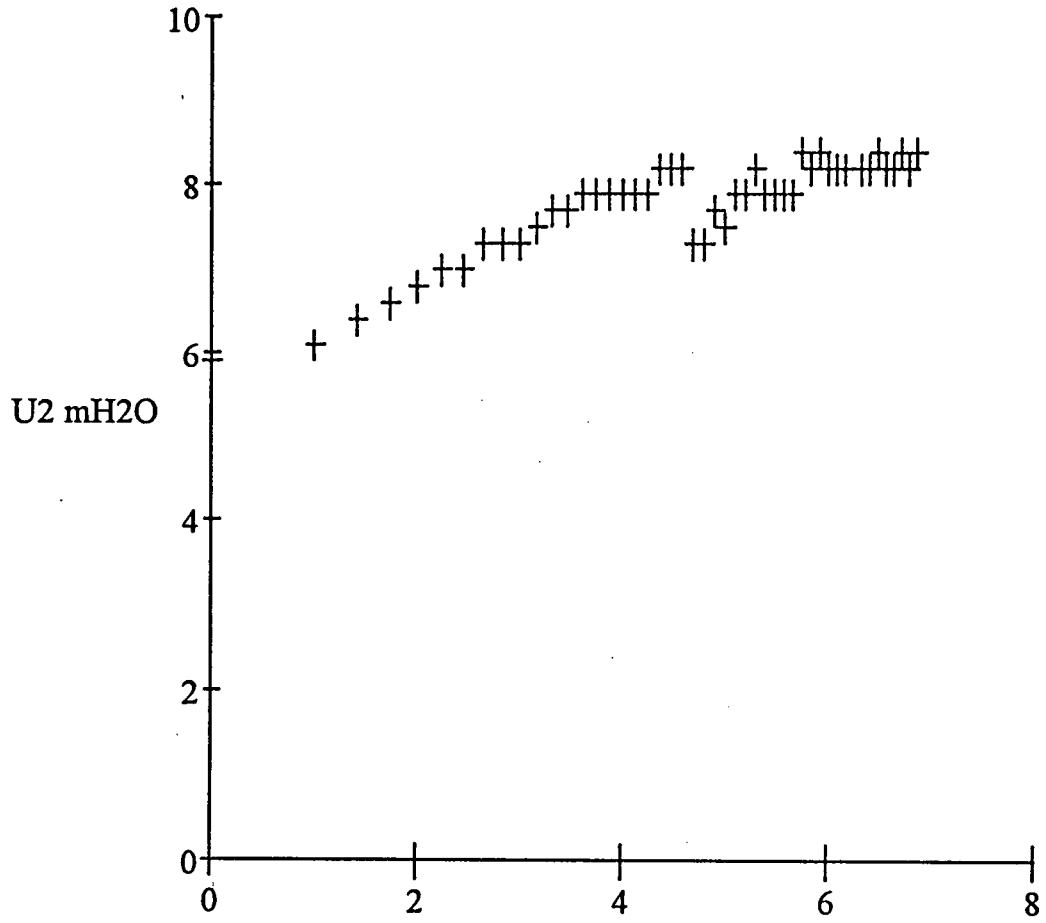

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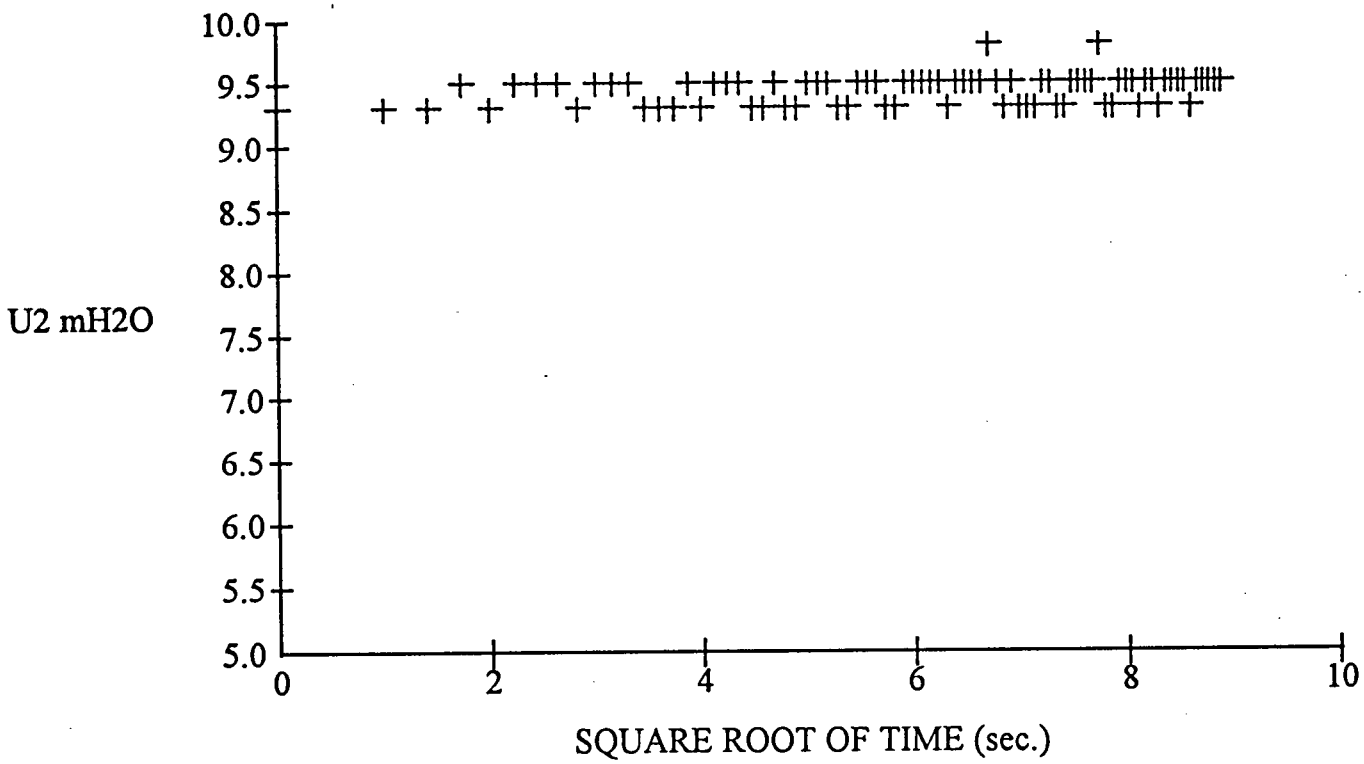

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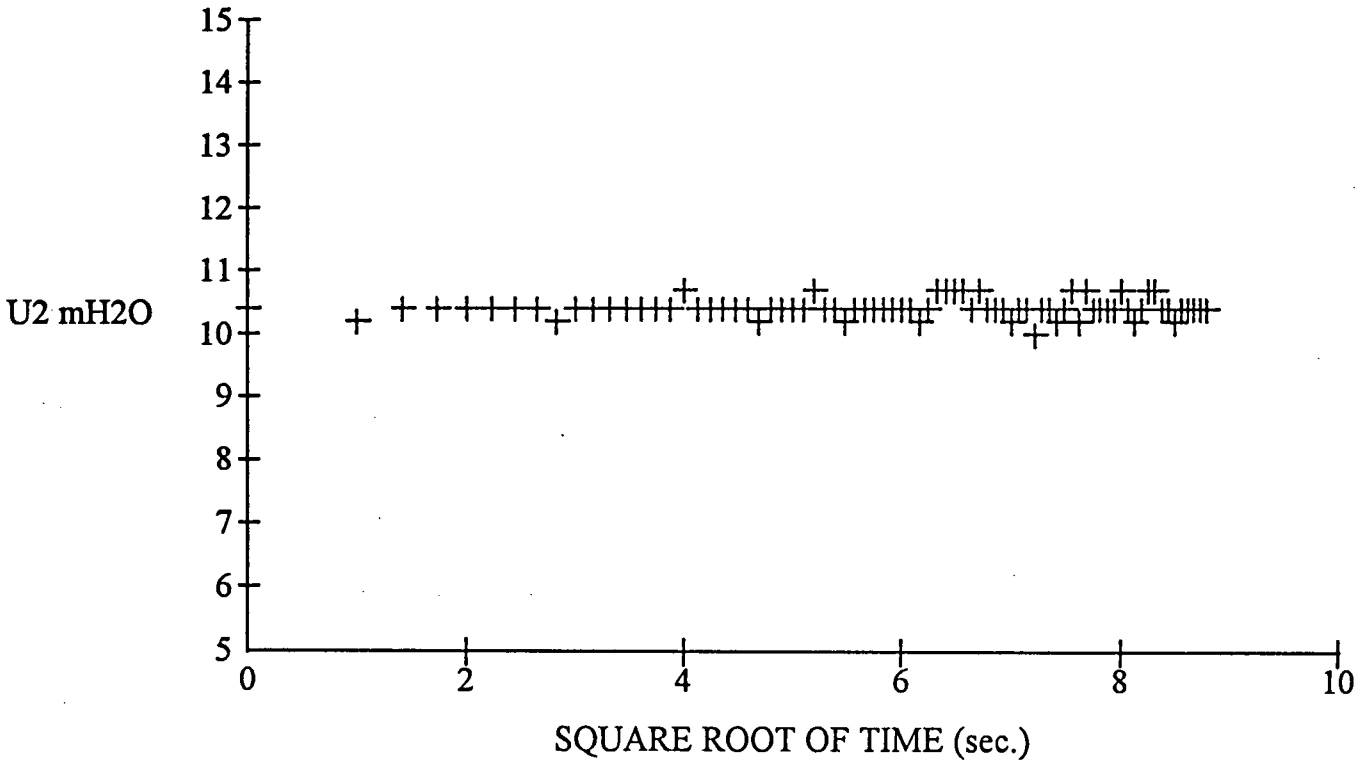
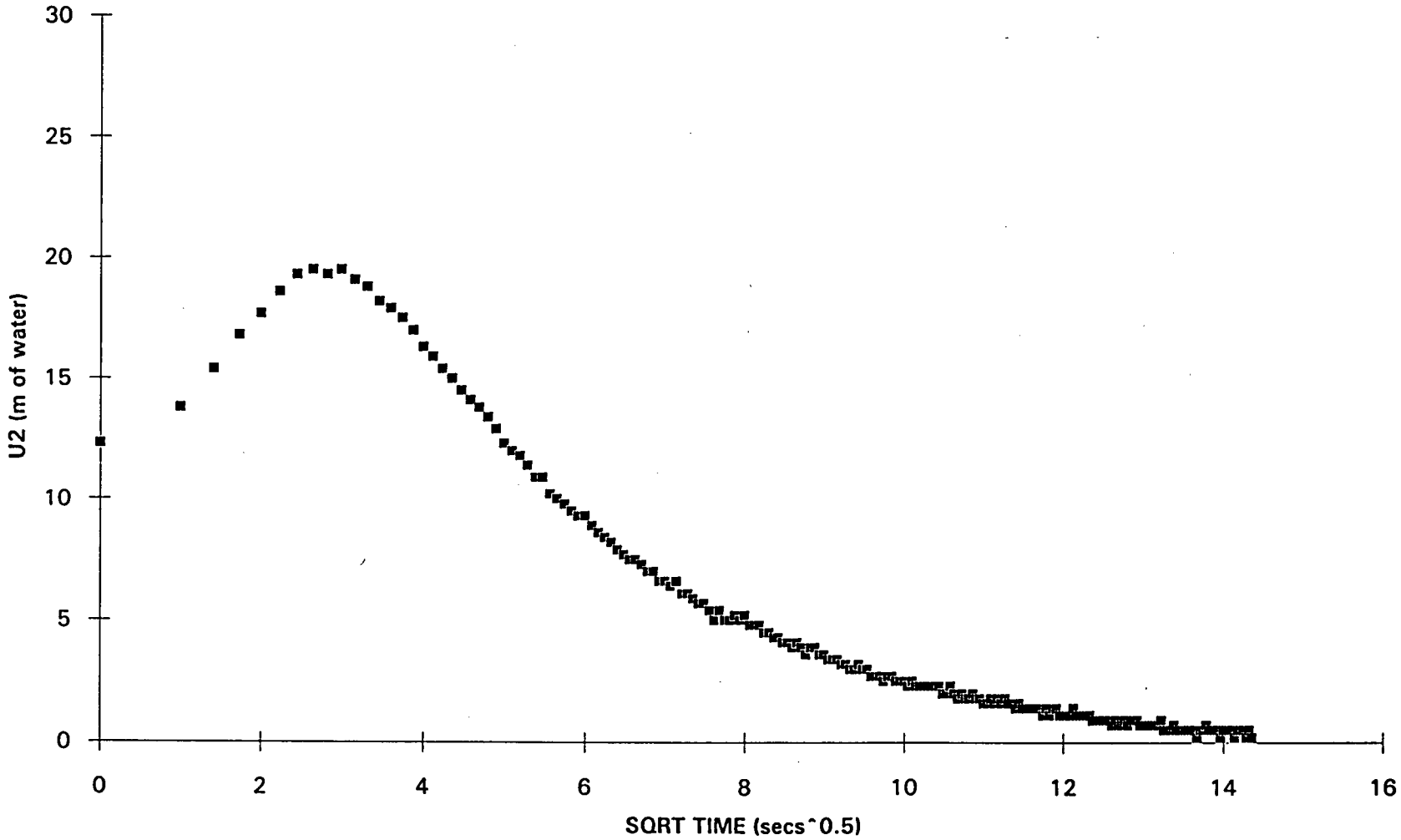
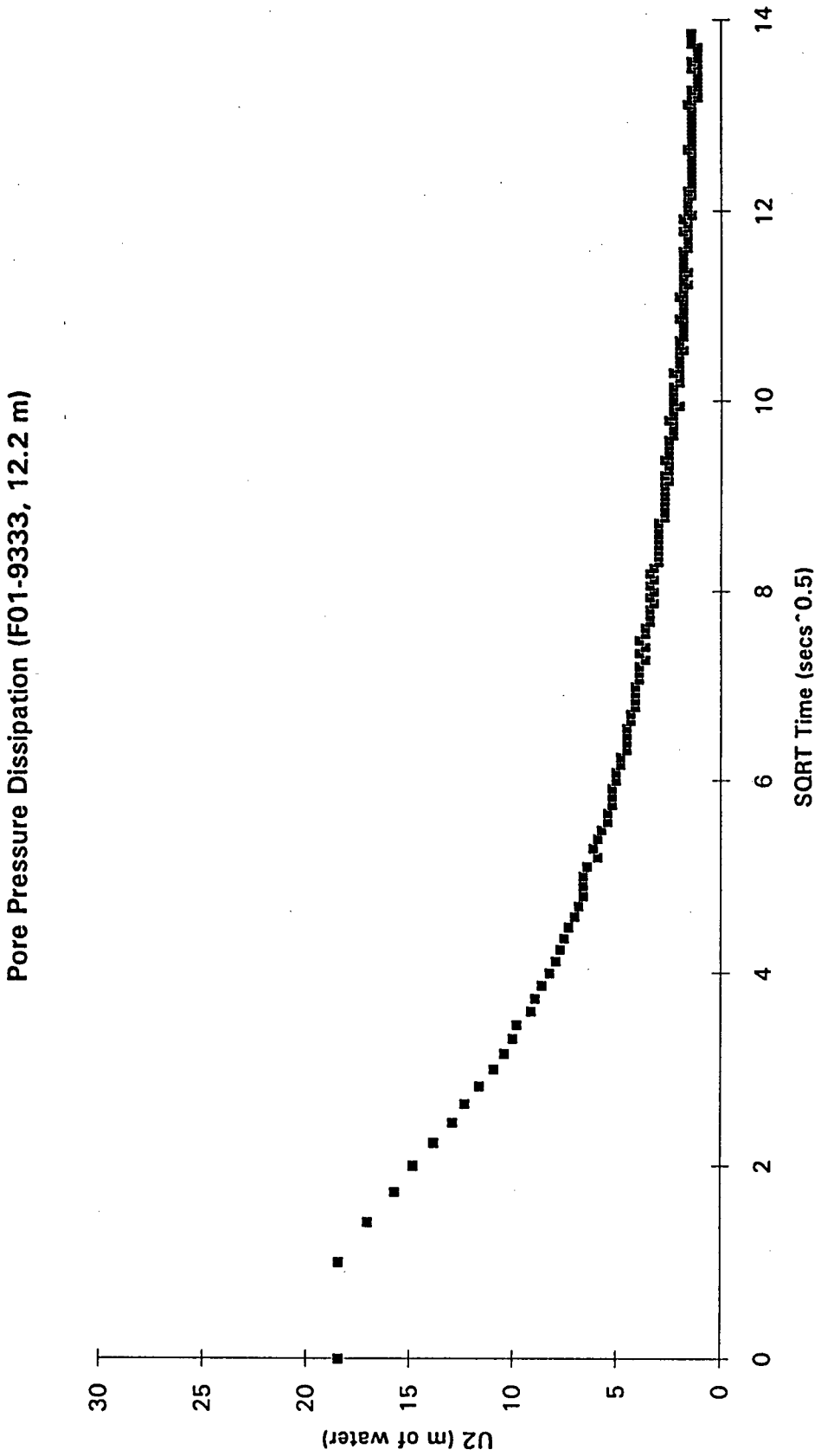


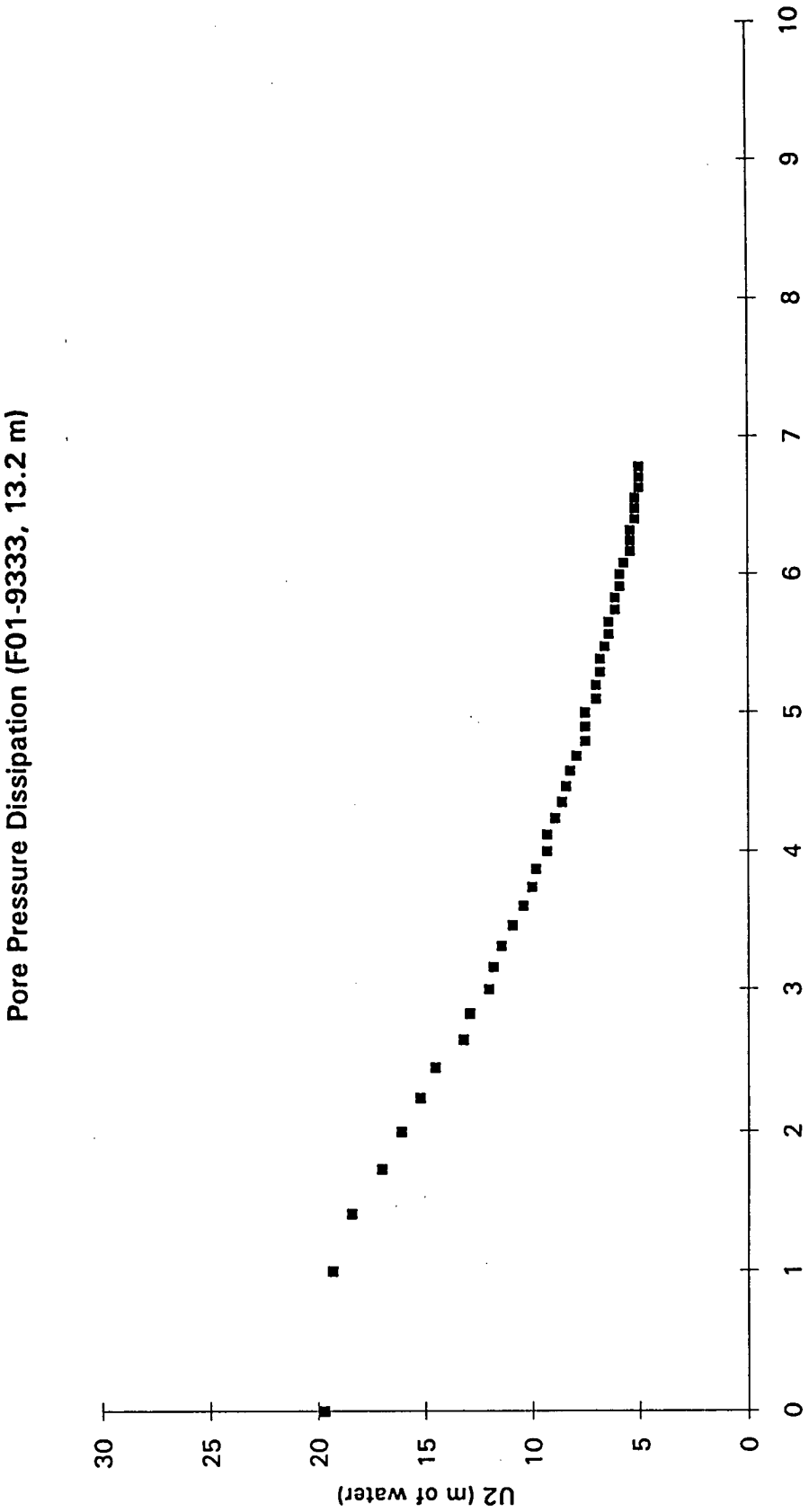
Pore Pressure Dissipation (F01-9333, 10.2 m)



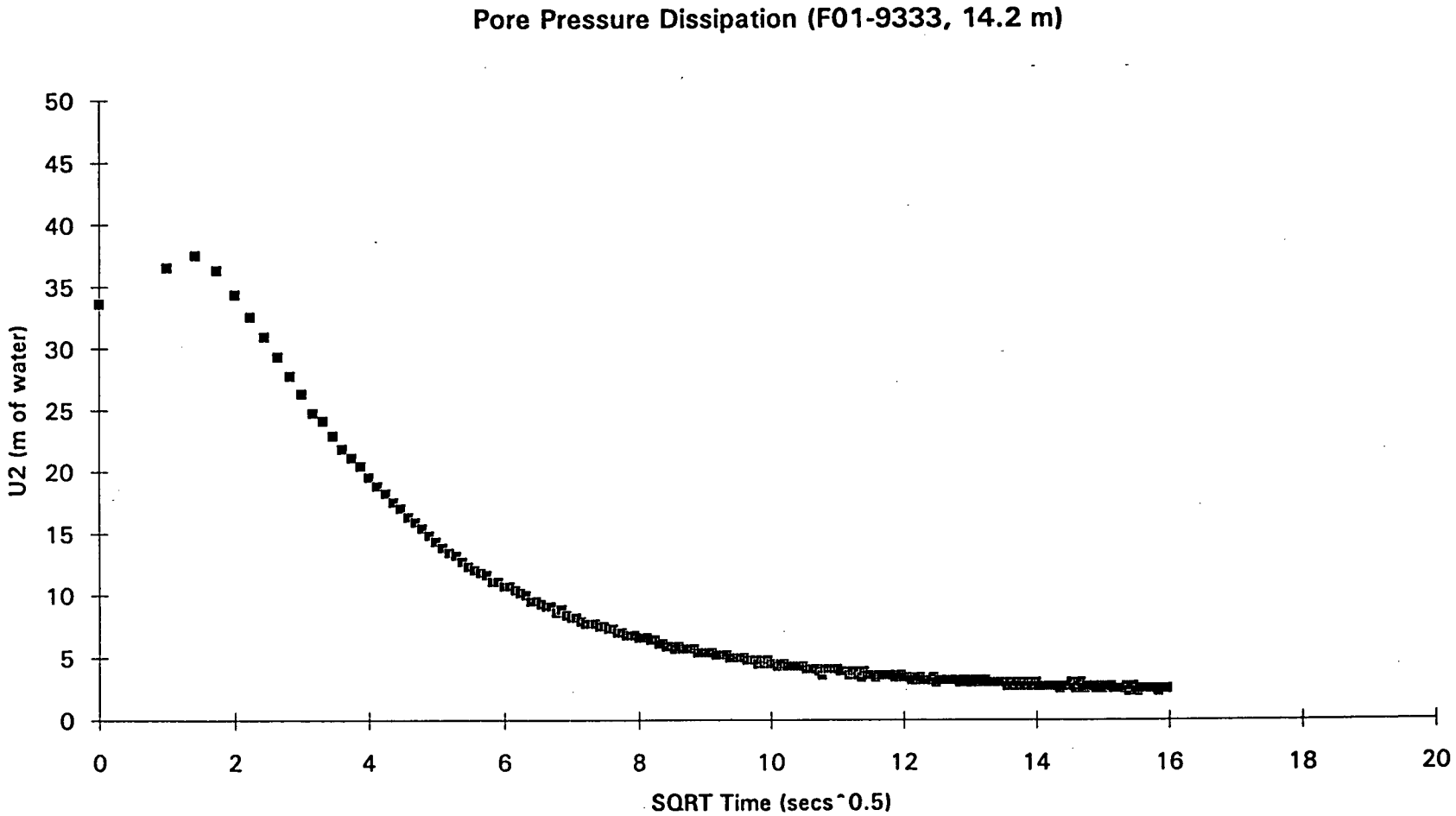
Fault Lake Tailings Site



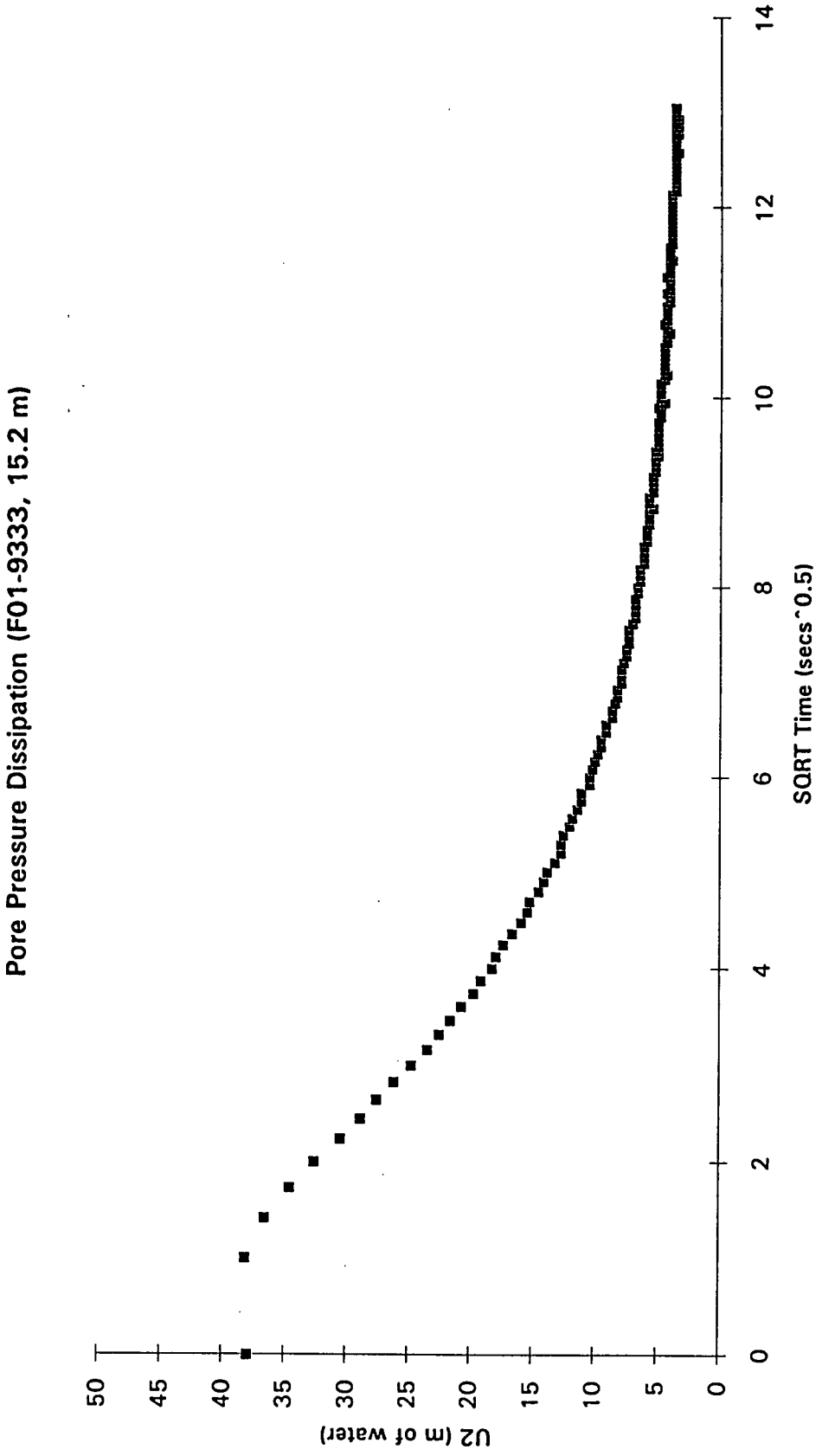
Fault Lake Tailings Site



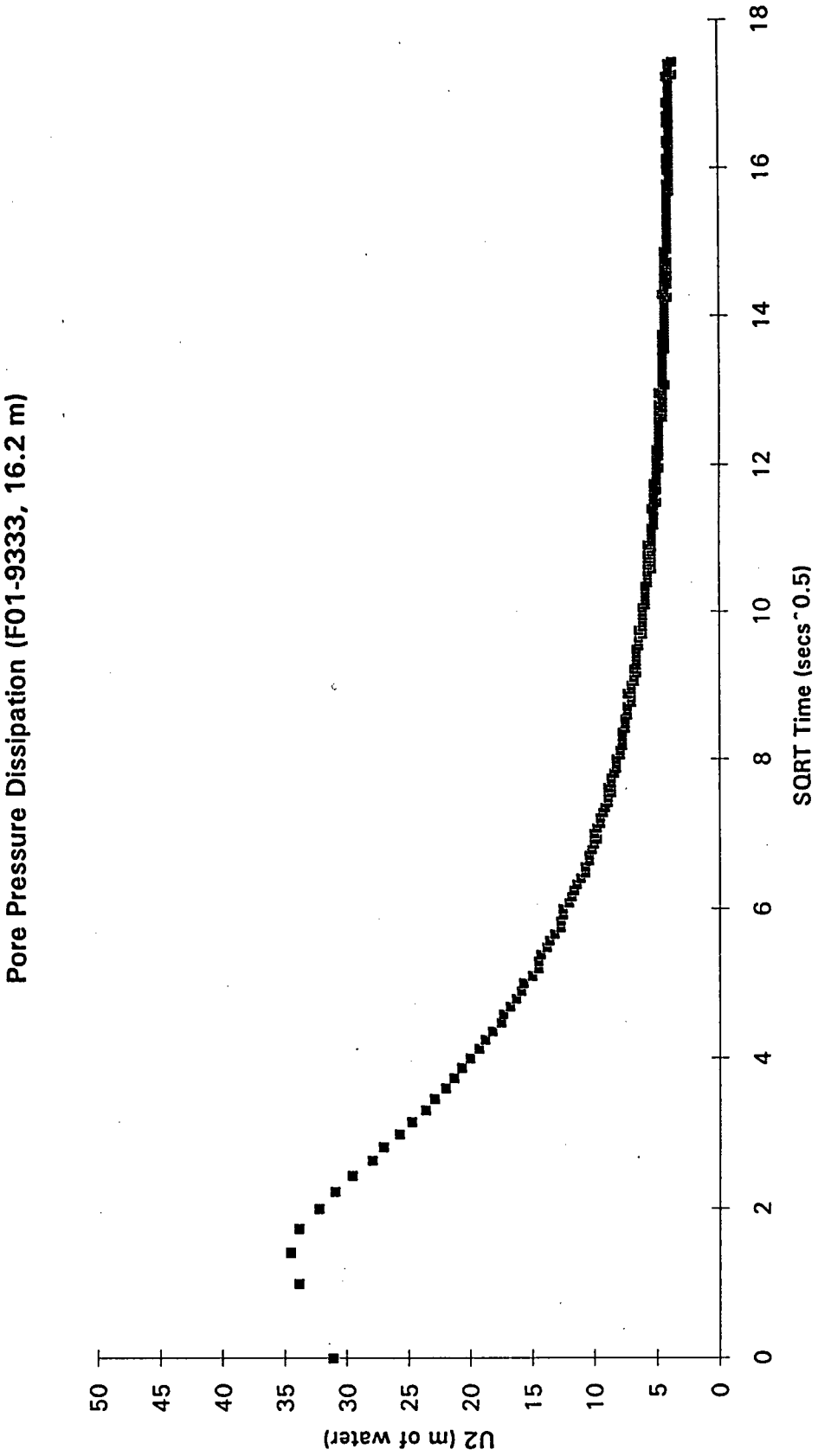
Fault Lake Tailings Site

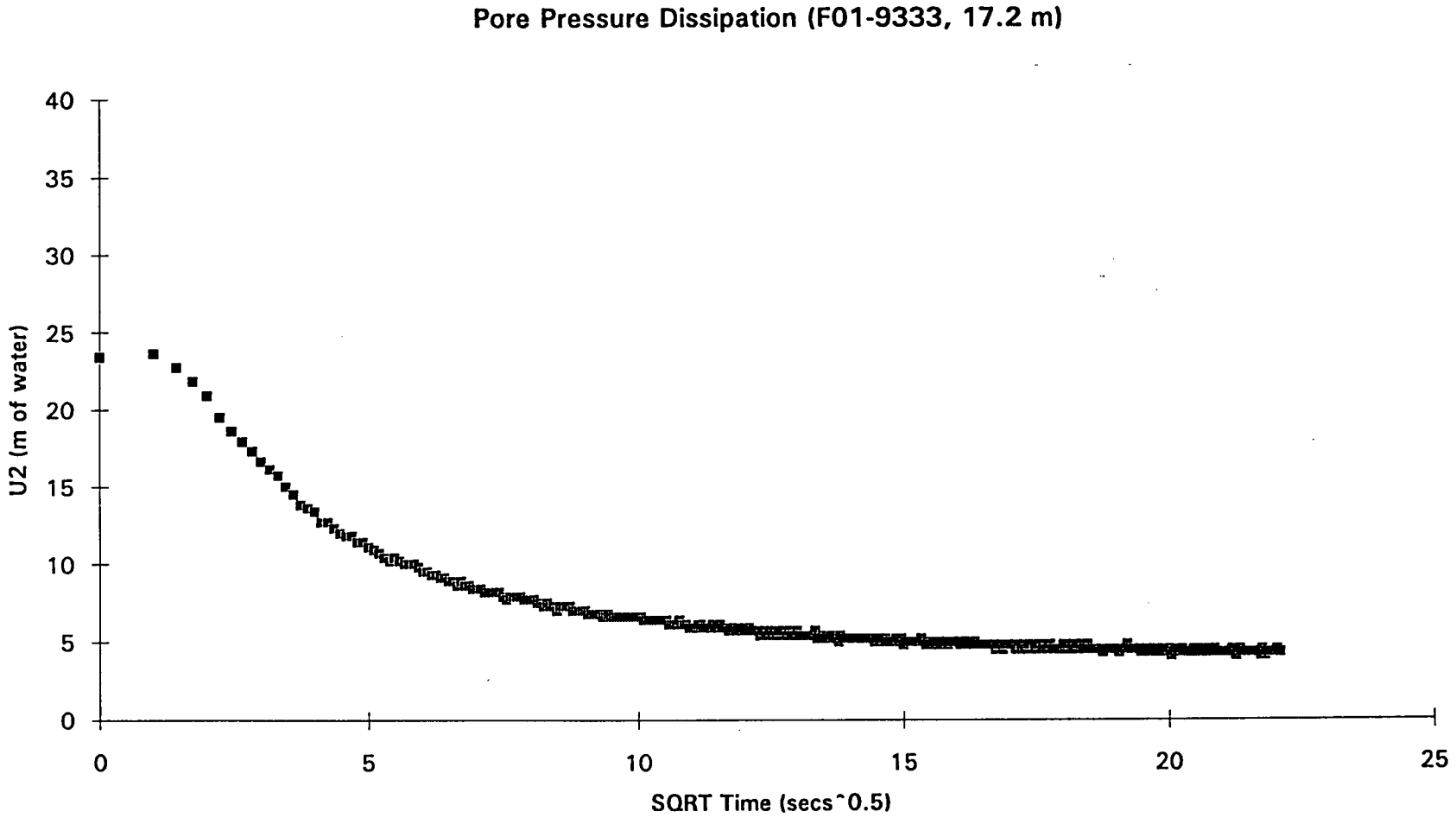


Fault Lake Tailings Site

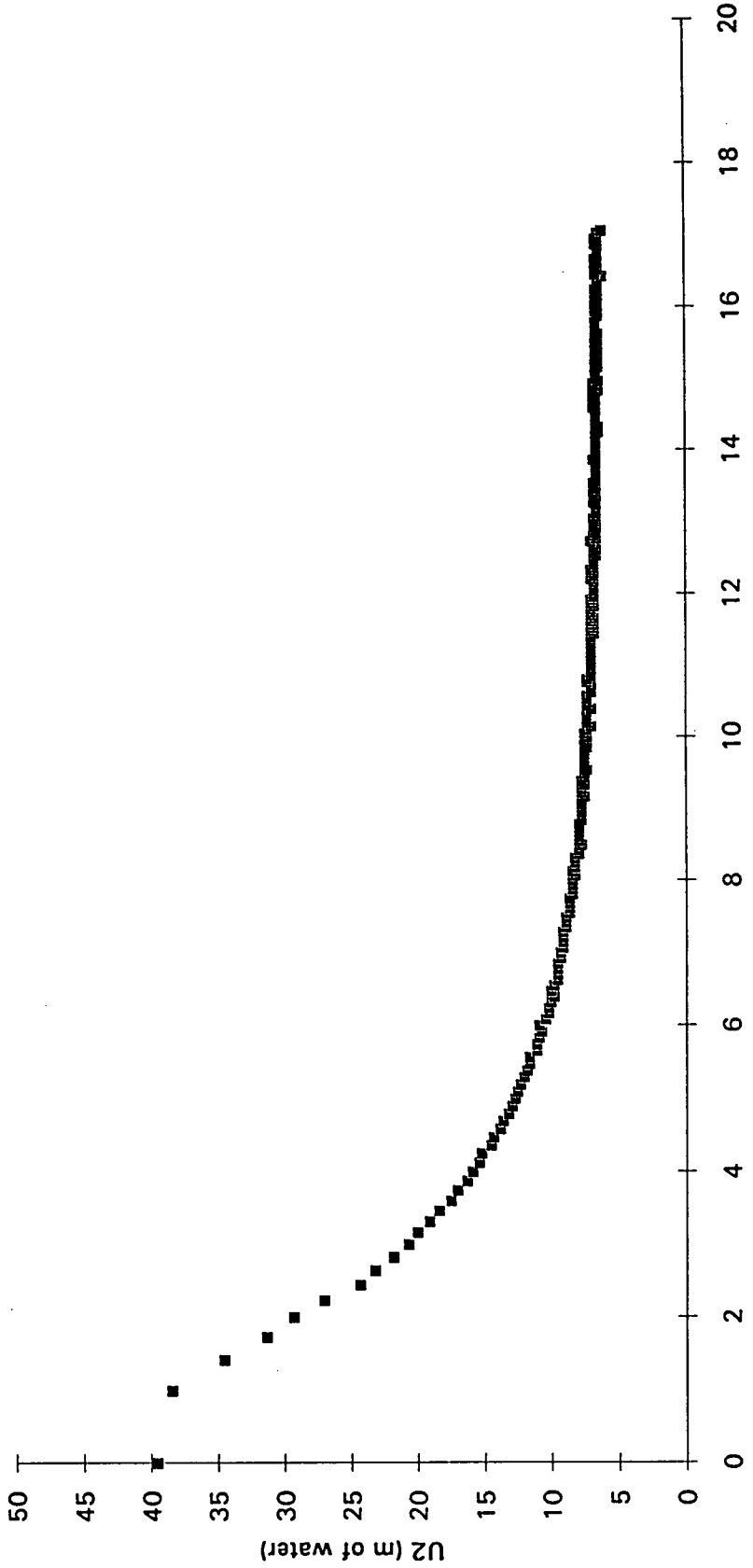


Fault Lake Tailings Site

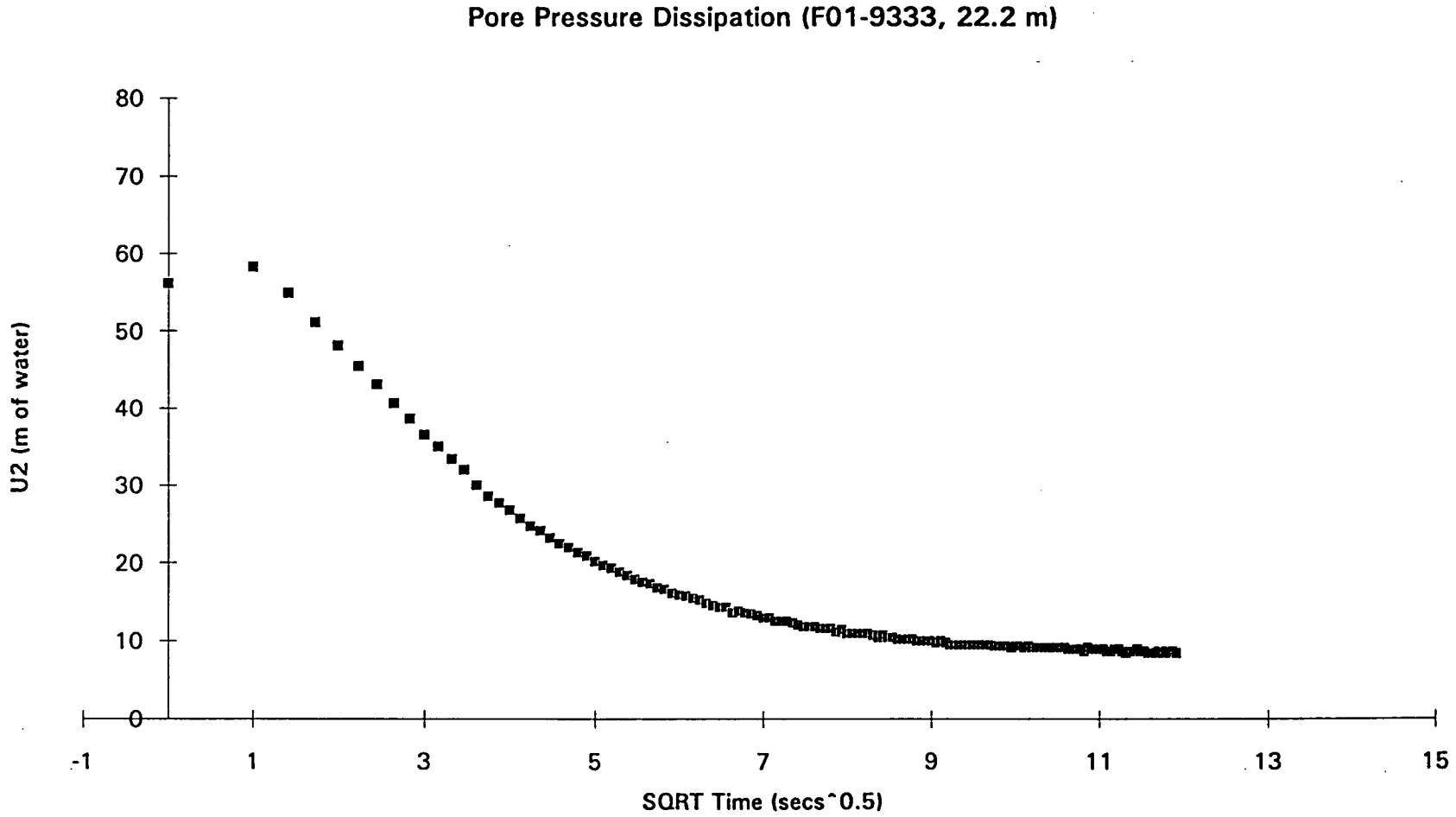

Pore Pressure Dissipation (F01-9333, 16.2 m)
U2 (m of water)
50
45
40
35
30
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
18
SQRT Time (secs^0.5)
Fault Lake Tailings Site

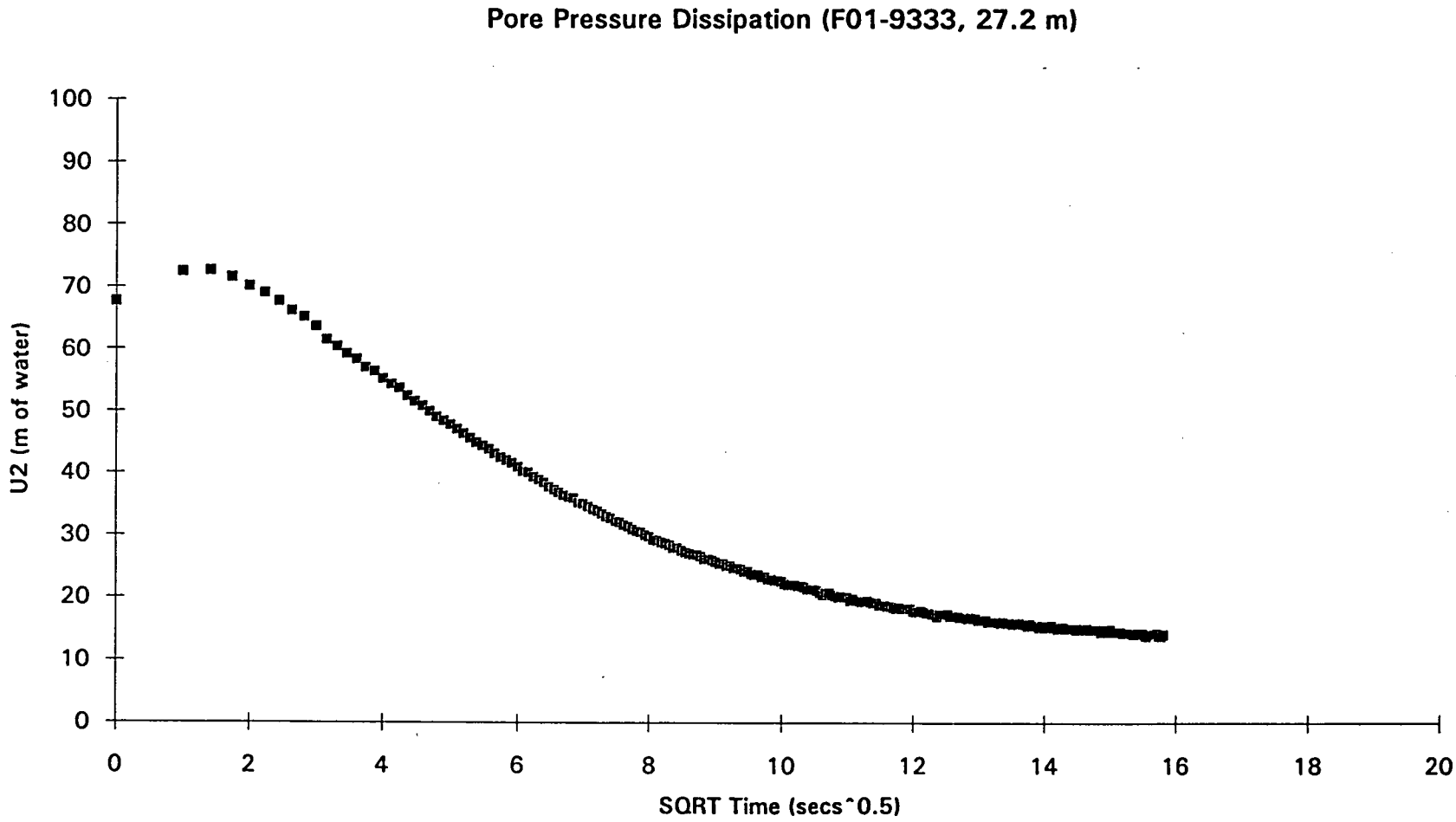


Fault Lake Tailings Site



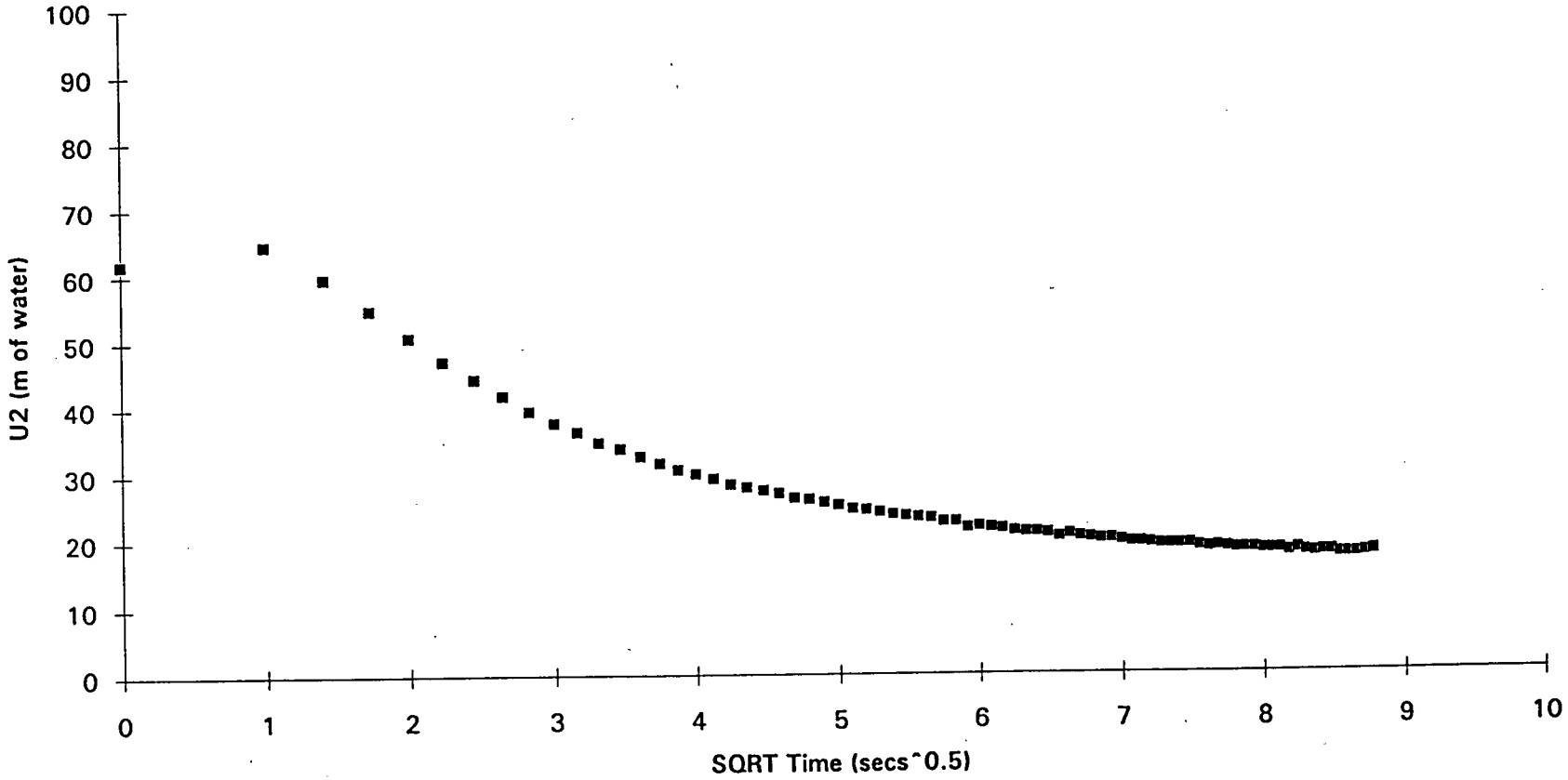
Fault Lake Tailings Site


Pore Pressure Dissipation (F01-9333, 22.2 m)
U2 (m of water)
80
70
60
50
40
30
20
10
0
-1
1
3
5
7
9
11
13
15
SQRT Time (secs^0.5)

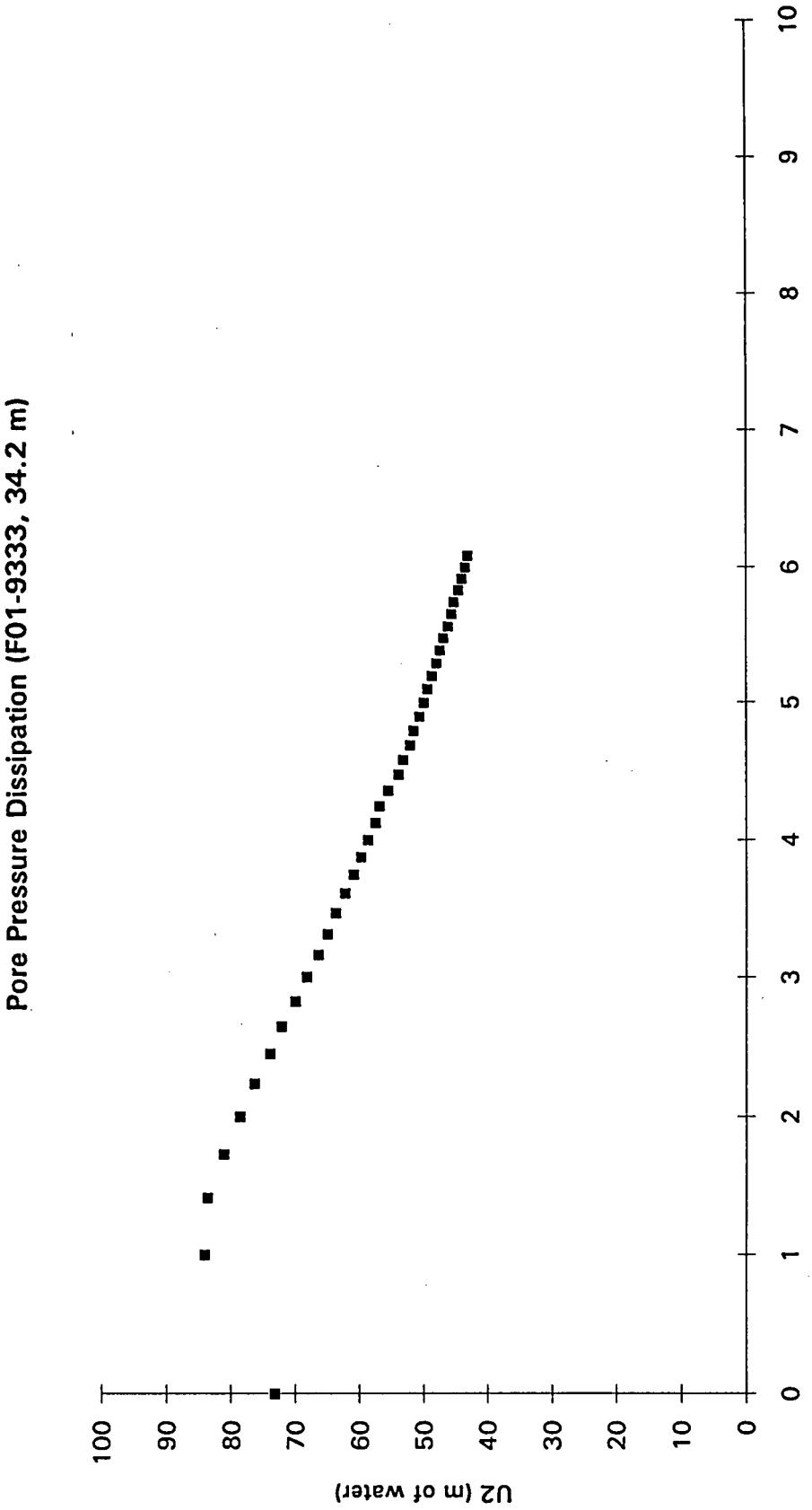


Fault Lake Tailings Site

Pore Pressure Dissipation (F01-9333, 28.2 m)



Fault Lake Tailings Site



Fault Lake Tailings Site

APPENDIX D - PORE WATER CHEMISTRY

Comparison of RCPT Bulk Resistivity Measurements and Chemistry Data From Pore Water Samples

Sounding:	I06-9321
Cone ID:	HOG3RES
Date:	10/10/93
GWT =	2.0 m

	RCPT DATA			BAT DATA						
DEPTH (m)	RES010 (ohm-m)	RES025 (ohm-m)	RES075 (ohm-m)	pH	SULPHATE (mg/l)	COND. (uS/cm)	RES (ohm-m)	Fe (mg/l)	Ni (mg/l)	Mg (mg/l)
4.00	8.00	8.17	7.28	5.56	5010	6190	1.62	7951.0	52.6	457.0
5.00	7.86	8.17	7.23	5.68	5090	6150	1.63	7256.0	47.4	464.0
6.00	8.35	8.81	7.61	6.01	3220	4180	2.39	1884.0	10.4	344.0
6.00	8.35	8.81	7.61	5.54	4580	5820	1.72	5236.0	44.4	430.0
7.00	9.40	9.97	9.98	5.94	2680	3880	2.58	498.0	1.6	318.0
8.00	12.84	10.65	11.92	5.41	2760	4160	2.40	535.0	10.2	345.0

Comparison of RCPT Bulk Resistivity Measurements and Chemistry Data From Pore Water Samples

Sounding:	I11-9330
Cone ID:	HOG3RES
Date:	10/13/93
GWT =	15.0

	RCPT DATA			PORE FLUID EXTRACTIONS FROM TAILINGS SOLIDS						
DEPTH (m)	RES010 (ohm-m)	RES025 (ohm-m)	RES075 (ohm-m)	pH	SULPHATE (mg/l)	COND. (uS/cm)	RES (ohm-m)	Fe (mg/l)	Ni (mg/l)	Mg (mg/l)
0.23	10.52	16.10	18.05		4320					
0.70	17.33	19.82	22.70		5080					
1.15	33.75	33.55	26.37		3730					
1.60	41.68	44.88	34.59		3090					
2.05	36.42	36.92	33.91		6068					
4.80	20.28	21.54	20.38		6222					
9.38	19.37	18.14	17.04		6750					
13.95	19.58	17.34	9.06		9600					
18.53	8.84	8.61	8.87		2770					
20.10	10.88	11.53	9.89		2090					
27.68	13.89	15.05	14.38		3120					
32.23	12.84	13.93	12.98		2060					
36.83	29.89	32.75	29.75		1500					
41.40	36.21	41.04	39.57		2550					

Comparison of RCPT Bulk Resistivity Measurements and Chemistry Data From Pore Water Samples

Sounding:	I16-9320
Cone ID:	HOG3RES
Date:	10/9/93
GWT =	1.6 m

		RCPT DATA				BAT DATA						
DEPTH												
(m)		RES010	RES075	RES150		pH	SULPHATE	COND.	RES	Fe	Ni	Mg
		(ohm-m)	(ohm-m)	(ohm-m)			(mg/l)	(uS/cm)	(ohm-m)	(mg/l)	(mg/l)	(mg/l)
4.00		6.77	6.17	5.56		5.96	1450	2950	3.39	176.0	10.3	47.8
5.00		12.05	12.20	12.67		5.96	1830	3500	2.86	206.0	5.7	60.6
6.00		10.80	10.77	11.34		5.12	1610	2920	3.42	87.1	3.1	48.3

Comparison of RCPT Bulk Resistivity Measurements and Chemistry Data From Pore Water Samples

Sounding:	I19-9323
Cone ID:	HOG3RES
Date:	10/11/93
GWT =	0.0 m

		RCPT DATA				UNIVERSITY OF WATERLOO PIEZOMETER DATA:					IN21,IN23,IN82	
DEPTH (m)		RES010 (ohm-m)	RES025 (ohm-m)	RES075 (ohm-m)		pH	SULPHATE (mg/l)	COND. (uS/cm)	RES (ohm-m)	Fe (mg/l)	Ni (mg/l)	Mg (mg/l)
1.70		10.03	9.45	11.72		5.83		4930	2.03			
2.50		9.82	9.89	10.03		6.96		3230	3.10			
2.70		11.09	10.45	12.06		6.58		3990	2.51			
5.20		10.38	11.41	10.18		6.98		3100	3.23			

Comparison of RCPT Bulk Resistivity Measurements and Chemistry Data From Pore Water Samples

Sounding:	I20-9324
Cone ID:	HOG3RES
Date:	10/11/93
GWT =	0.0 m

		RCPT DATA			UNIVERSITY OF WATERLOO PIEZOMETER DATA:					IN23	
DEPTH (m)		RES010 (ohm-m)	RES025 (ohm-m)	RES075 (ohm-m)	pH	SULPHATE (mg/l)	COND. (uS/cm)	RES (ohm-m)	Fe (mg/l)	Ni (mg/l)	Mg (mg/l)
2.70		9.47	9.85	9.50	6.58		3990	2.51			

Comparison of RCPT Bulk Resistivity Measurements and Chemistry Data From Pore Water Samples

Sounding:	I21-9325
Cone ID:	HOG3RES
Date:	10/11/93
GWT =	0.0 m

	RCPT DATA			UNIVERSITY OF WATERLOO PIEZOMETER DATA:					IN23	
DEPTH (m)	RES010 (ohm-m)	RES025 (ohm-m)	RES075 (ohm-m)	pH	SULPHATE (mg/l)	COND. (uS/cm)	RES (ohm-m)	Fe (mg/l)	Ni (mg/l)	Mg (mg/l)
2.70	9.40	9.25	8.39	6.58		3990	2.51			

Comparison of RCPT Bulk Resistivity Measurements and Chemistry Data From Pore Water Samples

Sounding:	I22-9326
Cone ID:	HOG3RES
Date:	10/11/93
GWT =	0.0 m

		RCPT DATA			UNIVERSITY OF WATERLOO PIEZOMETER DATA:					IN32	
DEPTH (m)		RES010 (ohm-m)	RES025 (ohm-m)	RES075 (ohm-m)	pH	SULPHATE (mg/l)	COND. (uS/cm)	RES (ohm-m)	Fe (mg/l)	Ni (mg/l)	Mg (mg/l)
2.10		19.44	20.07	22.07	7.13						
2.10		19.44	20.07	22.07	7.28		2710				

Comparison of RCPT Bulk Resistivity Measurements and Chemistry Data From Pore Water Samples

Sounding:	I23-9327
Cone ID:	HOG3RES
Date:	10/12/93
GWT =	0.0 m

		RCPT DATA				UNIVERSITY OF WATERLOO PIEZOMETER DATA:					IN22	
DEPTH (m)		RES010 (ohm-m)	RES025 (ohm-m)	RES075 (ohm-m)		pH	SULPHATE (mg/l)	COND. (uS/cm)	RES (ohm-m)	Fe (mg/l)	Ni (mg/l)	Mg (mg/l)
2.20		16.98	16.30	17.57		6.89		2640	3.79			
6.90		78.04	74.35	81.72		8.31		225	44.44			
7.00		77.51	74.47	80.56		8.23	17.7	190	52.63	0.6	0.05	9.4
8.80		83.01	69.07	76.04		8.07	29.9	225	44.44	4.3	0.05	14.4
10.00		58.52	55.65	57.10		7.94	235	680	14.71	2.2	0.05	35.7
10.60		43.40	43.40	42.95		7.37	461	1300	7.69	4.1	0.05	62.5
13.20		18.94	20.46	20.38		6.96	705	1720	5.81	18.6	0.05	85.3

Comparison of RCPT Bulk Resistivity Measurements and Chemistry Data From Pore Water Samples

Sounding:	I25-9331
Cone ID:	HOG3RES
Date:	10/14/93
GWT =	0.0 m

	RCPT DATA			UNIVERSITY OF WATERLOO PIEZOMETER DATA:					IN33	
DEPTH (m)	RES010 (ohm-m)	RES025 (ohm-m)	RES075 (ohm-m)	pH	SULPHATE (mg/l)	COND. (uS/cm)	RES (ohm-m)	Fe (mg/l)	Ni (mg/l)	Mg (mg/l)
2.00	9,82	10.57	10.76	4.51		970				

Comparison of RCPT Bulk Resistivity Measurements and Chemistry Data From Pore Water Samples

Sounding:	I26-9332
Cone ID:	HOG3RES
Date:	10/14/93
GWT =	0.0 m

	RCPT DATA			UNIVERSITY OF WATERLOO PIEZOMETER DATA:					IN34	
DEPTH (m)	RES010 (ohm-m)	RES025 (ohm-m)	RES075 (ohm-m)	pH	SULPHATE (mg/l)	COND. (uS/cm)	RES (ohm-m)	Fe (mg/l)	Ni (mg/l)	Mg (mg/l)
6.10	64.69	64.34	59.53	7.44		537				
9.10	70.80	66.54	69.15	9.95		320				

Comparison of RCPT Bulk Resistivity Measurements and Chemistry Data From Pore Water Samples

Sounding:	F01-9333
Cone ID:	HOG3RES
Date:	10/14/93
GWT =	10.2

	RCPT DATA			PORE FLUID EXTRACTIONS FROM TAILINGS SOLIDS						
DEPTH (m)	RES010 (ohm-m)	RES025 (ohm-m)	RES075 (ohm-m)	pH	SULPHATE (mg/l)	COND. (uS/cm)	RES (ohm-m)	Fe (mg/l)	Ni (mg/l)	Mg (mg/l)
0.50	5.82	3.24	2.35	3.91	36600	10270	0.97	8008.0	3200.0	388.0
1.10	3.93	3.36	2.88	3.89	27840	5040	1.98	12500.0	200.7	794.8
3.90	7.30	1.36	20.04	6.27	17130	3730	2.68	20.2	84.2	521.4
5.70	8.49	9.61	9.40	6.50	3300	2800	3.57	16.1	0.9	457.5
5.90	9.89	10.01	8.82	6.53	2751	2680	3.73	8.0	1.0	337.8
7.30	10.95	11.85	12.69	7.27	3720	4300	2.33	0.2	2.5	313.7
8.95	8.56	8.77	7.47	7.01	3060	3320	3.01	1.8	2.9	409.8
10.72	10.03	9.65	10.08	6.55	3210	3110	3.22	10.0	0.9	443.1
12.25	9.89	11.01	9.84	6.41	2285	2490	4.02	2.1	1.8	174.9
13.77	22.03	15.50	21.10	6.43	2290	2520	3.97	1.5	2.3	146.6
15.30	19.37	15.05	17.43	6.88	2067	2850	3.51	5.8	2.1	136.9
16.75	24.07	17.26	26.76	6.48	1862	2560	3.91	66.3	6.7	102.4
18.25	19.86	14.57	22.36	6.42	2308	2480	4.03	3.1	1.2	149.3
20.40	11.79	9.97	11.34	6.48	2590	2820	3.55	2.6	1.1	204.3
21.95	8.91	8.97	8.48	6.51	2805	3280	3.05	0.1	3.1	205.1
23.32	23.93	16.42	21.78	6.88	3060	3750	2.67	0.6	2.6	246.2
24.35	25.40	16.98	21.83	7.70	2433	3340	2.99	0.3	1.9	209.0
26.35	28.21	18.58	30.38	7.55	2552	3530	2.83	0.5	3.0	210.3
28.00	14.45	15.17	13.95	6.54	2775	3020	3.31	0.8	0.8	194.2
28.50	19.44	17.34	19.26	7.89	1592	2050	4.88	0.2	2.9	119.3
29.32	23.72	19.30	24.15	7.42	1452	2180	4.59	0.7	3.7	104.7
31.07	30.38	23.50	30.14	7.51	1401	2110	4.74	24.0	2.3	111.3
32.50	19.51	19.22	19.75	6.52	1572	2120	4.72	0.3	0.5	106.5
33.22	34.66	25.42	32.65	6.53	1704	2290	4.37	1.8	0.6	137.9
34.00	34.52	25.50	33.81	7.59	1592	2360	4.24	1.1	3.2	131.5
36.37	22.80	20.82	21.39	6.70	2329	2070	4.83	0.4	3.0	125.6

Comparison of RCPT Bulk Resistivity Measurements and Chemistry Data From Pore Water Samples

Sounding:	GB-T9411
Cone ID:	UBC9RES2
Date:	09/03/94
GWT =	15.1 m

	RCPT DATA			BAT DATA						
DEPTH (m)	RES010 (ohm-m)	RES025 (ohm-m)	RES075 (ohm-m)	pH	SULPHATE (mg/l)	COND. (uS/cm)	RES (ohm-m)	Fe (mg/l)	Ni (mg/l)	Mg (mg/l)
16.70	15.30	12.62	24.43		1010	2580				
16.70	15.30	12.62	24.43		1006	2320				
17.30	17.10	15.11	22.12		910	2160				
17.30	17.10	15.11	22.12		770	2060				

Historical Data of Bulk Resistivity versus Pore Water Sulphate Concentration (after Merkel, 1972)	
Bulk Resistivity (ohm-m)	Sulphate Concentration (mg/l)
180.0	14
86.7	40
66.7	33
64.3	60
44.6	72
37.5	96
35.7	94
19.2	331
13.3	659
12.7	600
11.2	500
12.1	592
11.5	640
12.6	660
11.1	640
11.2	680
11.1	727
8.6	982
7.9	1019
6.1	1029
5.7	1032
4.8	1184
3.8	5526
3.3	5050
3.1	4818