APPLICATIONS OF GEOPHYSICAL METHODS FOR MONITORING ACID MINE DRAINAGE[1]

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Abstract: Following preliminary studies which indicated the potential for using geophysical methods for mapping acid mine drainage (AMD), the Mine Environmental Neutral Drainage or MEND committee, a Canadian industry-government forum for the development of new technology for the prevention, prediction and monitoring of AMD sponsored a study to demonstrate the applications of geophysical methods to the AMD problem.

High quality airborne, ground and borehole geophysical data were acquired over areas with well documented AMD problems, including tailings impoundments, waste rock piles and AMD ground water plumes. The geophysical data were correlated with hydrological and chemical data from ongoing ground water investigations to establish the utility of the methods.

The results confirmed that electromagnetic (EM) methods that remotely measure the conductivity of the subsurface are very useful for location and detailed three-dimensional mapping of AMD in ground water. Airborne surveys can provide rapid reconnaissance scale surveys, while ground surveys and borehole surveys provide progressively more detail.

In addition to the EM work, combined Induced Polarization (IP) and electrical resistivity surveys were tested on a large revegetated tailings area. Since the IP method detects disseminated sulphides, the combination of IP and resistivity surveys can be used for simultaneous three-dimensional mapping of sulphides and ground water quality in tailings.

All of these methods require measurement of the electrical properties of the subsurface and are adversely affected by electrical noise from power lines and surface and buried metal. The response of AMD may be masked by naturally conductive ground water, bedrock lithologies, or clay soils.

Additional Key Words: geophysics, electromagnetics, induced polarization.

Introduction

In 1991 INCO Limited proposed a program to investigate the applications of geophysical methods to Acid Mine Drainage (AMD) problems. This proposal was subsequently implemented with funding from the federal and provincial governments, through the Northern Ontario Development Agreement (NODA) program and INCO Limited under the technical sponsorship of the Canadian Mine Environmental Neutral Drainage (MEND) Committee. The proposal was based on evidence from work in related fields and tests on INCO properties that indicated that a number of the subsurface investigation techniques developed for geotechnical applications and mining exploration had direct application to AMD problems.

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In this work we have focused mainly on the electrical and electromagnetic methods since they had the potential for direct, low cost, non-intrusive, three-dimensional mapping of subsurface AMD problems. Airborne conductivity surveys were ground truthed with ground conductivity surveys which were in turn confirmed by borehole surveys and chemical analysis of water samples. The induced polarization method was also tested for direct mapping of sulphides in tailings.

Sudbury Basin

The Sudbury Igneous Complex (SIC), located 400 km north of Toronto in eastern Canada, hosts one of the largest concentrations of economic sulphide deposits in the world, with production of nickel, copper, cobalt and platinum group elements. The SIC is the result of a major meteor impact approximately 1.8 billion years ago. It is believed that the complex was originally circular in shape and subsequent tectonic events have deformed it to its present elliptical shape. It consists of basal crystalline intrusive rocks overlain successively by a tuff-like fallback breccia and an upper layer of carbonaceous sediments.

The major deposits and the associated mine facilities are all found at or near the contact between the basal crystalline intrusive rocks of the complex, which measures approximately 30 by 60 km, and surrounding metamorphosed volcanic, sedimentary and intrusive rocks. These host rocks are all electrically very resistive - an important factor in the application of electrical geophysical methods.

The first deposits were discovered in the 1890's and mining has been carried out continuously since then. There are currently 14 operating mines, and approximately 40 abandoned sites around the perimeter of the basin.

Mining has produced approximately one billion tons of reactive sulphide-bearing waste rock. Most of this is in tailings, with some in waste rock piles. The principal sulphide in the waste rock is pyrrhotite with concentrations in tailings ranging from less than one percent up to 60% sulphides in pyrrhotite storage areas. As is well known, on exposure to air the sulphides oxidize to produce dilute sulphuric acid plus metals, mainly Fe, but enough Ni and Cu to potentially affect drinking water quality.

The tailings are stored in large impoundments in topographically low areas and contained, where necessary, by large, semi-permeable dams. The two main INCO tailings are at Copper Cliff (6,000 acres) and Levack (150 acres). The Copper Cliff tailings are being expanded to handle future mine waste and are currently receiving about 40,000 tons per day of tailings. The Levack tailings are no longer active. Ongoing geotechnical and hydrogeological studies at both sites are gathering the detailed information required to design optimum containment, treatment and eventual closure plans.

The tailings areas are net recharge areas due to natural precipitation (0.2 m per year approximately, Coggans et al, 1991) and the addition of mine waters. The hydraulic gradients in the tailings areas are generally downward and outward, resulting in ground water flow through and below the dams. This results in plumes of tailings water which manifest themselves as low Ph, high sulphate, high iron, surface AMD seeps. All surface drainage is collected through an extensive network of interception ponds and pumping stations and is treated at a central facility.

Study Area

Originally, two sites, one at the INCO Copper Cliff tailings and the other at the INCO Levack tailings, were selected for geophysical tests. Subsequently, some excellent data provided by Falconbridge Ltd. at their Fault Lake tailings resulted in the inclusion of this site in the study as well.

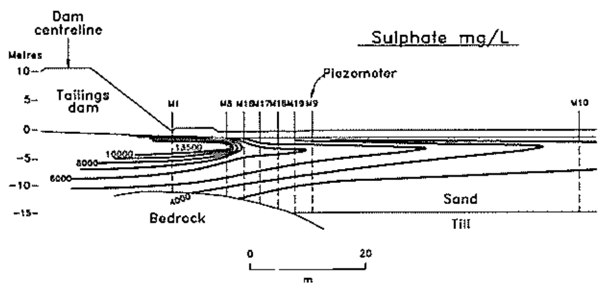

Figure 1. Nordic Mine - Sulphate in ground water.

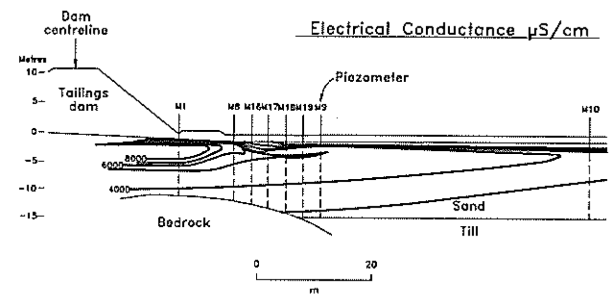

Figure 2. Nordic Mine - Ground water conductivity.

These areas were selected as known AMD sites where data from concurrent geotechnical and hydrological studies could be used to correlate with our geophysical work. This presentation focuses on selected results from the Copper Cliff and Levack tailings areas which are representative of the overall results of the study.

Basic Principles of Geophysical Methods

Geophysical methods rely on contrasts in bulk physical properties such as electrical conductivity, magnetic susceptibility, density, seismic velocity, etc. If there is a suitable physical property contrast, geophysical methods can be used to remotely map variations in physical properties in three dimensions. For these methods to be effective as direct detection methods for AMD, there has to be a correlation between ground water chemistry and a mappable physical property - in this case, electrical conductivity.

The correlation between AMD and conductivity is best demonstrated by work done by the University of Waterloo on sulphide-bearing uranium tailings at Elliot Lake, Ontario (Blair et al, 1980). As shown in figures 1 and 2, multilevel monitoring wells were used to measure the chemistry of a ground water AMD plume extending below one of the tailings dams. The measured data were plotted on a vertical section through the plume and contoured. Figure 1 shows the sulphate concentration in milligrams per litre and figure 2 shows the electrical conductivity in microsiemens per centimetre as measured on ground water samples. The correlation is excellent, and it is obvious that if the distribution of conductivity can be measured remotely using geophysical methods and there are no other sources of anomalous conductivity, then the location and concentration of AMD can be inferred.

Based on the work at Elliot Lake, particularly a pioneering ground conductivity survey by Pehme (1981), work in similar ground water investigations (King and Sartorelli, 1991), and ground conductivity tests at the Copper Cliff tailings, it was obvious that there was considerable potential for geophysical applications in AMD applications, and we proposed a project to the Canadian MEND (Mines Environmental Neutral Drainage) Committee to demonstrate and document the use of geophysics for AMD investigations.

In particular, we have tested airborne, ground and borehole electromagnetic (EM) conductivity surveying as well as ground and borehole electrical conductivity and induced polarization (IP) surveying. The principal use of the IP method in exploration has been the mapping of disseminated sulphides in bedrock. It was proposed at the start of this study that the method could be used to determine the distribution of sulphides in tailings. These methods and their applications to AMD mapping were described in more detail in King and Sartorelli (1991).

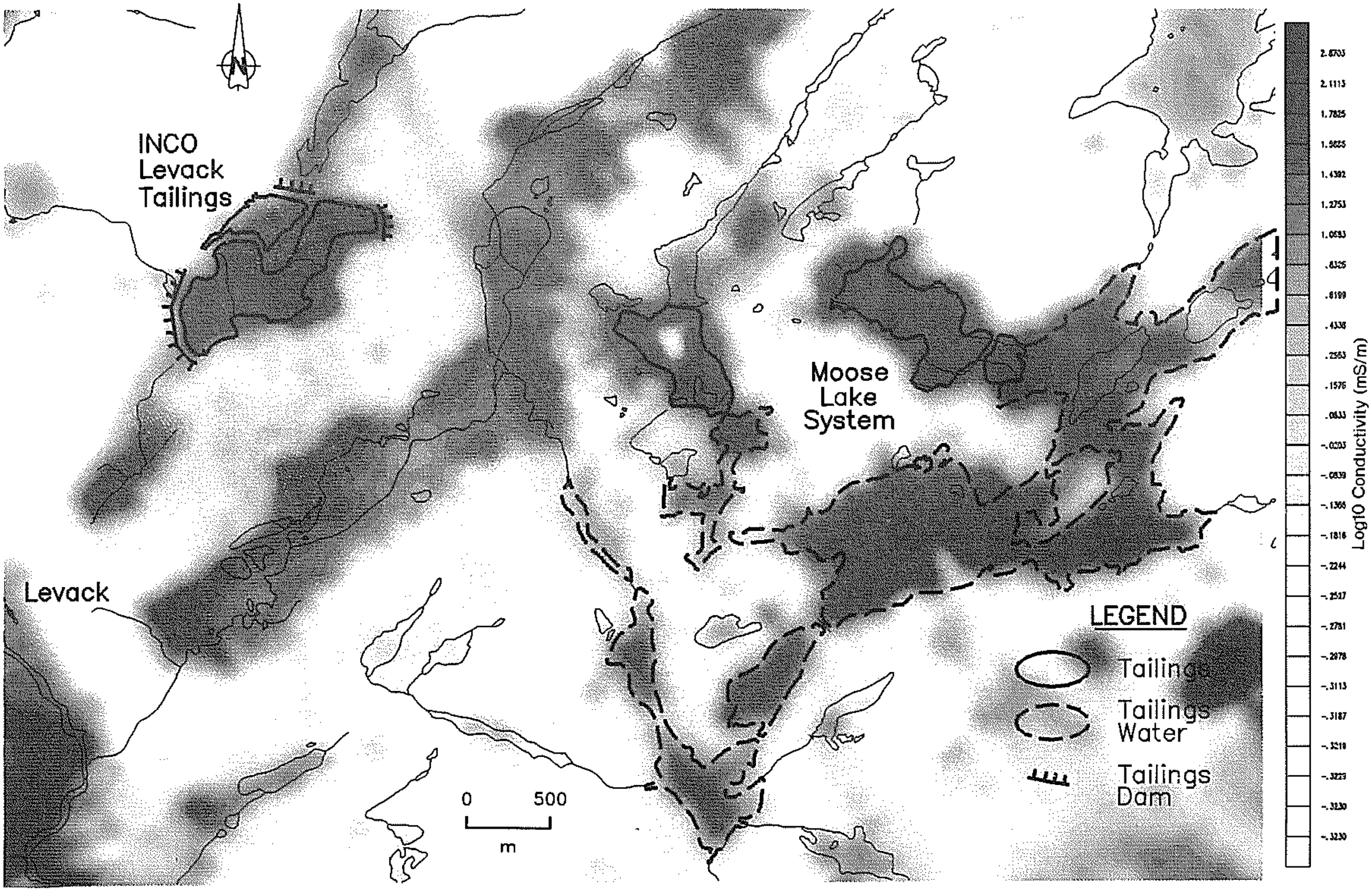

Figure 3. Levack Area - Airborne conductivity data and surface drainage.

Description of Results

Helicopter EM Surveys

In 1987 most of the Sudbury Basin was flown with a multifrequency, multicoil, helicopter electromagnetic system as part of a regional minerals exploration program. It was immediately obvious from the responses over the tailings areas that the data would be useful for environmental applications as well as exploration.

The survey consisted of approximately 32,000 km of data acquisition at 100 m line spacing over a 40 km by 80 km area. The survey was navigated and the data positioned using a radio beacon triangulation system with an accuracy of better than 10 m. The data were sampled digitally at 5 m intervals along the survey lines and recorded. Following the calculation of conductivity values, the data were interpolated onto a 25 m by 25 m grid, contoured and presented in colour image form. The final gridded data file is a 15 megabyte digital data file suitable for input to image-processing or geographical information systems (GIS). This data set covers most of the existing and abandoned mine sites and provides an abundance of detailed conductivity information. A sample of these data over the Levack area was selected for ground truthing.

Figure 3 shows a grey scale version of the airborne electromagnetic (AEM) conductivity data superimposed on a topographic map of the Levack area showing surface drainage with the tailings areas highlighted. The grey scale is logarithmic with peak values over 30,000 mS/m.

The Falconbridge tailings and tailings water drainage are confined to rock-bounded lakes of the Moose Lake drainage system in the eastern part of the map area. The INCO Levack tailings are located to the north of the town of Levack in an elevated valley and are bounded by large dams to the north and south.

The outstanding features of the conductivity map are the strong conductivity highs (greater than 10,000 mS/m) over the tailings areas. The high conductivity over the tailings is due to high total dissolved solids in the tailings water. The water may be low pH, high sulphate, typical AMD where the tailings have been exposed to oxygen, or high pH, high sulphate, high calcium where the water is in its unoxidized state. Tailings are limed before discharge so unoxidized tailings are basic.

Background values over most of the survey area are very low (less than 5 mS/m) owing to the electrically resistive crystalline bedrock and freshwater-saturated, thin, sandy and gravelly overburden. This high contrast in electrical conductivity between background values and tailings water makes this an ideal environment for mapping ground water quality using geophysics.

The AEM data shows that the tailings in the Moose Lake system are confined to the rock-bounded lake and drainage system. There is no large scale migration of tailings water beyond the limits of the tailings themselves.

The AEM data over the INCO Levack tails clearly delimit the tailings area but also show moderate conductivity anomalies extending under the north dam into the lake to the north and beneath the south dam into the sand and gravel-filled valley to the south. These conductivity anomalies are due to AMD flowing in a sand and gravel aquifer which extends beneath the dams and the tailings. The AMD is apparent in a few iron-stained seeps in both areas. The airborne data show the essentially continuous nature of this conductive ground water in the valley. They also show that these are the only directions of leakage from the tailings and that the ground water flow is confined to the narrow valley. This information immediately focuses follow-up plans into well-defined areas, reducing sampling and monitoring costs as well as defining the approximate scope of future interception and treatment plans.

The low conductivity area over the town of Levack is an artifact of the data acquisition process. The helicopter is required to fly much higher than its normal survey altitude (aircraft 80 m; survey coils 30 m) over towns, so that the system is essentially measuring the conductivity of air.

Other areas of anomalous conductivity are due to cultural features such as mine buildings, power lines, railroads, etc., sulphides in bedrock (the original target of the survey), sulphides in waste rock piles, and other areas of ground water contamination in the vicinity of the mines. Most of these areas have yet to be followed up on the ground.

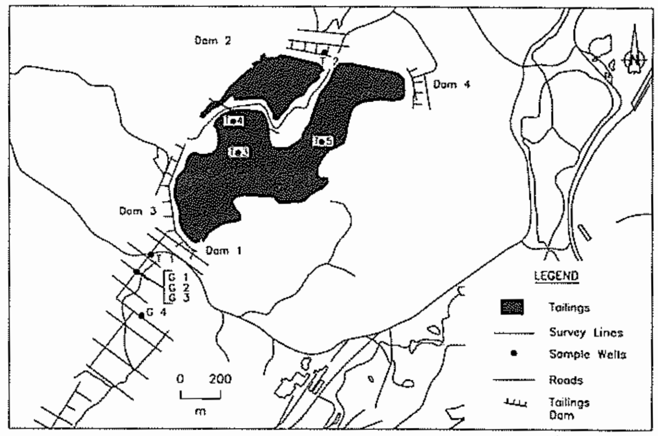

Figure 4. Levack Tailings - Ground survey lines and sampling well locations.

An alternative presentation of the airborne data provides more information on the variation of conductivity with depth. The helicopter system acquires data at three separate frequencies simultaneously (900 Hz, 4,000 Hz and 32,000 Hz.). Since depth penetration is inversely proportional to frequency, the multifrequency data can be used to create approximate sections or pseudosections of conductivity versus depth along the survey line. These are called Sengpiel sections after the developer of the method.

Sengpiel sections were calculated for all the lines over the INCO tailings and when stacked one above the other show the horizontal and vertical conductivity variations over the tailings and the north and south ground water plumes.

Ground EM Surveys

The airborne surveys in the vicinity of the INCO Levack tailings were followed up with detailed ground surveys using the EM31 (1-5 m depth penetration) and the EM34 (10-40 m depth penetration) ground conductivity systems. The larger scale topographic map shown in figure 4 shows the location of the survey lines as well as the location of the water sampling wells at the site. Most of these wells are multilevel, plastic-cased piezometers. Water samples were taken at regular intervals and analyzed for major ions and metals.

A sample of the EM31 data over the northern part of the tailings is shown plotted in profile form in figure 5. These data confirm the very high conductivities over the tailings themselves, the moderate but still highly anomalous conductivities over the northern ground water plume below the dam, and the very low background values. The rapid variations in values within the conductive areas are due largely to topographic variations or variations in the thickness of nonconductive fill. Because of the shallow depth penetration of the system, the readings are quite sensitive to the height of the instrument above the water table.

A sample of the EM34 data is shown in figure 6. These data were collected over the south ground water plume using vertical coplanar coils with a coil separation of 20 m and has an effective depth penetration of 10 m. The conductive area correlates well with airborne data in the area, but the conductivity values are somewhat lower. We believe that this is largely due to an improvement in water quality between the 1987 airborne survey and the 1991 ground survey due to flushing of the system with fresh water since the closure of the tailings.

At each station in the ground survey a total of five readings with different effective depths of penetration were taken with the EM31 and EM34. One-dimensional inversions were carried out on selected lines to produce approximate conductivity versus depth sections. One such section from the line along the base of the north dam

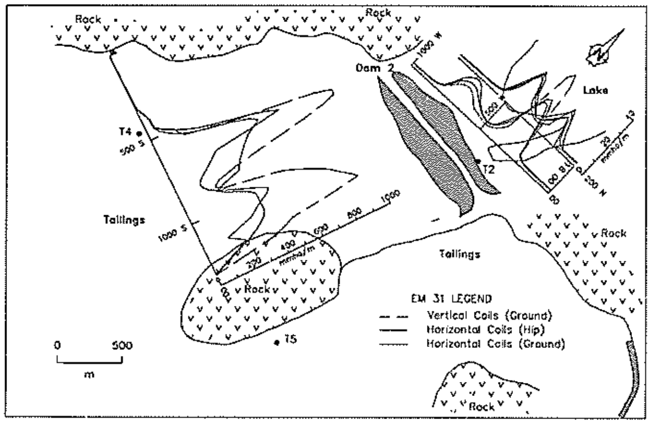

Figure 5. Levack Tailings North Dam - Shallow ground conductivity data (EM31).

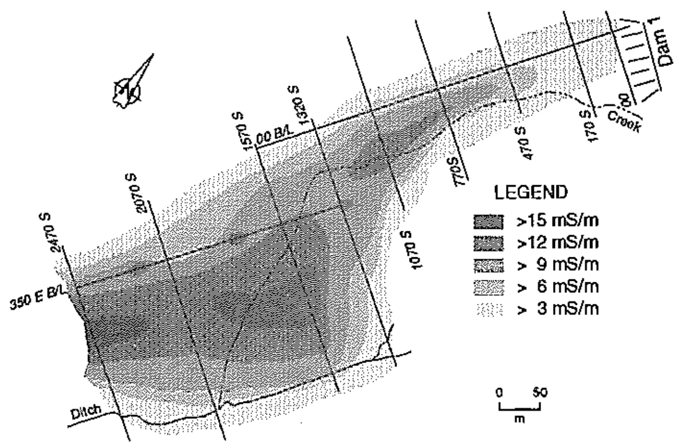

Figure 6. Levack Tailings South Dam - Deep ground conductivity (EM34, 20 metre coil separation, vertical coils).

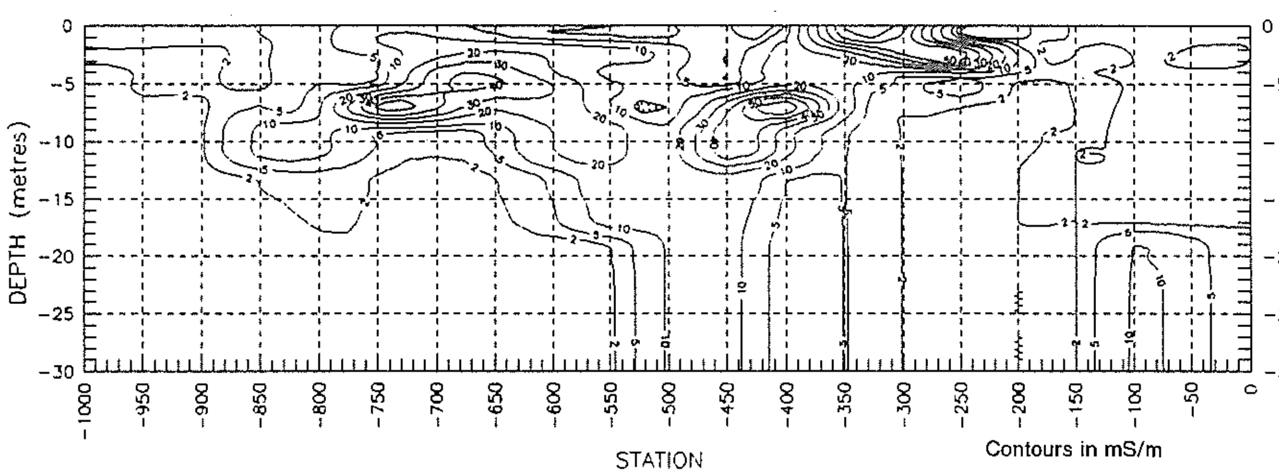

Figure 7. North Dam Line 00 - Vertical conductivity section.

is shown in figure 7. The general shape of the bedrock valley that contains the conductive ground water is apparent in the section. This shape has been confirmed by seismic refraction surveying and drilling.

Borehole EM Surveys

To establish a detailed correlation between bulk conductivity and ground water chemistry, downhole conductivity surveys were conducted in all available holes. Downhole natural gamma surveys were carried out at the same time to assist in mapping soil stratigraphy. The downhole electromagnetic conductivity tool measures the average electrical conductivity in the vicinity of the hole and can operate in plastic-cased boreholes. Readings are digitally recorded at 10 cm intervals, providing a very detailed conductivity profile.

Figure 8 shows a sample of logs from borehole T-2 located in the ground water plume just to the north of the north dam. Below the water table at 10 m, the conductivity log shows moderate bulk conductivity values throughout the sand and gravel aquifer associated with anomalous pore fluid conductivity values as measured on water samples. These values are consistent with measured airborne and ground conductivity values results.

The source of the conductivity is acidic ground water, as indicated by the low pH's.

Both the conductivity and gamma log show that the aquifer is not as uniform as indicated by the stratigraphic log. In general, the gamma values are inversely correlated with the conductivity. High gamma and low conductivity indicate areas of higher clay content and presumably lower permeability. Low gamma, high conductivity areas correspond to areas of lower clay content and higher permeability.

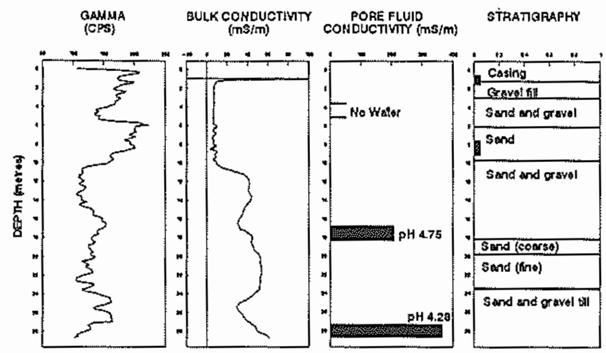

Figure 8. Downhole geophysical logs - Hole T2.

The relationship between chemistry and conductivity is illustrated in the next two figures. Figure 9 shows the concentration of all significant ionic species in a water sample from 28.9 m in depth in well T-2. This is a characteristic AMD chemical signature with sulphate as the dominant ionic species, followed by iron and calcium.

Figure 10 shows the contribution that each ionic species makes to the total conductivity as calculated from the chemical concentrations using the formulae given by McNeil (1980). It is apparent that the conductivity, like the concentration, is dominated by the sulphate, iron and calcium ions. At this moderately low pH (4.28) the H_3O+ ion makes a negligible contribution to the conductivity. However, due to the logarithmic nature of the pH measurement, the H_3O+ concentration and its contribution to the conductivity increase rapidly with decreasing pH.

Borehole conductivity measurements provide a detailed log of conductivity and can be used to locate precisely the source of anomalous conductivity, to interpolate water quality between water sample point and to locate suitable sampling points.

Induced Polarization and Resistivity

Combined induced polarization and electrical resistivity surveys were carried out along two lines on the Copper Cliff tailings. These two lines had been previously studied by the University of Waterloo, and a number of shallow stratigraphic holes together with ground water monitoring wells were available for correlation with the geophysics.

Different parts of the Copper Cliff tailings contain very different concentrations of sulphide with values ranging from over 50% in the pyrrhotite storage area to less than 1% in some of the low sulphide areas. The low sulphide tailings were deposited when an iron ore recovery plant was in operation and recovered iron and sulphuric acid from the rejected pyrrhotite. The lateral and vertical boundaries between different types of tailings are not always well known, particularly in older areas of the tailings. Since knowledge of the total volume of sulphide and the distribution of sulphides is important in predicting AMD production, it was hoped that the IP data could provide some information on sulphide distribution.

A sample of the data from one of the survey lines, shown in figure 11, extends from an area of known moderate pyrrhotite content (about 3% sulphides) around Station 0+00 into an area of lower pyrrhotite (less than 0.5% sulphides) around 340S. In this case the horizontal scale is in metres along the survey line and the vertical scale is measured in units of the electrode spacing. Since an increase in electrode spacing results in an increase in depth penetration this figure is an approximate vertical section through the earth to the maximum depth penetration of the system, which in this case is about 20 m. The IP results correlate well with the known sulphide distribution with values around 4 milliseconds (msec.) of chargeability at Station 0+00 and values

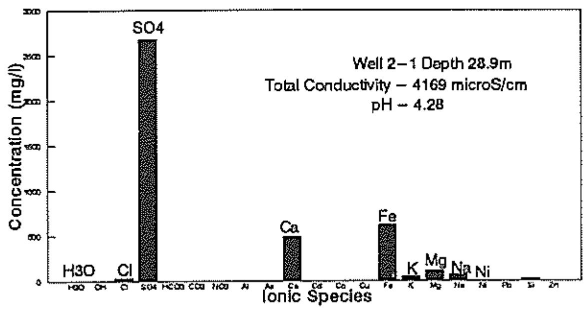

Figure 9. Groundwater chemistry - Hole T2.

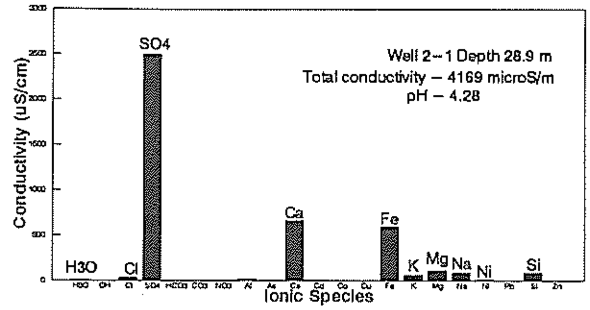

Figure 10. Conductivity per ion - Hole T2.

below 1 msec. south of 2+00S. The feature at 2+90S is due to a steel pipe. It appears from the data that the low sulphide area at the south end of the line onlaps the zone of higher sulphides as indicated by the higher chargeability values extending to depth to the south.

The conductivity values are higher over the higher chargeability area indicating higher concentrations of AMD associated with the sulphides. Based on the results of this work it appears that electrical IP and resistivity surveys are a useful tool for mapping the distribution of sulphides and AMD in tailings.

Conclusions

In the course of this work, we have demonstrated that, in suitable areas, electromagnetic and electrical geophysical methods can be used to map the three-dimensional distribution of sulphides in tailings and AMD in and around tailings. The airborne and surface methods are non-intrusive, fast and inexpensive when compared to reconnaissance drilling and sampling programs. The borehole methods provide detailed conductivity logs which can complement limited downhole water sampling.

It should be emphasized that geophysical methods should not be used in isolation. Because they do not uniquely identify the source of anomalies and the accuracy of interpretations is often limited by data density, signal noise, or the equivalent signatures of different sources, they should only be used as a guide to drilling and sampling, not as a replacement.

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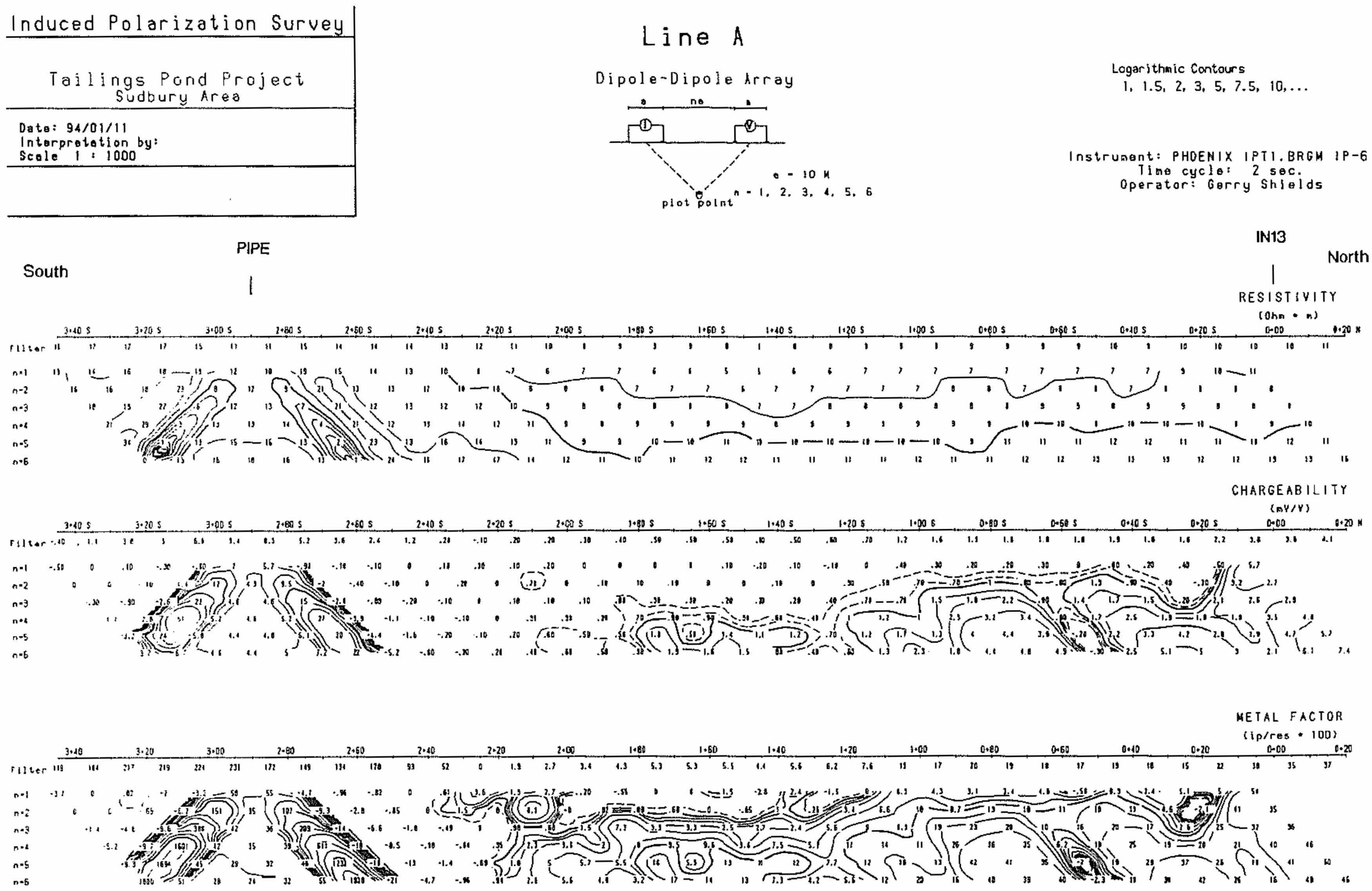

Figure 11. Induced polarization and resistivity data Copper Cliff Tailings.