



**WHISTLE MINE WASTE ROCK  
STUDY:  
VOLUME I**

**MEND Project 1.41.4**

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**WHISTLE MINE WASTE ROCK STUDY  
VOLUME I**

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in collaboration with

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to

Mine Environment Neutral Drainage (MEND) Program  
Prediction Committee  
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## **EXECUTIVE SUMMARY**

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Golder Associates Ltd. in association with SENES Consulting was retained by Public Works and Government Services Canada to carry out a study to characterize the Whistle Mine Waste Rock Pile at the Whistle Mine site near Sudbury Ontario. The intent of the Whistle waste rock project was to develop and illustrate technology for evaluating waste rock piles and to provide a database of information for characterizing the waste rock.

During the study quality data on the acid mine drainage characteristics of the Whistle Mine waste rock pile were collected and compiled. The field investigation involved collection of waste rock samples, drilling of five boreholes and excavation of three test pits. Wells, gas sampling ports and thermistors were installed in the boreholes, and lysimeters were installed in the test pits. Water quality data was collected from seepage locations, wells, and lysimeters. Measurements of oxygen and carbon dioxide and measurements of temperature distribution were collected. Solid samples collected on the site were analysed for chemical properties. Laboratory testing of solid samples included elemental analysis, static tests, kinetic tests, wash tests and bacterial analysis.

The database collected is quite extensive and should be useful for supporting other investigations; however, it should be noted that the Whistle waste rock pile is different from the other waste rock piles at MEND study sites, and at other mines, in several ways:

- the waste rock is coarse and angular, and comprised of very large hard rocks;
- the pile was very difficult to drill and sample due to high porosity and large void spaces;
- the pile contains zones of rock fines, which are interspersed between the large rocks;
- air penetrates to the bottom of the pile, therefore the supply of oxygen is not limiting the oxidation of sulphide; and,
- the interior of the pile is cold, as noted from the temperature data collected, temperature of the collected seepage, and from field observations of venting of cold air from the base and top of the pile.

These differences should be kept in mind when attempting to apply the data and information obtained from the Whistle waste rock study to the interpretation of waste rock piles at other sites.

The following is a summary of some of the key conclusions and recommendations.

- Tests for acid generation potential indicate that the pile is acid generating and oxidation of sulphide minerals is not limited by oxygen flux into the pile.
- Concentrations and loading rates for column tests and seepage indicate that the water from the column test is still somewhat buffered. The loading rates from the column tests for sulphate and nickel respectively are about 39 and 1.8 times greater than those measured in seepage from the waste rock pile. The smaller difference in nickel loading is due to neutral conditions in the column. If the column test had been continued until the leachate became acidic, the nickel loading would have increased significantly.
- The differences between leachate produced from the column test and from the waste rock pile have illustrated that caution should be used in applying the results of short-term kinetic tests to longer term behaviour of waste rock. Practice has shown that it can take a year or more for a sample to become acidic in a column test. This acidity greatly increases metal loading rates. Another caution regarding column tests relates to loading rates from the columns. The absolute rate from columns can be much greater than that observed in the field (as illustrated above) due to high proportion of finer, more reactive material in the column, and due to accelerated rainfall cycles.
- Grain size distribution and structural composition of the rock was used to estimate the water content, and porosity of the pile. This data was then combined with a hydrologic assessment to assess the flow through the waste rock. The results indicate that infiltration into the waste rock will take anywhere from days to months to reach the seepage collection point. Most of the flow will occur under heavy infiltration events such as heavy rainfall or spring runoff. The water balance indicates that the most significant loadings will occur during the spring runoff period.
- A unique opportunity to expand the Whistle waste rock database will become available

when the waste rock pile is relocated to the pit as part of site closure activities. When this occurs, it is recommended that further study be conducted while the pile is being relocated.

- Additional study on bacterial catalysed oxidation at low temperatures is required to determine the potential implications of low temperature, bacterially catalysed oxidation for arctic and subarctic tailings, and waste rock deposition.
- Additional investigation into the relationship between pile structure and flow characteristics should be completed. This, coupled with a detailed evaluation of existing literature, and research in the fields of unsaturated flow and geotechnical engineering would be of benefit in understanding flow through unsaturated waste rock.
- Based on our experience at the Whistle Mine site the following data is of critical importance for an assessment of any waste rock dump:
  - structural parameters of the dump (grain size distribution, porosity, water content, distribution of material and dump construction);
  - acid generation potential of the waste rock (based on Acid:Base Accounting, kinetic test work, detailed mineralogical characterization, seepage characterization, and analysis of temperature and gas composition data); and,
  - a detailed site water balance (based on detailed precipitation data, estimates of flow rates through the pile, estimates of evaporation, estimates of water retention in the pile, and measurement of the surface area of the pile).

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Durant l'étude, on a recueilli et compilé des données qualitatives sur les caractéristiques du drainage minier acide (DMA) provenant de la halde de stériles de la mine Whistle. Les travaux sur le terrain ont consisté à prélever des échantillons de stériles, à forer cinq trous de sondage et à excaver trois fosses d'essai. Des puits, des systèmes d'échantillonnage des gaz et des thermistors ont été installés dans les trous de sondage et des lysimètres dans les fosses d'essai. Les données sur la qualité de l'eau proviennent de zones de suintement, des puits et des lysimètres. On a mesuré la teneur en oxygène et en dioxyde de carbone et on a établi la distribution des températures. Les échantillons solides extraits *in situ* ont été analysés pour déterminer leurs propriétés chimiques. Les essais en laboratoire sur les échantillons solides ont été les suivants : analyse des éléments, essais statiques, essais cinétiques, essais de lavage et analyses bactériennes.

La base de données ainsi mise sur pied est très exhaustive et devrait être utile à d'autres études; cependant, il faut noter que la halde de stériles à la mine Whistle diffère des autres haldes qu'elles soient situées aux sites d'étude du NEDEM et aux autres mines, et ce pour plusieurs raisons:

- les roches sont grossières et anguleuses et comportent de très gros fragments résistants;
- la halde a été très difficile à forer et à échantillonner à cause de la porosité élevée et la grande taille des espaces interstitiels;
- la halde contient des zones de fines intercalées entre les gros blocs;
- comme l'air pénètre jusqu'à la base de la halde, l'apport en oxygène ne limite donc pas l'oxydation des sulfures; et
- l'intérieur de la halde est froid, comme l'indiquent les données sur la température recueillies, la température de l'eau de suintement et les observations *in situ* de l'expulsion d'air froid à partir de la base et du sommet de la halde.

Il faut garder ces différences à l'esprit lorsqu'on tente d'appliquer les données et les informations fournies par l'étude des stériles de Whistle à l'interprétation des haldes de stériles à d'autres sites.

Les conclusions et les recommandations clés sont résumées ci-dessous.

- Les essais pour déterminer le potentiel d'acidification indiquent que la halde est acidogène et que l'oxydation des minéraux sulfurés n'est pas limitée à l'afflux d'oxygène dans la halde.
- Les concentrations et les vitesses de dissolution dans les colonnes d'essai et les eaux de suintement indiquent que l'eau des colonnes d'essai est encore quelque peu tamponnée.
- Les vitesses de dissolution dans les colonnes d'essai pour le sulfate et le nickel sont respectivement 39 et 1,8 fois environ plus élevées que celles mesurées dans les eaux de suintement de la halde. La différence plus faible notée dans la dissolution du nickel est due aux conditions neutres qui existent dans la colonne. Si l'essai en colonne avait été poursuivi jusqu'à l'acidification du lixiviat, la dissolution du nickel aurait augmenté significativement.
- Les différences observées entre le lixiviat produit par l'essai en colonne et celui provenant de la halde de stériles ont mis en évidence la prudence dont il faut faire preuve lorsqu'on applique les résultats d'essais cinétiques à court terme au comportement à plus long terme des stériles. L'expérience a montré qu'il peut s'écouler un an ou plus avant qu'un échantillon devienne acide dans une colonne d'essai. Cette acidité a pour effet d'accroître considérablement les vitesses de dissolution dans les colonnes. Le taux absolu enregistré dans les colonnes peut être beaucoup plus élevé que celui observé *in situ* (tel qu'illustré ci-dessus) à cause d'une proportion plus élevée de matériaux plus réactifs et plus fins dans la colonne et à cause des cycles accélérés des précipitations.
- La granulométrie et la composition structurale de la roche ont servi à évaluer la teneur en eau et la porosité de la halde. Ces données ont ensuite été combinées à celles d'une évaluation hydrologique visant à estimer l'écoulement traversant la halde de

stériles. Les résultats indiquent que l'infiltration dans les stériles prend toujours entre plusieurs jours à quelques mois pour atteindre le point de collecte des eaux d'infiltration. L'écoulement résulte principalement de fortes infiltrations d'eau de pluie et d'eau de ruissellement au printemps. Le bilan hydrique indique que les taux de dissolution les plus significatifs ont lieu durant le ruissellement printanier.

- Le déplacement de la halde de stériles vers la mine dans le cadre des activités de fermeture du site offrira une occasion unique d'accroître la base de données sur les stériles de Whistle. Il est recommandé d'entreprendre une autre étude pendant le déménagement de la halde.
- Il faudra mener une autre étude sur l'oxydation catalysée par des bactéries à températures basses pour déterminer les répercussions possibles des températures basses, de l'oxydation catalysée par des bactéries dans les résidus de milieux arctiques et subarctiques et du dépôt de stériles.
- Il faudrait entreprendre des recherches supplémentaires sur le lien entre la structure de la halde et les caractéristiques de l'écoulement. Combinées à une évaluation détaillée de la documentation actuelle et à des recherches *in situ* sur l'écoulement non saturé et les propriétés géotechniques, ces recherches permettraient d'élucider l'écoulement à travers des stériles non saturés.
- En se basant sur l'expérience acquise à la mine Whistle, les données suivantes ont une importance cruciale pour évaluer toute halde de stériles:
  - les paramètres structuraux de la halde (distribution granulométrique, porosité, teneur en eau, répartition des matériaux et construction de la halde);
  - le potentiel d'acidification des stériles (basé sur le rapport acide-base, les essais cinétiques, la caractérisation détaillée de la minéralogie, la caractérisation des eaux de suintement et l'analyse des données sur la température et la composition des gaz); et
  - un bilan hydrique détaillé du site (basé sur des données détaillées sur les précipitations, l'estimation des débits à travers la halde, des estimations de l'évaporation, des estimations de la rétention d'eau dans la halde et la superficie de la halde).



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# 1. INTRODUCTION

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In August 1995, a team comprising Golder Associates Limited (Golder) and SENES Consultants Limited (SENES) were retained jointly by the federal Scientific Directorate and Public works and Government Services Canada (PWGSC) under the Mine Environment Neutral Drainage (MEND) programme to undertake the collection of AMD data at Whistle Mine near Capreol Ontario. INCO Limited (INCO) is also an active partner in the project providing funding, the project site and other assistance. The contract number assigned to this project by PWGSC is 23440-5-1125/01-SQ (file number 028SQ.23440-5-1125). This report is the final report and presents the data collected and analysis of the data.

## ***Report Breakdown***

In a study of this complexity it is often difficult to organize and present the data and interpretation in a meaningful and concise manner. It is hoped that the format presented will lend itself to ease of information retrieval for design, implementation and assessment of other studies as well as for further assessment and interpretation at this study location.

The report is divided into *Introduction, Review of Existing Data, Methodology, Results, Data Assessment, Conclusions and Recommendations*. Each individual task is identified and expanded upon in Section 3.0 *Methodology* and Section 4.0 *Results*. In Section 5.0 *Data Assessment* more complex issues (which require assessment of data from many of the tasks), such as site water balance, loading estimates and assessment of laboratory results are addressed. Conclusions, and recommendations are then presented. Figure and Table references are numbered according to section and subsection, (e.g. the first figure of Section 3, Subsection 1 would be labelled Figure 3.1-1). For references to figures and tables appearing in the appendices, the figure or table number appearing in the appendix is preceded by the appropriate appendix letter, (e.g. for Figure G-1 “G” refers to Appendix G thus this is Figure 1 located in Appendix G).

## **1.1. BACKGROUND**

The economical exploitation of ore bodies and the related milling and refining of minerals typically results in the generation of significant volumes of waste materials in the form of tailings and waste rock. If present, residual sulphide minerals in the waste, in contact with air and without the presence of sufficient buffering (neutralisation) capacity will produce acid mine drainage (AMD) or acid rock drainage (ARD) through oxidation processes. The acid drainage then tends to mobilise residual metals in the waste rock or tailings and the metal laden runoff and seepage from these facilities may be toxic and harmful to the biota.

There are numerous sites in Canada and elsewhere where the historic lack of control of acidic runoff have caused significant environmental impact, particularly in water courses. Further, at operating sites where AMD/ARD related problems are significant and currently controlled, the effort and costs associated with control and treatment of AMD/ARD can be an important component of operating costs. In fact, the economic viability of mining projects can be and have been negatively impacted by acid drainage related problems.

While mining companies have made significant progress in managing tailings and mine effluents, waste rock has historically been considered to be an inert pile of rubble whose management represented a major cost only during the development phase of a mine. It is now apparent that waste rock can represent a serious long-term environmental concern, and a significant economic liability. Often these liabilities are far greater than those associated with tailings disposal.

Understanding the scope and chemical processes involved in AMD/ARD can lead to good initial planning and rational engineered solutions, which may help to mitigate potential environmental concerns and reduce financial liabilities associated with acid rock drainage. In order to understand these processes, quality data must be gathered from a number of sites which can then be used as baseline data with which to compare other waste rock dumps.

Considerable research has been carried out in the past decade related to the aspects of AMD/ARD in tailings, and many case studies have been documented; however, data collection and case studies related to waste rock piles have been limited. Since 1989, MEND, through its

federal, provincial and industrial partners, has sponsored research and development into ways of evaluating and reducing the environmental impact and financial liabilities of AMD/ARD from tailings and waste rock. The ability to provide a comprehensive, scientific, technical and economic basis to predict with confidence the long-term management requirements for reactive mine walls and mine wastes is one of the main objectives of the MEND program. The major focus of the MEND related work has been to establish techniques which will enable the operation and closure of acid generating sites in a predictable, affordable, timely and environmentally acceptable manner. In order to continue to establish these valuable techniques, more quality data on AMD/ARD is required. Several waste rock dumps in Canada are being monitored, including those at Cape Breton, N.S.; Heath Steele, (Bennett et al., 1995; MEND 2.13.10, 1990) La Mine Doyon, Québec (MEND 1.14.2, 1994); and Island Copper, Myra Falls, Mount Washington, B.C. (MEND 1.11.1, 1991). These dumps are providing useful information for a database of rock pile monitoring. In general, the acid generating behaviour of waste rock is not well documented in Canada with the exception of the softer rock of La Mine Doyon, Québec.

The Whistle Mine waste rock dump was selected as an ideal candidate site for a field and laboratory program. The site is relatively new (less than 8 years old at the outset of this project); it is relatively small in size (5 M tonnes); sampling points for monitoring water quality coming from the dump were already available; geophysical surveys (including EM-31) have been conducted on the site; and the site is not affected by metallurgical operations or contaminated with “foreign” material. Data from the Whistle Mine waste rock dump will provide valuable baseline data for further AMD/ARD empirical characterisation. This may assist in prediction of potential acid generating conditions in waste rock.

## **1.2. SCOPE AND OBJECTIVES**

The scope of this project comprises the collection of field and laboratory data at the Whistle Mine site near Sudbury Ontario (Figure 1.2-1, Plate 1.2-1) and to provide some analysis of the data. Specifically, the objectives of the Whistle Mine waste rock project are to:

- assess the present chemical and physical conditions;

- determine proper sampling techniques, adapting methods outlined in manuals developed by MEND for waste rock sampling;
- establish and implement laboratory and field programs to collect data;
- provide interpretation of the data; and
- provide recommendations for future waste rock monitoring programs, building on the experience gained from this and other projects to establish protocols that may apply to a broader range of waste rock piles.

It is envisioned that these data will be added to existing data from a number of other waste rock disposal sites, most notably La Mine Doyon, Québec, in order to develop an understanding of the future behaviour of waste rock piles with an emphasis on predictive techniques.

### **1.3. SPECIAL CONDITIONS**

Although the Whistle Mine waste rock pile has been selected for study because of its relative freedom from extraneous contamination, there are several unique factors which have significantly influenced work at the site, and which may affect any future work at the site. These factors include the following:

- active mining and waste rock dumping limited the study to the northeast portion of the northeast waste rock dump;
- a gossan zone, which was first stripped from the mineral deposit, forms part of the base of the pile, and may have a significant effect on current water quality. Strongly oxidized waste rock is also intermingled with fresh waste rock in the pile due to recent and ongoing lateral expansion of the pit;
- the pile is heterogeneous with respect to sulphide mineralogy;
- the rock is tough and hard; thus, special drilling and sampling techniques were required; and,
- pile decommissioning plans include relocation of the waste rock back into the nearby open pit, capping and interim water treatment.

### **1.4. WHISTLE MINE SITE**

#### **1.4.1. History of the Whistle Mine and Whistle Mine Rock Dump**

The history of the Whistle Mine has been summarized by Bill Dyck (1993) of INCO. The



deposit was discovered by Isaac Whistle on July 24, 1897. In 1910 the property was tested by means of diamond drilling, shafts, and pits. An adit was driven into the side of the hill a distance of about 130 m. Drilling indicated ore to a depth of about 270 m and the calculated reserve was 1.2 million tonnes of ore. The discovery of the Murray ore body resulted in the abandonment of the Whistle property in 1912.

INCO obtained the property in 1929 and began mining in January, 1988. Over the years, a series of drill holes were completed on the property. Mining was contracted to MacIsaac Mining and Tunnelling (MacIsaac) and the mine was developed as an open pit mine. A total of 3 million tonnes of ore and 4.3 million tonnes of rock were removed from the pit from January, 1988 to September, 1991 by MacIsaac. The mine was closed between September, 1991, and November, 1994, after which INCO contracted Carman Construction (Carman) to continue mining operations in the open pit. Currently, Carman is mining the open pit. Current production rate is approximately 2,300 tonnes of ore per day, with a waste to ore ratio of 2:1.

As shown on Figure 1.4-1, waste rock has been historically deposited in two areas, one area to the northwest of the open pit, and another larger area to the northeast of the pit. The rock pile to the northwest is composed of mainly granitic (non-reactive) rock; thus, the focus of the study is on the rocks contained in the northeast rock dump. To the south of the waste rock pile is a gossan zone of highly weathered mineralised outcrop on surface. This gossan zone is referred to as the Whistle Wildcat.

#### **1.4.2. Site Description**

The Whistle Mine is located 12 km northwest of the Town of Capreol, in Lot 6, Concession IV of Norman Township as shown on Figure 1.2-1. The plant limit of the mine comprises approximately 58 ha. Within the plant limit, the major components of the mining operation are:

- an open pit;
- the Northwest Waste Rock Dump;
- the Northeast Waste Rock Dump;
- an ore stockpiling and loading area;
- an effluent treatment plant; and

- the dry and maintenance areas.

The relative locations of these facilities are shown on Figure 1.4-1.

The mine site is part of the Post Creek watershed, an area of approximately 5400 ha which drains into Lake Wanapitei, some 3 km east of the mine. The area immediately surrounding the mine site is undeveloped wilderness. The nearest neighbours to the mine are a trapper's cabin located at the outlet of Selwyn Lake, and the Wanapeti First Nation some 3 km downstream, at the mouth of Post Creek, on Lake Wanapitei.

The topography surrounding the mine site is controlled by the irregular nature of the bedrock surface. Bedrock outcrops are frequent and typically form hills that rise, up to 50 m, above the surrounding areas. A thin discontinuous blanket of glacial till covers the bedrock. Confined depressions in the bedrock surface are typically infilled with sediments and organic soils. Because these areas are poorly drained, they form swamps or bogs.

The igneous and metamorphic rocks which underlie the site are relatively impermeable in their intact form. Groundwater flow in these environments is therefore restricted to fissure flow within the rock mass and Darcy flow in the overburden. The rocks in the mine area are relatively unfractured and "tight" as evidenced by the good stability encountered during mining and the relatively small amounts of infiltration into the mine workings. The overburden deposits around the mine tend to be thin, discontinuous and not highly permeable. Therefore, the flow of water within and through the site is dominated by the surface water systems. The groundwater flow systems are shallow, local and contribute a relatively small component to the overall drainage system.

Two mineralized zones have been identified on the property. The main orebody is being mined at the open pit location. To date there has been no mining activity on the secondary orebody (the Whistle Wildcat). The ore is primarily composed of several sulphide compounds of copper (Cu), nickel (Ni), and cobalt (Co). The waste rock is composed of iron sulphides, silicates and some carbonate minerals.

The Post Creek watershed straddles the geological boundary between the mineralized zone of the Sudbury basin and the surrounding felsic plutonic rocks of the Superior Province of the Canadian

Shield. The site and the upstream portion of the watershed are within the mineralized zone, and as a result, the natural background concentrations of metals in the surface water and groundwater are often elevated relative to normal natural background levels. This results from direct contact with weathered surface exposures of sulphide mineralization such as Whistle Wildcat.

An effluent treatment system has been constructed to collect and process the runoff and seepage water from the open pit and ore loading areas of the site. A concrete core cut-off dam (the Crusher Dam) and a collection sump intercept groundwater seepage and surface runoff from the ore loading area and transmit accumulated water via pump to the open pit. An excavation to 20 metres depth was required to expose rock from the foundation of the Crusher Dam. A pump within the open pit transmits water from a sump in the bottom of the pit to the effluent treatment facility.

The treatment facility consists of a series of 4 ponds, a lime station, and related process controls. Water is pumped into the upper pond where lime is added by automatic feed according to the pH of the lowest pond. The water flows by gravity through two intermediate ponds to the lowest (fourth) pond where, if the pH is between 9.5 and 10.5, it is discharged to Post Creek. If the pH is either below or above this range an automatic valve is closed and the water is recirculated to the upper pond.

The Northwest Waste Rock Dump and the Northeast Waste Rock Dump are named for their position relative to the open pit. The dumps are graded so that most direct runoff flows back into the open pit. Rainfall which falls on the perimeter slopes facing away from the pit, and much of the rainfall which infiltrates the rock dumps flows to Post Creek, or to a seepage collection pond. The off-site component of runoff and seepage from the Northeast Rock Dump flows east via several small streams to Post Creek, or is collected and pumped to the treatment facility.

During site development for the present mine, large quantities of sulphur rich debris were removed from the pit and treatment facility locations. At the pit location, the material removed was weathered sulphide ore that had been blasted from the deposit as part of the original development work circa 1910. The material removed from the treatment pond area was an erosion product from the original Whistle orebody outcrop. The material removed from both of these sites was placed as the first layer of the Northeast Waste Rock Dump.

The mine administration and service areas are located near the site entrance, along the mine access road. A fueling facility exists south of the road, across from the garage and dry facility. A sand and gravel storage area was constructed north of the site access road near the site entrance. During initial (1987) construction, a crushing plant was set up at this location to process waste rock to make aggregates for site development. Selected rock, mostly granite, was used as feed stock for the crushing plant to avoid acid rock drainage (ARD) problems.

Road salt or a salt sand mixture was previously stored at the sand and gravel storage area. There is no waste disposal facility on the Whistle Mine site. All garbage is removed from the site by a waste management contractor. Sewage treatment at the Whistle Mine consists of a septic tank and septic tile bed located between the garage and dry and the mine access road. Gray water is discharged to a ditch near the garage and dry facility.

## **2. REVIEW OF EXISTING DATA**

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Previous work relevant to the study of the Whistle Mine waste rock pile includes:

- a hydrological and hydrogeological study by Golder Associates (1994);
- a waste rock sampling program and acid:base accounting analyses (INCO 1991 and 1995);
- geological and geochemical studies of the Whistle ore deposit and other Sudbury ore deposits; and
- other miscellaneous information, mapping, EM survey, etc.

In addition, INCO staff involved in the exploration and development of the Whistle Mine were a significant source of information on geological characteristics and waste rock production information, etc. for the Whistle Mine.

### **2.1. HYDROLOGICAL AND HYDROGEOLOGICAL STUDY**

In September 1994, Golder completed a report entitled *Hydrological and Hydrogeological Site Characterization Study of the Whistle Mine* for INCO. The report included:

- results of field monitoring to characterize groundwater and surface water contaminant concentrations and flow from the mine site;
- compilation and review of existing water quality data;
- a hydrologic and hydrogeological model of the site;
- estimation of contaminant mass loading from the site and an assessment of their impact on downstream water quality; and
- other information - miscellaneous mapping, etc.

### **2.2. EXISTING ACID BASE ACCOUNTING RESULTS**

Mike McCann of INCO supplied results from 45 ABA (acid:base accounting) analyses of waste rock from the Whistle Mine from a 1991 sampling program and results of eight samples of pink granite that were submitted for acid:base accounting in 1995. The results are provided in Appendix A.

### **2.3. GEOLOGICAL INFORMATION AND STUDIES**

The Ontario Geological Survey, Mineral Deposits and Field Services Section, has been studying the Whistle Mine since 1992. Progress reports summarizing 1993 and 1994 work have been published in the annual OGS *Summary of Field Work and Other Activities* under the following titles:

- *Ultramafic Intrusions in the Sublayer of the Sudbury Igneous Complex, Whistle Mine, Sudbury, Ontario; (Lightfoot et al., 1994) and*
- *Geochemistry of the Sudbury Igneous Complex (Lightfoot and Farrell, 1993).*

The OGS study has culminated in the release of Open File Report 5959, Geochemistry of the Main Mass, Sublayer, Offsets, and Inclusions from the Sudbury Igneous Complex, Ontario (Lightfoot et al. 1997). This report contains a detailed description of the Whistle geology and geochemistry, a table describing mineralogy of the rock types, and photographs and descriptions of hand samples and thin sections from the Whistle Mine.

Dr. Peter Lightfoot, of the OGS, provided a database of major element oxide and trace element analyses for 139 rock samples from Whistle Mine that was obtained as part of the above-noted studies. This database is provided in Appendix B. A map showing sample locations and geology of the Whistle pit is available in Open File Report 5959.

Besides the OGS studies, there are numerous other geologic studies of the Sudbury Igneous Complex (SIC) and its associated Ni-Cu ore deposits which contain information relevant to the Whistle Mine waste rock pile. In particular, in 1984 the OGS published *Special Volume 1, The Geology and Ore Deposits of the Sudbury Structure (Ontario Geological Survey, 1984)*, which is a 600 page comprehensive summary of geological studies of the Sudbury area.

### **2.4. OTHER INFORMATION**

An electro-magnetic (EM) survey was carried out by Hyd-Eng Geophysics (1993). This work was carried out in the spring of 1993 to identify conductivity anomalies that might be associated with impacted groundwater on the Whistle Mine site. Other published information used for this study includes:

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- 1:50,000 and 1:250,000 National Topographic Series Mapping;
- 1:10,000 Ontario Base Mapping;
- Regional Municipality of Sudbury Mapping; and
- Atmospheric Environment Service Meteorological Data.

### **3. METHODOLOGY**

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Testing at the Whistle Mine waste rock pile involved both field and laboratory investigations. The methodology is outlined below and detailed field and laboratory protocols are given in Appendix C.

#### **3.1. PHYSICAL CHARACTERIZATION**

A preliminary site investigation was completed by Golder and SENES personnel prior to the actual field investigation of borehole drilling and test pit excavations. The preliminary field investigation consisted of developing an overview of the site and identifying potential test pit (Lysimeter) and borehole locations.

##### **3.1.1. Geological Investigation**

Geological characterization of the Whistle Mine waste rock involved an examination of the northeast pile, the pit, the ore and outcrops adjacent to the pit including the gossan called the Whistle Wildcat (WW). Discussions with INCO staff also assisted in characterization of the pile. A face of waste rock that was recently exposed in a cut made for a road was assumed to be most representative of the interior of the pile and was examined in detail. This area is referred to as the “Autopsy Zone”. From these studies, a waste rock field classification system was devised, and an estimate was made of the quantities of the various waste rock types present in the dump.

In addition to visual classification, solid samples were collected from various areas and submitted for mineralogy and elemental analysis. Eight samples were selected for X-ray diffraction (XRD) analysis from the test pit and Autopsy Zone samples in order to characterize secondary mineralization. Field descriptions of the selected samples are presented in the sample logs (Appendix D). In general, the samples selected for XRD were composed of partially oxidized to highly oxidized fine sand to pebble-sized material. Some samples of the finer fractions of waste rock were also obtained to assist with the analysis of Particle Size and Porosity/Permeability. A geological characterization of the pile is presented in Section 4.1.1.

Additional tests conducted under the chemical sampling program which assisted in determining

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mineralogy include acid:base accounting, whole rock analysis, elemental analysis of solids, sulphur speciation and CO<sub>2</sub> analysis (Section 3.2).

Because of the availability of numerous publications on the geology of the Sudbury Intrusive Complex (SIC), and the large number of thin sections available from the OGS studies of the Whistle Mine, no additional thin sections were made. Petrographic descriptions of rock type were based on existing petrographic analysis, and are presented in Section 4.1.1.

### **3.1.2. Drilling and Instrumentation**

Five boreholes were drilled and instrumented at the Whistle Mine site between August 29 and September 20, 1995. Four boreholes (BH-1, BH-2, BH-3, and BH-4) were installed into the Northeast Waste Rock Pile, and one borehole (BH-5) was installed to the west of the waste rock pile and open pit to obtain representative background water quality data (Figure 1.4-1). As this particular waste rock pile is blocky and likely well aerated, it was felt that if the oxygen monitoring locations were too close to the edge of the pile the readings would be indicative of atmospheric oxygen concentration only. Boreholes and lysimeters (within test pits) were installed in locations a significant distance (approximately 200 to 250 ft) from the pile's outer slopes in an attempt to reduce the effects of ambient air migration to the instrumentation. At other waste rock piles it may be great benefit to determine the oxygen concentration and temperature near the edges of the pile.

As the purpose of the study was to provide data on acid rock drainage, all drilling and test pit work was implemented in the northeast waste rock pile which contains significantly more sulphide minerals than the northwest waste rock dump. Deposition of waste rock was ongoing on the southern portion of the northeast rock dump. As a consequence, all boreholes and test pits were located in the northern portion of the northeast rock dump away from the current deposition area.

The drilling was conducted by G. Hart and Sons using a truck mounted percussion air rotary drill rig. Boreholes in the waste rock were advanced using an eccentric ODEX drilling bit with a down-the-hole hammer (DHH). Heavy walled 150 mm (6 inch) steel casing was advanced behind the bit. The extreme hardness of the waste rock resulted in excessive drill bit wear; as a

result three bits were used over the course of drilling and each had to be rebuilt several times. The difficult drilling conditions necessitated the reduction of the field work program to 5 boreholes, with a total of 138 m drilled. Originally, a total of 6 boreholes and 180 m of drilling was planned.

Boreholes 1 to 4, located on the pile, were drilled through the waste rock into the underlying overburden and bedrock. Borehole BH-5, located approximately 1 km west of the waste rock pile, was drilled to a depth of 22.6 m and terminated in the sand and gravel overburden material.

### ***3.1.2.1. Borehole Sampling***

Where possible samples of the drill cuttings were collected at 1 m intervals by connecting a clean bucket to the air return hose. The samples were analyzed for paste pH, conductivity and fizz. Protocols established for borehole chip sampling and the field tests are described in Appendix C. Borehole sample logs and records of borehole sheets for the four boreholes drilled into the Northeast Waste Rock Pile are presented in Appendix D. The logs include a description of each sample, and the results of field tests (conductivity, paste pH and fizz test) which were conducted in the field, or at Golder's Sudbury office.

The samples that were returned in the drill flush ranged from sand-sized particles to chips measuring up to 15 mm in diameter, with most of the material consisting of angular chips less than 10 mm in diameter. Most of the samples were relatively unweathered, and appeared to represent the interior composition of boulders encountered during drilling, as opposed to in-situ fine material. A few samples appeared to be representative of existing fine material in the dump. These samples included imported sand, and organic material from the bottom of the waste rock pile.

The quantity and volume of sample returned from the eccentric ODEX drilling was poor in comparison to samples obtained using the same drilling method elsewhere (such as in the much softer, micaceous rocks of La Mine Doyon). The number of samples obtained in each borehole and the length of the borehole is shown below:

| <b>Borehole</b> | <b>Number of Samples</b> | <b>Borehole Depth ( m )</b> |
|-----------------|--------------------------|-----------------------------|
| BH1             | 8                        | 32.9                        |
| BH2             | 3                        | 36.6                        |
| BH3             | 8                        | 37.5                        |
| BH4             | 18                       | 31.1                        |

In general, the samples were collected intermittently over drilling intervals (from 3 m to 5 m long) with sample return occurring over a portion of the drilling interval. Based on discussions with the drilling contractor, the sample return was poor because the casing was generally advanced several centimetres behind the drill bit, which resulted in much of the drill cuttings being flushed into any available pore space between the casing and the drill bit rather than returning up the casing. Samples could be collected only in areas of low dump porosity or when the casing could be lowered almost to the drill bit. Sample collection improved over the course of the drilling program. It should be noted that other drilling techniques could not be used to improve sample return, as it was evident that drilling in this pile would not have been possible without the ODEX bit.

Drilling was supervised by a member of Golder or SENES staff, who were responsible for field logging of the boreholes, collecting samples, installing instrumentation, and establishing protocols for sampling and field analysis.

### **3.1.2.2. Instrumentation**

Upon completion of the borehole drilling in the waste rock, instrumentation (consisting of two PVC wells, thermistor strings, and gas sampling ports) was installed through the casing (Figure 3.1-1) (Plate 3.1-1). The casing was then pulled from the borehole, as the hole was simultaneously backfilled. Backfill material consisted of silica sand, bentonite hole plug, and minus 10 mm gravel.

### **3.1.3. Test Pit Excavation and Instrumentation**

Three test pits were excavated. The test pits were located within 30 m of the boreholes so that results from the test pit sampling could be compared with results from an adjacent borehole, if possible. It was also necessary to locate the test pits directly adjacent to the newly constructed access roads to facilitate their excavation.

A large track-mounted excavator (equipped with a 1.5 m<sup>3</sup> bucket) was used to excavate the test pits to an approximate depth of 4 to 6 m and in the shape of a bowl, with one side stepped to allow access.

#### **3.1.3.1. Test Pit Sampling**

Once excavated, the test pits were inspected to obtain pertinent information with respect to particle size distribution, waste rock characterisation and sampling. The faces of the test pit excavations were video taped and photographed to obtain images that would be used with the *GoldSize* computer program. A measuring tape was laid out along the test pit sides and incremental logging and sampling was then completed. Additional samples were taken of interesting areas in each pit, such as heavily weathered zones or zones representative of materials that were not sampled along the tape line. Logs of the test pits with sample descriptions, and the results of the field tests (conductivity, paste pH and fizz tests) conducted on the samples, are presented in Appendix D.

#### **3.1.3.2. Lysimeter Installation**

Lysimeters were installed within the excavated test pits to collect recharge water that percolates down through the waste rock pile. The bottom section of the test pit was lined with a layer of sand to act as a cushion material for the base of the lysimeter. A small diameter hole, 0.6 m to 0.9 m deep was hand excavated within the sand cushion layer to accept the installation of the lysimeter collection tube. Once the sand layer was properly shaped a (5 m x 5 m) impermeable geomembrane material (HDPE liner), a collection pipe, and a riser were installed in the test pits (Figure 3.1-2). The test pits were then carefully backfilled with waste rock to ensure that the lysimeter was not damaged.

The water present in the lysimeter was collected and sent for analysis as described in Section 3.3.

The lysimeters were drained of water using a Waterra pump, and any residual oxygen in the collection pipe was displaced using nitrogen to prevent oxidation of the leachate collected within the collector pipe. The lysimeter was capped to prevent oxygen migration into the collection pipe.

#### **3.1.4. Particle Size / Permeability**

Sieve analysis of minus 100 mm samples was conducted at Golder Associates' Sudbury office, to determine a grain size distribution of the finer fraction of waste rock (Appendix E). Samples collected during the sampling program (generally minus 50 mm dia. particles) were also assessed at B.C. Research Inc. (BCRI), Vancouver, to determine the percentage of minus 2 mm material (by weight). Particle size analysis on the larger material in the pile was determined using a computer program, *GoldSize*, developed by Golder Associates. The program results are combined with physical sieve analysis results to approximate the waste rock size distribution (Appendix E).

For the particle size analysis a series of fourteen photographs were taken of the material in the walls of the test pits. Each photograph contained a pair of disks of known diameter which provided a scale for the images. The photographs were scanned to produce digital images and the images were analyzed using *GoldSize* to produce a distribution of rock particle sizes. The results from each photograph were grouped together to produce a size distribution for the material in the waste rock pile. This size distribution was corrected for the fine sized particles that could not be analyzed in the photographs. Protocols of the *GoldSize* analysis are presented in Appendix E and the results are presented in Section 4.1.2.

### **3.2. CHEMICAL CHARACTERIZATION**

The *Handbook for Waste Rock Sampling Techniques* (MEND 4.5.1-2, 1994) recommends a staged sampling program; however, since the schedule for the Whistle waste pile field program was very compressed, it did not allow for a staged approach. The rock sampling on surface was completed during the initial field visit (August/September, 1995). Sampling to obtain specific material for the kinetic test work (i.e. laboratory column studies) was completed in February,

1996.

A total of 140 solid samples were collected from the Whistle rock pile for chemical analysis including samples from the following areas:

- grab samples of waste rock from three test pits on the top of the waste pile;
- grab samples of waste rock from the exposed face of the Autopsy Zone;
- drill cuttings collected from four boreholes;
- a grab sample from the Whistle ore pile; and,
- chip samples from the Whistle Wildcat Gossan located near the waste pile.

The solid samples collected in the field were tested for paste pH, paste conductivity, and fizz in Golder Associates' Sudbury office. Fizz test results were described using a numeric rating from 0 (no fizz) to 3 (strong fizz) (i.e. where the fizz test comprised applying a 10% HCl solution to the sample and observing the amount of "bubbles" or reaction to the HCl). A strongly fizzing reaction is generally indicative of a higher carbonate content.

Solid samples were also sent to BC Research Laboratories (BCRI), for chemical test work as indicated in Table 3.2-1. The BCRI report containing the analytical data is provided in Appendix F. The chemical analyses test work performed is outlined below. The results are discussed in Section 4.2.

### **3.2.1. Chemical / Elemental Analyses**

Chemical analyses were performed according to the *Handbook for Waste Rock Sampling Techniques*, (MEND 4.5.1-2, 1994). The analyses were performed at BCRI and included determination of sulphide, sulphate, carbonate as CO<sub>2</sub>, iron, etc. as well as ICAP-OES analyses for elemental (metal) content. The Guide for Predicting Water Chemistry, (MEND 1.27.1a, 1996) was also reviewed. The type of carbonate analysis conducted may not detect all siderite or dolomite, thus may underestimate total carbonate. Waste rock particles less than 2 mm have a greater reactive surface area for sulphide oxidation, and are therefore more significant for prediction/modelling of acid mine drainage, thus the chemical analyses were carried out separately for two fractions: (1) the whole rock fraction, and (2) waste rock particles less than 2 mm in diameter.

In addition to the chemical/elemental analyses which were completed at BCRI, the Whistle waste rock samples were also subjected to whole rock (e.g. SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, etc.) and CO<sub>2</sub> analyses at ACME Analytical Laboratories Ltd., Vancouver. This data is included with the BCRI report in Appendix F. The whole rock analyses also provided data for several other trace metals, and additional (i.e. duplicate) analyses for nickel and several other metals using a different digestion method, (i.e. a more aggressive leach).

The laboratory analyses data from BCRI was provided in electronic format, and a database was developed for the Whistle waste rock pile to facilitate preparation of data summaries and interpretation of the data (Appendix G). The field data (paste pH, conductivity and fizz tests) has also been entered into the Whistle database.

The chemical/elemental and whole rock analyses have been summarized in the database by analyte, location (i.e. Autopsy Zone, test pit, borehole), and size fraction (i.e. minus 2 mm, whole rock fraction). The duplicate analyses for nickel and strontium, which were obtained using different analytical methods, have been summarized separately (i.e. they were not averaged), as the digestion method and units are different in each case.

Histogram plots of the solids analyses of the waste rock have been prepared to illustrate the frequency distribution of selected analytes and specific metals within the pile, as shown in Appendix G (Figures G-1 to G-11). The analyses for the gossan (Whistle Wildcat) and the ore sample were not included in the histogram plots. The analytes selected for the histogram plots include the paste pH and the metals noted to be at higher levels in the waste rock pile seepage: aluminum; cobalt; copper; iron; magnesium; manganese; nickel; sulphate; sulphide; and zinc. The histogram plots have been prepared using solid and shaded bars to illustrate the frequency distribution for whole rock, in comparison to that measured for the fine fraction (minus 2 mm). Several statistical parameters (e.g. minimum, mean, maximum, median, etc.) were calculated and are summarized on the plots; curves for the normal and log normal distribution are also shown on the plots.

### **3.2.2. Static (Acid-Base Accounting) Tests**

The Sobek method (Sobek, 1978) was routinely used by INCO until 1993, at which time, the

INCO Laboratories switched to the modified Sobek method. The modification to the Sobek method involves addition of hydrogen peroxide to eliminate the effects of siderite on the NP estimate. Acid-Base Accounting (ABA) data provided by INCO is shown in Appendix A; since this data was obtained in 1990, it was likely determined using the Sobek method (Stuparyk, 1995).

For the current program, the modified Sobek test (as outlined in Appendix H and above) was used to determine the NP of 87 samples from the test pits, boreholes and the gossan (as outlined in Table 3.2-1). The samples were selected to provide good spatial coverage of the pile. Although it is preferable to conduct the test on unweathered samples, unweathered samples were generally not available, as the area of the waste rock pile available for investigation was several years old.

Two alternate static testing methods were also investigated on a limited number of samples: (i) B.C. Research Initial test; and, (ii) the NAG (Net Acid Generation) test. The ABA (acid:base accounting) test work was performed by BCRI. The test protocols and the results are provided in Appendix F (pages F-4 and F-5 and Tables F-2 to F-7).

The ABA parameters measured at BCRI were entered into the Whistle Mine database, and have been tabulated by location (i.e. borehole, test pit, Autopsy Zone) in Appendix G (Table G-4). In addition to the current data collected for this program, previous ABA data provided by INCO Ltd. (Appendix A) was also incorporated into the Whistle database.

The Whistle database was used to prepare the following data summaries and cross-tabulations to assist in our interpretation of the ABA parameters as indicated in Section 4.2.2.

- tabulation of the frequency of analyses with  $NNP < -20$ ,  $-20 < NNP < 20$ , and  $NNP > 20$ ;
- tabulation of the frequency of analyses with  $NP/AP < 1$ ,  $1 < NP/AP < 3$ ,  $NP/AP > 3$ ;
- cross-tabulation of NNP with NP/AP for the above three categories for each parameter (Table G-6a);
- cross-tabulation of NNP with NP/AP for the ABA data provided by INCO (Table G-6b);
- preparation of plots of NP/AP versus paste pH (Figure G-15); and
- calculation of NP from the carbonate (%  $CO_2$ ) analyses and comparison to NP determined using the modified Sobek method (Table G-8).



The interpretation of the ABA test work data is presented in Section 4.2.2.

### **3.2.3. Buffering Tests**

Buffering tests are important to determine which minerals provide buffering at specific pH intervals, (e.g. carbonates provide buffering at pH 5 to 8, while silicates buffer at pH 4 to 5, and ferric hydroxide buffers from pH 3.5 to 4.) These tests are particularly important since the Whistle waste rock contains very little carbonate buffering minerals; therefore, the long-term neutralization will be provided by the silicate minerals. Buffering tests provide a titration curve of NP versus pH, which is particularly useful for interpretation of seepage monitoring data and for future predictive/modelling work.

The buffering tests were performed by BCRI in conjunction with the static testing. The BC Research Initial Test method was modified to include successive titration end-points at pH values of 6.0, 5.0, 4.0, and 3.5; this provided information regarding NP versus pH interval. For additional information, the changes in pH during the NAG test were also recorded over the 24 hours of the test. The information from both test methods is provided in Appendix F (Tables F-4 and F-7), Appendix G (Figures G-16 and G-17), and is discussed in Section 4.2.3.

### **3.2.4. Kinetic Testing**

The Waste Rock Sampling Manual (MEND 4.5.1-1, 1994) describes several methods for kinetic testing to determine the rate of acid generation and contaminant release in waste rock, (e.g. Soxhlet reactors, stirred reactors, and stationary bed reactors). The stationary reactor configuration is typically preferred and includes: columns, humidity cells, and lysimeters. This project involved installation of three lysimeters in the test pits (see Section 3.1.3). Column test work was also selected to perform an examination of the waste rock under more controlled conditions in the laboratory. Figure 3.2-1 illustrates the column setup used.

The purpose of the column test was to examine the response of waste rock from the Whistle waste rock pile to rainfall. The column test work was performed by Lakefield Research, located in Peterborough, Ontario. The experiment was conducted in duplicate using nominally minus 51 mm (2" mesh) waste rock loaded into 660 mm diameter columns. The test was divided into two stages: Stage 1 from weeks 0 to 20; and Stage 2 from weeks 21 to 30. The stages were

separated by an interval of approximately six months (Appendix H).

Samples of waste rock for column study were selected on February 27, 1996. Several potential sampling locations on the waste pile were excavated by backhoe on this date. Two locations that were visually determined to be representative of the main rock type within the dump were chosen for collection of the material for the column test work. The waste rock at these two locations was mainly mafic norite with minor to moderate visible sulphide oxidation. Five 200 L drums were filled with minus 635 mm waste rock for the column tests, and two 20 L pails were filled with waste rock from each of the barrels for preparation of a representative sample for analysis. Further details on sample collection are provided in Appendix H.

The representative sample was analyzed for moisture content, particle size, ICAP-OES multi-element scan, total S, sulfide S, carbonate carbon, and graphitic carbon. Conductivity, paste pH, and fizz tests were conducted on five samples.

The column test procedure for the first twenty weeks of the column test (Stage 1) is outlined in Appendix H in a proposal dated February 14, 1996. In summary, a weekly schedule was followed which consisted of application of (pH 6.25) river water into the column for six hours on day 0 at a rate of five times typical rainfall. This was followed by pumping 3 days of dry air followed by 3 days of humid air in and out of the top of the column. Leachate was collected immediately prior to the next rainfall application. The leachate was analyzed for pH, conductivity sulphate, acidity, and ICP metals scan. At week 6, it was decided to switch to the use of acidified (pH 4.2) river water. After Week 6, leachate samples were analyzed biweekly, using combined weekly samples. The twenty week test was conducted from April 1, 1996 to August 19, 1996.

Following the twenty week test, the columns were flooded with pH 4.2 river water (identical to rain water used for weeks 6-20) for 24 hours and then drained. The leachate drainage rate, pH, conductivity and temperature were recorded and are presented in Appendix H. The columns were then loosely covered and left in a moist condition for approximately six months.

The second stage of the column test (Weeks 21-30) was conducted from October 24, 1996 to December 23, 1996. The method is outlined in Appendix H in a proposal dated October 9, 1996.

In summary, the columns were to receive pH 3.5 rainwater daily (for five days/week) at the same rate as in Stage 1 until the pH of the effluent became less than 4. Once this occurred, the operation of the columns would continue as in Stage 1. The pH of the effluent remained above 4, so daily rainwater application continued for five days/week until Week 26. During Week 23, the volume of rainwater applied each day was doubled. The last rainfall was applied on Week 26 (November 27, 1996). For the remainder of the test, leachate was collected from the columns, however no further rainwater was added. During Stage 2, leachate samples were analyzed daily (five days/week) for weight of leachate, pH and conductivity. Every third sample was also analyzed for metals (ICP).

The results of the kinetic test work are presented in Appendix H, and discussed in Section 4.2.4.

### **3.2.5. Washing Tests (Water Extraction Test)**

Washing tests provide an indication of possible porewater quality, keeping in mind that the extraction procedure re-suspends any precipitates and soluble products. The wash test (water extraction test) consists of mixing a 2:1 ratio of deionized water to solids and agitating for 30 minutes. After agitation the solids are allowed to settle and a sample is decanted and filtered for analysis (Appendix F). Other methods are available for direct extraction of porewater (e.g. press, suction), but these are not appropriate for hard rock with low moisture content and were not investigated for the Whistle waste rock.

The samples selected for extraction test work were generally those samples where low paste pH and high conductivity measurements indicated that a chemical analyses of the extractant solution would provide some measurable or noteworthy qualities. We also selected several samples with "intermediate" paste pH and conductivity measurements to provide an indication of possible water quality within less active or possibly non acid-generating areas of the pile.

Extraction tests can be carried out in the field or in the laboratory. The field is typically preferred as storage or transportation prior to extraction may affect the rock samples. It was our original intention to perform all of the field tests at the site; however, due to site-specific constraints (i.e. difficult access to the pile and test pits), it was more appropriate to perform the field tests at the facility selected for storage of the rock samples.

The *Handbook for Waste Rock Sampling Techniques* (MEND 4.5.1-2, 1994) recommends that chemical characterization be carried out on two subsets of samples, (i.e. whole rock and particles minus 2 mm diameter). In this case, the laboratory is more convenient for sample preparation, extraction, agitation, etc. The washing or extraction test work was performed in the laboratory at BCRI (see Appendix F for procedure).

The water extract was analyzed for pH, conductance, acidity, sulphate, and metals (ICP scan) (see Tables F-11 and F-14 in Appendix F). The analyses included use of blanks and reference materials (Table F-15, Appendix F) and duplicate analyses (Table F-16). The concentrations obtained from the washing tests are not porewater concentrations and have not been corrected to match the original water (moisture) content of the sample. This data has been entered into the Whistle database, and summary statistics are provided in Appendix G (Tables G-2 and G-3).

### **3.2.6. Weathering/Physical Stability Tests**

Weathering tests can be conducted to determine how the waste rock reacts to slaking and freezing. Several standard methods are available (e.g. ASTM C88-90). The MEND report *Caracteristiques physico-chimiques et Mecaniques Des Principales Unites Lithologiques a la Mine Doyon* (MEND, 1.14.2, 1995) describes several hardness tests (e.g. Los Angeles, Micro Deval and Magnesium Sulphate).

Weathering and physical stability tests were originally considered for the Whistle waste rock project, but these tests were not carried out, as it was decided that the kinetic test work should be extended instead. Some general comments on weathering are provided in Section 4.2.6.

### **3.2.7. Bacteria Sampling and Analysis**

Biological test work was carried out on several samples to determine the presence and activity of iron-oxidizing bacteria in the Whistle waste rock pile. This information is required to support future predictive modelling assessments.

Two samples from each of Test Pit 2, Test Pit 3, and the Autopsy Zone were collected for biological analysis during the field program. The sampling protocol used to obtain the biological samples was based on descriptions provided in the *Handbook for Waste Rock Sampling*

*Techniques*, (MEND 4.5.1-2, 1994) and is provided in Appendix C. The procedure followed was for sampling in the unsaturated zone. The sampling locations and the waste rock samples collected are described in Appendix I.

The laboratory work was carried out at the University of Waterloo, Department of Chemical Engineering. The test work involved examination of growth and activity of the biological population on three different energy sources (thiosulphate, ferrous sulphate, and solid pyrrhotite) at 30°C, and at two temperatures (30° C and 8° C) in the ferrous sulphate medium (see Appendix I). A total of 32 flasks were prepared for analysis, 24 flasks for various media, and eight duplicates.

Visual observations of the bacteria using a light microscope and phase-contrast microscope were used to make relative comparisons of growth and activity and morphological forms. The bacteria were not identified or enumerated. Gram staining techniques were used in an attempt to broadly characterize the bacteria. Detailed methodology is provided in Appendix I, and the results are discussed in Section 4.2.7.

### **3.3. FIELD MONITORING PROGRAM**

The field monitoring program was conducted from October, 1995 through December, 1996, and included monitoring of water quality (boreholes, seepage and lysimeters) temperature, oxygen/carbon dioxide, precipitation, water level and flow measurements. The field sampling program is outlined in Table 3.3-1 which summarizes the locations, frequency and types of analyses conducted. The solution samples collected were analyzed at either Barringer Laboratories, Mississauga, or Near North Laboratories, North Bay. The monitoring program results are discussed in Section 4.3. It should be noted that a hydrological and hydrogeological assessment of the site was previously completed by Golder Associates, (1994). Thus the field monitoring program focused on geochemical characterization of the waste rock pile.

#### **3.3.1. Meteorology and Infiltration**

The site is located approximately 18 km north of the Sudbury airport, thus meteorological records from the airport should give a good approximation of the conditions at the Whistle Mine

Site. Precipitation data was collected on site daily from August 30, 1995 to October 31, 1995 and weekly from January 5, 1996 to December 2, 1996. This data is compared to airport records and is discussed in the meteorologic assessment presented in Section 4.3.1. Estimates of infiltration are based on precipitation data and on seepage data. Meteorological measurements for infiltration estimates and other methods including lysimeter measurements and predictive modelling are suggested in MEND report 4.5.1-2 (1994).

### **3.3.2. Flow and Seepage Characterization**

At four locations a total of eight wells were installed through the waste rock into the overburden and bedrock, or into the base of the waste rock pile. These wells were sounded for water levels immediately after drilling, and the wells were dry in all instances. Initial recovery of the water in the wells occurred over a period of 1 to 2 days. Subsequent to drilling water levels were taken at variable intervals from 2 weeks to three months. Seepage estimates were developed based on the data collected.

Seepage from the Whistle Waste Rock pile is collected in the pond at the base of the pile (Figure 1.2-1). This water is then pumped from the pond to the Water Treatment Facility. The seepage collection area was pumped intermittently by the mine operator and an inline flow meter was installed. Pumping rates were recorded; however the pumping rates were only recorded at the inlet to the treatment plant. This location also included water pumped from the open pit. Unfortunately it is not possible (for the most part) to identify the component of pumped water originating from the seepage collection area as was the original intention. As a result it was not possible to gather detailed flow monitoring data coinciding with water quality sampling as suggested in MEND report 4.5.1-2 (1994). Some flow measurements are, however, available from Golder Associates, (1994) and have been used in conjunction with some flow measurements (collected from May 25 to June 17, 1996 where there was minimal pumping of mine water), meteorological data, lysimeter data and hydrogeological data to determine flow and seepage characteristics of the site (see Section 4.3.2).

#### **3.3.2.1. Site Water Balance**

The site water balance refers to the sum of the inflows to the site (in this case precipitation) in

relation to the outflow or losses (i.e. evaporation, seepage to groundwater flow system). The site water balance performed in 1993 was based on surface water flow measurements, meteorological data, and surface area estimations. This water balance was re-evaluated for this project using watershed areas, 1996 precipitation records and, climate normal evaporation and precipitation data from the Sudbury Area. The site water balance is presented in Section 5.4.3.

### **3.3.3. Water Quality Characterization**

#### **3.3.3.1. Seepage**

Sampling of the seepage water was conducted on October 5, 1995, May 8, 1996, August 22, 1996 and November 1, 1996. It was not possible to collect a seepage sample in January, 1996 due to excessive snow over top of the discharge point. Samples of water at the seepage discharge point (near the collection pond) were collected by filling a 60 cc syringe or 4 L bottle at the seepage discharge point. The water was then filtered and analyzed as described below. A discussion on water quality is presented in Section 4.3.3.

#### **3.3.3.2. Boreholes**

Samples of water were collected from the boreholes for water quality analysis on October 5, 1995, January 29, 1996, May 8, 1996, August 22, 1996 and November 1, 1996. BH-1B and BH-4B were dry and no samples were collected.

Prior to sample collection piezometers were developed by evacuating all of the water from the sample well using a Waterra foot valve attached to 9.5 mm diameter polyethylene tubing. Where possible 3 well volumes were evacuated prior to sampling. Samples of porewater were collected from each monitoring point using 9.5 mm diameter polyethylene tubing connected to a Waterra foot valve. For the first sampling event (November, 1995) samples were collected in 60 cc syringes and filtered using a 15 mm diameter syringe filter with 0.45  $\mu\text{m}$  cellulose acetate filter paper. In subsequent sampling events samples were collected in a 4 L container, and from there were filtered using a peristaltic pump with a 0.45  $\mu\text{m}$  high flow cellulose acetate filter connected to the outlet.

Measurements were made in the field, on filtered samples, to determine pH, Eh, conductivity, and alkalinity. Conductivity and temperature values were recorded at each site. Reported

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conductivity values were adjusted to 10° C. Groundwater temperatures were obtained from the sampled water. Where values for groundwater temperature were not obtained 10° C was assumed as an approximation of the groundwater temperature. Detailed protocols of field measurement techniques are provided in Appendix C.

Two filtered 100 mL groundwater samples were collected at each location. Samples for anion analysis were left unacidified whereas samples for cation analysis were acidified using about 2 mL of 50 %, 12N nitric acid. Field blanks and/or duplicate samples were collected for each sampling event. Approximately 1 sample in 10 was a duplicate or field blank. The samples were kept in a cooler, or refrigerated and were shipped to the analytical labs within 2 days of sample collection. Turnaround time for the analytical lab results ranged from 2 to 4 weeks.

#### **3.3.3.3. *Lysimeters***

Initially some water was present in the lysimeters as a precipitation event occurred between lysimeter construction and back-filling (the contractor was unavailable to back-fill the pits when originally scheduled). No field analysis was conducted on this water, however unfiltered water samples were collected for analysis. This initial water was drained using a Waterra pump. The lysimeter sampling ports were capped to prevent oxygen migration into the lysimeter collection pipe. Any residual oxygen in the collection pipe was initially displaced using nitrogen to prevent oxidation of the leachate collected within the collector pipe.

Monitoring of the lysimeters for recharge and water quality was conducted on October 5, 1995, May 8, 1996, August 22, 1996 and November 1, 1996. Lysimeters were not sampled during the January 1996 sample event due to accessibility difficulties and low temperatures. Water was removed from the lysimeters using a peristaltic pump attached to 6 mm diameter polyethylene tubing. The volume of water removed was measured. Field analysis was conducted and samples were collected and filtered following the procedures indicated above.

#### **3.3.4. Gas Sampling**

Gas sampling ports are distributed in the boreholes as indicated in the Record of Borehole Logs (Appendix D). Gas sampling was conducted in the field using a Lantec GA90 portable combination gaseous oxygen, carbon dioxide meter for most sampling events. This device uses



non-dispersive infrared spectroscopy to analyze for these gases, and has an internal pump which pumps at a rate of 250 cc/min. During the February, 1996 sampling event, samples were analyzed in the field using a Nova model 305LBD combination gaseous oxygen, carbon dioxide meter. Due to equipment problems and cold weather, not all boreholes were sampled for gas concentrations during the February 1996 sampling.

Initially, during the October 1995 gas sampling event, the sample locations were only pumped for approximately 90 seconds due to the short battery life of the meter. It was later determined that this sample duration is not sufficient to obtain representative samples of gas content as the approximate sphere of influence at the end of the gas sample tube (based on 90 second sample interval) is less than 10 centimetres. Based on an 0.10 m sandpack radius, and a 30 m length of 0.06 m dia. gas sample tubing it was determined that 6.5 L of gas had to be removed from the sample port to obtain a representative reading of the waste rock gas concentrations. A peristaltic pump hooked to the gas port removed the gas at a rate of about 0.75 L/min, thus the peristaltic pump was hooked up to the port for 10 minutes before any readings were taken, at which time the outlet of the peristaltic pump was connected to the meter using Tygon tubing, and readings of % gaseous oxygen and gaseous carbon dioxide were taken every minute for 4 to 8 minutes. At some locations gas was pumped from the sample tube, and readings were recorded for a longer duration (up to 40 minutes).

Duplicate gas samples were collected at 4 borehole locations (BH-95-1 16 m, BH95-2 8 m, BH95-3 #3, and BH95-4 16 m) during the August 23, 1996 sampling event. One sample of ambient atmospheric gas was also collected on surface at BH95-4 (BH95-4B). The gas was collected by inverting a glass bottle full of distilled water in a water bath and allowing bubbled gas to displace the water in the bottle. When the bottle was half full of gas it was capped and stored upside down until analyzed. The gas was analyzed by the University of Waterloo, using a gas chromatograph. The results of the gas analysis are presented in Section 4.3.4.

### **3.3.5. Temperature Measurements**

Thermistors are distributed from 0 m to 30 m depth in the pile as indicated in the Record of Borehole Logs (Appendix D). Thermister distribution was determined based on recommendations in MEND report 4.5.1-2 (1994). In general the thermistors were placed to

coincide with the gas sampling ports. Temperature measurements were taken by attaching a hand held resistivity meter (MICRONTA LCD Multi Meter Model #22-166A) to the leads from the thermistors. The resistivity was recorded and converted to temperatures using the formula given in Appendix C.

Temperature measurements were taken weekly over the duration of the monitoring program and results are presented in Section 4.3.5.

## **4. RESULTS**

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As a consequence of the large, complex nature of the study it is very difficult to present the results and overall interpretation in one coherent section of the report. This section provides the detailed results of the individual study programs. Section 5.0 presents an assessment of these results and incorporation of the results into a large scale overview of the waste rock pile and overall site.

### **4.1. PHYSICAL CHARACTERIZATION**

#### **4.1.1. Geological Characterization**

The heterogeneous nature of the waste rock dump is illustrated in the photographs of the waste rock dump, test pits and Autopsy Zone (e.g. Plate 1.2-1, Plates 4.1-1 though 4.1-6). Individual truck loads of waste rock, and distinct zones of highly oxidized waste rock, norite, felsic norite and granite are present on surface, in the test pits and Autopsy Zone. It is inferred that the entire dump is composed of variable rock types in this fashion, although the relative percentage of each rock type likely changes with depth, depending on the type of material being excavated as development of the pit progressed. For example, the prominence of felsic norite in some photos is not representative of the dump as a whole, as only minor amounts of felsic norite were excavated in the early stages of mining. Layers of finer material were observed in the Autopsy Zone and test pits. These layers were thought to be working levels for previous dumping operations.

##### **4.1.1.1. Test Pits**

Figures 4.1-1, 4.1-2, and 4.1-3 comprise sketches of Test Pits 1, 2 and 3, respectively. The figures show the geology of the test pits, and the locations where the samples described in the logs were taken. Plate 4.1-2 is a view of Test Pit 1 and the sampling locations for the main (A) sample series are visible as steps in the centre of the photo. Plate 4.1-3 shows the variation in rock types found within Test Pit 2. Plate 4.1-4 illustrates Test Pit 3, which provides a good representation of the interior of the pile. These photos illustrate the sand layer laid down

between lifts, the variations in rock types that occur, the sharp boundaries between the units, and the abundance of fine material within the dump. Samples were collected from the test pits. These samples are described in Appendix D. Visual observations of the test pits are provided on Figures 4.1-1 to 4.1-3.

Assessment of waste rock characteristics was also aided through investigation of the Whistle Wildcat Gossan, and the Autopsy Zone.

#### ***4.1.1.2. Whistle Wildcat***

The Whistle Wildcat is a series of heavily weathered sulphide-bearing outcrops immediately southeast of the Whistle Mine. These areas were examined and sampled as they were assumed to be most representative of the 50,000 tonnes of gossan buried at the bottom of the northeast waste rock pile, which was taken from the Whistle Mine in preparation for production. A log describing four samples collected at the Whistle Wildcat, along with field test results, is presented in Appendix D.

#### ***4.1.1.3. Autopsy Zone***

The waste rock of the Autopsy Zone is more representative of the interior of the pile than other areas on the top or other sides of the pile (see Plate 4.1-5 and Plate 4.1-6). The rock is considered more representative because all grain sizes from fine sand to large boulders are present. This is similar to the conditions encountered in the test pits. In contrast, the side slopes elsewhere are preferentially composed largely of boulders due to segregation resulting from the end dumping construction method.

Twenty (20) samples were collected from the Autopsy Zone. Descriptions of these samples, along with the results of field tests (i.e. conductivity, paste pH and fizz tests) are presented in Appendix D and discussed on Section 4.2.

#### ***4.1.1.4. Field Definitions - Whistle Waste Rock Types***

The classifications described below are based on observations made during site visits and conversations with Bill Dyck (Chief Mine Geologist, Frood Mine, INCO). The percentage estimates are based on visual estimates by volume. No carbonate was detected in most of the

samples with the exception of the Mafic Norite, which typically contained less than 1% carbonate in fine veins.

The following five field classifications were established and are listed in order of overall abundance:

- (i) Mafic Norite
    - dark gray-black
    - fine-grained
    - variable composition - ~60% mafic minerals
      - ~20-30% feldspar
      - fine (mm-scale) white calcite veining is fairly common, rock preferentially fractures on these veins
      - highly variable sulphide content (2-20% pyrrhotite with pentlandite)
    - transitional to ore, based on sulphide content
    - ranges from a fresh appearance to heavily oxidized
    - often contains mafic inclusions
    - often heavily weathered
  - (ii) Granitoid, Granite
    - pink, with or without dark (mafic) veining
    - coarse grained
    - composition
      - quartz (variable %)
      - feldspar (variable %)
      - mafic mineral content is variable as numerous mafic dikes cut the granitoid on both a fine and a large scale. (The granitoid is sometimes described as a breccia with a mafic matrix.)
      - sulphide content usually low (<1%) but is quite variable and is distinct from other rock types as chalcopyrite veining can occur in this unit.
  - (iii) Felsic Norite
    - massive
    - white and black on fresh surfaces
    - light rust colour on some weathered surfaces
    - homogeneous
    - medium grained
    - composition
      - ~50% feldspar
      - ~30% mafic minerals
      - less than 1% sulphide, usually as fine isolated blebs of pyrrhotite
    - typically large (greater than 50 cm) competent blocks
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- (iv) Gossan or Heavily Oxidized Waste Rock
  - bright orange with local purple iron stain and some white gypsum stain
  - a sub-category of ore, or mafic norite (depending on original sulphide content)
  - very heavily oxidized, weathered
  - very friable, crumbles into gravel, sand and finer fragments
  - fragments are often weakly cemented together
  
- (v) Ore
  - greater than 20% sulphide minerals (mainly pyrrhotite containing pentlandite)
  - may contain close to 100% sulphide
  - remainder of rock is fine-grained mafic material
  - inclusions of fine-grained mafic material containing sulphides are common
  - ranges from almost fresh to very heavily oxidized

The gossan material is heavily weathered sulphide-bearing rock that comprised the surface and near-surface portion of the Whistle mineralized zone and the Whistle Wildcat Zone. Approximately 60% of this material was an oxide cap that has been weathering since the last glaciation approximately 10,000 years ago, while the remaining 40% has been weathering since exploration and development activities in the early 1900s left the near-surface portion of the deposit fractured and exposed, allowing the sulphide surfaces to oxidize. The Whistle gossan was not processed as ore because the oxidized material is not compatible with the INCO mill process.

When the origin of an oxidized rock sample is known to be either the original near-surface zone of the Whistle deposit or the Whistle Wildcat, the sample is referred to as a gossan. When the origin of an oxidized sample is uncertain, it is referred to as highly or strongly oxidized waste rock.

Additional details regarding the petrography and mineralogy of the rock types are discussed below.

#### **4.1.1.5. Mineralogy/Petrography**

The X-ray diffraction results are presented as an addendum to the BC Research lab report in Appendix F, and consist of a diffractogram and a written summary estimating the mineralogical composition for each sample. The composition varied from sample to sample; however, the samples typically consisted of the following minerals, (listed in their relative order of

abundance): quartz, plagioclase feldspar, amphibole, pyroxene, pyrrhotite, pyrite, clay minerals, mica, chlorite, and magnetite. In one sample (TP3-A3) gypsum may be present. One sample (RC-A5) was found to be comprised of goethite and quartz. The goethite and gypsum are secondary minerals formed by oxidation of the waste rock. In addition to these two secondary minerals, limonite staining was commonly observed.

Descriptions of the primary mineralogy and petrology of the Whistle mine area are available from OGS Special Volume 1, The Geology and Ore Deposits of the Sudbury Structure, (1984); Geochemical Relationships between the Sublayer Inclusions, Offsets and Main Mass of the Sudbury Igneous Complex (Lightfoot et al., in preparation); and Geochemistry of the main mass, sub layer, offsets and inclusions from the Sudbury Igneous Complex (Lightfoot et al. 1997).

Based on this data and other unpublished information supplied by Bill Dyck (INCO), descriptions of the field classifications have been expanded as presented below (and are listed in order of relative abundance in the pile):

(i) Mafic Norite

- much more heterogeneous than felsic norite
- up to 50% of the rock mass consists of various mafic inclusions, ranging from 1 cm to 10 m in size, and often rimmed by sulphide
- the matrix is typically dominantly non-poikilitic textured norite with a composition of approximately:
  - 40% - 60% pyroxene, mainly orthopyroxene (hypersthene)
  - remainder mainly plagioclase feldspar
  - variable content of disseminated, blebby, and heavily disseminated sulphides, 5-100 cm-sized pods of more massive sulphide, and rare stringers and veinlets
- the mafic inclusion types are listed below from most common to least common:
  - poikilitic-textured orthopyroxene melanorite inclusions or pods
  - olivine melanorite inclusions
  - diabase inclusions
  - rare altered anorthositic, troctolitic and gabbroic inclusions
- the inclusions are high Mg rocks which contain up to 10-15% biotite. When hosted in sulphide-rich zones, the biotite in the inclusions is partially altered to chlorite and the olivine to serpentine

(ii) Granitoid

- dominantly pink, porphyritic
- some pegmatite and aplite phases also occur
- sometimes contains massive chalcopyrite and irregular chalcopyrite blebs, with little pyrrhotite/pentlandite

- described as quartz monzonite by Lightfoot. A typical quartz monzonite mineralogy is as follows:
    - ~5-20% quartz
    - ~35% K-feldspar
    - ~35% plagioclase feldspar
    - ~10+% mafic minerals, usually biotite and hornblende
- (iii) Felsic Norite
- medium grained
  - relatively homogeneous
  - subhedral granular texture
  - mineralogy:
    - ~50% cumulus plagioclase feldspar
    - ~30% pyroxene, mainly clinopyroxene (augite)
    - ~20% quartz-feldspar micrographic intergrowth
    - up to 5% disseminated pyrrhotite containing pentlandite, usually less than 1%
- (iv) Massive Sulphide (Ore)
- dominantly pyrrhotite-rich massive sulphides with mafic inclusions
  - sulphide content varies from 20% to 100% with no sharp transition from ore to other rock types
  - pyrrhotite contains nickel as pentlandite, nickel is evenly distributed throughout pyrrhotite at a ratio of pyrrhotite:nickel of ~23:1
  - inclusions consist of altered, rounded fragments of: pyroxenite, melanorite, diabase, and non-poikilitic to poikilitic sulphide-mineralized norite
  - up to 5% of the sulphide is 1 mm to 10 mm equant pyrite porphyroblasts
  - ore typically grades 1% Ni, and 0.33% Cu, cut-off grade is 0.5% Ni
  - ore is generally poor in Cu compared to other Sudbury deposits
  - ratio of Ni:Cu in massive sulphides devoid of inclusions can be very low at 50-60:1

Further information on primary mineralogy can be found in Lightfoot et al. (1997). Specific information of interest includes:

- a detailed description of the geology of the Whistle Embayment (the area that hosts the deposit) along with maps showing the geology;
- a table of rock types which describes mineralogy, texture, and field associations;
- 14 plates illustrating hand samples and thin sections from the Whistle mine.

The OGS report only addresses “primary” or in-situ mineralization, and does not address “secondary” mineralization (oxidation products). Secondary mineralization was to be characterized by the XRD work. The XRD work performed identified secondary mineral phases gypsum and goethite, however a more detailed mineralogical study would certainly have been more beneficial. Budgetary constraints did not allow for alternative mineralogical tests for



secondary mineralization. Other testing which would be useful in determining secondary mineralogy includes petrographic analysis of thin sections of oxidized waste rock.

#### ***4.1.1.6. Composition of Northeast Dump***

The composition of the northeast waste rock pile by rock type could not be characterized through the drilling program, mainly due to the poor sample return. In the case of this waste rock pile, the best source of data on the dump composition was INCO Geologist Bill Dyck, as he has been observing the geology and mining operations over the entire life of the open pit. Table 4.1-1 provides a rough estimate of dump composition as of September 1995, derived from discussions with Bill Dyck and from observations made during the site investigations.

In addition to waste rock, the dump contains a small quantity of sand used for roadway construction, which was primarily taken from the borrow pit located northwest of the mine. The quantity of sand in the dump is estimated at 50,000 tonnes. The dump also contains minor amounts of overburden/soil excavated during pit development, and also some demolition concrete.

The northwest dump was not studied as part of this project; however, it is estimated to contain 450,000 tonnes of waste rock, consisting of 80% granitoid and 20% mafic norite. INCO supplied ABA analyses of this granitic material which are presented in Appendix A (Table A-2).

#### ***4.1.1.7. Waste Dump Construction***

The dump construction method used by both the present contractor (who has been operating the dump since the mine reopened in November 1994), and the former contractor (who operated the dump from 1988-1991) is a combination of horizontal lifts approximately 1.5 m high, and end dumping off the edges of the pile, as illustrated in Plate 4.1-1. Waste rock is brought to the dump in truckloads of approximately 20 tonnes. Trucks can be collecting waste from different areas of the pit simultaneously, so adjacent truck loads of waste rock often are of an entirely different rock type. The loads are dumped in piles and subsequently leveled by a bulldozer to provide a flat surface for the next lift. The former contractor used significantly more imported sand to construct roadways and dumping areas than the present contractor. These sand layers are visible in the test pits and Autopsy Zone.

In general, there has been no systematic segregation of different rock types to different areas, with the following exceptions:

- granitoid waste rock was concentrated in the Northwest dump, as previously noted; and
- most of the gossan excavated prior to mining (from above the present open pit ore zone) was placed at the bottom of the Northeast pile.

Ongoing expansion of the pit has resulted in placement of heavily oxidized rock throughout the top and side slopes of the dump, and likely throughout the entire waste rock pile.

#### **4.1.2. Particle Size**

It is important to determine particle size distribution of the waste rock pile, as particle size directly affects surface area, and surface area affects oxidation rates and acid production. It should also be noted that particle size also affects the rate of oxygen migration into the pile and as a result the availability of oxygen for oxidation within the pile (Otwinowski, 1997). Otwinowski's work suggests that particle size may be of more importance than previously thought in the generation of acid mine drainage. For further discussion on the effects of particle size on acid generation the reader is referred to Otwinowski (1997).

A visual assessment of the rock particles that formed the sides of the three test pits at the Whistle Mine site showed a layering in the particle sizes within each lift. A high proportion of very coarse material near the surface of each lift is underlain by a progressively finer material. On top of some lifts, a 10 cm to 30 cm layer of sand-sized waste rock (and sometimes imported sand) was observed. Based on the particle size distribution as estimated by *GoldSize* approximately 7.2% of the test pit material is minus 100 mm in diameter, and 69% of the material is minus 500 mm in diameter. It should be noted that the *GoldSize* particle size assessment system uses a fines correction technique. The fines correction is designed to adjust the particle size distribution for the small size particles that cannot be identified in the photographs. It does this by converting the size distribution to the Rosin-Ramler scale which then redistributes the material so the size distribution is linear. Published studies have shown that blasted material usually produces a size distribution that is linear on the Rosin-Ramler plot. This correction is conservative and probably underestimates the amount of fines material. The particle size distribution and the difference between the uncorrected and fines corrected size distributions for

the material is shown in Figure 4.1-4. Complete details of the *GoldSize* particle size assessment system are provided in Appendix E.

As additional fine material may have been added to the pile (i.e. sand for roadways) sieve analysis was conducted to supplement the *GoldSize* analysis and assist in the determination of the fine fraction of particles.

Sieve analysis was conducted on 3 samples of minus 100 mm material collected from the test pits (Appendix E). Approximately 25 to 35% of the minus 100 mm material collected from the test pits is sand sized (minus 2 mm). When the entire size distribution of material is taken into account the minus 2 mm fraction accounts for about 1.8 to 2.5% of the total volume of the pile (this assumes that the minus 100 mm material represents approximately 7.2% of the total material as determined in the *GoldSize* analysis).

#### **4.2. CHEMICAL CHARACTERIZATION**

The laboratory analyses data from BCRI was provided in electronic format, and a database was developed for the Whistle waste rock pile to facilitate preparation of data summaries and interpretation of the data. The data summaries provided in Appendix G are discussed below in each section. Additional interpretation of the overall dataset is provided in Chapter 5.0.

The field data (e.g. paste pH, conductivity and fizz tests) have also been entered into the Whistle database, and summary tables are provided in Appendix G (Tables G-7, G-9 and G-10). As expected, the samples from the more exposed areas and the surface of the pile (e.g. the gossan, Autopsy Zone, and test pits) showed lower average paste pH and higher average conductivity than the samples from the interior (i.e. the boreholes).

The reaction of the waste rock sample to HCl applied in the “fizz” test was recorded as indicated in Section 3.2. A summary of fizz test results by location, and a cross-tabulation of fizz test rating with the carbonate (% CO<sub>2</sub>) content of the waste rock is provided in Appendix G (Figure G-11). The fizz test is used to determine the presence of carbonate minerals in a rock sample and can be used to distinguish between carbonate minerals. Calcite fizzes vigorously when cold 10% HCl is added, while dolomite fizzes only when powdered, or when warm acid is

applied. Siderite fizzes only very slightly in room temperature HCl, but will fizz when heated acid is applied. The fizz test protocol is provided in Appendix C.

Most of the waste rock samples (82 out of 117, i.e. 70%) showed no fizz which suggests that little or no carbonate (as calcite) is present. The summary of fizz test results by location shows that Boreholes 1, 2 and 3, and Test Pit 1 had no fizz, while Borehole 4, Test Pits 2 and 3, and the Autopsy Zone had none to moderate fizz. The cross-tabulation of fizz test results with the measured carbonate content shows excellent agreement; therefore we can conclude that the fizz tests were applied correctly and consistently.

#### **4.2.1. Chemical / Elemental Analyses**

The chemical/elemental and whole rock analyses data were tabulated by location (i.e. Autopsy Zone, test pit, borehole) and by size fraction (i.e. minus 2 mm, whole rock) in Appendix G (Table G-4). Statistical comparisons were not performed as part of this project, but would be useful to support future predictive/modelling studies.

The levels of most analytes appear to be similar for the four boreholes, the three test pits and the Autopsy Zone while the samples of ore and gossan material (Whistle Wildcat) are obviously different from the samples of waste rock.

Histogram plots of the solids analyses of the waste rock have been prepared to illustrate the frequency distribution of selected analytes and specific metals within the pile, as shown in Appendix G (Figures G-1 to G-11). The analyses for the gossan (Whistle Wildcat) and the ore sample were not included in the histogram plots. The analytes selected for the histogram plots include the paste pH and the metals noted to be at higher levels in the waste rock pile seepage: aluminum; cobalt; copper; iron; magnesium; manganese; nickel; sulphate; sulphide; and zinc. The histogram plots have been prepared using solid and shaded bars to illustrate the frequency distribution for whole rock, in comparison to that measured for the fine fraction (particle minus 2 mm). Several statistical parameters (e.g. minimum, mean, maximum, median, etc.) were calculated and are summarized on the plots; curves for the normal and log normal distribution are also shown on the plots.

A review of the histogram plots (Figures G-1 to G-10) shows that the distribution of metals in

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the fine fraction is similar to that for the whole rock fraction; however, the sulphate levels are considerably higher in the fine fraction. Most of the analytes appear to be log normally distributed. The analytes that appear to be normally (as opposed to log normally) distributed include: aluminum, magnesium, and manganese.

A histogram plot was also prepared for the paste pH measurements made in the laboratory in association with the static testing (Figure G-11). This plot shows two sets of peaks centred at pH 5 and at pH 7. This apparent bimodal distribution is likely reflective of the different types of buffering minerals present in the pile. Ferric hydroxide provides buffering from pH 3.5 to pH 4, aluminosilicates can provide buffering in the pH range of 4 to 5, and carbonates can provide buffering from pH 5 to pH 8. It should be noted that the laboratory paste pH measurement is carried out on crushed samples and therefore tends to slightly overestimate the porewater pH of the waste rock sample.

#### **4.2.2. Static (Acid:Base Accounting) Results**

The Sobek method (i.e. U.S.EPA method) is the most common and reliable static test for determination of NP (Neutralization Potential) (MEND 4.5.1-2, 1994). The conditions of the Sobek test (i.e. hot acid digestion) should also measure some of the buffering available from non-carbonate minerals (e.g. silicates). For this project a modified Sobek test was used. The modification involved the addition of hydrogen peroxide to eliminate the effects of siderite on the NP estimate. The chemical analysis for sulphide provides estimates of AP (Acid Potential). The difference between the NP and AP estimates provides an indication of the potential for the sample to generate net acidity, and is referred to as acid:base accounting (ABA).

The 45 samples of Whistle waste rock analyzed by INCO prior to 1993 most likely used the Sobek method. These samples had an average AP (Acid Potential) of 69 kg CaCO<sub>3</sub> per tonne, and an average NP (Neutralization Potential) of 49 kg CaCO<sub>3</sub> per tonne. The average NNP (Net Neutralization Potential, NNP=NP-AP) was - 20 kg CaCO<sub>3</sub> per tonne; and the median NNP was 10 kg CaCO<sub>3</sub> per tonne (see summary Table A-1 provided in Appendix A). Based on the standard conventions described in the *Waste Rock Sampling Manual* (MEND 4.5.1-1, 1994), these NNP values indicate the samples were borderline with respect to acid generation potential, but were most likely acid generating.

For the current program, the ABA testing showed that 11 of the 87 samples (13%) had negative NP (based on the Sobek method modified by the addition of hydrogen peroxide), which indicates the presence of acidity in the original sample. Most of these samples also had low paste pH. Only 9 of the 87 samples (10%) had positive NNP (net neutralization potential), and most of these had low sulphide content. These results indicate that the majority of the waste rock samples are probably acid generating (see Appendix F, Table F-2).

The average MPA (maximum potential acidity, based on total sulphur analyses) calculated for each waste rock sampling location in the data base ranges from 57.5 to 103.3 kg CaCO<sub>3</sub> per tonne (see Table G-4, p. 21 in Appendix G). The ore sample had the highest MPA at 869 kg CaCO<sub>3</sub> per tonne, and the Whistle Wildcat gossan, had the lowest (average MPA of 30 kg CaCO<sub>3</sub> per tonne).

The average NP values for the boreholes, test pits and the Autopsy Zone are presented in Appendix G (Table G-4). The NP values (excluding ore and gossan) range from 9.9 to 23.6 kg CaCO<sub>3</sub> per tonne. Both the ore sample and the gossan samples show negative NP (i.e. contain acidity). The average and the median NNP values are negative for all sampling locations (Table G-4).

The criteria of NP/AP <1 and NNP <-20 are commonly applied to classify waste rock as potentially acid generating; the criteria at 1 < NP/AP < 3 and -20 < NNP < 20 is applied to classify waste rock as uncertain with respect to acid generation potential; and the criteria of NP/AP > 3 and NNP > 20 is applied to classify waste rock as non-acid generating (see MEND 4.5.1-1, 1994).

Results of the NNP measurements for data collected in the current study (Table G-6a) showed that most (60 out of 88, or 68%) of the waste rock samples would be classified as acid generating according to NNP < -20; the remainder of the samples (27 out of 88, or 31%) would be considered to be uncertain with respect to acid generation potential (i.e. -20 < NNP < 20); and, only 1% (1 out of 88 samples) was non-acid generating (NNP > 20).

Results of the NP/AP ratio calculated for data collected in this study (Table G-6a) suggests even more of the samples (79 out of 88, or 90%) would be acid generating according to NP/AP < 1; the remainder of the samples were either uncertain (5 out of 88 or 6%) according to 1 < NP/AP < 3; or,

non-acid generating (4 out of 88, or 4%) according to  $NP/AP > 3$ .

This result suggests that application of the NP/AP ratio provides a more conservative estimate of acid generating conditions, since a higher percentage of the samples were classified as acid generating according to NP/AP.

The cross-tabulation of NNP with NP/AP (Table G-6a) showed: 100% of the samples classified as acid generating according to  $NNP < -20$  were also acid generating according to  $NP/AP < 1$ , but 70% of the samples considered to be uncertain ( $-20 < NNP < 20$ ) would actually be considered to be acid generating according to  $NP/AP < 1$ .

A cross-tabulation of NNP with NP/AP ratio was also prepared for the ABA data provided by INCO (1990 data). The INCO summary (Table G-6b) shows very different results from those obtained for the current set of ABA analyses. The differences could be due to different ABA methods (Sobek versus Sobek modified by the addition of hydrogen peroxide) or due to different rocks being sampled, or due to a combination of these factors. Only 42% (19 out of 45 samples) would be acid generating according to  $NP/AP < 1$ , while 20% (9 out of 45) would be considered acid generating according to  $NNP < -20$ . A much larger proportion of the INCO samples approximately 38% according to  $1 < NP/AP < 3$  (17 out of 45 samples), and 51% according to  $-20 < NNP < 20$  (23 out of 45 samples) would be classified as uncertain with respect to acid generation potential. Approximately 20% of the samples (19 out of 45) would be considered non-acid generating according to  $NP/AP > 3$ , while 29% (13 out of 45) would be considered non-acid generating according to  $NNP > 20$ .

Plots of NP/AP ratio versus paste pH have been found to be very useful for illustrating the proportion of potentially acid generating samples (i.e.  $NP/AP < 1$ ) that are already acidic (e.g. paste pH  $< 5$ ). The plot of NP/AP versus paste pH for the current set of ABA analyses (Figure G-15) shows most of the NP/AP ratios are very low, but only a small proportion of the samples are currently acidic. Most of the acid generating and/or acidic samples are from the Whistle Wildcat gossan. Some non-acid generating and alkaline samples were collected from the test pits.

The paste pH measurements made on the field samples, and in the laboratory in association with

the static test work have been summarized according to pH interval (Table G-7). The summaries show that 27% of the (88) samples subjected to ABA test work were acidic (paste pH<5); while, 43% of the (125) field samples were noted as being acidic (pH<5). Therefore, it is likely that a higher proportion of the waste rock, particularly the fines fraction, is currently more acidic than indicated from Figure G-15 in Appendix G.

An alternate estimate of the NP can be calculated directly from the carbonate (% CO<sub>2</sub>) analyses. Calculated NP estimates have been compared with NP determined in the laboratory program using the modified Sobek method in Appendix G (see Table G-8). In general, the calculated NP is at least 50% less than the laboratory NP, which indicates that the NP determined by the laboratory method includes buffering provided by other minerals in addition to carbonate and/or that the CO<sub>2</sub> analysis did not detect all of the dolomite and siderite present. There are several (22 of 88 or 25%) exceptions where the calculated (% CO<sub>2</sub>) NP is greater than the laboratory NP; most of these samples (11 out of the 22) contained some initial acidity as indicated by negative NP from laboratory method.

#### ***4.2.2.1. Alternate Static Tests***

Two alternate static tests were investigated in the laboratory test work: the B.C. Research Initial test, and the Net Acid Generation (NAG) test. Both tests also provided additional information about buffering (see Section 4.2.3).

The ABA test work results (Appendix F, Table F-3) show there is general agreement between the modified Sobek and BCRI NP tests for the reference material, the borehole samples, the Autopsy Zone, and one of the test pit samples. However, for sample TP3-A1, the modified Sobek test provided a negative NP (-10.3 kg CaCO<sub>3</sub> per tonne) which indicates there was acidity present in this sample, but the BC Research Initial test showed positive NP of 13 kg CaCO<sub>3</sub> per tonne. The negative NP determination is consistent with the field observations for this sample (see sample logs in Appendix D). The QA/QC for the modified Sobek method has been adequately demonstrated (Table F-5); therefore, the difference in the two NP determinations may be related to the different acid digestion and different final pH conditions of the two tests. The BC Research Initial test stops at pH 3.5, and this terminal pH condition may not allow for complete dissolution of all potentially acid generating material.



The NAG test provided the net acid generation (in units of kg CaCO<sub>3</sub> equivalent/t, without showing the negative sign) and pH over time. The NAG results shown in Appendix F, Table F-3 are compared to the Modified Sobek NNP results in Appendix F, Figure F-1. As can be seen from Figure F-1, there is a good correlation between the NAG and the Modified Sobek NNP; The correlation coefficient is 0.97. The NNP results, however, are more than 5 times greater than that of the NAG results. The reason for this is most likely due to incomplete sulphide oxidation in the NAG test. The final NAG pH results (at 24 hours, shown in Table F-3) also correlate well with the Modified Sobek NNP results (Figure F-2).

One of the benefits of the static NAG test (where only the net acid generation is measured) is that it is simpler and faster than standard acid:base accounting, and therefore more suitable for uses such as ongoing classification of mine waste as mining progresses. Based on the correlation's discussed above, the NAG test could be suitable for such a purpose at the Whistle Mine, even though the NNP values of the tests do not coincide, which was the expected test result. Further comparison using samples with less extreme negative values of NNP, and positive NNP, is recommended to confirm this conclusion.

#### **4.2.3. Buffering Tests**

The buffering test results obtained from the modified BC Research Initial test (Table F-7) show that for the neutral samples from Borehole 4, a moderate amount of NP was being provided over each pH interval. This indicates that there are several minerals providing buffering in these samples. However, most (i.e. over 50%) of the NP was provided between pH 4 and pH 3.5 suggesting possible ferric hydroxide buffering. The samples from the test pits and the Autopsy Zone were slightly acidic, but still contained some NP over the interval from pH 5 to pH 4, and additional NP from pH 4 to pH 3.5.

The buffering information from the NAG test is depicted as a plot of pH versus time in Appendix G (Figures G-16 and G-17). The test pit and the Autopsy Zone samples were initially acidic (pH 2.5 to 3.5) and most of the NP was consumed within the first 2 hours of the NAG test. The borehole samples were initially neutral and the pH versus time plots for the NAG test illustrate the different levels of buffering provided over the duration of the test. The buffering provided from pH 2.5 to pH 6 was exhausted relatively quickly for sample BH4 (56-59), (in

under 2.5 hours); however, around 10 hours were required to consume the buffering to pH 3 that was present in sample BH4 (27-28).

#### **4.2.4. Kinetic Testing**

The kinetic column test work on the samples of Whistle waste rock was performed under unsaturated conditions for 20 weeks. The analyses results are presented as concentration profiles in Appendix H (Figure H-1). The pH of the rain (infiltration water) was initially neutral at 6.25; this was reduced to pH 4.2 at Week 6. The samples collected over the 20 weeks remained neutral and contained alkalinity. Delays in onset of acid generation observed in the kinetic testing compared to what one would expect given the static test results may be the result of the strong acid leach which is used in the static tests. The kinetic tests do not use a strong acid leach. In the kinetic testing the sulphate levels remained essentially constant, which indicated that sulphide oxidation was taking place as opposed to flushing of the sulphate. The levels of most metals remained low, due to neutral pH; however, the nickel concentration increased gradually over the duration of the test.

Nickel concentrations increased relative to other metals because pyrrhotite containing pentlandite (an iron-nickel sulphide) was likely oxidized, releasing nickel. The leachate was then neutralized to pH 7-8, most likely by carbonate minerals. This precipitated most metals, or prevented their subsequent leaching by acidic solutions. Nickel was not precipitated as effectively since more alkaline conditions are required to effectively precipitate it.

The data collected from operation of the columns has been used to prepare estimates of the leachable fractions of sulphate and metals in the waste rock material. The method applied and the estimates obtained are discussed in Section 5.4.5.

Ideally the test work should have proceeded uninterrupted for a longer period of time, however budgetary constraints resulted in some changes in the program as described below.

After 20 weeks, the waste rock appeared to contain sufficient neutralization potential to maintain neutral seepage for a very long time, possibly another year; therefore, the results suggested that the operation of the columns should be discontinued. An alternative close-out procedure was selected for the columns, which involved flooding the waste rock in the columns with pH 4.2

river water for a period of 24 hours. The columns were then allowed to drain and the flow rate, pH and conductivity were noted at regular intervals over the following week (see laboratory notes provided in Appendix H). The effluent remained neutral and the conductivity was essentially constant, which confirmed our previous interpretation that there was considerable neutralization potential remaining in the waste rock.

It was hoped that the samples collected following the flooding and draining of the columns would provide an additional estimate of the total inventories of releasable sulphate, nickel and other constituents that were residing within the waste rock in the unsaturated columns. However, the conductivity measurements were relatively constant which indicated that the collected samples probably had similar sulphate levels. Therefore, the samples collected from the flooding/flushing procedure were not analyzed.

In summary, the column test work was performed for the specified time of 20 weeks and provided useful information regarding release rates under (accelerated) infiltrative conditions. Acid generation was taking place, but there was sufficient neutralization potential within the waste rock to prevent the development of acidic conditions. The columns were flooded/flushed with pH 4.2 water which removed part of the remaining neutralization potential, as well as some of the stored oxidation products.

The waste rock samples remained in the columns for two months. The columns had been loosely covered to prevent excessive moisture loss. During this time period, the options for continuing the kinetic test work program were re-evaluated, and included:

- 1) resuming the column test work under conditions designed to accelerate the tests so that additional information could be obtained before the end of the Whistle project; and/or
- 2) performing alternate short-term laboratory scale test work (e.g. humidity cells) to examine the effect of certain factors on the sulphide oxidation rates for Whistle waste rock.

It was expected that the infiltrative column tests could be accelerated by flushing the waste rock with acidic water, and that perhaps only two additional washings would be required to further reduce the NP. The columns would then be operated on the same cycle as before, with the same water infiltration rate, but perhaps at higher oxygen supply rates. Adding a weak nutrient

solution to the first few rains, to stimulate the growth of bacteria was also considered. It was hoped that the columns would become acidic and strongly acid generating within the first month of resumed operation, and that we could obtain some new information on the release rates within a relatively short time frame.

As an alternative to continuing the column test, humidity cell test work on selected samples from the pile was considered. This could be used to examine distinct rock types, including the gossan materials, as well as the influence of certain factors such as oxygen supply rate, pH of rainwater, temperature, etc. However, it was decided by INCO and MEND that the column test work should be resumed.

Stage two of the column test work commenced with daily flushing of the columns with acidic river water (pH 3.5) to remove the remaining neutralization potential. However, the pH of the effluent did not decrease, even after five weeks of daily flushing. At this point, the column experiment was terminated. The concentration profiles for the second stage are provided in Appendix H (Figure H-2). These profiles illustrate the depletion of the leachable content of sulphate and metals over the time period of the test. The levels of nickel were initially high when the column was restarted and gradually diminished during the second stage of the column test. This indicates that significant oxidation occurred during the two month interval between stages. The pH remained neutral (7 to 8), and the calcium level remained essentially constant for most of the test, indicating the buffering was being provided by dissolution of the carbonate minerals.

The University of Waterloo (Dr. Ron Nicholson, Department of Earth Sciences, and Dr. Jenő Scharer, Department of Chemical Engineering) have conducted a separate laboratory program for INCO to determine the kinetic rates of oxygen consumption and sulphate generation for several of the major rock types from the Whistle waste rock pile (Nicholson et al. 1996). The study at the University of Waterloo was not part of the MEND Whistle waste rock project, but the researchers' findings are relevant for the interpretation of the kinetic test work and field data collected for the MEND Whistle waste rock project, and are discussed in Section 5.4.4.

#### **4.2.5. Washing Tests (Water Extraction Tests)**

The results of the washing tests have been summarized by analyte, location, and particle size fraction in Appendix G (see Tables G-3 to G-4). The test protocol is outlined in Appendix F, page F-6. Statistical comparisons have not been performed. A review of the tabulated data indicates that the waste rock fines appear to contain a higher proportion of soluble contaminants (i.e. metals, sulphate).

The wash waters had an average pH of 4.2, average conductance of 1900  $\mu\text{S}/\text{cm}$ , average sulphate content of 1026 mg/l and an average nickel content of 65 mg/l, although wash water composition did vary significantly by sample location. The wash water composition is generally similar to, but much more dilute, than seepage from the pile. Seepage quality is discussed in Section 4.3.2. The pH of the seepage and the wash water, however, was similar. Conversion of wash sample results to estimated pore water quality is discussed in Section 5.4.2.

The analyses of the extracts from the washing tests has not been corrected to match the original water (moisture) content. However the pH, conductance, sulphate and nickel levels can be compared with typical values measured for the seepage collected in lysimeters, boreholes and the base of the pile (see Section 5.0).

#### **4.2.6. Weathering/Physical Stability Tests**

The weathering or physical stability test work was not performed as it was decided that the kinetic test work should be extended instead. Weathering test work can provide useful information for preparing waste rock management plans for a proposed mine or during the initial stages of development; however, in this case, the Whistle waste rock pile itself can be studied directly for evidence of the effects of weathering and the physical stability of the rock.

The following general comments can be made based on observations made during the field program, and the subsequent return visit to the site to collect additional waste rock for the kinetic test work:

- the extent of weathering varies widely depending on the rock type and the sulphide content;
- weathering is controlled mainly by the sulphide content of the waste rock;

- waste rock described as highly oxidized probably contained greater than 15 to 20% sulphide prior to weathering;
- biotite can be present in quantities of up to 10-15% in areas of sulphide mineralization and may influence the weathering process due to expansion and contraction; and
- olivine is present in mafic norite inclusions and is a relatively unstable silicate.

#### 4.2.7. Bacterial Sampling and Available Test Work

The test work showed that iron-oxidizing bacteria were present in all of the waste rock samples. Positive identification of iron-oxidizing bacteria was their ability to utilize ferrous sulphate and pyrrhotite as a source of energy and carbon dioxide as a source of carbon. Visual observations using normal and phase contrast microscopes were used to make relative comparisons of growth and activity, and morphological forms.

All of the samples with the exception of RC-BAC2, showed growth in the three media, and all samples showed good or excellent growth at 8°C. The bacteria in sample RC-BAC2 grew well only at 8°C (Table 4.2-1). This could be due to the acclimatization of the bacteria to lower temperatures. In the natural environment the bacteria would be subjected to temperatures in the range of 10 to 15°C and this could lead to the selection of bacterial strains with low optimal growth temperatures.

Based on microscopic observation the cells in all of the slides were of the same size and shape and they often occurred in pairs. Cells that were commonly observed were rod-shaped, and most were motile by means of flagella. In some cases non-motile rod shaped bacteria were also present. A species of flagellated spiral bacteria was found in the culture from TP2-BAC1 growing in Fe<sup>2+</sup> medium. The motile and non-motile rods are likely *Thiobacillus ferrooxidans*, while the spiral bacteria are probably *Leptospirillum ferrooxidans* (see Appendix I).

Since the entire waste heap is oxygenated, metal sulphide oxidation is under kinetic (rather than mass transfer) control. Thiobacilli use both dissolved ferrous iron and sulphide sulphur as its energy source. It has been shown (E.C.M. Kwong, 1997, personal communication) that the biotic activation energy of pyrrhotite sulphide oxidation is 104 kJ/mol while both the biotic and abiotic activation energy of iron oxidation is approximately 54 kJ/mol. At higher temperatures (~30 °C) the rate of biotic iron oxidation is essentially equal to the rate of biotic sulphur oxidation. It was

shown that at 30 °C the biotic oxidation rate for both iron and sulphur is 5 to 10 times higher than the abiotic oxidation rate. However, at 8 °C (annual average temperature for the pile) the relative rates become 10% for iron and 2% for sulphur as compared to rates at 30 °C. Due to the differences in rates, partially oxidized sulphur compounds from pyrrhotite (elemental sulphur, thionates, for example) may accumulate at the sulphide surface. Thus, although biological metabolism does not cease at the low temperatures, the biotic oxidation of sulphide sulphur is not expected to be significantly different from abiotic rates. The differential rate of iron release may result in a sulphur-rich sublayer surrounded by ferric hydroxide precipitate. Ultimately, the surface conditions become unfavourable for bacterial attachment and biotic and abiotic oxidation rates will become identical.

### **4.3. MONITORING PROGRAM RESULTS**

As a result of ongoing waste rock deposition the field monitoring program focused on characterization of the northeast corner of the Northeast Waste Rock Dump (Figure 4.3-1) and included monitoring of boreholes and lysimeters. The field monitoring program implemented for this study focused on physical characterization of the waste rock properties. Monitoring of seepage water quality and groundwater quality below the waste rock pile was also conducted. A site hydrologic model which incorporates the meteorologic and flow data is presented in Section 5.4.1.

#### **4.3.1. Meteorology**

##### **4.3.1.1. Climate**

The mean annual precipitation in the Sudbury area is 861 millimetres (mm), as recorded at the Sudbury Airport, and varies from a mean monthly low in February of 47 mm to a mean monthly high in September of 106 mm. Mean annual snowfall is approximately 248 mm (water equivalent). Snowfall in the Sudbury area has historically occurred as early as September, however, significant snow pack accumulation typically does not result until late November when temperatures are below freezing. In the spring, the snowmelt tends to begin by mid-March with the majority of the accumulated snow pack depleting between April 1 and May 1. Mean daily temperatures vary from a low of minus 13.7°C in January to a high of 18.7°C in July. Sudbury

Airport records and on site precipitation measurements are presented in Appendix J.

Review of local Water Survey of Canada (WSC) stream flow data (WSC 1992) indicates that mean annual runoff in the Sudbury area is approximately 420 mm. Peak flows typically occur in April and early May and are due to either snowmelt or a combination of snowmelt and rainfall. Annual low flows generally occur in August and September.

Evaporation is significant during the summer months and is identified in Table 4.3-1. From May to August both pan and lake evaporation rates are greater than precipitation.

#### **4.3.1.2. *Summary of Temperature and Precipitation Patterns (1995-1996)***

Runoff volume is significantly influenced by precipitation characteristics, such as snowfall and rainfall depth, event duration, rainfall intensity, and spatial distribution. These precipitation characteristics vary between individual events, seasons, and years. Table 4.3-1 summarizes monthly precipitation depths and temperatures from August, 1995 to November, 1996 as reported by the Sudbury Airport. In general the precipitation measurements site were near those measured at the Sudbury airport, however there were some on site measurements which were slightly lower than the Sudbury Airport readings as a result of overtopping of the gauge. During the hydrological investigation in 1991 and 1992 annual-average precipitation was slightly above (within 10%) of the long term average. The average annual precipitation in 1995 and 1996 was also slightly above the long term average (within 5 percent). Precipitation is the most significant parameter that influences the magnitude of annual runoff.

#### **4.3.1.3. *Infiltration***

Infiltration into heterogeneous waste rock piles is related to the rate of flow into the pile and the distribution of fine grained material and hydraulic conductivity of the pile. In general precipitation and evaporation govern infiltration. In the blocky waste rock of the Whistle mine, most of the runoff water will infiltrate into the pile under heavy rainfall events. Evaporation will be significant for lighter rainfall events.

Infiltration into the lysimeters installed in the waste rock pile was not measured from December 1995 through to March, 1996. Freezing conditions occurred shortly after lysimeter installation,



thus there was effectively little or no flow to the lysimeters over this period. Lysimeter volume records are presented on Table 4.3-2. Flows are reported as total volume and equivalent rainfall assuming a surface area of 25 m<sup>2</sup>. Larger volumes of water were collected immediately following rainfall events. When water was not gathered immediately following the rainfall events water volume collected was low. It is possible that there was a leak in the lysimeter installed in TP-3 as it was dry over most of the monitoring period. The low water volumes collected during the sample program suggest that there was significant evaporation from the lysimeters.

#### **4.3.2. Flow and Seepage Characterization**

The northeast waste rock dump is situated on a bedrock high directly adjacent to the open pit. Visual observations made during the field investigations indicate that the toe of the waste rock dump along the northeast face fills in a series of depressions between bedrock ridges with drainage directed northeasterly and easterly to the site boundary and ultimately to Post Creek. The waste rock area studied is in Watershed W11 based on the boundaries defined in the Golder Associates (1994) report. Flow from this area is to the northeast exiting at the seepage collection pond at the location of former piezometer W-MP4 as indicated in Figure 4.3-1. The water balance for the study area and a hydrologic summary (based on the data available) is discussed in Section 5.4.3.

##### **4.3.2.1. Seepage**

Visual observations made during the course of the 1993 and 1995 field investigations indicate that continuous seepage occurs during the spring, summer and autumn from the toe of the waste rock dump near the seepage collection pond. Visual observations from winter of 1995/1996 indicate that seepage continues out of the base of the pile, even in the winter months. Flow data collected in 1993 indicate that flow tended to increase in July with the on-set of warm summer temperatures. This may be attributed to the melting of accumulated ice in the waste rock dump.

Current flow estimates are based on precipitation records, and incomplete pumping records provided by the site operator. Records of pumping rates and times are indicated in Appendix K. Most of these readings include water pumped from the open pit, thus determination of seepage

from the collection pond at the base of the rock pile is not possible over much of the monitoring duration. Intermittent pumping of the collection pond by the site operator with no detailed records of pumping time also make it difficult to assess flow from the waste rock pile.

Due to the coarse nature of the waste rock it is assumed that much of the heavy precipitation will infiltrate into the waste rock pile. Assuming a catchment area over the waste rock of approximately 10 Ha, and an average annual recharge rate of 861 mm/yr. the average annual flow through the pile would be approximately 15 L/min. Seepage over the year will fluctuate as a function of the precipitation and retention time in the pile. A discussion on factors that influence flow through the pile and a site water balance is provided in Section 5.4.

Flow rates observed downstream of the collection pond, (prior to its installation), range from 8-42 L/min (Golder Associates, 1994). The flow rate measured at the pumping station on June 7, 1996 was about 122 L/min. This measurement followed a rainfall event in which 27 mm of rain fell at the Sudbury Airport station over the week of May 31 to June 7, 1996. The flow rate measured in 1996 likely also included water pumped from other sources (possibly the open pit).

#### **4.3.2.2. *Hydrogeology***

The interpretation of the physical hydrogeological conditions for a portion of the Northeast Waste Rock Pile is based upon borehole logging, hydraulic conductivity testing and groundwater level monitoring conducted as part of the current investigation. A detailed understanding of overall site hydrogeology or the potential for migration through the underlying bedrock was beyond the scope of this investigation. A summary of borehole and test pit instrumentation details is presented in Table 4.3-3.

A summary of the current “state of the art” in hydrogeologic flow through a waste rock pile and assessment of the current data (in this framework) is provided in Section 5.4.1.

Based on the data collected in October, 1996 the water table in the waste rock is near the base of the pile (Table 4.3-4) and ranges in elevation from 343.3 masl at BH-4 (near the centre of the pile) to 338.8 masl at BH-3 (near the seepage discharge point) (Figure 4.3-1). A previous hydrological survey indicates that a watershed divide crosses through the Northeast Rock Dump (Golder Associates, 1994). Response test data indicates that near wells BH-2A and BH-3A the

hydraulic conductivity is greater than  $10^{-2}$  cm/s. This suggests that the wells may be in the base of the waste rock pile. Literature values for the saturated hydraulic conductivity of porous waste rock suggest that it may be as high as  $10^{-1}$  cm/s (Newman et al. 1997). Wells BH-1A and BH-4A have a lower hydraulic conductivity suggesting that these boreholes may be located in the overburden below the waste rock. The hydraulic conductivity at BH-4A is approximately  $1 \times 10^{-7}$  cm/s. It is possible that some minor water table mounding occurs at the base of the waste rock pile, however flow at the base of the pile is likely governed to a large degree by bedrock topography and pre-depositional drainage conditions.

Table 4.3-4 summarizes the water level data. In general saturated shallow groundwater flow at the base of the pile in the study area appears to be to the northwest, exiting at the collection pond. A plan showing the groundwater contours and the conceptual shallow groundwater flow paths determined from the relative groundwater and surface water levels is shown in Figure 4.3-1. It should be noted that groundwater will preferentially flow along the base of the waste rock above the overburden to the seepage collection point at a rate much higher than the seepage through the overburden, assuming saturated conditions both in the waste rock base, and overburden.

Once the infiltration reaches the base of the pile (saturated zone) it will migrate at a rate governed by the hydraulic conductivity ( $10^{-2}$  cm/s) and the hydraulic gradient (about 0.04). The flow along the base of north portion of the northeast pile (in the saturated zone) will be about 0.3 m/d directed towards the seepage collection pond (Figure 4.3-1). Assuming flow occurs in a 1 m thick zone, 300 m wide, (above the overburden), this corresponds to a flux of 48 L/min at the seepage collection pond.

Further discussion on flow through the pile (unsaturated zone) is presented in Section 5.4.1.

### **4.3.3. Water Quality Characterization**

Water quality sampling conducted at all locations near the waste rock show indications of acid mine drainage. The certificates of analysis for all samples analyzed are presented in Appendix L. A discussion of the water quality results is provided below. Loading estimates based on hydrologic, hydrogeologic and water quality characterization are presented in

#### Section 5.4.4.

##### **4.3.3.1. Seepage**

Seepage discharge water quality measurements were conducted just upstream of the seepage collection pond, west of the northeast pile as this is the likely discharge point for the area of study.

This seepage water contains high sulphate (1760 mg/L to 5200 mg/L) and high nickel concentrations (118 mg/L to 297 mg/L), (Table 4.3-5). Elevated concentrations of iron (0.73 to 6.9 mg/L), copper (3.5 to 13.4 mg/L), cobalt (4.3 to 12.7 mg/L) and zinc (3.1 to 7.6 mg/L) were also measured. The pH measured in the field ranged from 3.65 to 4.2. The concentrations of metals and sulphate measured in the seepage are lower than those measured in the boreholes (see Table 4.3-6). This suggests that precipitation reactions or dilution may be reducing the concentrations of metals in solution. Selected chemical analysis results of the seepage water are presented in Table 4.3-5.

##### **4.3.3.2. Boreholes**

The results of the water quality analysis from the wells indicate that low pH conditions and oxidizing conditions with little alkalinity exist in the water table below the waste rock. These low pH (3.85 to 4.51) conditions are accompanied by high sulphate concentrations (5,400 to 18,100 mg/ L), and very high concentrations of the dissolved metals, aluminum (166 to 878 mg/L) and nickel (438 to 954 mg/L). Elevated concentrations of iron (5.5 to 271 mg/L), cobalt (20.8 to 42.2 mg/L), copper (5.5 to 28.8 mg/L), and zinc (8.6 to 56.5 mg/L) also occur. Boreholes BH-5 and W-MW1 are located outside of the watersheds influenced by the Whistle rock pile (Figure 4.3-1). Higher pH values, greater alkalinity and low metal concentrations occur at these locations.

High concentrations of nickel from the wells in the waste rock can likely be attributed to oxidation of pentlandite material in the waste rock. Field and laboratory chemical results for selected parameters in the wells are presented in Table 4.3-6.

#### **4.3.3.3. *Lysimeter samples***

The initial (November, 1995) water samples from the lysimeters were not filtered, thus these results are not included in the discussion, or in Table 4.3-7. Subsequent sample analyses indicates that the lysimeter recharge water contains elevated concentrations of nickel (0.18 to 0.99 mg/L) and sulphate (28 to 1000 mg/L). The pH (4.87 to 8.05) and chemical composition of the water is quite variable (Table 4.3-7). This likely results from the significant influence of rainfall events and evaporation on the water quantity and quality. The May 1996 observation of pH 8.05 may be the result of some influence of the granular backfill filter material at the base of the Lysimeter.

#### **4.3.4. Gas Sampling**

The percentages of gaseous oxygen (O<sub>2</sub>) and carbon dioxide (CO<sub>2</sub>) measured in the first sampling event (October, 1995) were relatively uniform with depth, however there were concerns that the 90 second pumping duration was too short. The sample protocols and gas sampling duration were reviewed and for all future monitoring each sampling port was pumped for a minimum of 10 minutes prior to sampling, however there did not appear to be a significant difference in results.

The result of the sampling events indicate that the gas composition throughout the pile is uniform with depth, however it varies from location to location. The oxygen concentration within the pile ranged from 19.7% O<sub>2</sub> to 20.6% O<sub>2</sub> by volume, whereas the % CO<sub>2</sub> was below the detection limit of the meter (Table 4.3-8). A typical profile of the oxygen concentration with depth is presented in Figure 4.3-2 for borehole BH-1.

Some gas sampling ports were pumped for up to 40 minutes with relatively little change in oxygen concentration. The results of the 5 samples sent to the University of Waterloo (Appendix M) show slightly higher concentrations of % O<sub>2</sub> in some samples, however all samples indicate that oxygen concentration with depth in the pile is relatively constant at near atmospheric concentrations. There are, however, concerns that the meter used was not calibrated properly (see Section 5.2.1).

#### **4.3.5. Temperature Monitoring**

Current data does not show the high temperatures associated with other waste rock environments such as La Mine Doyon. Temperatures at depth in the waste rock are typically low ( $<10^{\circ}\text{C}$ ). The temperature in the upper 10 m of waste rock is affected by surface temperature variations and ranges from  $0^{\circ}\text{C}$  to approximately  $20^{\circ}\text{C}$  (October 4, 1995) (Figure 4.3-3). The temperature near the middle of the waste rock pile appears to be approximately  $10^{\circ}\text{C}$ . Seasonal fluctuations in waste rock pile temperature are apparent in Figures 4.3-3 a, b, c, d. These fluctuations result from heating of the waste rock in the summer and cooling in the winter months, and are attenuated with depth in the pile. Some variability is observed at depth in BH-2. This may be the result of advective flow of air into the base of the waste rock.

Water vapour was observed exiting the pile at some locations on the waste rock in the winter months indicating that evaporation (at low temperature) is occurring in the pile. The source of heat for this evaporation may be “stored” heat remaining in the waste rock from the summer months. There are no distinct zones of heat that can be directly attributed to sulphide oxidation. In BH-1 at a depth of approximately 5 m there appears to be consistently elevated temperatures with respect to the data at 3 m depth. It is possible that there is an error in the thermistor identification at this location.

The temperature variations in the pile are due to seasonal variations in the surface temperature and heat storage within the pile. The temperature at the base of the pile is typically on the order of the average annual surface temperature.

A summary of all of the temperature data collected is presented in Appendix N.

## **5. DATA ASSESSMENT**

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### **5.1. OBJECTIVES RE-VISITED**

The primary objective of this project was to obtain a healthy database of waste rock information for characterizing the Whistle waste rock pile. The overall requirements were to:

- assess the present chemical and physical conditions;
- determine proper sampling techniques, adapting methods outlined in manuals developed by MEND for waste rock sampling;
- establish and implement laboratory and field programs to collect data;
- provide interpretation of the data; and
- provide recommendations for future waste rock monitoring programs, building on the experience gained from this and other projects to establish important protocols that may apply to a broader range of waste rock piles.

The field and laboratory programs for collection of the data were implemented and the compilation of a database for characterization of the Whistle Waste Rock pile is now complete. The sampling techniques employed in this study were based on the techniques described in the *Waste Rock Sampling Manual* (MEND 4.5.1-1, 1994), and the adaptations required for application of these methods to this site have been described. Additional assessment of the field data and laboratory data, and an overall assessment of the combined data, is provided in this chapter. The main conclusions derived from this study and our recommendations for future programs are provided in Section 6.0.

### **5.2. COMMENTS REGARDING QA/QC**

#### **5.2.1. Field Methods**

Standard methods have been used for the sampling of the Whistle waste rock pile (see Appendices C and D). Some minor changes were required to account for site-specific considerations, and these have been documented in the written protocols, and are discussed in Section 3.0 of the report.

For the chemical analysis of the borehole water samples standards, blanks, and repeats were all run and are in very good agreement with the expected results (Appendix L). In the field, pH, redox and conductivity meters and probes were calibrated and checked periodically. Drift was less than 0.05 pH units and 10 mV for the pH and redox calibrations and checks respectively. Recalibration for pH was conducted when readings were more than 0.05 pH units from that expected.

Oxygen and carbon dioxide measurements were conducted using a portable combination gaseous oxygen, carbon dioxide meter. The meter was calibrated at the rental agency (Toronto) and shipped to the site (Sudbury). The values in the field were lower than the values measured in the duplicate samples submitted to the University of Waterloo for the August sampling event by 0.3 to 1.1% O<sub>2</sub>. It is possible that the meter calibration was affected by transport. The gas readings for the June 1996 sample event were closer to atmospheric values, while the October 1995 readings are likely not representative of in situ conditions (i.e. 1 to 2% lower than expected). The accuracy of the gas readings could have been improved through recalibration of the instrument on site; however, the data is certainly suitable enough to conclude that the oxidation rates of the pile are not oxygen limited.

The temperature data collected from the near surface thermistors correlates well with the expected temperatures just below ground surface, and at ground surface. The readings of September 26, 1996 appear to be mislabeled or incorrectly calculated.

### **5.2.2. Laboratory Methods**

The chemical analysis program conducted at BCRI included written protocols, and both BCRI and Barringer Laboratories conducted analyses of replicate samples, used standard reference materials and spiked samples to check the accuracy of the analytical methods (see Appendices F and L). In general, there was very good agreement between the duplicate analyses.

### **5.2.3. Comparison of Solid Sample Analyses Performed by Different Labs**

Samples of Whistle waste rock were examined at three different laboratories, including:

- analyses for metals at BCRI (Appendix F);



- analyses for whole rock elements plus some metals at Acme (this data is provided in Appendix F); and,
- analyses of metals and whole rock elements at Lakefield Research (Appendix H).

The following elements were analyzed at all three labs: aluminum; calcium; chromium; iron; magnesium; manganese; nickel; strontium; and titanium. All three labs utilized ICAP-OES spectroscopy for metals. During interpretation of the chemical/elemental data, it was noted that the analytical results for the same samples differed between the BCRI and Acme labs. Therefore, the analyses results were summarized separately in Appendix G.

BCRI prepared samples for analysis using a weak or partial acid digestion (aqua regia). Acme prepared the same samples using a strong acid digestion (borate fusion followed by  $\text{HNO}_3$ ). Lakefield Research analyzed one composite sample of the material collected for the column test work. The column test material was selected to be representative of the overall waste rock pile, and was intended to be similar to the overall composition of the main waste rock type in the pile, mafic norite. Lakefield used a strong acid digestion ( $\text{HNO}_3$ , HF,  $\text{HClO}_4$ , and HCl) followed by ICAP-OES analysis. For some elements Lakefield also used XRF analysis.

A comparison of the elemental/rock solids analytical results obtained from each of the three labs is presented in Table G-12 in Appendix G.

A comparison of the average of the BCRI results to the average of the Acme results shows that the BCRI results are 12% to 53% lower than the Acme results on average, except for nickel, for which the BCRI average is 175% of the Acme average. For the ore sample, the difference is even greater; the BCRI nickel result is 28,560 ppm, while the Acme result is 513 ppm.

Lakefield used the same digestion but different analysis methods (ICAP-OES versus XRF) for some analytes, and there are only minor differences. A comparison of the column test sample results from Lakefield to the overall mean sample results, shows that the Lakefield results agree well with the Acme results.

This comparison shows that the selection of the digestion method can make a significant difference in the results obtained. Since the total composition of the waste rock is desired, a strong acid digestion should be specified for the analysis of waste rock. Partial digestions should

be used only where appropriate, (i.e. for sediment sampling where it is understood that a partial extraction is being used).

These comparisons also show that analysis of duplicate samples at different labs is very useful and should be part of the QA/QC procedure, as it can point out potential analyses problems. In this case, the problem was incomplete digestion, and therefore, incomplete analyses for several analytes. Other problems that can be detected in this way include: mislabeling of results (i.e. Mg versus MgO); errors in calculating the dilution of samples (which may explain the variation in nickel results described above); introduced contamination in the lab; etc.

Seepage and groundwater analyses conducted at Barringer Laboratories and Near North Laboratories (Appendix L) show similar values for selected parameters. Differences in reported values may be attributed to variability in water composition which would result from variable oxidation rate and flushing rates which would occur over the course of the field program.

### **5.3. WHISTLE WASTE ROCK DATABASE**

The Whistle waste rock program provided numerous field measurements (e.g. paste pH, conductivity, fizz tests and water quality analysis) that were combined with the detailed chemical analyses data and ABA test work data from the laboratory program to obtain a complete geochemical characterization of the Whistle waste rock pile. The combined database of field measurements and chemical analyses prepared for this project is considered to be adequate for supporting the following types of assessments:

- developing a mechanistic understanding of the processes occurring in the waste rock pile;
- preparation of summary statistics (e.g. frequency tables, histograms) for various chemical analytes and field measurements;
- performing correlation analyses of chemical analytes and field measurements;
- performing statistical comparisons of sample sub-sets (e.g. whole rock versus fine fraction, test pits versus borehole samples, etc.);
- estimation of the leachable fractions of metals from the extraction test work and solids analyses data; and
- performing spatial, or geostatistical evaluations of specific parameters (e.g. NP, AP).

The above assessments were not intended to be carried out in the current phase of the Whistle waste rock project; however, the Whistle database was created and simple summaries and comparisons were prepared to assist in our data assessment tasks. The summaries prepared are provided in Appendix G, and some have already been discussed in Section 4.0, in conjunction with the results of the chemical characterization. Additional interpretation of the combined field and laboratory data is provided below.

### **5.3.1. Comparison of Field and Laboratory Measurements**

The following comparisons illustrate the potential differences between field and laboratory measurements of the same or similar parameters. This type of information is useful for planning and interpretation of waste rock sampling/characterization programs at other sites.

The paste pH was measured in the field program and was also measured in the laboratory (BCRI) in conjunction with the static testing. A plot comparing the two separate measurements is provided in Appendix G (see Figure G-12). The data points have been annotated with the sample location, and a line has been fitted to the data by linear regression (slope = 0.72, y-intercept = 2.18,  $r^2=0.63$ ). In the low pH range, the laboratory paste pH measurements are almost one pH unit higher than those measured in the field; this is because the laboratory test is performed on the crushed sample (i.e. previously unavailable buffering has been released by crushing).

The pH and conductivity of the water extracts from the laboratory washing tests can be compared with the other measurements of these parameters in the field and laboratory programs. A plot of paste pH measured in the lab versus pH of the water extract from the wash test is provided in Appendix G (see Figure G-13). In the low pH range, the pH measured for the water extract from the washing test is almost two pH units lower than the paste pH measured on the solid sample; this is because acidity present (stored) as precipitates and secondary minerals in the waste rock sample was released (dissolved) in the washing tests. Plots of conductivity measured for the water extract versus the paste conductivity measured in the field are provided in Appendix G (see Figures G-14a and b). These plots show a greater proportion of leachable metals were released in the washing tests conducted in the laboratory, for the same reason.

It should be noted that the pH of the extract from the extraction (wash test) is in the range 3.4 to 4 for most samples. This is similar to what is observed in seepage and groundwater, however conductivities of seepage and groundwater in the field are significantly higher (5000-8000  $\mu\text{s}/\text{cm}$ ) than field conductivity measured by washing the solid samples, or measured in the lab (generally 300-2000  $\mu\text{s}/\text{cm}$ ). In general TDS is more dilute in the wash samples than in the seepage. As pH is measured on a log scale, it does not show this same change due to dilution. Although the wash tests do not reflect the exact seepage quality, they do give a good indication of the nature of the seepage. Conversion of wash sample results to estimated pore water quality is discussed in Section 5.4.2.

Water samples collected in the lysimeters more closely resemble the kinetic laboratory test program samples than the seepage from the pile. Comparing the lysimeter data with the first 20 weeks of the column test data shows that Ni levels are similar, pH is approximately 1 unit lower in the lysimeters, lysimeter sulphate levels are approximately 50% of the column levels, and Fe is much lower in the columns than in the lysimeters (due to the differences in pH).

### **5.3.2. Examination of Sample Sub-Sets**

The number of samples collected and analyzed for the Whistle waste rock program is considered to be adequate for application of statistical methods for examining the similarities and/or differences between sub-sets or groupings derived from the data set. The sub-sets that could be examined for the Whistle waste rock include:

- separation of the samples according to sampling location (i.e. test pits, boreholes, Whistle Wildcat Gossan, Autopsy Zone, ore);
- comparisons of the chemical/elemental analyses of the whole waste rock sample versus the fines fraction (minus 2 mm), as recommended in MEND 4.5.1-1, (1994);
- separation of the database into rock types according to the field observations made during collection of the samples; and/or
- classification of the samples into categories of potential acid generation behaviour, (i.e. according to NP/AP ratio or NNP).

The statistical summaries provided in Appendix G are predominantly tabulated according to sample location, which has facilitated our assessment of the physical and chemical conditions within various parts of the pile and may provide useful information for supporting future

predictive modelling assessments.

The analyses of the whole rock and fines samples have been tabulated separately, but statistical comparisons between the whole samples and the fine fraction of the samples (minus 2 mm) have not been made. Such comparisons would be very useful for supporting future predictive modelling assessments.

Selected summaries of the ABA data were prepared to support the assessment of the acid generation potential; the samples were tabulated into three separate sub-sets, for two specific ABA parameters, NP/AP and NNP. This assessment could easily be extended to determine whether there were any trends in the levels of sulphate and metals in each of the ABA sub-sets.

Assessment of the influence of specific rock types, such as the gossanous material from the top of the pit that was placed at the bottom of the pile and that occurs locally throughout the pile, was considered to be very important for this project. Therefore, special summaries have been prepared to assess the influence of strongly oxidized materials (see Appendix G, Tables G-13 and G-14, and Figures G-18 and G-19).

The sample logs (Appendix D) were reviewed to identify the strongly oxidized samples. The samples were grouped as follows:

- 1) three samples from test pit 1 (TP1-A11, -A12, -A13);
- 2) four samples from test pit 2 (TP2-A1, -A5, -A7, -B1);
- 3) two samples from test pit 3 (TP3-A1, -A3); and,
- 4) eight samples from the Autopsy Zone (RC-A1, -A2, -A3, -A5, -A9, -10, -2,-7)

Plots of nickel in the rock versus sulphide content were prepared for the entire dataset (Appendix G, Figures G-18 and G-19). The data points were annotated according to the above four groupings. These plots show there is a direct relationship between the nickel and sulphide contents, as expected. The samples of strongly oxidized waste rock are shown to cover the full range of nickel and sulphide levels in the rock; however, the samples from group 4 (Autopsy Zone) appear to contain the highest levels of nickel and sulphide.

Summary statistics were calculated for the solids analyses and the washing tests for each of the

above groups, the entire set of strongly oxidized samples (i.e. groups 1 to 4 inclusive), the remaining samples in the database, and the overall database (Tables G-13 and G-14) to allow for comparison of strongly oxidized material from various locations to the remaining samples. Statistical tests were not applied. A summary of the means calculated for several key analytes (sulphide, sulphate, iron, nickel, copper, cobalt, and zinc) is provided in Table 5.3-1.

Table 5.3-1(a) shows the summary of the solids analyses results. The samples of strongly oxidized waste rock are generally more acidic (lower paste pH), have a much higher sulphide and sulphate content, and higher levels of metals compared to the remaining samples collected from the pile. The strongly oxidized samples represent only 16% of the analyzed samples (16 out of 98 samples), but obviously exert a strong influence on the overall average for each analyte.

Table 5.3-1(b) shows a summary of the washing test results. In this case there are fewer samples for comparison, and the strongly oxidized samples represent 33% of the analyzed samples (5 out of 15 total). The influence of the highly oxidized samples on the overall average (and most likely on the seepage from the pile) is again quite apparent. These samples are more acidic, have a higher average conductivity, and contain a higher proportion of easily released sulphate and metals, in comparison to the remaining samples collected from the pile.

## **5.4. OVERALL ASSESSMENT AND SUMMARY OF WHISTLE MINE DATA**

### **5.4.1. Hydrological and Hydrogeological Assessment**

#### **5.4.1.1. Porosity**

The proposed standard procedures for determination of void spaces in aggregate (ASTM C29-91, ASTM C127-88 as recommended in MEND 4.5.1-2, 1994) are not adequate for identification of porosity of the pile where the grain size range is larger than 6 inches (e.g. Whistle Mine). Alternatives methods suggested in MEND 4.5.1-2 (1994) for determining porosity include: structural analysis; total volume and total mass determination from mine records; conducting a gravimetric survey of the dump and water content measurement; nuclear back scatter; measuring water level changes during storms; and sand cones. Of these alternate

methods structural analysis and volume-mass determinations may be feasible alternatives for determination of porosity at the Whistle mine site.

An estimated range of porosity for the waste rock material can be also be determined from volume expansion due to blasting. Glover (1996) indicates that the expansion for Basalt, Gneiss and Granite is as high as 75 to 80% when mined. Generally when sizing waste rock dumps the Sudbury Area it has been found that the volume of rock generally increases by about 20 to 40% after blasting (Cameron, 1997). This corresponds to a porosity of 16 to 29%. Based on the *GoldSize* analyses and sieve analysis results the percentage of minus 100 mm material accounts for less than 7.5% of the pile and the minus 2 mm material accounts for less than 2.5% of the overall pile. Even accounting for addition of 50,000 tonnes or 1% of sand to the 5 Mt. pile there is not enough fine-grained material to fill the larger voids.

The actual size of the voids is a function of the size distribution and particle contact geometry. For homogeneous spherical particles the constriction size of the void is about 0.16 times the diameter of the particles (for spheres of 100 mm is diameter this would result in void constriction size of 16 mm in diameter). As more than 90% of the material in the Whistle Mine waste rock is greater than 100 mm in diameter it is reasonable to expect that the average pore diameter will larger than 16 mm. The fine grained material in the pile will be contained within these larger pore spaces. A more detailed discussion on particle size porosity relationships is provided in Kenney et al. (1985).

Work was conducted by Newman et al. (1997) on coarse-grained samples from the Golden Sunlight Mine. In these samples 39% of the material passed a #4 mesh (4.75 mm) sieve and the samples still did not contain enough fine material to fill the larger inter-particle voids. While each waste rock pile has characteristics particular to the site, Newman's work supports the assertion that at Whistle Mine (where there is significantly more coarse material) there is not enough fine material to fill larger inter-particle voids. Visual inspection of the pile also confirms that this is the case (in most areas).

#### **5.4.1.2. Hydraulic Conductivity**

Using Hazen's relationship (Dominico and Schwartz, 1990; Hazen, 1911) for the sieve analysis

of the minus 100 mm fraction from Test Pit 1, the saturated hydraulic conductivity of the fine fraction is about  $6 \times 10^{-3}$  cm/s. This was the lowest hydraulic conductivity measured. Given that some of the material in the pile appeared to be medium grained sand a lower hydraulic conductivity of  $10^{-3}$  to  $10^{-4}$  cm/s may be more applicable in some locations. The saturated hydraulic conductivity of the coarse waste rock at the base of the pile was greater than  $10^{-2}$  based on piezometer response tests. It should be noted that coarse to medium sand appears to have been placed in lifts over some locations on the tailings. A typical hydraulic conductivity for a coarse to medium sand would be about  $1 \times 10^{-3}$  cm/s (Freeze and Cherry, 1979).

#### **5.4.1.3. *Water Content***

The degree of saturation and water content at a certain pressure head is dependent on the pore size and distribution. The relationship between water storage properties and median grain size of alluvium in large valleys is given in Bear (1972). According to the data in Bear (1972) water content on material of grain size greater than 100 mm is about 7% by volume.

As stated in MEND report 4.5.1-2 (1994) the evaluation of water content in waste rock is very challenging and no good methods for determining the water content of waste rock have been proven. In the case of the Whistle Mine Rock pile where the material is very blocky this is certainly true. Water content estimation was not included as part of this study, however it is required for determination of flow in the unsaturated zone. Ritchie (1994) indicates that typical water content for waste rock piles range from 5% to 15% by volume. Additional structural evaluation of the pile may yield a more refined estimate of water content, however this is beyond the scope of this report.

#### **5.4.1.4. *Flow through the Pile***

There is currently much debate on flow mechanisms in the unsaturated zone of waste rock. The issue has not yet been decided. Flow through waste rock is largely governed by the configuration and construction of the waste rock pile (i.e. grain size and packing of the rock), the mineralogical composition of the parent rock, weathering processes, and climatic conditions of the mine site.

Bear (1972) indicates that for porous media in the unsaturated zone an effective hydraulic conductivity governs unsaturated flow and is defined by the porosity and water content of the



material. The reader is referred to Bear (1972) for a detailed discussion on unsaturated flow. At low moisture contents (such as those observed in the waste rock pile) the effective hydraulic conductivity and thus the flow rate will be low.

Recent work relating to flow in waste rock (Newman et al. 1997; Lopez et al. 1997) suggests that (under unsaturated conditions), preferential flow may occur in interconnected fine grained material within the waste rock under low recharge rates, while at times of heavy precipitation water will preferentially flow in coarse waste rock. Other research by Culligan et al. (1997) suggests that in unsaturated coarse sand, water may flow in fingers which may have large flow velocities (driven by the unit gradient).

When the infiltration rate exceeds the saturated hydraulic conductivity of the waste rock the water will flow under a unit gradient (this is the theoretical maximum flow rate). Assuming a hydraulic conductivity of  $10^{-1}$  to  $10^{-2}$  cm/s, flow downward through the waste rock (for a unit area) would be equal to the hydraulic conductivity. This corresponds to a flow rate of 8.6 m/day at the Whistle mine waste rock pile. Assuming a pile thickness of approximately 30 m, infiltrating water would reach the base of the pile in about 0.35 to 3.5 days.

If medium sand sized material of hydraulic conductivity  $1 \times 10^{-3}$  cm/s were to be segregated in specific areas on the pile, such as in lifts or as columns of material (from end dumping), the flow rate through the pile would be about 0.85 m/day under a unit gradient. Assuming a pile thickness of approximately 30 m infiltrating water would reach the base of the pile in about 35 days.

Based on visual observation of the Northeast waste rock pile, layering of rock and sand sized material occurs. Assuming alternating layers of 0.1 m sand and 1.4 m waste rock, and a pile thickness of 30 m, ( $k_{\text{sand}} = 1 \times 10^{-3}$  cm/s,  $k_{\text{rock}} = 1 \times 10^{-2}$  cm/s) the infiltrating water would reach the base of the pile in about 6 days. This again assumes a unit gradient.

Only under large rainfall events will a unit gradient be achieved for a significant amount of time. For smaller rainfall events flow will be governed by the effective hydraulic conductivity of the residual water. Given the low water content (< 15%) the flow rate will be reduced significantly. If the residual water in the pores is not interconnected flow will essentially stop (Bear, 1972).

This may occur in the blockier portions of the pile under dry conditions. In the saturated zone at the base of the pile water will migrate at about 0.3 m/day (see Section 4.3.2).

Also affecting flow in the pile may be formation of ice within the pile and layering of fine grained material in the pile. The time it takes for infiltration to reach the base of the Whistle mine rock pile likely ranges from a day or less for heavy rainfall events through coarse material to months for precipitation in winter months and flow through finer grained material. The time it takes for water to flow along the base of the pile ranges from days to a year or more depending on the length of the flow path and the hydraulic gradient.

A better understanding of flow through the pile is required. It is hoped that the data set developed will assist in directing this research.

#### **5.4.2. Water Quality Data**

The average water quality measurements in the five boreholes (BH-1 to BH-5), the three lysimeters (TP-1 to TP-3) and the seepage are compared in Table 5.4-1. The overall results for the eluate obtained from the extraction or washing tests on the samples of waste rock from the boreholes and test pits are also provided for comparison.

The pH values and concentrations measured in the laboratory washing tests are in general agreement with the levels measured inside the pile. The concentrations reported for the washing tests include results obtained from washing tests performed on the whole rock sample (generally less than 10 cm diameter), as well as the fines fraction (diameter less than 2 mm). The levels shown have not been corrected to the original moisture content of the waste rock samples, (i.e. to porewater concentrations). At a washing ratio of 2:1 (water:solids), and assuming an initial moisture content of 20% in the smaller particles, the actual porewater concentrations within the waste rock would be 10 times higher than the values shown in Table 5.4-1. This suggests that the porewater concentrations within the smaller waste rock particles are likely similar to the levels currently measured for the heap water collected in the boreholes at the bottom of the pile.

The monitoring data for the boreholes shows that the pH and metal concentrations are very similar in all the boreholes, located within the waste rock pile. The pH of the water collected in these boreholes averages about 4.0 to 5.0. The current seepage collected from the pile has a

slightly lower pH, about 3.9. The average pH measured in the lysimeters is 6 to 7; although one of the lysimeters (TP-2) appears to be approaching more acidic conditions (pH 4.87).

The results of the lysimeter and column tests show that waste rock at the surface of the pile is generating acid from sulphide oxidation, but that the acid produced is immediately buffered by neutralizing minerals. Estimated sulphide oxidation rates for the lysimeters and the columns are discussed below in Section 5.4.4.

### **5.4.3. Water Balance**

A water balance for the Whistle Mine site was completed in 1992 and in 1993 to quantify the sources and areas contributing to acid rock drainage. This water balance was based on measured seepage values rather than hydrologic data. Watershed areas were estimated based on original topography, deposition patterns, and mine configurations as indicated in Golder Associates (1994). These boundaries are indicated on Figure 1.4-1. The current study focuses on the portion of watershed W11 that intersects the Northeast waste rock dump. For an evaluation of the water balance for the entire site, the reader is referred to Golder Associates (1994).

Watershed W11 includes the Eastern portion of the Northeast waste rock dump, the seepage collection pond, and some native ground to the east of the waste rock dump. Prior to installation of the seepage collection pond precipitation reporting to the surface of the waste rock dump in watershed W11 would report as seepage at the toe of the waste rock and would flow along a small creek to the east where it joins Post Creek. The surface area of the waste rock dump over which seepage reports to the toe of the waste rock is about 10 ha. The watershed boundaries have been used in conjunction with water budget data available through Atmospheric and Environment Services Canada (AES) for 30 year climate normal data from the Sudbury Airport (AES, 1997) to estimate monthly infiltration to the pile. It was assumed that water infiltrating into the waste rock in watershed W11 will report as seepage at the seepage collection pond.

Evaporation from the waste rock will likely behave in a similar manor to a paved surface with the surface area governing the rate of evaporation. Evaporation rates were assigned assuming a water retention in the upper waste rock of 10 mm (i.e. 10 mm of every rainfall event is ultimately available for evaporation). This value is slightly higher than the 3 mm value that is typical of a

paved, drained, surface. A water retention of 100 mm may be possible in the sand layers deposited on the waste rock (this is the lower boundary for water retention in a coarse soil). Based on water budget data available from Atmospheric and Environment Services (AES, 1997) water retention of 3 and 100 mm correspond to average annual evaporation rates of 39 and 54 percent respectively. Assuming a water retention of 10 mm for the waste rock the average annual evaporation rate of 42 % (AES data, 1997).

It may be possible as part of future work to refine the evaporation estimate by estimating the surface area of the particles and applying a 1 to 2 mm water retention to the entire surface area but that is beyond the current scope of work. The monthly average precipitation and evaporation is presented in Table 5.4-2.

The results of the water balance calculations indicate that for the 30 year normal evaporation and precipitation data, (assuming a water retention of 10 mm) the average seepage from the waste rock to the seepage collection pond would be about 49,700 m<sup>3</sup>/a (Table 5.4-2). It should be noted that the majority of the seepage occurs during the spring snowmelt. It should also be noted that the waste rock pile is elevated with respect to the surrounding topography, thus the snow accumulation may not be as high on the waste rock pile as that measured at the Sudbury Airport or at the on site station. The calculated seepage rate is lower than the seepage rate (66,430 m<sup>3</sup>/a) estimated in Golder Associates (1994). Possible causes of this discrepancy are differences in snow accumulation on the pile vs. Sudbury airport data, and timing of flow measurements made in the 1994 data. As the flow measurements were visually estimated for the winter months in the Golder Associates (1994) report the most significant difference is likely due to errors in flow measurements.

The water balance presented does not take into account flow times through the pile, as discussed in Section 5.4.1. Detailed flow monitoring data from the seepage point is required to define delay times for infiltration events and refine potential evaporation and seepage estimates for the pile.

#### **5.4.4. Estimation of Sulphide Oxidation Rates and Loading Estimates**

The overall average sulphate release rate in the Whistle waste rock pile can be determined as

follows:

- seepage collected from 1993/94 had an average sulphate level of 3048 mg/L ;
- the annual flow through station W11 for 1993/94 was 66, 430 m<sup>3</sup>/a;
- therefore, the annual sulphate loading for 1993/94 was 202,479 kg/a

Based on Golder (1994) we assume that approximately 80% of the pile (4 Mt.) drains through W11, which equates to an overall sulphate release rate of 0.139 (mg SO<sub>4</sub>/kg rock/day), or 1.1 (mg SO<sub>4</sub>/kg rock/week). The intrinsic oxidation rate expressed in terms of oxygen consumption rates (moles O<sub>2</sub>/kg/s) can be converted to sulphate release rates (mg SO<sub>4</sub>/kg rock/week) assuming a sulphide particle surface area. These conversions are completed below for the intrinsic oxidation rates determined by Nicholson et al. (1996).

A similar estimate of the sulphate release rate can be determined from the kinetic test work. The cumulative sulphate released from the 825 kg of waste rock present in column No. 1 over 20 weeks (126 days) of the test was approximately 570,000 mg. This provides an overall sulphate release rate of 34.5 (mg/kg/week). The rate for column No. 2 was 31.1 mg/kg/week for an average of 32.8 mg/kg/week. The estimate from the kinetic column test is much higher (33 to 46 times higher) than the overall estimate for the pile since the maximum rock particle size in the columns was 50 mm. The pile contains a much smaller proportion of small particles, therefore the overall sulphate release rate is much lower.

Nickel loading rates have also been calculated based on the seepage quality and on from the column test work. The nickel loading rate calculated from the column test work is 0.17 mg Ni/kg rock/week, and the loading rate calculated from seepage is 0.065 and 0.048 mg Ni/kg rock/week for the 1993/1994 and 1996 data respectively. The calculated sulphate and nickel loading rates are summarized on Table 5.4-3. As was discussed above, the ratio of sulphate loading in the columns versus the seepage is approximately 39:1. The ratio of nickel loading in the column versus is only about 1.8:1. The smaller difference in nickel loadings, in the columns relative to the seepage, is due to the neutral conditions in the column. If the column test had been continued until the leachate became acidic, the nickel loading would have increased significantly.

The University of Waterloo conducted a separate research project that involved measurement of

the rates of sulphide oxidation for samples of Whistle waste rock (Nicholson et al. 1996). The objective of their study was to demonstrate the application of a new method, and to use this technique to study the effects of various operating conditions on the oxidation rate. This technique involves the measurement of oxygen concentration over time in a closed vessel containing a known amount of waste rock. The findings from their research study are briefly listed below.

- *“The oxygen consumption rates of smaller particles (0.7 cm) was found to be positively correlated with the sulphide content, although the trend was poor. Similar behaviour was found for larger rocks (10 cm size).*
- *The sulphide content was found to be an unreliable indicator of the oxygen consumption rate.*
- *The rate of oxygen consumption was shown to be inversely proportional to the size of the particle raised to the power,  $n$ , where  $n$  varies from 1.1 to 2.3, over the range of particle sizes from 0.01 to 10 cm.*
- *The oxidation rates for 1 cm size materials were as much as 100 times faster than rates measured for 10 cm material.” (Nicholson et al. 1996)*

The chemical/elemental composition of the Whistle waste rock used in the University of Waterloo research study is compared with the waste rock used in the kinetic column experiments, and the overall average characteristics of the samples collected from the Whistle pile (test pits, boreholes, Autopsy Zone) in Table 5.4-4. The material used in the column test work had a lower average sulphide content and higher carbonate content than the material tested by the University of Waterloo.

The researchers at the University of Waterloo used the new technique to measure the oxygen consumption rate, and also measured the sulphate release rate using a rinsing method. The estimated rate of oxidation was always higher using the oxygen consumption method compared to the sulphate release rate, and several explanations were offered, including:

- *“storage of sulphate in the form of secondary mineralization or in dissolved form within the porespaces of the waste rock particles;*
- *incomplete rinsing and therefore recovery of the sulphate released from the sample;*
- *transformation of FeS to FeS<sub>2</sub> during oxidation of pyrrhotite by ferric ion resulting in lower sulphate release” (Nicholson et al. 1996).*

The oxidation rates for Whistle waste rock that were measured in the University of Waterloo

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study were compared with values reported in the literature, and were found to be on the same order of magnitude. The lowest rates were determined for the 10 cm material and were as follows:

- $4.7 \times 10^{-11}$  to  $7.8 \times 10^{-11}$  moles  $O_2$ /kg/s based on oxygen consumption; or
- 1.4 to 2.3 mg  $SO_4$ /kg rock/week, based on sulphate release.

The highest rates were measured for the 7 mm size materials that had been inoculated with bacteria, and these values were as follows:

- $8.1 \times 10^{-9}$  to  $2.8 \times 10^{-8}$  moles  $O_2$ /kg/s based on oxygen consumption; or
- 235 to 813 mg  $SO_4$ /kg rock/week, based on sulphate release.

For comparison, the average sulphate release rate determined from the kinetic test work performed on waste rock particles less than 60 mm diameter was 32.8 mg  $SO_4$ /kg rock/week, which is between the ranges outlined above.

Nicholson et al. (1996) used the particle size distribution and the overall sulphide content determined from the Whistle waste rock project to estimate an intrinsic oxidation rate for the Whistle waste rock pile, as follows:

- $4.5 \times 10^{-11}$  (moles  $O_2$ /kg/s); or
- 1.3 (mg  $SO_4$ /kg rock/week).

This estimate is based on assuming the pile behaves as medium-sulphur norite since 83% of the pile is composed of mafic norite containing 3% sulphide. The above value compares favorably with the rough estimate of 1.0 mg  $SO_4$ /kg rock/week, determined from the pile seepage for 1993/94.

#### **5.4.5. Estimation of Leachable Inventories of Contaminants**

The data obtained from the initial kinetic test work (Stage 1, unsaturated columns, prior to additional changes) was used to estimate the leachable fractions of sulphate, major species, and metals that were released during the column studies. These estimates are summarized in Table 5.4-5. The released fractions of each species are expressed as a percentage of the total inventory of that species present in the original rock sample. In general, the percentages released over the 20 weeks of the test are quite small, but are similar to releases observed from

test work performed on low sulphur nickel tailings.

## **5.5. ASSESSMENT OF MEND PROTOCOLS**

For this study protocols used in the field were used or adapted based on MEND 4.5.1-2 (1994).

In most cases the prescribed protocols were adequate, applicable and useful. The following comments provide additional suggestions for changes to protocols or suggest additional information which should be included or stressed in these types of studies (based on our experience).

- The suggested protocol for determining porosity (ASTM C29-91) is not adequate for determining the porosity distribution of a more blocky waste rock such as that encountered at Whistle Mine. Where the rock is too blocky it is necessary to determine the particle size distribution and porosity based on a structural analysis of the pile.
- The MEND protocols do not include methods which can be used to interpret structural analysis of the pile. For instance a great deal of information can be obtained through detailed evaluation of grain size analysis, water content of the pile and definition of construction methods (i.e. range of flow rates through the pile can be estimated).
- There are no adequate methods outlined in the protocols to adequately determine the water content of a large blocky pile. A review of the literature relating to similar types of blocky material and review of theoretical methods of water content determination would be of benefit.
- X-ray diffraction (XRD) and petrographic analysis of thin sections were suggested in MEND 4.5.1-2 as means of determining the mineralogy of the pile. Due to budgetary considerations it was decided to use only XRD to determine secondary mineralogy. While XRD did identify some of the secondary minerals present, thin section petrographic analysis would have provided much better data and is recommended for future studies.
- The ABA data collection and assessment protocols were suitable for determining acid generation potential.
- The MEND protocols lack a summary which stresses the key parameters which are required for adequate characterization of waste rock piles (see Section 6.1). The end use of the data and general scope and objectives of monitoring and characterization studies on waste rock also needs to be addressed. It should be stressed that all of the protocols should be assessed and used with sound judgement, keeping in mind the overall objectives of the program.



## 6. CONCLUSIONS AND RECOMMENDATIONS

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### 6.1. CONCLUSIONS

Based on our experience at the Whistle Mine site the following data is of critical importance for an assessment of any waste rock dump:

- Knowledge of dump structural parameters such as:
  - grain size distribution
  - porosity
  - water content, and
  - distribution of material (dump construction)
- Knowledge of acid generation potential determined through:
  - Acid:Base Accounting
  - kinetic test work
  - detailed mineralogical characterization (X-ray diffraction, thin section petrographic analysis),
  - seepage characterization, and
  - analysis of temperature and gas composition data.
- Assessment of the site water balance through analysis of:
  - detailed precipitation and evaporation data
  - estimates of flow through pile (based on structural analysis and hydrogeologic assessment)
  - estimates of water retention in the pile, and
  - measurement of the surface area of the pile.

Proper interpretation of the above data will give loading estimates and potential metal release from waste rock environments. It should be stressed that the reason for carrying out these detailed studies is to assess the magnitude and duration of impacts to the environment and, as an end result, to determine methods of mitigating, reducing or eliminating these impacts.

In general investigative studies should not focus solely on the source of the problem (i.e. the waste rock pile) but also on the impacts in the receiving water body, the end use of the resource, and the potential adverse impacts to terrestrial and aquatic life. All of the factors must be integrated into an overall understanding of the site in order to determine the best course of

action for a particular waste rock dump.

The conclusions derived from the Whistle waste rock project have been summarised as follows:

#### **6.1.1.1. Field Program**

- Drilling in Sudbury Igneous Complex waste rock is difficult, but possible using an eccentric bit (allowing for frequent bit rebuilding and replacement). When drilling in blocky waste rock using this method, chip sample return can be expected to be poor and often representative of the interior of boulders.
- The waste rock composition in the pile at Whistle Mine is very heterogeneous. The heterogeneity is a result of the differing composition of the truckloads of waste rock and the dump construction method (a combination of horizontal lifts approximately 1.5 m high and end dumping).
- Field work and historical information suggest that the north-east waste rock pile is composed of over 80% mafic norite, with a variable sulphide content which averages approximately 3% (pyrrhotite containing pentlandite). The pile is also estimated to contain ~1% ore, and ~1% gossan (heavily weathered ore). The remainder of the pile is composed of ~4% felsic norite, and ~10% granitoid. The felsic norite contains <1% sulphide, mainly as pyrrhotite. The granitoid also contains <1% sulphide, however chalcopyrite is the main sulphide present.
- The pile is composed of less than 7.5 % of minus 100 mm material and less than 2.5% of minus 2 mm material. The porosity of the pile is greater than 20%. The fine grained material is generally contained within the larger voids with ample void space remaining. A review of relevant literature (Newman, 1997; Bear, 1972) suggests that the residual water content of the pile will be from 7 to 15 %.
- The water table in the waste rock is generally near the waste rock/overburden interface. Porewater measured from the boreholes has low pH values (3.85 to 4.51) which are accompanied by very high concentrations of sulphate (5,400 to 18,100 mg/L), aluminum (166 to 878 mg/L), and nickel (438 to 954 mg/L). Elevated concentrations of iron (5.5 to 271 mg/L), cobalt (20.8 to 42.2 mg/L), copper (5.5 to 28.8 mg/L), and zinc (8.6 to 56.6 mg/L) also occur.
- Water quality at the seepage discharge (at the seepage collection pond) is characterized by high sulphate (1760 to 5200 mg/L) and nickel (118 to 297 mg/L) concentrations with elevated concentrations of iron (0.73 to 6.9 mg/L), copper (3.5 to 13.4 mg/L), cobalt (4.3 to 12.7 mg/L), and zinc (3.1 to 7.6 mg/L).
- Lysimeter water quality is characterized by variable pH (4.87 to 8.05), elevated nickel (0.18 to 9.9 mg/L) and elevated sulphate (28 to 1000 mg/L) concentrations. Precipitation and evaporation events likely have a significant influence on the concentrations measured.

- The gas monitoring showed that the transport of air (oxygen) into the pile is not limited and that there is ample oxygen in the pile for oxidation reactions. The values measured ranged from 19.2 to 20.7 % gaseous O<sub>2</sub>, however it is suspected that the measured values may be lower than the actual values, possibly due to poor instrument calibration. Carbon dioxide concentrations were below the detection limit of the instrument (<0.1% gaseous CO<sub>2</sub>).
- Temperature variations in the pile appear to be mainly due to changes in surface temperature. Temperatures deep within the pile are about 5 to 7°C. Temperatures near the surface of the pile range from less than 0 to greater than 20°C and closely reflect ambient surface temperatures.

#### **6.1.1.2. Laboratory Program**

- A summary of chemical/elemental composition by sampling location showed that the levels of most analytes are similar in the three test pits and the four boreholes, and that samples from the gossan and ore are very different.
- Comparison of chemical/elemental analyses of whole rock and fine fraction (particles less than 2 mm diameter) indicates that the distribution of metals appears to be similar in both fractions, though sulphate concentrations appear higher in the fine fraction.
- The static testing, or ABA (acid base accounting) results indicate that most of the waste rock samples would be expected to be acid generating.
- The use of the modified Sobek method for static testing showed good reproducibility; previous ABA data using the Sobek method was provided by INCO for comparison.
- In alternate testing methods (BC Research Initial test, and Net Acid Generation test) the neutralisation potential (NP) estimates obtained using the BC Research Initial test generally agreed with those obtained using the modified Sobek method. The Net Acid Generation (NAG) test results correlated well with the modified Sobek NNP results, although the NNP results are more than five times greater than the NAG results.
- The waste rock fines appear to contain a higher proportion of soluble contaminants (i.e. metals, sulphate) based on washing tests performed on whole rock and fine fraction.
- Buffering tests performed in conjunction with the alternate static testing showed that buffering (i.e. NP) was available over several pH intervals (e.g. above pH 6, from 6 to 5, from 5 to 4, and from 4 to 3.5). This indicates that several different minerals are providing buffering. The majority (i.e. over 50%) of the buffering (i.e. NP) was provided over the pH interval from 4 to 3.5.
- Biological test work shows that iron-oxidising bacteria are present and are active at lower temperatures, however their effect on the overall oxidation rate is unknown.

### 6.1.1.3. *Data Assessment*

- Tests for acid generation potential indicate that the pile is acid generating and oxidation of sulphide minerals is not limited by oxygen flux into the pile.
- Concentrations and loading rates for column tests and seepage indicate that the water from the column test is still somewhat buffered. The loading rates from the column test for sulphate and nickel are about 32.8 mg SO<sub>4</sub>/kg rock/week and 0.17 mg Ni/kg rock/week respectively. These loading rates are about 39 and 1.8 times greater than those measured for the seepage.
- The differences between leachate produced from the column test and from the waste rock pile have illustrated that caution should be used in applying the results of short-term kinetic tests to longer-term behaviour of waste rock. Practice has shown that it can take a year or more for a sample to become acid in a column test, which greatly increases metal loading rates. Another caution regarding column tests relates to loading rates from the columns. The absolute rate from columns can be much greater than that observed in the field due to high proportion of finer, more reactive material in the column, and due to accelerated rainfall cycles.

## 6.2. **RECOMMENDATIONS FOR FURTHER ASSESSMENT**

The intent of the Whistle waste rock project was to develop and illustrate technology for evaluating waste rock piles and to provide a database of information for characterizing the waste rock. The database collected is quite extensive and should be useful for supporting this purpose; however, it should be noted that the Whistle waste rock pile is different from the other waste rock piles at MEND study sites, and at other mines, in several ways:

- the waste rock is coarse and angular, and comprised of very large hard rocks;
- the pile was very difficult to drill and sample due to high porosity and large void spaces;
- the pile contains zones of rock fines, which are interspersed between the large rocks;
- air penetrates to the bottom of the pile, therefore the supply of oxygen is not limiting the oxidation of sulphide; and,
- the interior of the pile is cold, as noted from the temperature data collected, temperature of the collected seepage, and from field observations of venting of cold air from the base and top of the pile.

These differences should be kept in mind when attempting to apply the data and information obtained from the Whistle waste rock study to the interpretation of waste rock piles at other sites.

### **6.2.1. Additional Field Work**

A unique opportunity to expand the Whistle waste rock database will become available when the waste rock pile is relocated to the pit as part of site closure activities. When this occurs, it is recommended that further study be conducted while the pile is being relocated. The type of information that should be collected would include:

- an evaluation of the relative proportions of the Whistle rock types with depth;
- a systematic waste rock sampling and analysis program as excavation proceeds;
- an evaluation of secondary mineralization with depth;
- an assessment of grain size and structural characterization throughout the dump; and
- a detailed characterization of the “gossan” placed at the bottom of the dump.

The results should then be compared to the current study to see how closely they agree.

Since the Whistle waste rock pile is already acid generating, the entire pile, and the three lysimeters and four boreholes installed in the waste rock in 1995 could be studied in greater detail before the pile is relocated. There is no need for, and we do not recommend, the installation of additional lysimeters or boreholes in the pile; however, the main flow paths and the collection points for the pile seepage could be better defined and monitored.

Additional work to better define the drainage flow paths through the pile could be considered. The original topographic maps could be studied in more detail to define possible flow boundaries. Tracer studies could be useful for identifying the preferred flow paths through the pile. The paths of the tracers could be easily monitored by sampling the existing boreholes. Gaseous tracers could also be used to monitor gas flow through the pile. A more detailed structural analysis of the pile may yield additional refinements in unsaturated flow analysis of the pile.

Boreholes 2 and 3 currently contain 1.5 and 3 m of water above the bedrock surface, respectively. It is recommended that a study be undertaken to determine how much of the original gossan material that was placed on the bottom of the pile is currently under water.

The Whistle waste rock pile was constructed on top of an existing bog. The possible extent of the bog and the influence of the bog on the flow and quality of the acid mine drainage could be

investigated. For example, some level of sulphate reduction and precipitation of metals as metal sulphides could be occurring in the ponded water located at the base of the pile.

### **6.2.2. Additional Laboratory Test Work**

The chemical analyses and test work conducted for the Whistle waste rock program is considered to be adequate for characterization of the waste rock with the exception of a detailed mineralogical study as discussed below. We do not recommend any additional chemical analyses; however, there are several additional statistical analyses that could be performed with the existing database, which would improve the current understanding, for example:

- correlation analyses of chemical analytes and field measurements, which would be useful for planning programs for the sampling and characterization of waste rock piles, in general;
- statistical comparisons of the chemical analyses and extraction test results for rock fines versus the whole rock sample, which would support future predictive AMD modelling studies;
- spatial or geostatistical evaluations of specific parameters (e.g. NP, AP, leachable metals, etc.), which would support the characterization of specific zones of different material types within the pile.

In terms of primary mineralogy, the nature and distribution of the main minerals present in the various geologic units is well understood. Further studies could be conducted to quantify the nature of the carbonate mineralization in the waste rock. Calcite has been assessed through visual examination, the fizz test, and CO<sub>2</sub> analyses. The carbonate mineral siderite (FeCO<sub>3</sub>) was not observed; however, its presence is of interest because it may affect ABA test results by causing an overestimation of NP. Dolomite may also be present in the waste rock. It would be of interest to characterize the ratio of calcite to dolomite in the pile, and to determine if the CO<sub>2</sub> analyses reflect only calcite, or both calcite and dolomite. A combination of thin section analysis, mineral staining techniques, and HCl effervescence (fizz) testing could be used to differentiate and quantify the various carbonate minerals.

Secondary mineralization was characterized through visual examination and XRD analysis. A detailed mineralogical study including thin section analysis was not possible due to budgetary constraints but would be of great benefit in future studies. Further characterization of secondary

mineralization could be performed through the use of other techniques such as polished section petrography, scanning electron microscopy, and X-ray photoelectron spectroscopy.

The kinetic test work performed on the Whistle waste rock provided some interesting and useful information regarding the oxidation of sulphides and the release of contaminants, but it was obvious that the columns would not become strongly acid generating for a very long time under the conditions employed in the test due to the remaining inventory of buffering minerals present in the waste rock. Some additional shorter-term kinetic tests, such as small-scale humidity cells are recommended, to examine the possible influence of certain factors (i.e. pH, temperature, airflow, rain rate, etc. ) by examining different operating conditions for the humidity cells. Similar test work has already been performed through a separate research project at the University of Waterloo (Nicholson et al. 1996).

Additional study on bacterial catalyzed oxidation at low temperatures is required to understand their significance in the rate of oxidation at the Whistle site. This data would also help to determine the potential implications of low temperature, bacterially catalyzed oxidation for arctic and sub-arctic tailings, and waste rock, deposition.

### **6.2.3. Future Predictive Modelling**

The Whistle waste rock project was intended to acquire information for future predictive modelling of acid mine drainage; however, the current phase of the project did not involve any modelling. The field and laboratory programs have provided a good understanding of the major geochemical and physical processes that occur within the Whistle Mine waste rock pile. Any model(s) developed and/or applied at the Whistle pile in the future would be expected to consider most of these processes, and ideally, the possible interactions between these processes.

There are several types of modelling studies that could be considered for obtaining a greater understanding of the mechanisms of acid generation in the Whistle waste rock pile, and that would also provide useful information for understanding other similar waste rock piles:

- hydrological modelling to better define the paths of infiltration and seepage;
- chemical speciation modelling to identify the controlling minerals and other factors;
- empirical modelling to examine possible trends in the quality of the seepage leaving the

pile; and/or,

- geochemical modelling to better characterize the oxidation of sulphide, the generation of acid mine drainage, and the interaction of the minerals and porewater.

As part of an empirical modelling exercise a correction can be made based on comparison of particle size distributions and loading rates between the pile and the columns which would allow extrapolation of column oxidation rates to field oxidation rates based on existing data.

MEND 1.42.1 (1995) evaluates the available geochemical computer models with respect to their abilities to simulate geochemical processes to predict the quality of acid mine drainage. The existing models are divided into five classes: equilibrium thermodynamic models, mass transfer models, coupled mass transport-mass transfer models, support models, and empirical and engineering models. For information on the advantages and disadvantages, applications, etc. of specific models, please see MEND 1.42.1 (1995).

#### **6.2.4. Flow Through Waste Rock**

Flow through waste rock is undoubtedly a complex topic which requires further investigation; however it often the case that the current topic of interest in one discipline is, or has already been, studied in another. Soil scientists have been studying flow through unsaturated porous medium for years, (e.g. Bear 1972) while geotechnical engineers have looked at structural relationships between grain size, pore size distribution, film growth on rocks used in filter material for dams (Taylor and Jaffe, 1990), and of constriction sizes of pore spaces in dam filter material (Kenney et al., 1984).

We would suggest that a thorough review of existing research and theoretical relationships between rock structure, grain size, porosity, permeability etc. may assist in predicting flow through rock piles.

It may be of some benefit to construct a matrix of existing data on rock pile structure, climate, geology, age, water quality, water flow rates, etc. which can be used as a guideline to assist in determining potential environmental problems for other waste rock piles (based on a few key parameters).



### **6.2.5. Comments Regarding Decommissioning Options**

As of September 1997, the decommissioning option selected by INCO is relocation of waste rock back into the open pit followed by covering with an oxygen barrier, or impermeable cover. As described in Section 6.2.1 this will provide a unique opportunity to expand the Whistle waste rock database and expand the general knowledge waste rock dump structure.

A good understanding of the current rate and extent of acid generation, and the possible future profiles for release of acidity and metals is useful for evaluating this option. It may be possible that the data and information collected from the Whistle waste rock project can be used to support the evaluation of this decommissioning option.

Relocation of the Whistle waste rock to the pit could be complicated by the fact that some of the most acid material is located on the bottom of the pile; also, not all of the waste rock relocated to the pit would be completely flooded. The extraction/washing tests and the kinetic test work provided some information regarding the releasable fraction of contaminants.

The kinetic test work provided useful information for evaluating the effect of increasing the infiltration rate. However, there is little information available for describing the possible effects of reducing the infiltration rate from the current value by placement of a cover. Empirical estimates of the future contaminant loadings from the covered pile could be obtained by assuming lower rates for the leaching and release of the pre-dissolved contaminants. Geochemical (computer) modelling could also be used to examine the combined effects from reducing both the transport of oxygen and the infiltration rate, and to provide long-term predictions for the concentrations in the seepage released from a covered pile.

It will be necessary to conduct diffusion modelling of oxygen through the cover in order to evaluate the cover and accurately characterize the potential loadings from the site at closure.

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**Table 3.2-1: Whistle Waste Rock - Sample Test Work Analyses**

| Sample Location     | Number of Samples | Mineralogy XRD | Chemical Analysis * |            |               | Physical Analysis |          | Static ABA Testwork |               |          |               |
|---------------------|-------------------|----------------|---------------------|------------|---------------|-------------------|----------|---------------------|---------------|----------|---------------|
|                     |                   |                | Major               | ICAP       | Extract. Test | Lab Grain Size    | Weath.   | Modified Sobek      | BC Res. Init. | NAG      | Buff Np vs pH |
| Test Pits           | 61                | 5              | 78                  | 78         | 16            | 3                 | 0        | 46                  | 3             | 3        | 3             |
| Autopsy Zone        | 16                | 3              | 24                  | 24         | 7             | 0                 | 0        | 16                  | 1             | 1        | 1             |
| Whistle Wildcat     | 4                 | 0              | 5                   | 5          | 0             | 0                 | 0        | 4                   | 0             | 0        | 0             |
| Ore from Cruster    | 1                 | 0              | 1                   | 1          | 0             | 0                 | 0        | 1                   | 0             | 0        | 0             |
| Boreholes           | 58                | 0              | 31                  | 31         | 7             | 0                 | 0        | 20                  | 2             | 2        | 2             |
| <b>Total Number</b> | <b>140</b>        | <b>8</b>       | <b>139</b>          | <b>139</b> | <b>30</b>     | <b>3</b>          | <b>0</b> | <b>87</b>           | <b>6</b>      | <b>6</b> | <b>6</b>      |

Note:

- \* Chemical analysis performed separately for (1) whole rock and (2) whole rock and fine fraction (particles less than 2 mm diameter).
- \*\* Number of analysis includes duplicates.

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**Table 3.3-1: Sample/Monitoring Frequency And Associated Measurements/Analyses**

|   | <b>Monitoring Frequency</b>      | <b>Associated Measurements/ Analysis</b>          | <b>Total Number of Measurements/Analysis</b>   |
|---|----------------------------------|---|--|
| <b>PRECIPITATION</b>                                      |                                  |   |  |
| (rain/snow)   | Daily or Weekly on site readings | Additional data from Sudbury Airport              |  |
| <b>SEEPAGE DISCHARGE</b>                                  |                                  |   |  |
| Near Collection Pond                                      | Quarterly                        | Characterization                                  | 6  |
| <b>INFILTRATION</b>                                       |                                  |   |  |
| Lysimeters  | Quarterly                        | Volume + Chemical Characterization                | 8  |
| <b>BOREHOLES</b>  |                                  |   |  |
| waste rock boreholes                                      | Quarterly                        | Chemical Characterization                         | 31   |
| background  | Quarterly                        | Chemical Characterization                         | 7  |
| <b>GAS SAMPLING</b>                                       |                                  |   |  |
| waste rock boreholes<br>O <sub>2</sub><br>CO <sub>2</sub> | Quarterly                        | field measurements + some laboratory measurements | O <sub>2</sub> Field samples: 157 O <sub>2</sub> Lab samples: 5<br>CO <sub>2</sub> Field samples: 147 CO <sub>2</sub> Lab samples: 5 |
| <b>TEMPERATURE MEASUREMENTS</b>                           |                                  |   |  |
| waste rock boreholes                                      | Weekly                           | temperature                                       | 1904   |



**Table 4.1-1: Estimate Of The Quantity Of Waste Rock By Type In The Northeast Dump**

| <b>Rock Type</b>                         | <b>Quantity<br/>(tonnes)</b> | <b>Proportion of Pile<br/>(% by mass)</b> | <b>Estimated Sulphide Content<br/>(% by volume)</b> |
|--|------------------------------|---|---|
| Mafic Norite                             | 3,650,000                    | 83%                                       | variable, average 3%                                |
| Granitoid                                | 500,000                      | 10%                                       | generally <1% *                                     |
| Felsic Norite                            | 200,000                      | 4%  | <1%   |
| Gossan or Heavily<br>Oxidized Waste Rock | 50,000 *                     | 1%  | >20%*   |
| Ore                                      | 50,000 *                     | 1%  | >20%*   |
| Sand/Overburden/Soil                     | 50,000 *                     | 1%  | nil   |
| Total                                    | 5,000,000                    | 100%                                      | 3%  |

Notes:

\* Approximate quantities

Estimate of sulphide content based on visual observation

**Table 4.2-1: Relative Abundance Of Bacteria**

| <b>LIGHT MICROSCOPY OF FIRST SUBCULTURE</b>                  |                        |  |                   |                             |
|--|------------------------|--|-------------------|-----------------------------|
| <b>Location</b>  | <b>Medium</b>          |  |                   |                             |
|  | <b>Fe<sup>2+</sup></b> | <b>S<sub>2</sub>O<sub>5</sub><sup>2-</sup></b> | <b>Pyrrhotite</b> | <b>Fe<sup>2+</sup>, 8°C</b> |
| RC-BAC1  | +                      | ++   | ++                | +++                         |
| RC-BAC2  | +                      | +  | -                 | ++                          |
| TP2-BAC1   | +++                    | +++  | ++                | +++                         |
| TP2-BAC2   | +++                    | +  | +                 | ++                          |
| TP3-BAC1   | +                      | ++   | +                 | +++                         |
| TP3-BAC2   | +++                    | ++   | +                 | +++                         |
| <b><i>PHASE-CONTRAST MICROSCOPY OF SECOND SUBCULTURE</i></b> |                        |  |                   |                             |
| RC-BAC1  | +                      | +  |                   |                             |
| RC-BAC2  | -                      | -  |                   |                             |
| TP2-BAC1   | ++                     | ++   |                   |                             |
| TP2-BAC2   | +                      | -  |                   |                             |
| TP3-BAC1   | ++                     | +  |                   |                             |
| TP3-BAC2   | +++                    | ++   |                   |                             |

+++ between 3 to 5 cells in field of view  
 ++ between 1 to 3 cells in field of view  
 + only a few cells on the entire slide  
 - no cells were found

**Table 4.3-1: Monthly Precipitation And Temperature Data**

|        | Average Temperature (°C) |        | Monthly Total Precipitation (mm) |        |        |
|--------|--------------------------|--------|----------------------------------|--------|--------|
|        | Airport                  | Normal | Airport                          | Normal | Site   |
| Aug-95 | 19.3                     | 17.4   | 72.0                             | 87.4   | 22.3   |
| Sep-95 | 10.9                     | 12.3   | 62.2                             | 102.9  | 68.3 * |
| Oct-95 | 7.4                      | 6.1    | 93.0                             | 76.0   | 91.2 * |
| Nov-95 | -5.9                     | -1.3   | 112.8                            | 79.3   | -      |
| Dec-95 | -12.2                    | -9.9   | 55.3                             | 66.2   | -      |
| Jan-96 | -14.6                    | -13.5  | 92.5                             | 60.3   | 6.5    |
| Feb-96 | -12.8                    | -11.9  | 87.3                             | 48.6   | 30.2   |
| Mar-96 | -7.8                     | -5.6   | 26.0                             | 61.4   | 5.5    |
| Apr-96 | 0.2                      | 3.0    | 127.3                            | 63.2   | 4.6    |
| May-96 | 9.5                      | 10.8   | 37.2                             | 71.1   | 10.7   |
| Jun-96 | 17.4                     | 15.8   | 56.6                             | 84.1   | 41.0   |
| Jul-96 | 17.8                     | 19.1   | 95.3                             | 71.3   | >51.2  |
| Aug-96 | 18.3                     | 17.4   | 57.6                             | 87.3   | 71     |
| Sep-96 | 14.5                     | 12.3   | 166.0                            | 103.0  | >71.6  |
| Oct-96 | 5.8                      | 6.1    | 75.8                             | 76.0   | >95.4  |
| Nov-96 | -3.5                     | -1.3   | 51.0                             | 79.3   | 33.6 * |
| Dec-96 |                          |        |                                  |        | -      |

Normals based on thirty year averages from Sudbury Airport

Errors in on-site measurements may have resulted from overtopping of guage

- no reading

\* precipitation as snowfall

**Table 4.3-2: Lysimeter Recharge Data**

| Date             | Recharge to Test Pits |                          |            |                          |            |                          |
|------------------|-----------------------|--------------------------|------------|--------------------------|------------|--------------------------|
|                  | TP1                   |                          | TP2        |                          | TP3        |                          |
|                  | Volume (L)            | Equivalent Rainfall (mm) | Volume (L) | Equivalent Rainfall (mm) | Volume (L) | Equivalent Rainfall (mm) |
| January 30, 1996 | N/M                   |                          | N/M        |                          | N/M        |                          |
| May 1, 1996      | 0.465                 | 0.02                     | 0.435      | 0.02                     | dry        | -                        |
| May 8, 1996      | dry                   | -                        | 0.005      | 0.0002                   | 0.097      | 0.004                    |
| August 22, 1996  | 1.4                   | 0.06                     | dry        | -                        | N/M        | -                        |
| October 30, 1996 | 0.450                 | 0.02                     | 4.0        | 0.16                     | 0.451      | 0.02                     |

Notes:

N/M - not measured

Lysimeter surface area = 25 m<sup>2</sup>

$$\text{Equivalent Rainfall (mm)} = \frac{\text{Volume (m}^3\text{)}}{\text{Area (m}^2\text{)}} \times \frac{1000 \text{ mm}}{1 \text{ m}}$$

**Table 4.3-3: Summary Of Piezometer And Test Pit Installations**

| BOREHOLE           |       | UTMCO-ORDINATES (m) |         | GROUND          | STICK-UP | TOP OF              | BOREHOLE        | RISER PIPE      | SCREEN           |   | SAND FILTER      |        | UNIT |        |                       |
|--------------------|-------|---------------------|---------|-----------------|----------|---------------------|-----------------|-----------------|------------------|---|------------------|--------|------|--------|-----------------------|
| NO.                | PIEZ. | NORTHING            | EASTING | ELEV.<br>(masl) | (m)      | CASING ELEV.<br>(m) | DEPTH<br>(mbgs) | DIAMETER<br>(m) | ELEVATION<br>(m) |   | ELEVATION<br>(m) |        |      |        |                       |
| 95-1               | A     | 5179960             | 509635  | 370.69          | 0.8      | 371.49              | 32.92           | 0.025           | 338.57           | - | 340.09           | 338.57 | -    | 341.29 | Bedrock               |
|                    | B     | 5179960             | 509635  | 370.69          | 0.8      | 371.49              | 29.67           | 0.051           | 341.82           | - | 343.34           | 341.82 | -    | 343.69 | Overburden/Waste Rock |
| 95-2               | A     | 3179913             | 509705  | 370.55          | 1.1      | 371.65              | 36.58           | 0.025           | 335.07           | - | 336.59           | 335.07 | -    | 338.15 | Bedrock               |
|                    | B     | 3179913             | 509705  | 370.55          | 1.1      | 371.65              | 33.22           | 0.051           | 338.43           | - | 339.95           | 338.43 | -    | 340.35 | Overburden/Waste Rock |
| 95-3               | A     | 5179971             | 509696  | 370.81          | 1        | 371.81              | 37.49           | 0.025           | 334.32           | - | 335.84           | 334.32 | -    | 338.17 | Bedrock               |
|                    | B     | 5179971             | 509696  | 370.81          | 1        | 371.81              | 35.05           | 0.051           | 336.76           | - | 338.28           | 336.76 | -    | 339.20 | Overburden/Waste Rock |
| 95-4               | A     | 5179933             | 509591  | 371.46          | 1.25     | 372.71              | 31.09           | 0.025           | 341.62           | - | 343.14           | 341.62 | -    | 343.72 | Bedrock               |
|                    | B     | 5179933             | 509591  | 371.46          | 1.25     | 372.71              | 28.8            | 0.051           | 343.91           | - | 345.43           | 343.91 | -    | 346.61 | Overburden/Waste Rock |
| 95-5*              |       | See Figure 1.4-1    |         | 321             | 1        | 322                 | 22.58           | 0.051           | 299.42           | - | 300.94           | n/a    | -    | n/a    | Sand                  |
| W-MW1              |       | See Figure 1.4-1    |         | 319.9           | 0.88     | 320.78              | 5.18            | 0.051           | 315.60           | - | 318.65           | n/a    | -    | n/a    | Sand                  |
| TP#1               |       | 5179915             | 509680  | 370.33          |          |                     |                 | 0.076           |                  |   |                  |        |      |        | Waste Rock            |
| TP#2               |       | 5179950             | 509600  | 371.57          |          |                     |                 | 0.076           |                  |   |                  |        |      |        |                       |
| TP#3               |       | 5179967             | 509646  | 370.41          |          |                     |                 | 0.076           |                  |   |                  |        |      |        |                       |
| Seepage Collection |       |                     |         | 334             |          |                     |                 |                 |                  |   |                  |        |      |        |                       |

Notes: \* Location and Elevation estimated based on 1:2000 topographic mapping. All other elevations were surveyed by INCO Limited.

mbgs: meters below ground surface

masl: meters above sea level

**Table 4.3-4: Summary Of Water Table Elevations**

| BOREHOLE |       | WATER TABLE ELEVATIONS (masl) |           |           |          |           |           |
|----------|-------|-------------------------------|-----------|-----------|----------|-----------|-----------|
|          |       | 1-Dec-95                      | 15-Dec-95 | 30-Jan-96 | 2-May-96 | 22-Aug-96 | 29-Oct-95 |
| NO.      | PIEZ. |                               |           |           |          |           |           |
| 95-1     | A     | 339.99                        | 339.71    | n/m       | 340.84   | 339.57    | 340.11    |
|          | B     | dry                           | dry       | n/m       | dry      | dry       | dry       |
| 95-2     | A     | 338.85                        | 338.78    | 338.80    | 340.36   | 338.79    | 338.92    |
|          | B     | 338.85                        | 338.78    | 338.82    | 340.36   | 338.79    | 338.92    |
| 95-3     | A     | 338.76                        | 338.76    | 338.77    | 340.58   | 338.76    | 338.82    |
|          | B     | 338.79                        | 338.76    | 338.76    | 340.26   | 338.76    | 338.83    |
| 95-4     | A     | 343.11                        | 343.11    | n/m       | 343.65   | 342.95    | 343.3     |
|          | B     | dry                           | dry       | n/m       | 344.06   | dry       | dry       |
| 95-5*    |       | n/m                           | n/m       | n/m       | 320.69   | n/m       | 320.37    |
| W-MW1    |       | n/m                           | n/m       | n/m       | n/m      | n/m       | 319.64    |

Note: masl: meters above sea level.

n/m: no measurement

**Table 4.3-5: Seepage Water Quality Data (For Selected Parameters)**

| Parameter              | Unit                      | SEEPAGE  |           |          |           |          | Average |
|------------------------|---------------------------|----------|-----------|----------|-----------|----------|---------|
|                        |                           | 5-Oct-95 | 29-Jan-96 | 8-May-96 | 22-Aug-96 | 1-Nov-96 |         |
| <i>Field Chemistry</i> |                           |          |           |          |           |          |         |
| pH                     | pH unit                   | 3.7      | n/a       | 4.2      | 3.65      | n/a      | 3.9     |
| EH                     | mV                        | 438      | n/a       | 361      | 370       | n/a      | 389.7   |
| Conductivity           | µS                        | 4400     | n/a       | 3800     | 4200      | n/a      | 4133.3  |
| Temperature            | °C                        | 4        | n/a       | 4        | 9         | n/a      | 5.7     |
| Alkalinity             | mg/L as CaCO <sub>3</sub> | nil      | n/a       | nil      | nil       | n/a      |         |
| <i>Lab Chemistry</i>   |                           |          |           |          |           |          |         |
| Iron (Fe)              | mg/L                      | 5.1      | n/a       | 1.6      | 6.9       | 0.73     | 3.6     |
| Nickel (Ni)            | mg/L                      | 297      | n/a       | 175      | 223       | 118      | 203.3   |
| Copper (Cu)            | mg/L                      | 13.4     | n/a       | 9.5      | 11.7      | 3.51     | 9.5     |
| Cobalt (Co)            | mg/L                      | 12.7     | n/a       | 10.2     | 9.0       | 4.32     | 9.1     |
| Zinc (Zn)              | mg/L                      | 7.6      | n/a       | 6.7      | 5.6       | 3.11     | 5.8     |
| Sulphate               | mg/L                      | 5200     | n/a       | 3600     | 3890      | 1760     | 3612.5  |

N/S - No sample

n/a - no analysis

**Table 4.3-6: Borehole Water Quality Data (For Selected Parameters)**

| Parameter              | Unit                      | BAH - 1A |           |          |           |          | Average | BAH - 1B |           |          |           |          | Average |
|------------------------|---------------------------|----------|-----------|----------|-----------|----------|---------|----------|-----------|----------|-----------|----------|---------|
|                        |                           | 5-Oct-95 | 29-Jan-96 | 8-May-96 | 22-Aug-96 | 1-Nov-96 |         | 5-Oct-95 | 29-Jan-96 | 8-May-96 | 22-Aug-96 | 1-Nov-96 |         |
| <b>Field Chemistry</b> |                           |          |           |          |           |          |         |          |           |          |           |          |         |
| pH                     | pH unit                   | 4.1      | 4.5       | 4.05     | 3.97      | 4.13     | 4.2     | N/A      | N/A       | dry      | N/A       | N/A      |         |
| EH                     | mV                        | 58       | 285       | 400      | 363       | 337      | 288.6   | n/a      | n/a       | dry      | n/a       | n/a      |         |
| Conductivity           | mS                        | 6100     | 9200      | 9600     | 9200      | 10100    | 8840.0  | n/a      | n/a       | dry      | n/a       | n/a      |         |
| Temperature            | °C                        | 7.5      | 4.5       | n/a      | 15        | 7        | 8.5     | n/a      | n/a       | dry      | n/a       | n/a      |         |
| Alkalinity             | mg/L as CaCO <sub>3</sub> | nil      | nil       | nil      | nil       | 105      | 105.0   | n/a      | n/a       | dry      | n/a       | n/a      |         |
| <b>Lab Chemistry</b>   |                           |          |           |          |           |          |         |          |           |          |           |          |         |
| Iron (Fe)              | mg/L                      | 79.8     | 74.5      | 2.76     | 6.5       | 4.4      | 33.6    | n/a      |           |          | n/a       | n/a      |         |
| Nickel (Ni)            | mg/L                      | 483      | 739       | 954      | 705       | 828      | 741.8   | n/a      |           |          | n/a       | n/a      |         |
| Copper (Cu)            | mg/L                      | 8.54     | 19.1      | 23       | 21.2      | 28.8     | 20.1    | n/a      |           |          | n/a       | n/a      |         |
| Cobalt (Co)            | mg/L                      | 20.8     | 38        | 42.2     | 29.1      | 35.4     | 33.1    | n/a      |           |          | n/a       | n/a      |         |
| Zinc (Zn)              | mg/L                      | 29.3     | 46.4      | 43.2     | 43.1      | 56.5     | 43.7    | n/a      |           |          | n/a       | n/a      |         |
| Sulphate               | mg/L                      | 7540     | 11000     | 18100    | 10200     | 13800    | 12128.0 | n/a      |           |          | n/a       | n/a      |         |
| Parameter              | Unit                      | BH-2A    |           |          |           |          | Average | BH - 2B  |           |          |           |          | Average |
|                        |                           | 5-Oct-95 | 29-Jan-96 | 8-May-96 | 22-Aug-96 | 1-Nov-96 |         | 5-Oct-95 | 29-Jan-96 | 8-May-96 | 22-Aug-96 | 1-Nov-96 |         |
| <b>Field Chemistry</b> |                           |          |           |          |           |          |         |          |           |          |           |          |         |
| pH                     | pH unit                   | 4.2      | 4.32      | 4.38     | 4.06      | 4.1      | 4.2     | 4.3      | 4.28      | 4.48     | 4.21      | 4.21     | 4.3     |
| EH                     | mV                        | 183      | 247       | 266      | 279       | 296      | 254.2   | 230      | 251       | 256      | 267.3     | 263      | 253.5   |
| Conductivity           | mS                        | > 2000   | n/a       | 8200     | 9400      | 9800     | 9133.3  | > 2000   | 7100      | 7500     | 7500      | 8000     | 7525.0  |
| Temperature            | °C                        | 12       | 8         | 15       | 16        | 7        | 11.6    | 8.5      | 8         | 9        | 16        | 7        | 9.7     |
| Alkalinity             | mg/L as CaCO <sub>3</sub> | nil      | nil       | nil      | nil       | 144      | 144.0   | 30       | nil       | nil      | 18        | 102      | 50.0    |
| <b>Lab Chemistry</b>   |                           |          |           |          |           |          |         |          |           |          |           |          |         |
| Iron (Fe)              | mg/L                      | 85       | 136       | 136      | 159       | 67.5     | 116.7   | 141      | 128       | 151      | 88.6      | 151      | 131.9   |
| Nickel (Ni)            | mg/L                      | 666      | 803       | 734      | 487       | 778      | 693.6   | 446      | 548       | 595      | 784       | 513      | 577.2   |
| Copper (Cu)            | mg/L                      | 16.6     | 13.4      | 5.89     | 5.5       | 46.6     | 17.6    | 4.28     | 4.42      | 2.87     | 23.1      | 9.8      | 8.9     |
| Cobalt (Co)            | mg/L                      | 28.2     | 40.6      | 34.2     | 20.4      | 33.5     | 31.4    | 18.9     | 27.2      | 28.6     | 34        | 21.1     | 26.0    |
| Zinc (Zn)              | mg/L                      | 14.2     | 16.9      | 9.25     | 9         | 22.5     | 14.4    | 6.67     | 6.72      | 7.38     | 20.3      | 10.4     | 10.3    |
| Sulphate               | mg/L                      | 8720     | 13200     | 9600     | 10500     | 12900    | 10984.0 | 7500     | 8200      | 11900    | 7470      | 9190     | 8852.0  |
| Parameter              | Unit                      | BH-3A    |           |          |           |          | Average | BH - 3B  |           |          |           |          | Average |
|                        |                           | 5-Oct-95 | 29-Jan-96 | 8-May-96 | 22-Aug-96 | 1-Nov-96 |         | 5-Oct-95 | 29-Jan-96 | 8-May-96 | 22-Aug-96 | 1-Nov-96 |         |
| <b>Field Chemistry</b> |                           |          |           |          |           |          |         |          |           |          |           |          |         |
| pH                     | pH unit                   | 4.3      | 4.24      | 4.51     | 3.96      | 4.41     | 4.3     | 4.4      | n/a       | 4.5      | 4.31      | 4.48     | 4.4     |
| EH                     | mV                        | 179      | 233       | 236      | 226.7     | 238      | 222.5   | 57       | n/a       | 247      | 234       | 259      | 199.3   |
| Conductivity           | mS                        | 8300     | 9200      | 8800     | 8800      | 8700     | 8760.0  | 8500     | n/a       | 8700     | 8900      | 7800     | 8475.0  |
| Temperature            | °C                        | n/a      | 6         | n/a      | 15        | 6        | 9.0     | n/a      | n/a       | 13       | 16        | 6        | 11.7    |
| Alkalinity             | mg/L as CaCO <sub>3</sub> | nil      | nil       | nil      | 30        | 120      | 75.0    | 0.5      | n/a       | 8        | 51        | 93       | 38.1    |
| <b>Lab Chemistry</b>   |                           |          |           |          |           |          |         |          |           |          |           |          |         |
| Iron (Fe)              | mg/L                      | 164      |           | 186      | 207       | 206      | 190.8   | 159      |           | 167      | 212       | 138      | 169.0   |
| Nickel (Ni)            | mg/L                      | 760      |           | 845      | 768       | 733      | 776.5   | 663      |           | 843      | 765       | 587      | 714.5   |
| Copper (Cu)            | mg/L                      | <1       |           | <0.01    | <0.1      | <0.1     |         | 1.08     |           | 1.98     | 0.5       | 2        | 1.4     |
| Cobalt (Co)            | mg/L                      | 35.8     |           | 45.7     | 37.1      | 35.2     | 38.5    | 30.7     |           | 41.1     | 36.9      | 278      | 96.7    |
| Zinc (Zn)              | mg/L                      | 10.1     |           | 9.15     | 9.9       | 9        | 9.5     | 8.58     |           | 9.03     | 9.6       | 7.9      | 8.8     |
| Sulphate               | mg/L                      | 9130     |           | 13250    | 9280      | 10200    | 10465.0 | 8780     |           | 12400    | 8960      | 8750     | 9722.5  |



**Table 4.3-6 (Continued): Borehole Water Quality Data (For Selected Parameters)**

| Parameter              | Unit                      | BH-4A    |           |          |           |          | Average | BH - 4B  |           |          |           |          | Average |
|------------------------|---------------------------|----------|-----------|----------|-----------|----------|---------|----------|-----------|----------|-----------|----------|---------|
|                        |                           | 5-Oct-95 | 29-Jan-96 | 8-May-96 | 22-Aug-96 | 1-Nov-96 |         | 5-Oct-95 | 29-Jan-96 | 8-May-96 | 22-Aug-96 | 1-Nov-96 |         |
| <b>Field Chemistry</b> |                           |          |           |          |           |          |         |          |           |          |           |          |         |
| pH                     | pH unit                   | 4.3      | 3.92      | 4.08     | 3.85      | 4.07     | 4.0     | n/a      | n/a       | dry      | n/a       | n/a      |         |
| EH                     | mV                        | 130      | 288       | 400      | 325       | 394      | 307.4   | n/a      | n/a       | dry      | n/a       | n/a      |         |
| Conductivity           | mS                        | > 2000   | 12300     | 10100    | 10700     | 10800    | 10975.0 | n/a      | n/a       | dry      | n/a       | n/a      |         |
| Temperature            | °C                        | 7.5      | 6.5       | 9        | 15        | 4        | 8.4     | n/a      | n/a       | dry      | n/a       | n/a      |         |
| Alkalinity             | mg/L as CaCO <sub>3</sub> | nil      | nil       | nil      | 8         | 69       | 38.5    | n/a      | n/a       | dry      | n/a       | n/a      |         |
| <b>Lab Chemistry</b>   |                           |          |           |          |           |          |         |          |           |          |           |          |         |
| Iron (Fe)              | mg/L                      | 271      | 432       | 5.35     | 30.4      | 5.5      | 148.9   | n/a      |           |          | n/a       | n/a      |         |
| Nickel (Ni)            | mg/L                      | 438      | 780       | 690      | 663       | 696      | 653.4   | n/a      |           |          | n/a       | n/a      |         |
| Copper (Cu)            | mg/L                      | <1       | 8.86      | 17       | 23.1      | 18.4     | 16.8    | n/a      |           |          | n/a       | n/a      |         |
| Cobalt (Co)            | mg/L                      | 20.8     | 41.5      | 36       | 33.1      | 33.9     | 33.1    | n/a      |           |          | n/a       | n/a      |         |
| Zinc (Zn)              | mg/L                      | <1       | 8.75      | 6.12     | 7.4       | 7.6      | 7.5     | n/a      |           |          | n/a       | n/a      |         |
| Sulphate               | mg/L                      | 9660     | 14500     | 5418     | 13200     | 6500     | 9855.6  | n/a      |           |          | n/a       | n/a      |         |
| Parameter              | Unit                      | BH-5     |           |          |           |          | Average | W-MW1    |           |          |           |          | Average |
|                        |                           | 5-Oct-95 | 29-Jan-96 | 8-May-96 | 22-Aug-96 | 1-Nov-96 |         | 5-Oct-95 | 29-Jan-96 | 8-May-96 | 22-Aug-96 | 1-Nov-96 |         |
| <b>Field Chemistry</b> |                           |          |           |          |           |          |         |          |           |          |           |          |         |
| pH                     | pH unit                   | 6.3      | n/a       | 7.43     | 7.67      | 7.42     | 7.2     | n/a      | n/a       | 6.96     | 6.86      | 6.72     | 6.8     |
| EH                     | mV                        | 124      | n/a       | 214      | 236       | n/a      | 191.3   | n/a      | n/a       | 261      | 260       | 164      | 228.3   |
| Conductivity           | mS                        | 260      | n/a       | 270      | 250       | 250      | 257.5   | n/a      | n/a       | 300      | 540       | 680      | 506.7   |
| Temperature            | °C                        | n/a      | n/a       | 7        | 15        | 9        | 10.3    | n/a      | n/a       | 9        | 15        | 10       | 11.3    |
| Alkalinity             | mg/L as CaCO <sub>3</sub> | 127.5    | n/a       | 38.5     | 159       | 192      | 129.3   | n/a      | n/a       | 103      | 63        | 132      | 99.3    |
| <b>Lab Chemistry</b>   |                           |          |           |          |           |          |         |          |           |          |           |          |         |
| Iron (Fe)              | mg/L                      | <0.01    |           | 0.132    | 0.2       | 0.3      | 0.2     |          |           | 0.39     | 0.3       | 0.2      | 0.3     |
| Nickel (Ni)            | mg/L                      | <0.05    |           | 0.033    | <0.5      | <0.5     | <0.5    |          |           | 0.071    | <0.5      | 0.5      | 0.29    |
| Copper (Cu)            | mg/L                      | <0.01    |           | <0.01    | <0.1      | <0.1     | <0.1    |          |           | 0.014    | <0.1      | <0.1     | 0.01    |
| Cobalt (Co)            | mg/L                      | <0.01    |           | <0.01    | <0.1      | <0.1     | <0.1    |          |           | <0.010   | <0.1      | <0.1     |         |
| Zinc (Zn)              | mg/L                      | <1       |           | 0.012    | <0.1      | <0.1     | <1      |          |           | 0.011    | <0.1      | <0.1     | 0.01    |
| Sulphate               | mg/L                      | 25.3     |           | 39       | 14        | 246      | 81.1    |          |           | 39       | 90        | 204      | 111.0   |

**Table 4.3-7: Lysimeter Water Quality Data (For Selected Parameters)**

| Parameter              | Unit                      | TP-1     |           |          |           |          | Average | TP-      |           |          |           |          | Average |
|------------------------|---------------------------|----------|-----------|----------|-----------|----------|---------|----------|-----------|----------|-----------|----------|---------|
|                        |                           | 5-Oct-95 | 29-Jan-96 | 8-May-96 | 22-Aug-96 | 1-Nov-96 |         | 5-Oct-95 | 29-Jan-96 | 8-May-96 | 22-Aug-96 | 1-Nov-96 |         |
| <b>Field Chemistry</b> |                           |          |           |          |           |          |         |          |           |          |           |          |         |
| pH                     | pH unit                   | n/a      | n/a       | dry      | 5.17      | 6.56     | 5.9     | n/a      | n/a       | 8.05     | n/a       | 4.87     | 6.5     |
| EH                     | mV                        | n/a      | n/a       | dry      | 307       | 315      | 311.0   | n/a      | n/a       | 247      | n/a       | 303      | 275.0   |
| Conductivity           | µS                        | n/a      | n/a       | dry      | 1050      | 430      | 740.0   | n/a      | n/a       | 610      | n/a       | 1530     | 1070.0  |
| Temperature            | °C                        | n/a      | n/a       | dry      | 16        | 4        | 10.0    | n/a      | n/a       | n/a      | n/a       | 6        | 6.0     |
| Alkalinity             | mg/L as CaCO <sub>3</sub> | n/a      | n/a       | dry      | 18        | 33       | 25.5    | n/a      | n/a       | 28       | n/a       | 27       | 27.5    |
| <b>Lab Chemistry</b>   |                           |          |           |          |           |          |         |          |           |          |           |          |         |
| Iron (Fe)              | mg/L                      | n/a      | n/a       |          | 0.3       | <0.1     | 0.3     | dry      | 299       |          | n/a       | 1.1      | 150.1   |
| Nickel (Ni)            | mg/L                      | n/a      | n/a       |          | 8.6       | 2.5      | 5.6     | dry      | 10.3      |          | n/a       | 9.9      | 10.1    |
| Copper (Cu)            | mg/L                      | n/a      | n/a       |          | <0.1      | <0.1     | <0.1    | dry      | 1.29      |          | n/a       | 0.3      | 0.8     |
| Cobalt (Co)            | mg/L                      | n/a      | n/a       |          | 0.3       | <0.1     | 0.3     | dry      | 0.567     |          | n/a       | 0.4      | 0.5     |
| Zinc (Zn)              | mg/L                      | n/a      | n/a       |          | 0.1       | <0.1     | 0.1     | dry      | 0.574     |          | n/a       | 0.3      | 0.4     |
| Sulphate               | mg/L                      | n/a      | n/a       |          | 598       | 248      | 423.0   | dry      | 885       |          | n/a       | 971      | 928.0   |
|                        |                           |          |           |          |           |          |         |          |           |          |           |          |         |
| Parameter              | Unit                      | TP -3    |           |          |           |          | Average |          |           |          |           |          |         |
| 5-Oct-95               | 29-Jan-96                 | 8-May-96 | 22-Aug-96 | 1-Nov-96 |           |          |         |          |           |          |           |          |         |
| <b>Field Chemistry</b> |                           |          |           |          |           |          |         |          |           |          |           |          |         |
| pH                     | pH unit                   | n/a      | n/a       | 7.55     | 6.64      | 6.56     | 6.9     |          |           |          |           |          |         |
| EH                     | mV                        | n/a      | n/a       | 240      | 244       | 167      | 217.0   |          |           |          |           |          |         |
| Conductivity           | µS                        | n/a      | n/a       | 230      | 1710      | 8000     | 3313.3  |          |           |          |           |          |         |
| Temperature            | °C                        | n/a      | n/a       | n/a      | 16        | 4        | 10.0    |          |           |          |           |          |         |
| Alkalinity             | mg/L as CaCO <sub>3</sub> | n/a      | n/a       | 20       | 24        | 24       | 22.7    |          |           |          |           |          |         |
| <b>Lab Chemistry</b>   |                           |          |           |          |           |          |         |          |           |          |           |          |         |
| Iron (Fe)              | mg/L                      | n/a      |           | 0.135    | 0.1       | <0.5     | 0.1     |          |           |          |           |          |         |
| Nickel (Ni)            | mg/L                      | n/a      |           | 0.183    | 3.7       | <0.1     | 1.9     |          |           |          |           |          |         |
| Copper (Cu)            | mg/L                      | n/a      |           | 0.014    | <0.1      | <0.1     | <0.1    |          |           |          |           |          |         |
| Cobalt (Co)            | mg/L                      | n/a      |           | <0.01    | <0.1      | <0.1     | <0.1    |          |           |          |           |          |         |
| Zinc (Zn)              | mg/L                      | n/a      |           | <0.01    | <0.1      | <0.1     | <0.1    |          |           |          |           |          |         |
| Sulphate               | mg/L                      | n/a      |           | 106      | 1000      | 28       | 378.0   |          |           |          |           |          |         |

**Table 4.3-8 Gas Sampling Data**

|           |  | <b>BH - 1</b>        |            |          |           |                       |          |            |          |           |          |
|-----------|--|----------------------|------------|----------|-----------|-----------------------|----------|------------|----------|-----------|----------|
|           |  | <b>O<sub>2</sub></b> |            |          |           | <b>CO<sub>2</sub></b> |          |            |          |           |          |
| Depth (m) |  | 5-Oct-95             | 29-Jan-96* | 4-Jun-96 | 23-Aug-96 | 1-Nov-96              | 5-Oct-95 | 29-Jan-96* | 4-Jun-96 | 23-Aug-96 | 1-Nov-96 |
| 21        |  | 19.8%                | n/a        | 20.6%    | 19.5%     | n/a                   | 0.2%     | n/a        | 0.0%     | 0.0%      | n/a      |
| 16        |  | 20.2%                | n/a        | 20.6%    | 19.6%     | n/a                   | 0.1%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 11        |  | 20.1%                | n/a        | 20.6%    | 19.6%     | n/a                   | 0.1%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 8         |  | 20.2%                | n/a        | 20.6%    | 19.5%     | n/a                   | 0.0%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 6         |  | 20.2%                | n/a        | 20.6%    | 19.5%     | n/a                   | 0.1%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 4.5       |  | 20.2%                | n/a        | 20.6%    | 19.5%     | n/a                   | 0.1%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 3         |  | 20.1%                | n/a        | 20.6%    | 19.4%     | n/a                   | 0.1%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 2         |  | 20.1%                | n/a        | 20.4%    | 19.4%     | n/a                   | 0.1%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 0         |  | 20.3%                | n/a        | n/a      | 19.6%     | n/a                   | 0.0%     | n/a        | n/a      | 0.0%      | 0.0%     |
|           |  | <b>BH - 2</b>        |            |          |           |                       |          |            |          |           |          |
|           |  | <b>O<sub>2</sub></b> |            |          |           | <b>CO<sub>2</sub></b> |          |            |          |           |          |
| Depth (m) |  | 5-Oct-95             | 29-Jan-96* | 4-Jun-96 | 23-Aug-96 | 1-Nov-96              | 5-Oct-95 | 29-Jan-96* | 4-Jun-96 | 23-Aug-96 | 1-Nov-96 |
| 0         |  | 20.3%                | n/a        | n/a      | 20.0%     | n/a                   | 0.1%     | n/a        | n/a      | 0.0%      | n/a      |
| 31        |  | 20.3%                | 20.9%      | n/a      | 20.0%     | n/a                   | 0.1%     | n/a        | n/a      | 0.0%      | 0.0%     |
| 26        |  | 20.3%                | 20.9%      | 20.7%    | 20.0%     | n/a                   | 0.1%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 21        |  | 20.0%                | 18.4%      | 20.6%    | 20.1%     | n/a                   | 0.2%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 16        |  | n/a                  | n/a        | 20.7%    | n/a       | n/a                   | n/a      | n/a        | 0.0%     | n/a       | 0.0%     |
| 11        |  | 20.1%                | n/a        | 20.8%    | 19.9%     | n/a                   | 0.1%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 8         |  | 20.1%                | n/a        | 20.6%    | 19.8%     | n/a                   | 0.1%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 6         |  | 20.2%                | n/a        | 20.5%    | 19.8%     | n/a                   | 0.1%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 4.5       |  | 20.1%                | n/a        | 20.5%    | n/a       | n/a                   | 0.1%     | n/a        | 0.0%     | n/a       | 0.0%     |
| 3         |  | 20.1%                | n/a        | 20.5%    | 19.8%     | n/a                   | 0.1%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 2         |  | 20.1%                | 20.9%      | n/a      | n/a       | n/a                   | 0.1%     | n/a        | n/a      | n/a       | n/a      |
|           |  | <b>BH - 3</b>        |            |          |           |                       |          |            |          |           |          |
|           |  | <b>O<sub>2</sub></b> |            |          |           | <b>CO<sub>2</sub></b> |          |            |          |           |          |
| Depth (m) |  | 5-Oct-95             | 29-Jan-96* | 4-Jun-96 | 23-Aug-96 | 1-Nov-96              | 5-Oct-95 | 29-Jan-96* | 4-Jun-96 | 23-Aug-96 | 1-Nov-96 |
| 0         |  | 20.3%                | n/a        | n/a      | 19.6%     | n/a                   | 0.0%     | n/a        | n/a      | 0.0%      | n/a      |
| #1 (4)    |  | 20.3%                | 20.7%      | 20.7%    | 19.8%     | n/a                   | 0.0%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| #2 (1)    |  | 20.3%                | 20.9%      | 20.7%    | 19.9%     | n/a                   | 0.0%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| #3 (31)   |  | 20.0%                | 20.9%      | 20.0%    | 19.5%     | n/a                   | 0.1%     | n/a        | 0.1%     | 0.0%      | 0.0%     |
| #4 (?)    |  | 20.3%                | 20.9%      | 20.2%    | 19.8%     | n/a                   | 0.0%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| #5 (26)   |  | 20.2%                | n/a        | 20.2%    | 19.7%     | n/a                   | 0.0%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| #6 (?)    |  | 20.3%                | n/a        | 20.6%    | 19.7%     | n/a                   | 0.0%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 36        |  | 20.2%                | 20.6%      | 20.7%    | 19.7%     | n/a                   | 0.1%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
|           |  | <b>BH - 4</b>        |            |          |           |                       |          |            |          |           |          |
|           |  | <b>O<sub>2</sub></b> |            |          |           | <b>CO<sub>2</sub></b> |          |            |          |           |          |
| Depth (m) |  | 5-Oct-95             | 29-Jan-96* | 4-Jun-96 | 23-Aug-96 | 1-Nov-96              | 5-Oct-95 | 28-Feb-96  | 4-Jun-96 | 23-Aug-96 | 1-Nov-96 |
| 0         |  | 20.6%                | n/a        | n/a      | 19.6%     | n/a                   | 0.0%     | n/a        | n/a      | 0.0%      | n/a      |
| 26        |  | 20.5%                | n/a        | 20.3%    | 19.6%     | n/a                   | 0.0%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 21        |  | 19.8%                | n/a        | 19.9%    | 19.2%     | n/a                   | 0.0%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 16        |  | 20.4%                | n/a        | 20.6%    | 19.6%     | n/a                   | 0.1%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 11        |  | 20.5%                | n/a        | 20.6%    | 19.4%     | n/a                   | 0.0%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 8         |  | 20.7%                | n/a        | 20.8%    | 19.5%     | n/a                   | 0.0%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 6         |  | 20.6%                | n/a        | 20.4%    | 19.2%     | n/a                   | 0.0%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 4.5       |  | 20.7%                | n/a        | 20.7%    | 19.3%     | n/a                   | 0.0%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 3         |  | 20.7%                | n/a        | 20.7%    | 19.4%     | n/a                   | 0.1%     | n/a        | 0.0%     | 0.0%      | 0.0%     |
| 2         |  | 20.7%                | n/a        | 20.7%    | 19.4%     | n/a                   | 0.1%     | n/a        | 0.0%     | 0.0%      | 0.0%     |

\* Taken using NOVA LBD  
 All other readings taken using Lantec GA90

**Table 5.3-1: Strongly Oxidized Samples Of Whistle Waste Rock****a) Solids Analysis (mean values)**

| Group       | No. of Samples | Paste pH<br>μmho/cm <sup>2</sup> | Sulphide<br>% | Sulphate<br>% | Iron<br>ug/g | Nickel<br>ug/g | Copper<br>ug/g | Cobalt<br>ug/g | Zinc<br>ug/g |
|-------------|----------------|----------------------------------|---------------|---------------|--------------|----------------|----------------|----------------|--------------|
| 1 (TP1)     | 2              | 3.45                             | 5.98          | 0.49          | 101870       | 5900           | 2090           | 281            | 91           |
| 2 (TP2)     | 4              | 5.08                             | 4.46          | 0.25          | 70875        | 5065           | 1840           | 200            | 105          |
| 3 (TP3)     | 2              | 5.2                              | 1.86          | 0.24          | 63200        | 1880           | 1210           | 157            | 97           |
| 4(Rock Cut) | 8              | 4.34                             | 5.23          | 0.34          | 92015        | 6300           | 2193           | 434            | 251          |
| 1 to 4      | 16             | 4.53                             | 4.71          | 0.32          | 84360        | 5389           | 1969           | 321            | 175          |
| Others      | 82             | 6.38                             | 2.44          | 0.15          | 68097        | 2681           | 1393           | 158            | 127          |
| Overall     | 98             | 6.06                             | 2.86          | 0.18          | 70752        | 3123           | 1487           | 185            | 135          |

**b) Water Quality from Washing Test**

| Group       | No. of Samples | pH  | Conduct.<br>μmho/cm <sup>2</sup> | Sulphate<br>mg/L | Iron<br>mg/L | Nickel<br>mg/L | Copper<br>mg/L | Cobalt<br>mg/L | Zinc<br>mg/L |
|-------------|----------------|-----|----------------------------------|------------------|--------------|----------------|----------------|----------------|--------------|
| 1 (TP1)     | 1              | 2.9 | 3700                             | 1990             | 103.0        | 121.0          | 13.0           | 4.9            | 1.1          |
| 2 (TP2)     | 1              | 3.7 | 930                              | 590              | 8.1          | 48.0           | 1.5            | 2.5            | 1.4          |
| 3 (TP3)     | 1              | 3.2 | 1870                             | 885              | 52.0         | 94.0           | 0.6            | 2.0            | 1.9          |
| 4(Rock Cut) | 2              | 3.4 | 1255                             | 777.5            | 20.0         | 27.0           | 0.5            | 1.3            | 0.7          |
| 1 to 4      | 5              | 3.3 | 1802                             | 1004             | 40.6         | 63.4           | 3.2            | 2.4            | 1.2          |
| Others      | 10             | 4.3 | 1698                             | 815              | 18.6         | 26.8           | 0.5            | 1.1            | 0.4          |
| Overall     | 15             | 4   | 1725                             | 865              | 24.4         | 36.4           | 1.2            | 1.4            | 0.6          |

**Table 5.4-1: Comparison Of Average Water Quality**

| <b>Parameter</b> | <b>Unit</b> | BH - 1A<br>Average | BH - 1B<br>Average | BH - 2A<br>Average | BH - 2B<br>Average | BH - 3A<br>Average | BH - 3B<br>Average | BH - 4A<br>Average | BH - 4B<br>Average | BH - 5<br>Average | Seepage<br>Average |
|------------------|-------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|-------------------|--------------------|
| pH               | pH unit     | 4.2                | n/a                | 4.2                | 4.3                | 4.3                | 4.4                | 4.0                | n/a                | 7.2               | 3.9                |
| Conductivity     | µS          | 8840               | n/a                | 9133               | 7525               | 8760               | 8475               | 10975              | n/a                | 258               | 4133               |
| Iron (Fe)        | mg/L        | 33.6               | n/a                | 116.7              | 131.9              | 190.8              | 169.0              | 148.9              | n/a                | 0.2               | 3.6                |
| Nickel (Ni)      | mg/L        | 741.8              | n/a                | 693.6              | 577.2              | 776.5              | 714.5              | 653.4              | n/a                | <0.5              | 203.3              |
| Copper (Cu)      | mg/L        | 20.1               | n/a                | 17.6               | 8.9                | <1                 | 1.4                | 16.8               | n/a                | <0.1              | 9.5                |
| Cobalt (Co)      | mg/L        | 33.1               | n/a                | 31.4               | 26.0               | 38.5               | 96.7               | 33.1               | n/a                | <0.1              | 9.1                |
| Zinc (Zn)        | mg/L        | 43.7               | n/a                | 14.4               | 10.3               | 9.5                | 8.8                | 7.5                | n/a                | <1                | 5.8                |
| Sulphate         | mg/L        | 12128              | n/a                | 10984              | 8852               | 10465              | 9723               | 9856               | n/a                | 81                | 3012               |

| <b>Parameter</b> | <b>Unit</b> | TP-1<br>Average | TP-2<br>Average | TP-3<br>Average | Laboratory Washing Tests<br>Mean |
|------------------|-------------|-----------------|-----------------|-----------------|----------------------------------|
| pH               | pH unit     | 5.9             | 6.5             | 6.9             | 4.2                              |
| Conductivity     | µS          | 740             | 1070            | 3313            | 1901                             |
| Iron (Fe)        | mg/L        | 4.5             | 150.1           | 0.1             | 31.3                             |
| Nickel (Ni)      | mg/L        | 6.8             | 10.1            | 1.9             | 65.3                             |
| Copper (Cu)      | mg/L        | <0.1            | 0.8             | <0.1            | 2                                |
| Cobalt (Co)      | mg/L        | 0.3             | 0.5             | <0.1            | 2.2                              |
| Zinc (Zn)        | mg/L        | 0.1             | 0.4             | <0.1            | 1.2                              |
| Sulphate         | mg/L        | 463             | 928.0           | 378.0           | 1026                             |

**Table 5.4-2: Water Balance (Waste Rock Seepage Estimate)**

| <b>Month</b>  | <b>Average Monthly Rainfall / Snowmelt<sup>1</sup> (mm)</b> | <b>Average Monthly Evaporation (assuming 10 mm water retention<sup>2</sup>) (mm)</b> | <b>Predicted Infiltration Rate<sup>3</sup> (mm)</b> | <b>Total Yearly Seepage at Seepage Collection Pond<sup>4</sup> (m<sup>3</sup>)</b> |
|---------------|---|--|---|--|
| Jan           | 7   | 0  | 7   | 700  |
| Feb           | 11  | 0  | 11  | 1100   |
| Mar           | 43  | 2  | 41  | 4100   |
| Apr           | 220   | 21   | 199   | 19900  |
| May           | 72  | 49   | 23  | 2300   |
| June          | 74  | 60   | 14  | 1400   |
| Jul           | 91  | 79   | 12  | 1200   |
| Aug           | 73  | 62   | 11  | 1100   |
| Sept          | 119   | 64   | 55  | 5500   |
| Oct           | 71  | 28   | 43  | 4300   |
| Nov           | 59  | 8  | 51  | 5100   |
| Dec           | 30  | 0  | 30  | 3000   |
| <b>Annual</b> | <b>870</b>  | <b>373</b>   | <b>497</b>  | <b>49700</b>   |

Notes and Assumptions:

- 1) Based on Atmospheric Environment Service climate normal data from 1956 to 1996\
- 2) Based on Atmospheric Environment Service water balance calculations (AES, 1997)
- 3) Infiltration rate (to waste rock) = Average Monthly Rainfall - Average Monthly Precipitation
- 4) Assumes infiltration through a Surface area of 10 hectares
- 5) Retention time in waste rock not accounted for.

**Table 5.4-3: Summary Of Sulphate And Nickel Loadings**

|   | Column testing (average values) | Seepage     |          | Column Release Rate / Seepage Release Rate* |
|---|---------------------------------|-------------|----------|---|
|   |                                 | 1993 / 1994 | 1996     |   |
| Flow (m <sup>3</sup> /yr)                           |                                 | 66430       | 49700    |   |
| Sulphate Concentration (mg/L)                       |                                 | 3048        | 3012     |   |
| Sulphate Loading (kg/yr)                            | 1.41                            | 202479      | 149696.4 |   |
| Sulphate Release (mg SO <sub>4</sub> /kg rock/week) | 32.8                            | 0.97        | 0.72     | 45.7  |
| Nickel Concentration (mg/L)                         |                                 | 204.1       | 203.3    |   |
| Nickel Loading (kg/yr)                              | 0.0073                          | 13557       | 10104    |   |
| Nickel Release (mg Ni/kg rock/week)                 | 0.17                            | 0.065       | 0.048    | 3.5   |

Notes:

Mass of columns = 825 kg

\* 1996 seepage release rate used

**Table 5.4-4: Comparison Of Column Sample To Medium Sulphur Norite And Average Of Whistle Waste Rock Database**

| Parameter         | Column Test Composite Sample | Univ. of Waterloo Research Study Medium Sulphur Norite (Nicholson et al. 1996) | Overall Whistle Mine database average |                 |
|-------------------|------------------------------|--|---------------------------------------|-----------------|
|                   |                              |  | (BCRI analyses)                       | (ACME analyses) |
| Sulphide (S %)    | 1.79                         | 2.63   | 2.86                                  |                 |
| CO <sub>2</sub> % | 0.55                         | 0.30   | 0.69                                  |                 |
| Fe %              | 12.00                        | 7.68   | 7.30                                  | 12.97           |
| Cu (ppm)          | 1100                         | 1191   | 1503                                  |                 |
| Ni (ppm)          | 1700                         | 1550   | 3370                                  | 1925            |



**Table 5.4-5: Whistle Waste Rock Column Test Cumulative Leachate Loading Compared To Original Column Composition**

| Week                         | Leachate Weight | Alkalinity                | Sulfate | Al         | Ca         | Mg         | Mn      | Na         | Ni        | S          | Zn      |
|------------------------------|-----------------|---------------------------|---------|------------|------------|------------|---------|------------|-----------|------------|---------|
|                              | kg              | mg/L as CaCO <sub>3</sub> | mg/L    | mg/L       | mg/L       | mg/L       | mg/L    | mg/L       | mg/L      | mg/L       | mg/L    |
| <b>Column 1</b>              |                 |                           |         |            |            |            |         |            |           |            |         |
| 0                            | 26.3            | 65                        | 1934    | 0.44       | 721        | 112        | 1.45    | 10.5       | 7.63      | 666        | 0.059   |
| 1                            | 17.9            | 65                        | 1701    | 1.99       | 611        | 86.7       | 0.86    | 10.2       | 4.30      | 567        | 0.048   |
| 2                            | 13.8            | 65                        | 1649    | 0.57       | 589        | 69.7       | 0.6     | 8.25       | 3.48      | 570        | 0.020   |
| 3                            | 15.2            | 65                        | 1637    | 0.45       | 547        | 56.6       | 0.65    | 9.14       | 4.72      | 515        | 0.07    |
| 4                            | 15.7            | 65                        | 3635    | 0.66       | 492        | 55.2       | 0.5     | 7.68       | 3.94      | 460        | 0.020   |
| 5                            | 16.8            | 58                        | 1279    | 0.34       | 493        | 53         | 0.41    | 8.24       | 3.88      | 463        | 0.1     |
| 6                            | 17.4            | 53                        | 1450    | 0.51       | 514        | 52.2       | 0.39    | 7.98       | 4.22      | 493        | 0.084   |
| 7/8                          | 33.8            | 59                        | 1495    | 0.51       | 575        | 56.9       | 0.35    | 10.4       | 4.91      | 496        | 0.13    |
| 9/10                         | 32.4            | 55                        | 1448    | 0.13       | 587        | 51         | 0.28    | 9.42       | 5.15      | 546        | 0.020   |
| 11/12                        | 27.4            | 57                        | 1487    | 0.1        | 529        | 49.7       | 0.38    | 9.59       | 4.45      | 485        | 0.03    |
| 13/14                        | 28.0            | 52                        | 1556    | 0.1        | 533        | 60.4       | 0.38    | 9.67       | 7.41      | 500        | 0.09    |
| 15/16                        | 35.0            | 43                        | 1499    | 0.1        | 499.0      | 67.6       | 0.50    | 10.20      | 9.67      | 509        | 0.020   |
| 17/18                        | 35.4            | 38                        | 1456    | 0.21       | 493.0      | 75.5       | 0.70    | 10.1       | 12.1      | 512        | 0.24    |
| 19/20                        | 35.4            | 38                        | 1456    | 0.40       | 577.0      | 111.0      | 4.26    | 8.1        | 28.9      | 618        | 0.15    |
| Cumul. Load (mg)             |                 | 18,666                    | 570,065 | 139        | 194,517    | 24,583     | 328     | 3,302      | 3,050     | 186,509    | 30      |
| Mass in column at start (mg) |                 |                           |         | 51,937,200 | 45,342,000 | 37,922,400 | 989,280 | 13,190,400 | 1,401,480 | 18,796,320 | 131,904 |
| Percent to leachate          |                 |                           |         | 0.00%      | 0.43%      | 0.06%      | 0.03%   | 0.03%      | 0.22%     | 0.99%      | 0.02%   |
| <b>Column 2</b>              |                 |                           |         |            |            |            |         |            |           |            |         |
| 0                            | 33.5            | 31                        | 1713    | 0.53       | 636        | 84.8       | 1.62    | 9.47       | 7.76      | 571        | 0.066   |
| 1                            | 17.8            | 31                        | 1590    | 2.08       | 590        | 70.1       | 0.93    | 10.6       | 4.72      | 530        | 0.032   |
| 2                            | 14.4            | 31                        | 1665    | 0.53       | 592        | 62.5       | 0.79    | 8.61       | 4.75      | 555        | 0.020   |
| 3                            | 14.9            | 31                        | 1647    | 0.49       | 576        | 69.3       | 0.57    | 9.04       | 4.17      | 551        | 0.020   |
| 4                            | 15.6            | 31                        | 1214    | 1.56       | 449        | 43.5       | 0.52    | 7.43       | 4.08      | 413        | 0.020   |
| 5                            | 16.7            | 30                        | 1086    | 0.26       | 391        | 35.4       | 0.38    | 7.87       | 3.51      | 362        | 0.1     |
| 6                            | 16.9            | 27                        | 1196    | 0.43       | 447        | 38.2       | 0.41    | 7.42       | 4.31      | 421        | 0.084   |
| 7/8                          | 34.1            | 32                        | 1197    | 0.42       | 515        | 44.8       | 0.44    | 8.55       | 5.18      | 436        | 0.08    |
| 9/10                         | 31.8            | 26                        | 1333    | 0.1        | 500        | 38.1       | 0.34    | 8.52       | 5.09      | 409        | 0.03    |
| 11/12                        | 30.1            | 32                        | 1511    | 0.1        | 520        | 49.7       | 0.59    | 10.1       | 6.62      | 481        | 0.03    |
| 13/14                        | 28.6            | 30                        | 1312    | 0.1        | 451        | 43.4       | 0.61    | 8.91       | 6.40      | 419        | 0.27    |
| 15/16                        | 36.4            | 22                        | 1468    | 0.2        | 512.0      | 52.2       | 0.76    | 9.43       | 10.9      | 507        | 0.07    |
| 17/18                        | 33.5            | 14                        | 1526    | 0.18       | 548.0      | 58.6       | 0.96    | 10.4       | 12.8      | 533        | 0.10    |
| 19/20                        | 33.5            | 14                        | 1526    | 0.27       | 585.0      | 73.2       | 1.43    | 8.6        | 11.4      | 572        | 0.19    |
| Cumul. Load (mg)             |                 | 9,415                     | 513,272 | 150        | 188,567    | 19,724     | 281     | 3,238      | 2,598     | 174,139    | 31      |
| Mass in column at start (mg) |                 |                           |         | 51,937,200 | 45,342,000 | 37,922,400 | 989,280 | 13,190,400 | 1,401,480 | 18,796,320 | 131,904 |
| Percent to leachate          |                 |                           |         | 0.00%      | 0.42%      | 0.05%      | 0.03%   | 0.02%      | 0.19%     | 0.93%      | 0.02%   |

Shaded numbers are assumed/estimated values.

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Figure 1.4-1: Site Plan, showing Locations of Boreholes and Testpits

Figure 3.1-1: Typical Borehole Installation

Figure 3.1-2: Typical Lysimeter Installation

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Figure 4.1-1: Whistle Waste Rock Pile Test Pit No. 1

Figure 4.1-2: Whistle Waste Rock Pile Test Pit No. 2

Figure 4.1-3: Whistle Waste Rock Pile Test Pit No. 3

Figure 4.1-4: Plot of Rock Particle Size Distribution

Figure 4.3-1 Interpreted Groundwater Contours for Northeast Rock Dump

Figure 4.3-2 Typical Oxygen Concentration Profile with Depth (BH-1)

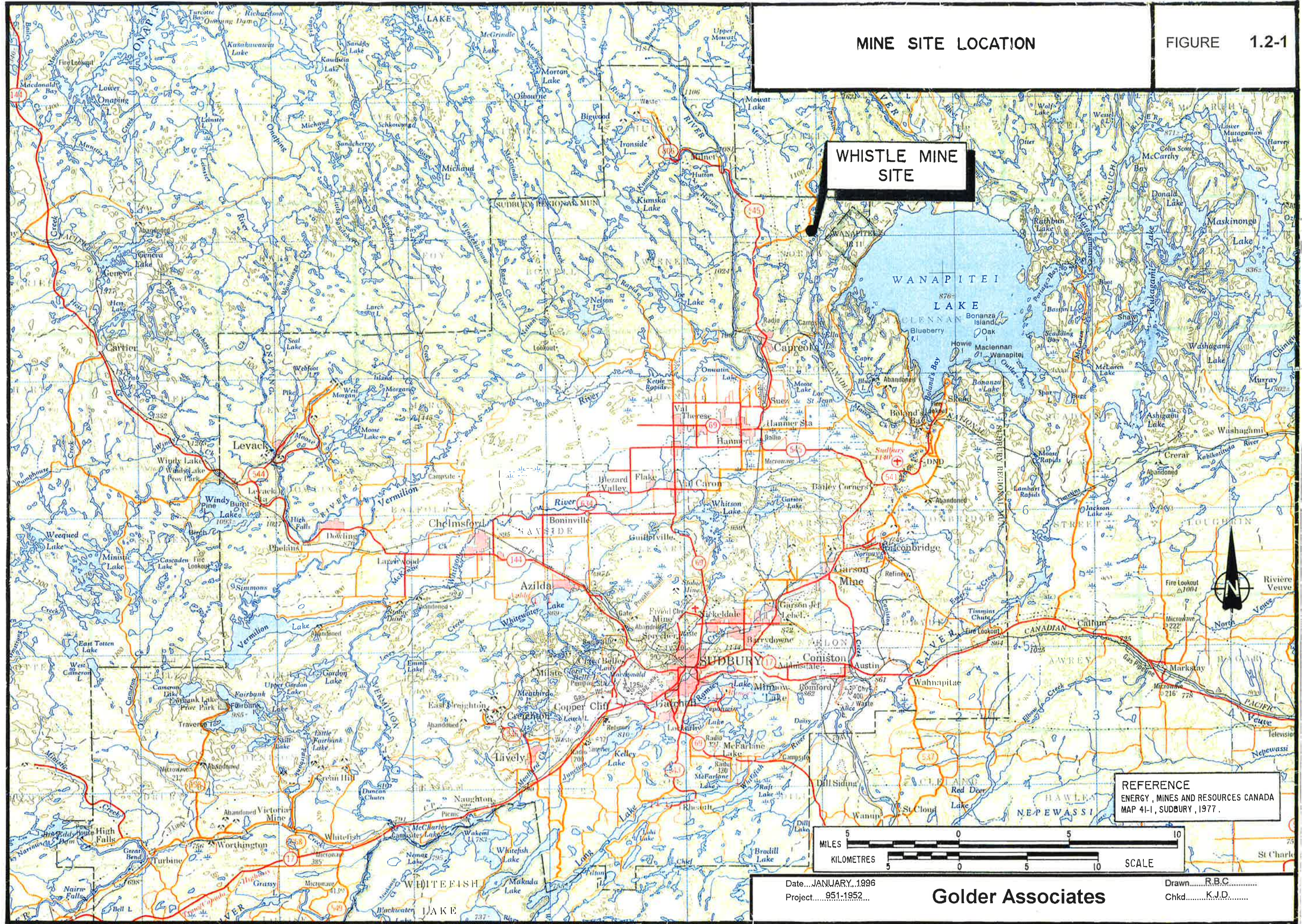
Figure 4.3-3a Temperature Variation with Depth, BH-1

Figure 4.3-3b Temperature Variation with Depth, BH-2

Figure 4.3-3c Temperature Variation with Depth, BH-3

Figure 4.3-3d Temperature Variation with Depth, BH-4





WHISTLE MINE SITE

REFERENCE  
ENERGY, MINES AND RESOURCES CANADA  
MAP 41-1, SUDBURY, 1977.



Date... JANUARY, 1996  
Project... 951-1952...

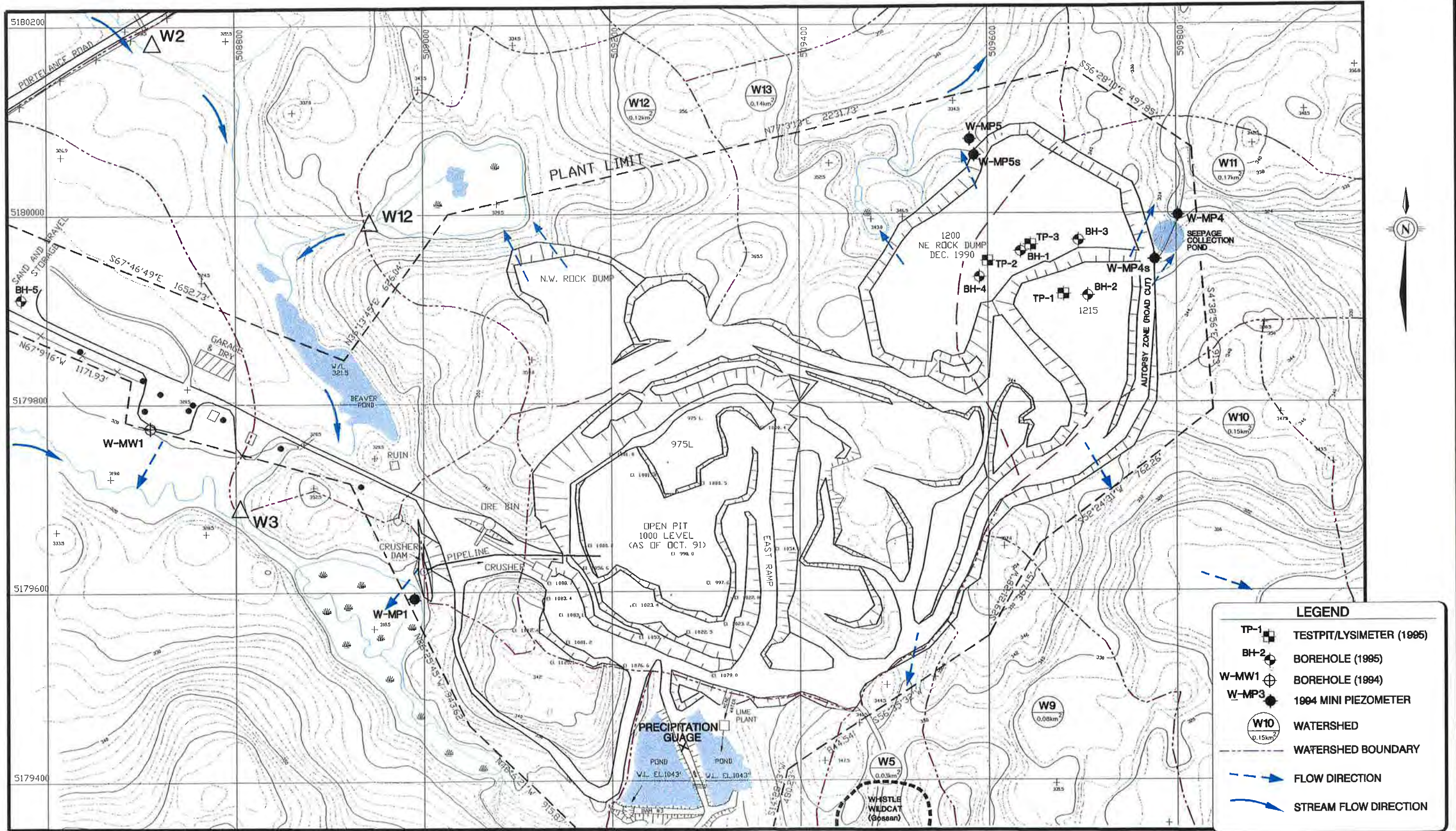
Golder Associates

Drawn... R.B.C.  
Chkd... K.J.D.



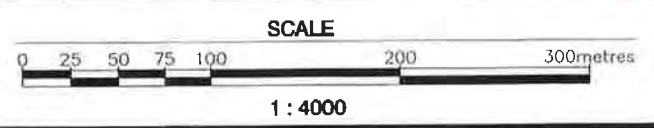
**SITE PLAN, SHOWING LOCATIONS OF BOREHOLES AND TESTPITS**

**FIGURE 1.4-1**



**LEGEND**

- TP-1 [Symbol] TESTPIT/LYSIMETER (1995)
- BH-2 [Symbol] BOREHOLE (1995)
- W-MW1 [Symbol] BOREHOLE (1994)
- W-MP3 [Symbol] 1994 MINI PIEZOMETER
- W10 [Symbol] WATERSHED
- WATERSHED BOUNDARY
- [Symbol] FLOW DIRECTION
- [Symbol] STREAM FLOW DIRECTION



Date ..FEBRUARY...1997.....  
 Project ..951-1952.....

**Golder Associates**

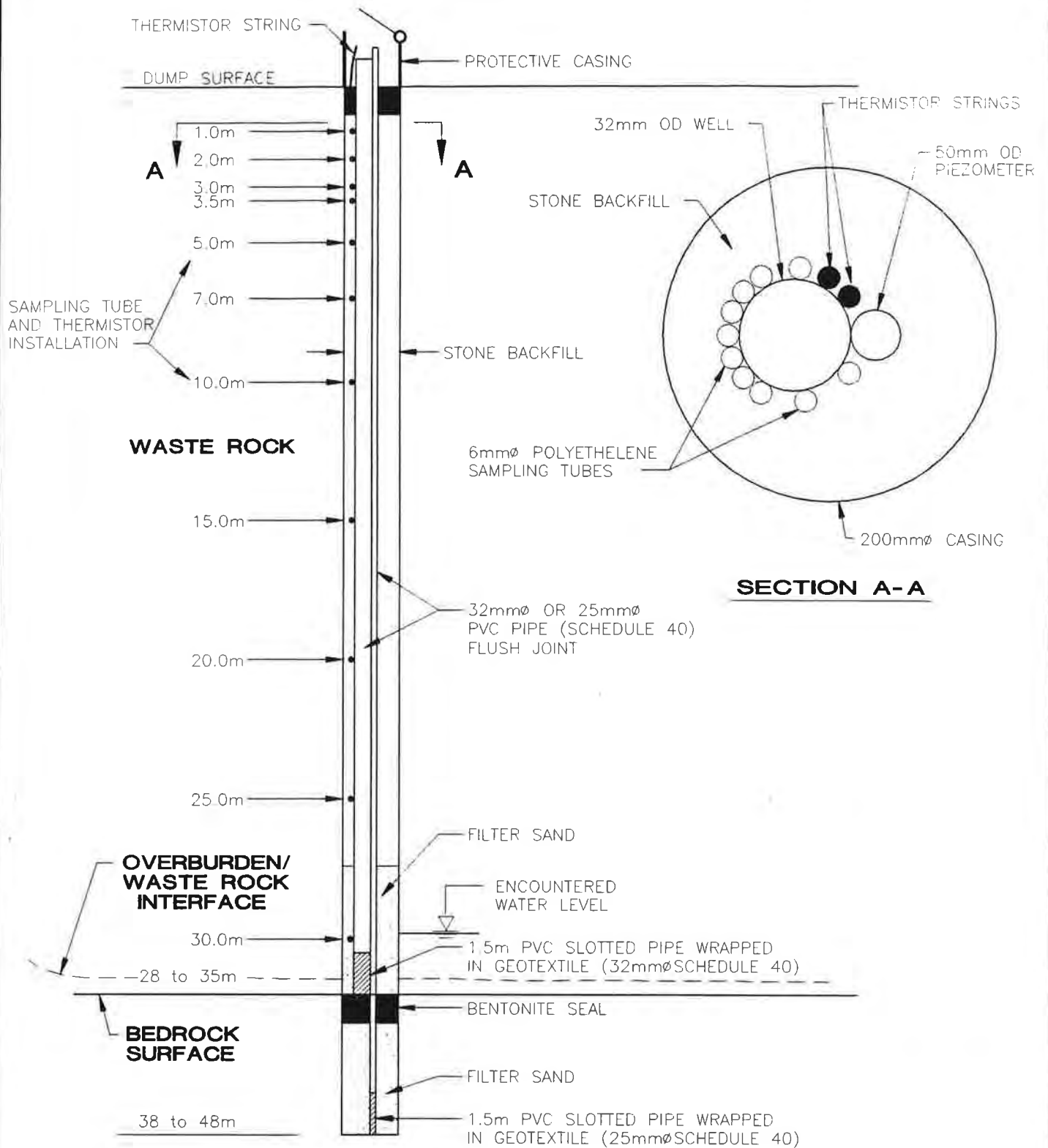
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 Chkd ..KJD.....

K195202.DWG



# TYPICAL BOREHOLE INSTALLATION WHISTLE MINE - ARD STUDY

FIGURE 3.1-1



ACAD FILE No.L1952003.DWG

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Project .951-.1952....

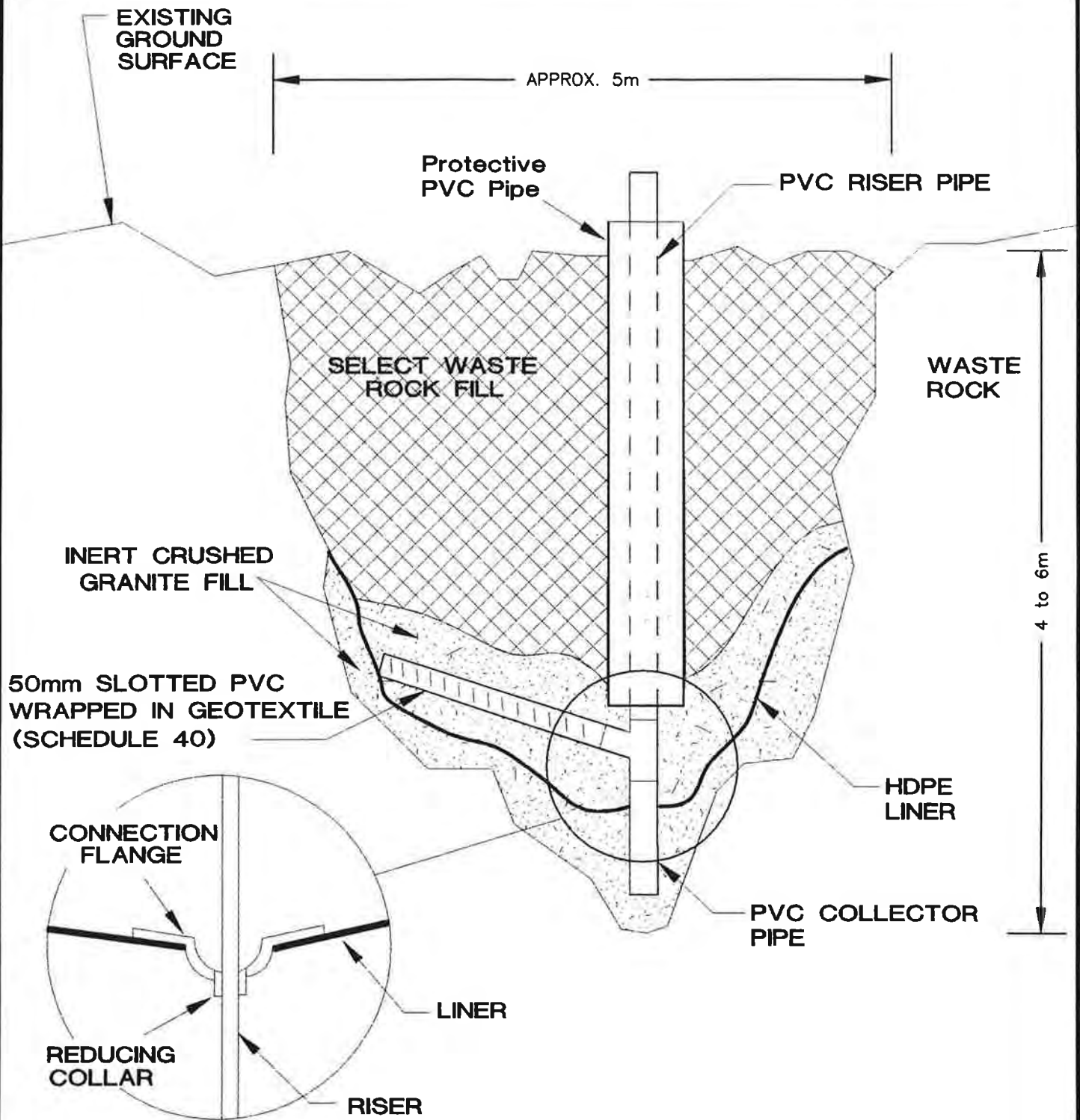
**Golder Associates**

Drawn ..JFG.....

Chkd ...KJD.....

# TYPICAL LYSIMETER INSTALLATION WHISTLE MINE - ARD STUDY

FIGURE 3.1-2



NOT TO SCALE

Date OCTOBER...1997

Project .951...1952...

**Golder Associates**

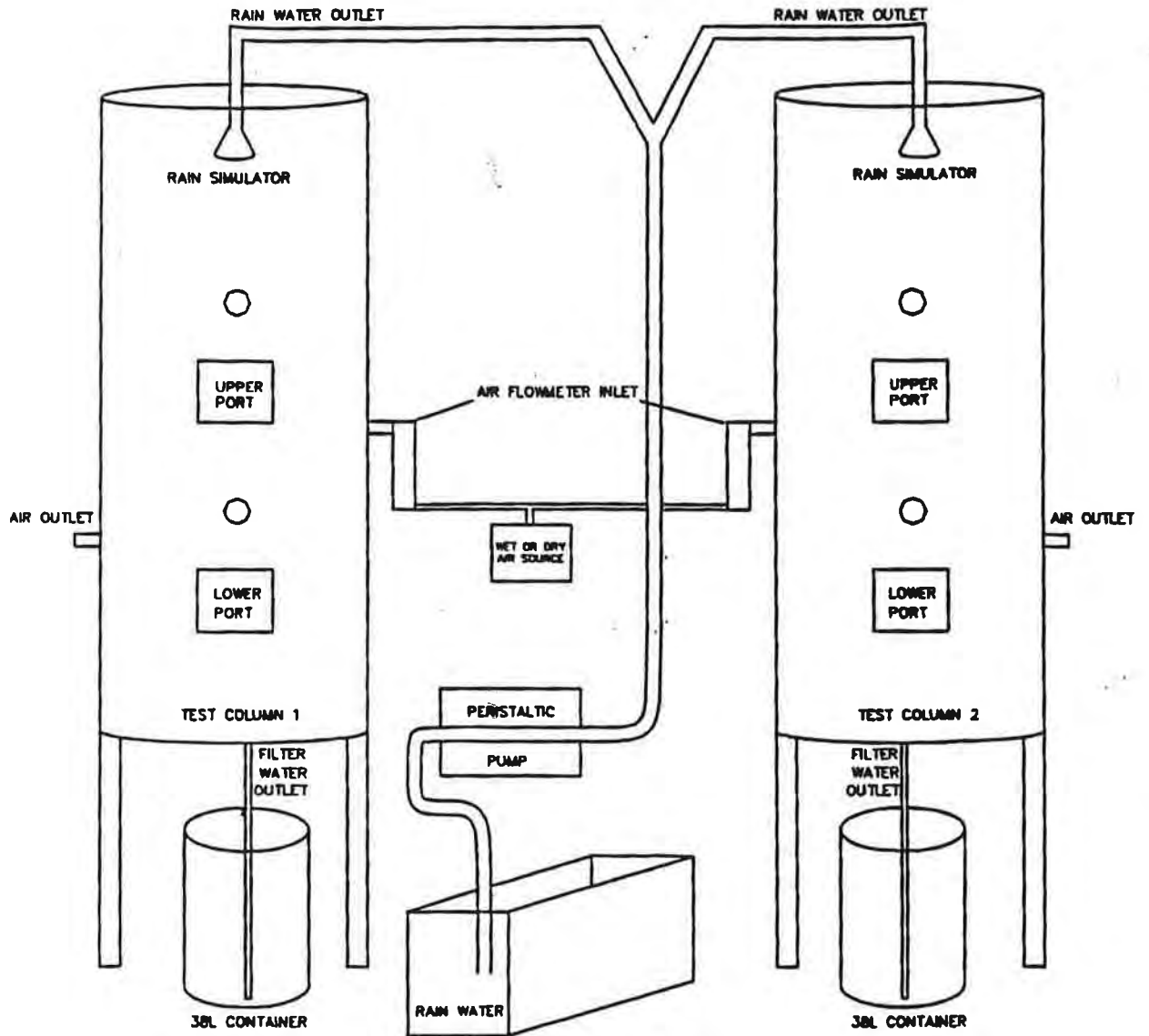
Drawn MHW/KKD

Chkd ...KJD...

1:1imp  
ACAD FILE No. L1952004.DWG

# SCHEMATIC DIAGRAM SHOWING HUMIDITY COLUMN SETUP

FIGURE 3.2-1

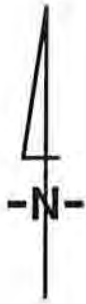


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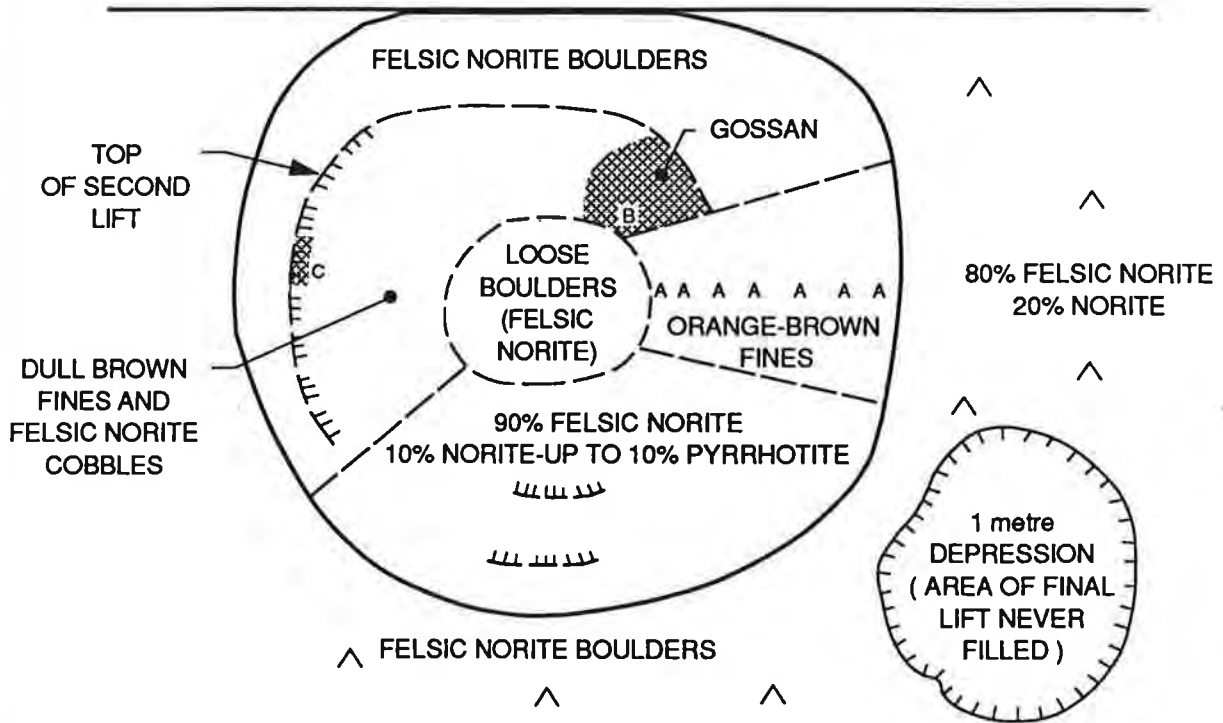
BASEPLAN WAS PROVIDED BY THE COURTESY OF LAKEFIELD RESEARCH LIMITED.

FIGURE 4.1-1




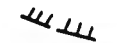

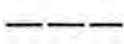
# WHISTLE WASTE ROCK PILE TEST PIT No. 1



DRILL ROAD



### LEGEND:

-  EDGE OF PIT
-  A,B,C SAMPLE LOCATIONS
-  BOULDERS
-  STEEP FACE (TOP OF SECOND LIFT)
-  STRONG GOSSAN
-  BOUNDARY BETWEEN ROCK TYPES

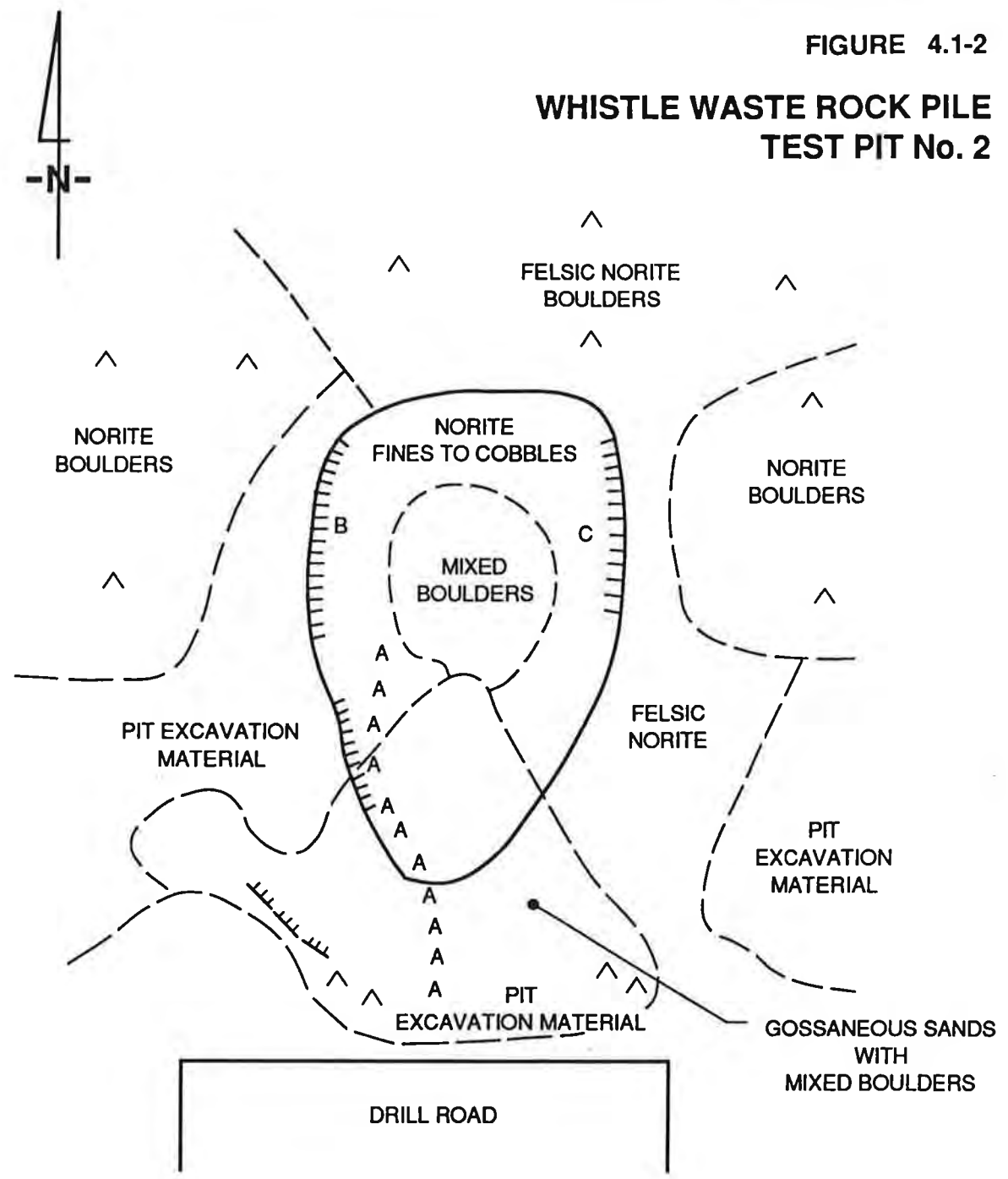
0 2m






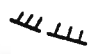



FIGURE 4.1-2

# WHISTLE WASTE ROCK PILE TEST PIT No. 2



**LEGEND:**

-  EDGE OF PIT
-  SAMPLE LOCATIONS
-  BOULDERS
-  STEEP FACE (TOP OF SECOND LIFT)
-  BOUNDARY BETWEEN ROCK TYPES

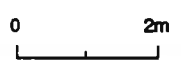
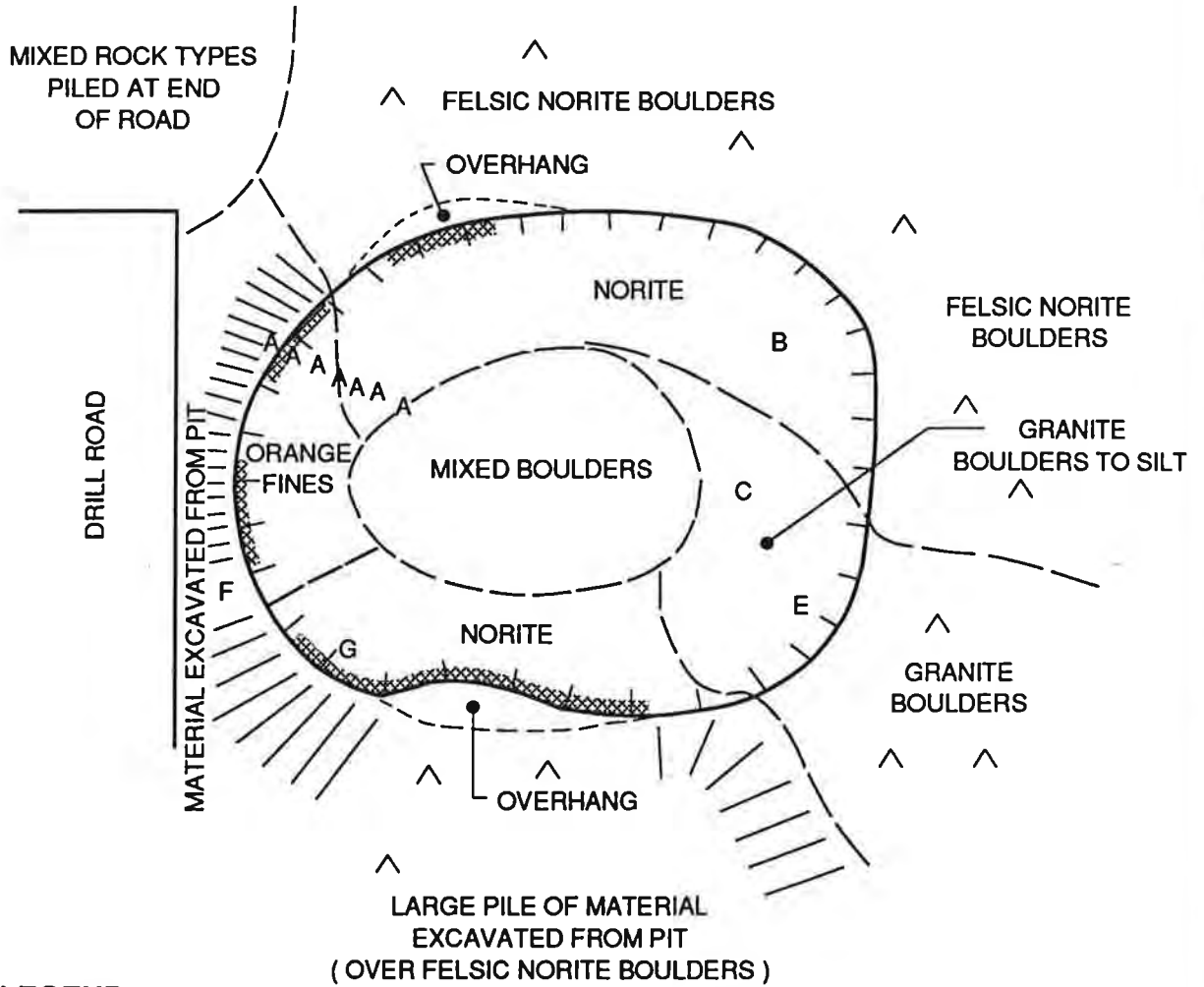







FIGURE 4.1-3

# WHISTLE WASTE ROCK PILE TEST PIT No. 3

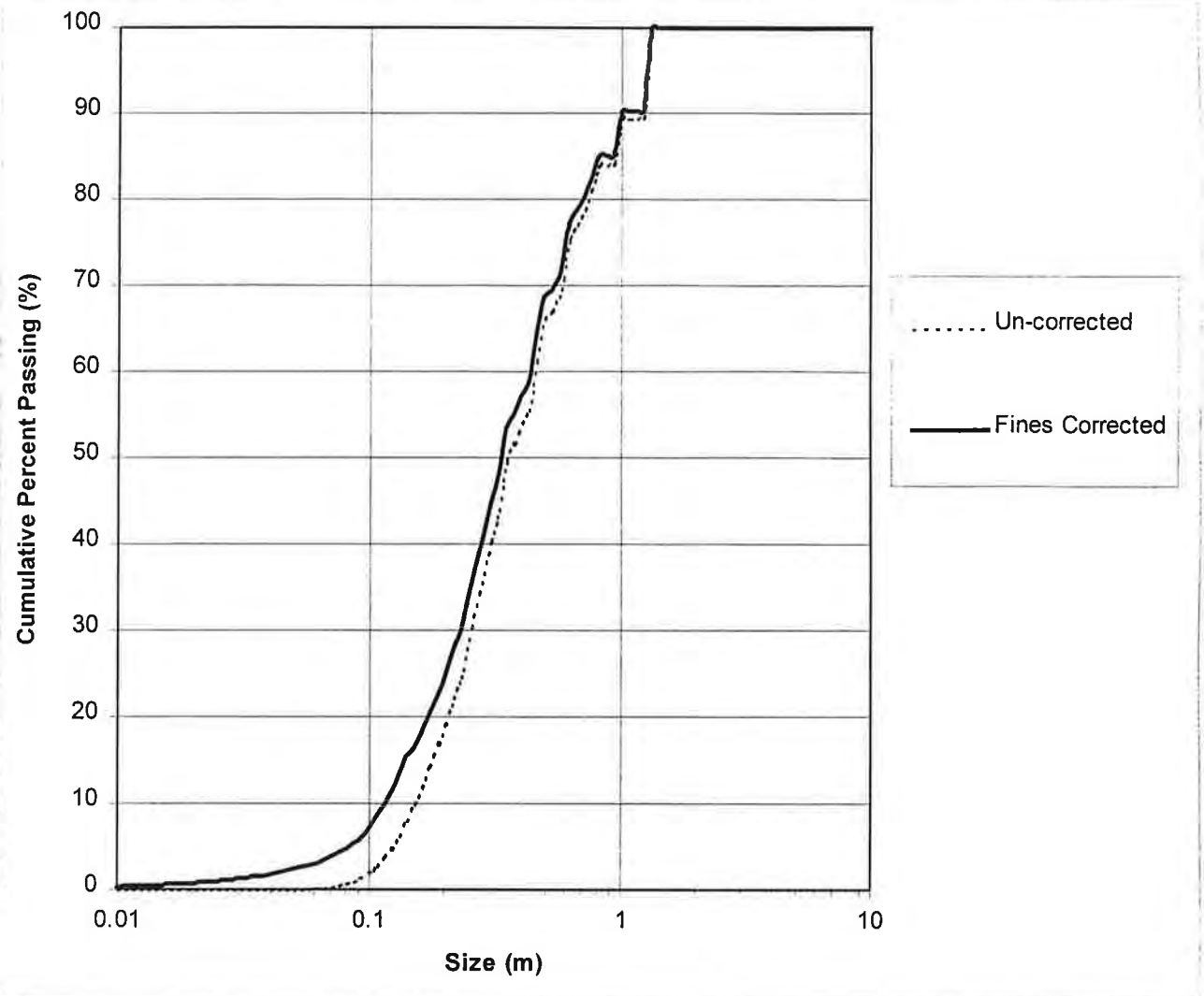


## LEGEND:

-  EDGE OF PIT (TOP OF SECOND LIFT)
- A,B,C      SAMPLE LOCATIONS
-  BOULDERS
-  STEEP FACE
-  STRONG GOSSAN / IRON STAINING
-  BOUNDARY BETWEEN ROCK TYPES

0      2m

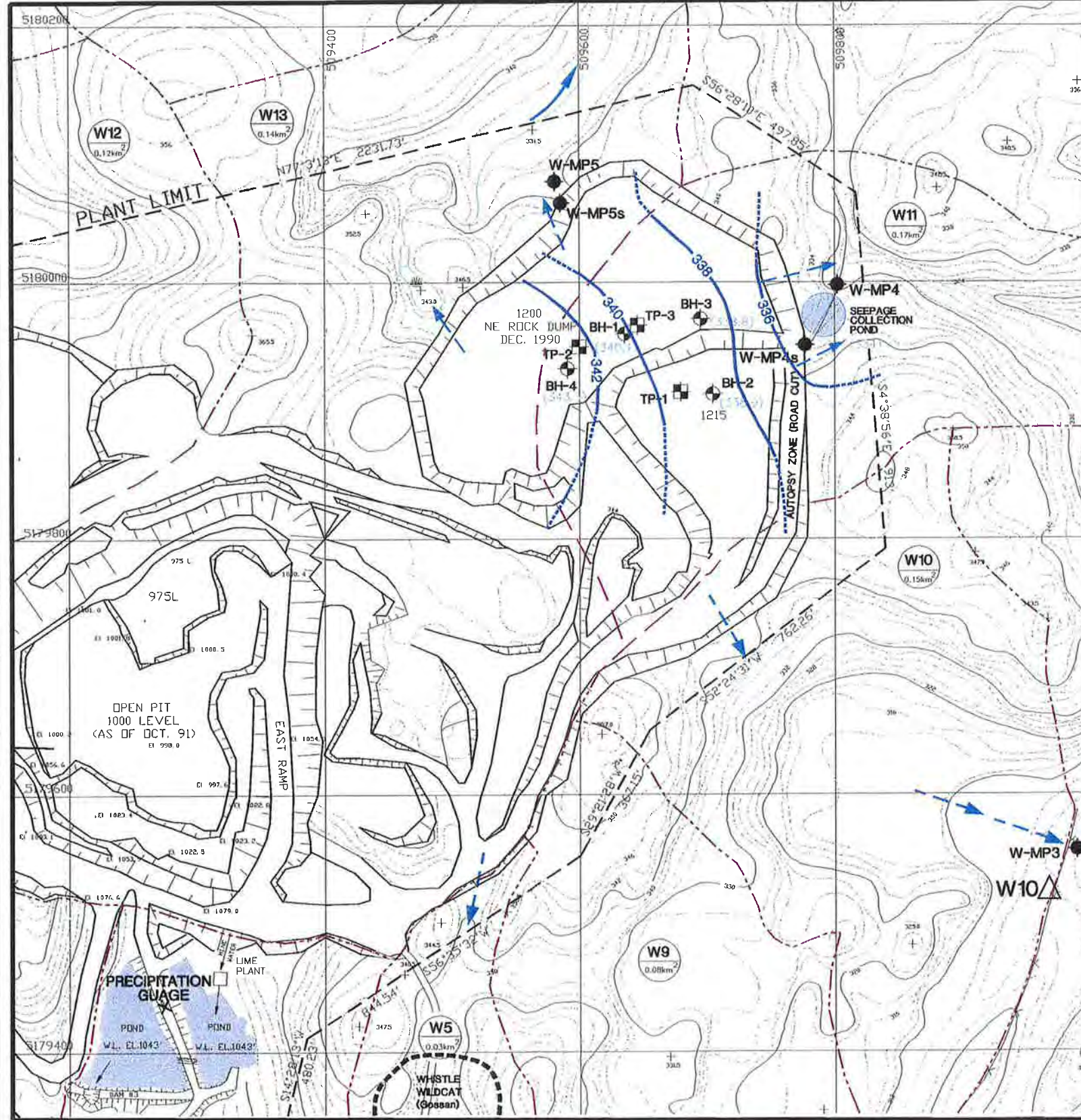






INTERPRETED GROUNDWATER CONTOURS FOR  
NORTHEAST ROCK DUMP

FIGURE 4.3-1



LEGEND

- TP-1 TESTPIT/LYSIMETER (1995)
- BH-2 BOREHOLE (1995)
- (340) WATER LEVEL (m.a.s.l.) OCTOBER 29, 1996
- W-MW1 BOREHOLE (1994)
- W-MP3 1994 MINI PIEZOMETER
- W10 WATERSHED
- WATERSHED BOUNDARY
- FLOW DIRECTION
- STREAM FLOW DIRECTION
- GROUNDWATER CONTOUR

SCALE

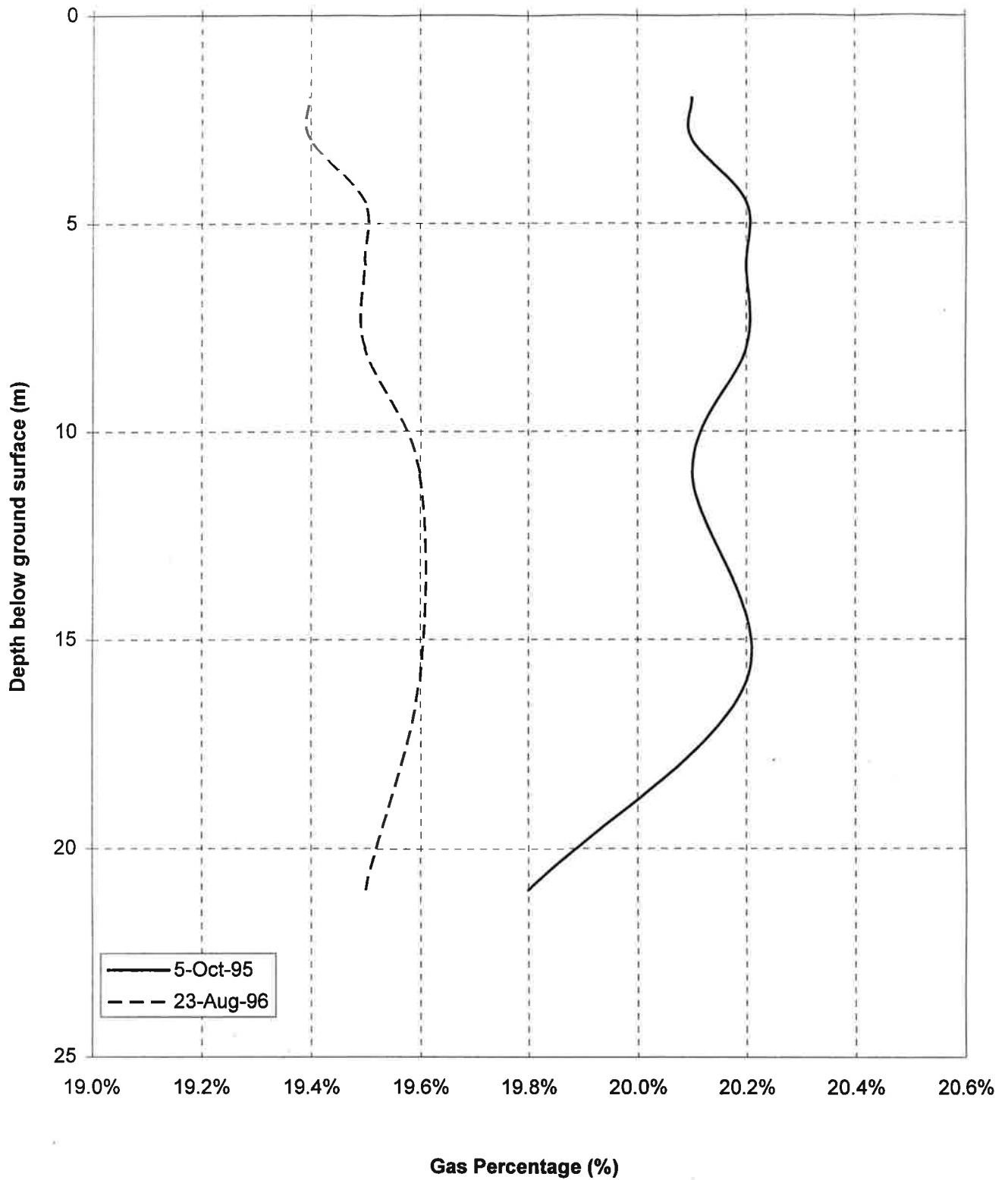


Date ..FEBRUARY..1997.....  
Project ..951..1952.....

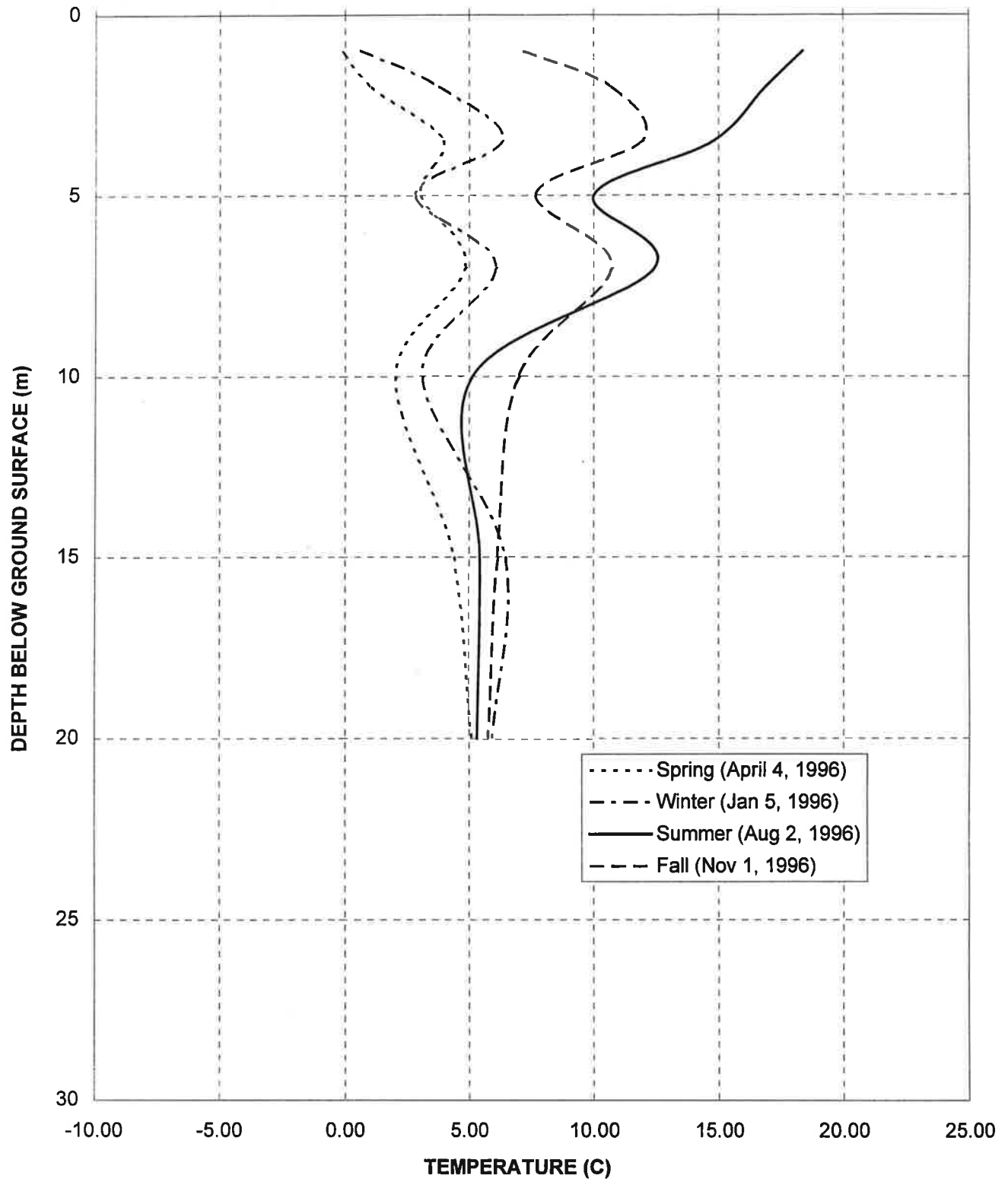
**Golder Associates**

Drawn .KD.....  
Chkd .KJD.....

**Figure 4.3-2**  
**Typical Oxygen Concentration Profile with Depth (BH-1)**

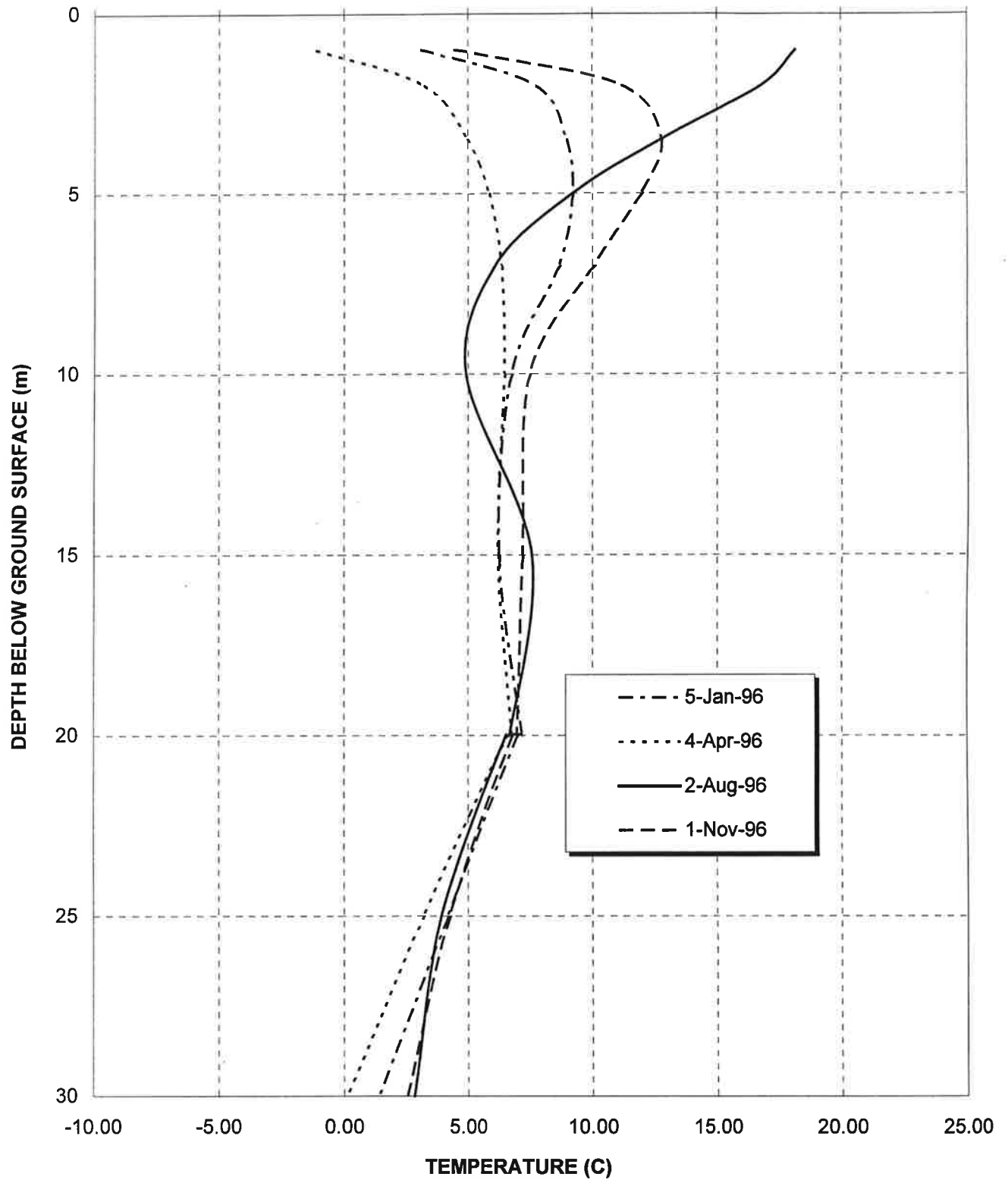


**FIGURE 4.3-3a**  
**TEMPERATURE VARIATION WITH DEPTH, BH-1**

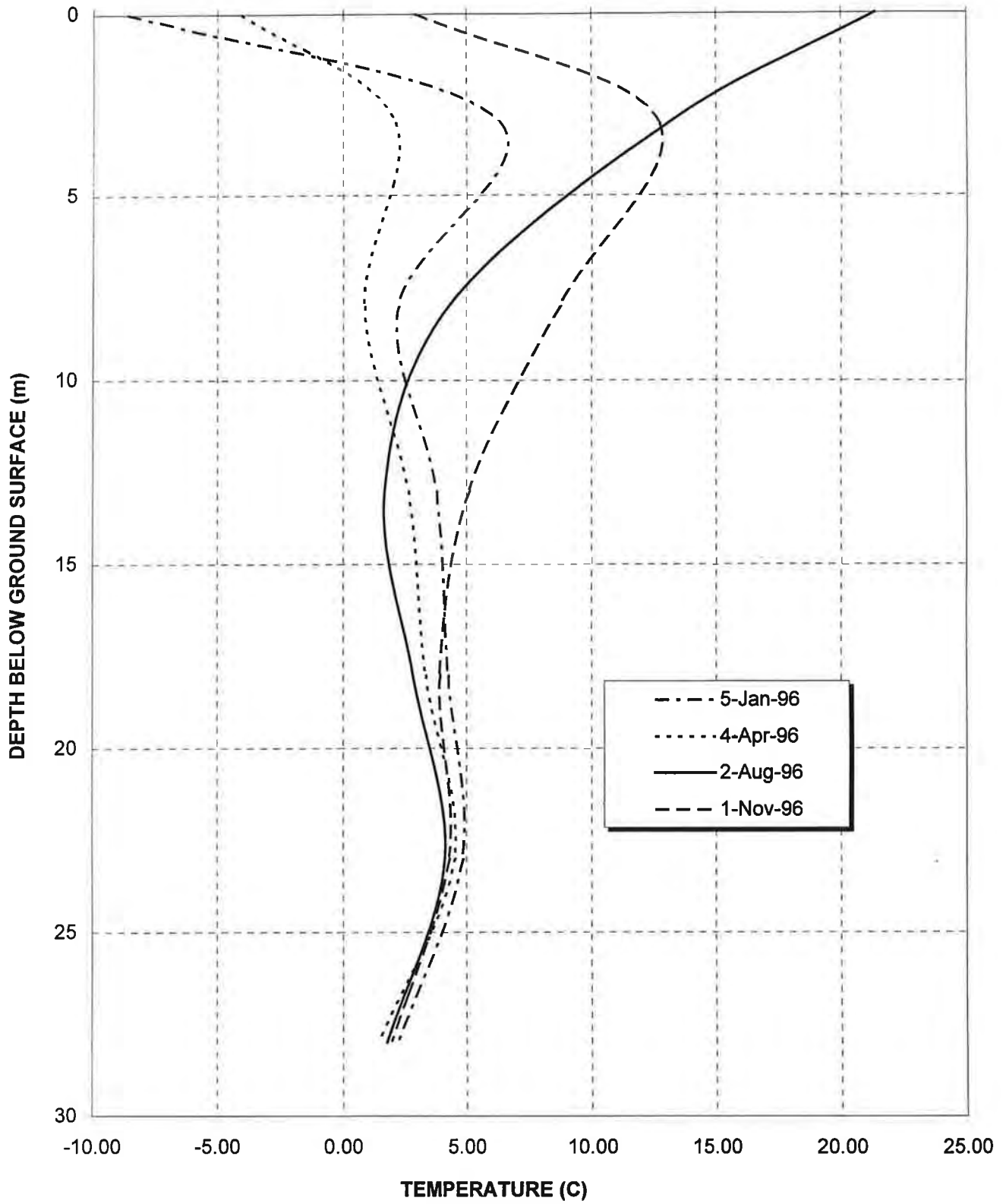




**FIGURE 4.3-3b**  
**TEMPERATURE VARIATION WITH DEPTH, BH-2**

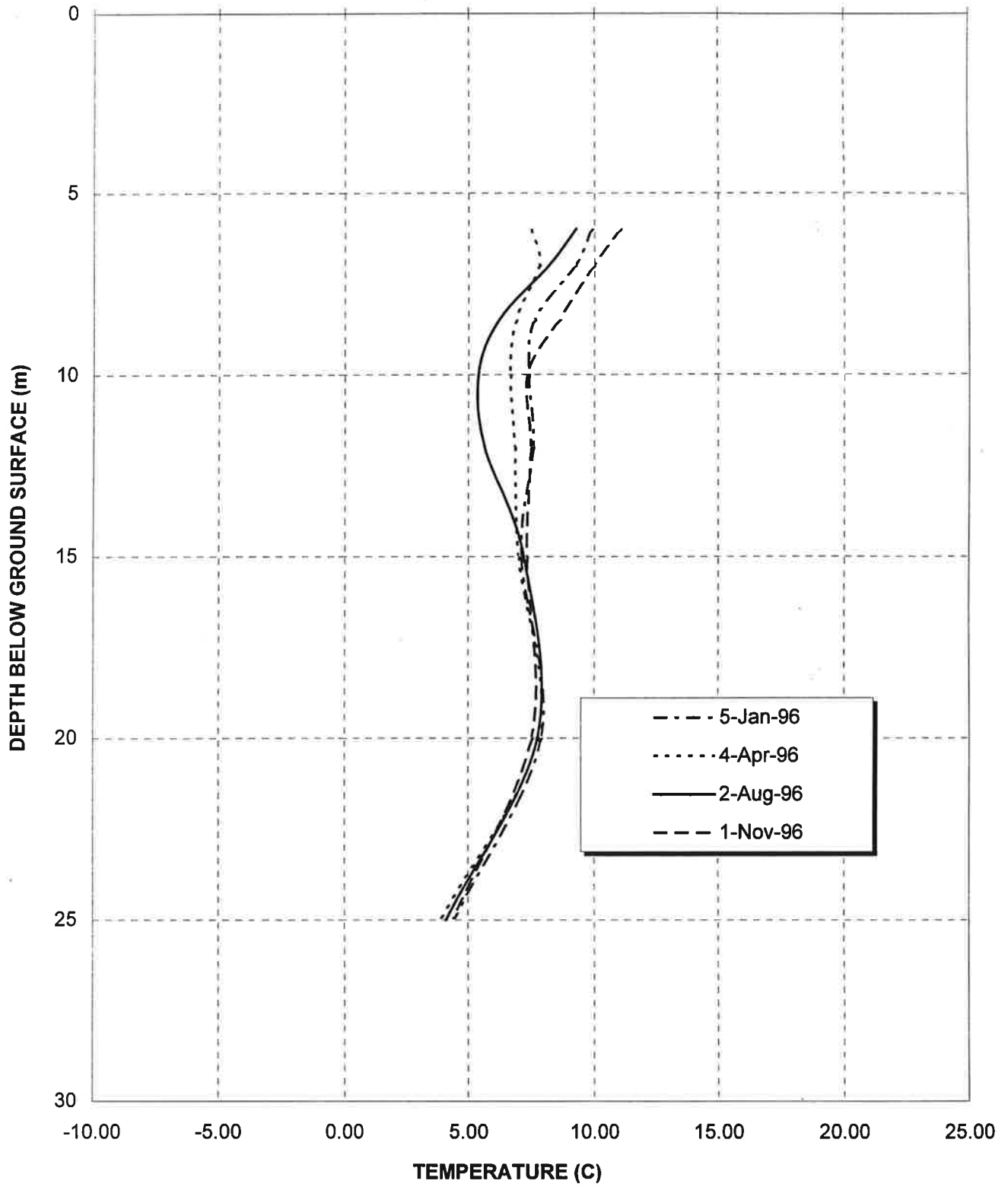


**FIGURE 4.3-3c**  
**TEMPERATURE VARIATION WITH DEPTH, BH-3**





**FIGURE 4.3-3d**  
**TEMPERATURE VARIATION WITH DEPTH, BH-4**



## **LIST OF PHOTOGRAPHS**

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- Plate 1.2-1: North End of Northeast Pile - Facing Northeast
- Plate 3.1-1 Borehole Installation (BH-2)
- Plate 4.1-1 Dump Construction
- Plate 4.1-2 Test Pit 1 Facing East
- Plate 4.1-3 Test Pit 2 Facing South
- Plate 4.1-4 Test Pit 3 Facing Northeast
- Plate 4.1-5 Autopsy Zone - Facing Northwest from South End of Road Cut
- Plate 4.1-6 Autopsy Zone Near Seepage Discharge

NORTH END OF NORTH EAST PILE - FACING NORTH EAST

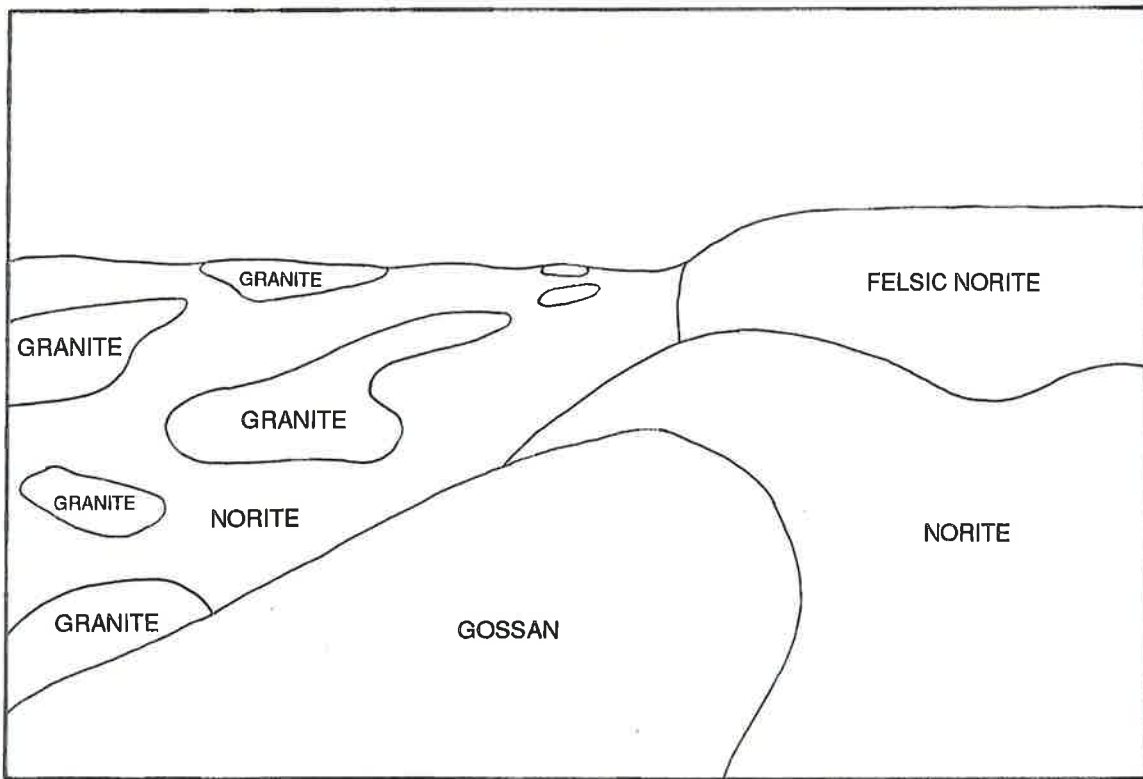




PLATE 3.1-1  
BOREHOLE INSTALLATION (BH-2)



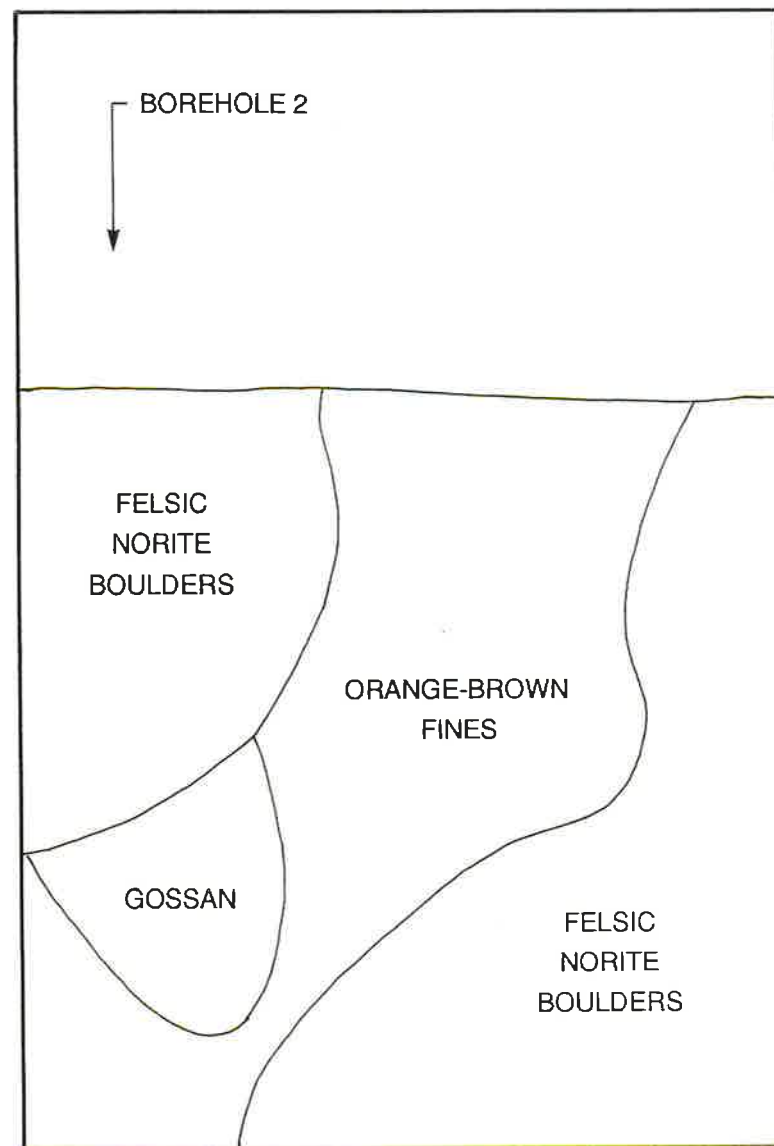


PLATE 4.1-1  
DUMP CONSTRUCTION



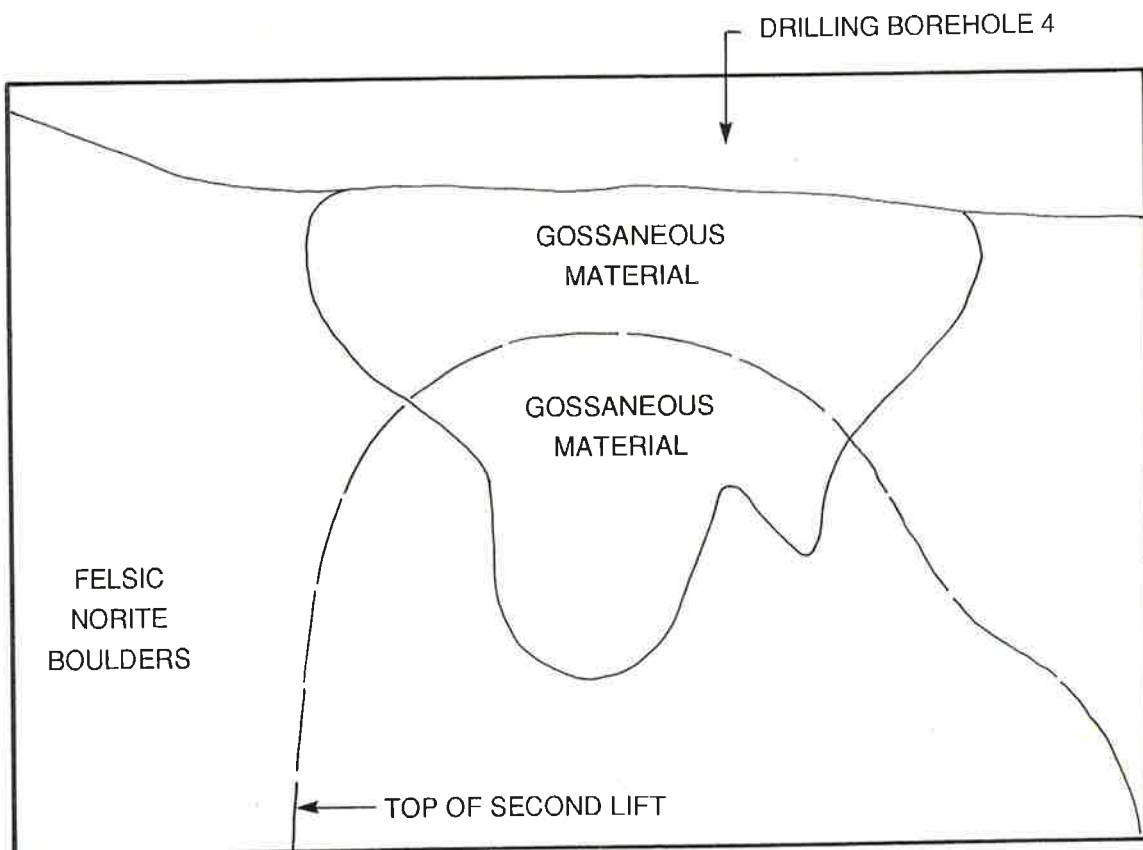
PLATE 4.1-2

TEST PIT 1 - FACING EAST

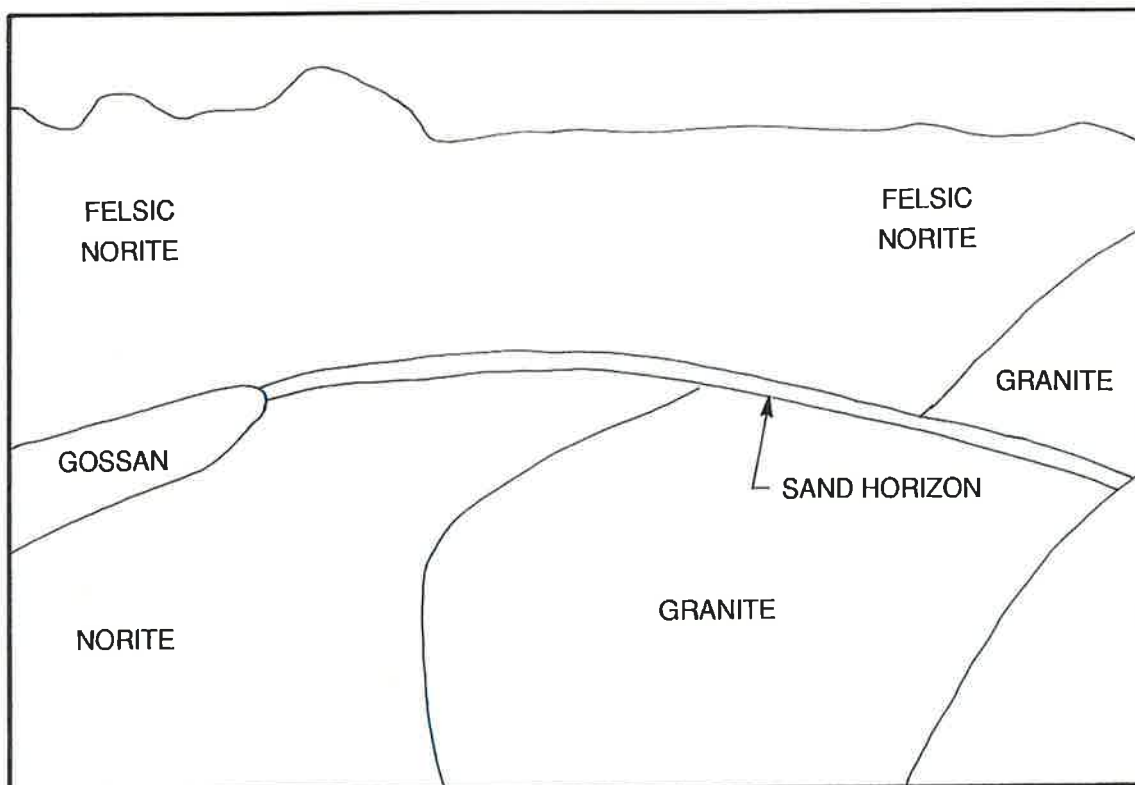




TEST PIT 2 - FACING SOUTH

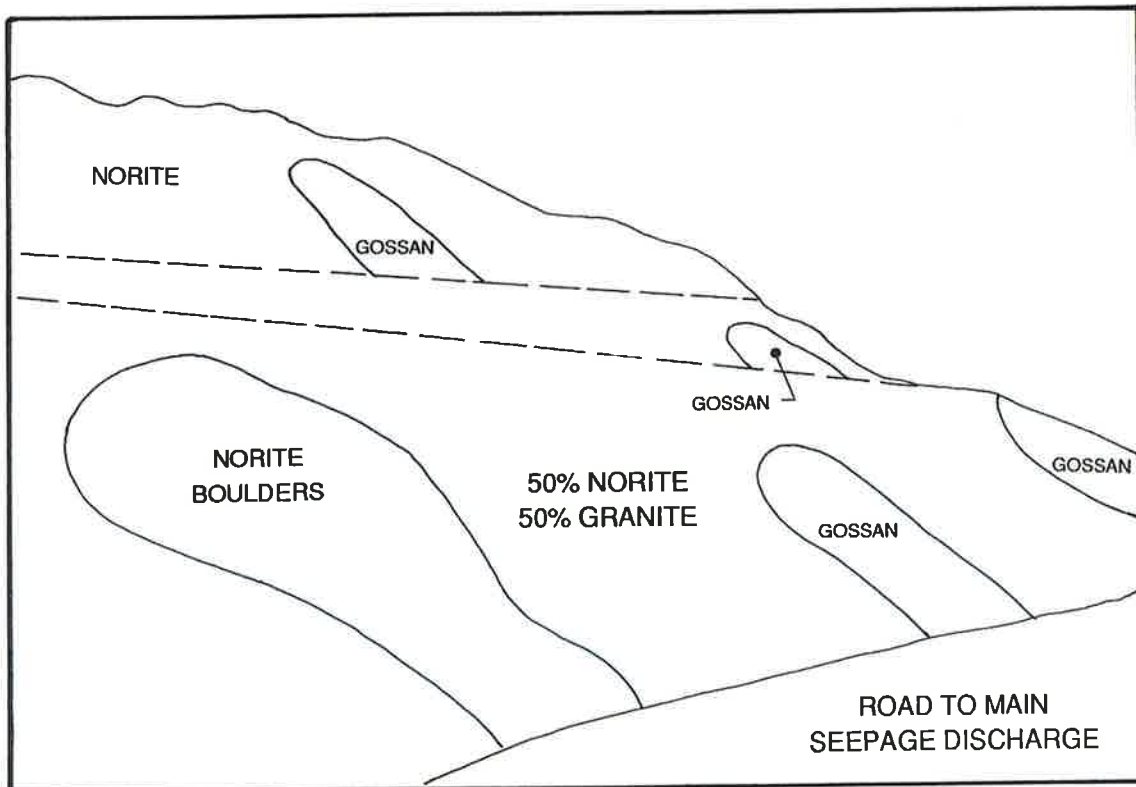


TEST PIT 3 - FACING NORTH EAST





AUTOPSY ZONE - FACING NORTH WEST  
FROM SOUTH END OF ROAD CUT



AUTOPSY ZONE NEAR SEEPAGE DISCHARGE

