Ground Geophysical Surveys For Mine Wastes

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ABSTRACT

This paper presents and discusses the results of two contrasting geophysical surveys to detect acid mine drainage. One is a large, multi-institutional research study of contamination below a tailings dam, in which several methods have been applied in order to compare their usefulness. The surface geophysical surveys are found to be good at identifying the pathways for contamination movement, but limited in their ability to distinguish between contaminated groundwater and naturally conductive sediments. Overall, however, good geophysical coverage is obtained which proves highly effective for planning the hydrogeological program. In the second example a small consulting job is described, in which limitations of time, access and funding require that a bare minimum of data be collected to address the problem. This survey basically locates anomalies around the perimeter of a suspected contaminant source, and largely leaves the explanation of these anomalies to drilling and sampling. We conclude that in this case, which is probably very typical of the practice in general, full advantage of the potential of geophysics has not been received.

INTRODUCTION

Geophysics is widely associated with the mineral industries, and primarily with exploration. Our voracious appetite for minerals, the promise of wealth for those who find them, and the fascination of the search itself have together provided explorationists with the sort of challenge that mankind's creativity thrives on. In exploration geophysics this has resulted in a huge array of methods, software and instruments for probing the subsurface. Not all of them actually work, most are simply restatements of others, and a majority are useful only under very specialized conditions. From this mass of inventiveness, however, some truly remarkable methodologies have risen to the surface to form the basis of modern geophysical practice.

Exploration technology has naturally tended to advance fastest, and cost the most, for those applications with the highest expectations for returns. Applications judged to be less rewarding also benefit from these advances, but in a "trickle-down" manner. Thus many university departments have been the beneficiaries of excellent but obsolete equipment from mining and petroleum exploration companies, with which they have been able to examine important but less immediate problems. Similarly geophysicists working on less valuable resources such as groundwater, or on geotechnical and environmental problems, generally found themselves well behind the technical vanguard.

The rise in environmentalism in the past two decades has been driven fundamentally by a rise in the value of air and water. In the geological sciences there has been a very substantial shift of the discipline away from traditional fields such as economic geology towards environmental geology and hydrogeology. In geophysics this shift, though real, has been smaller. There is now a small but well-established field of environmental geophysics that has the protection and exploitation of groundwater resources as its focus. It has not reversed (and probably will not reverse) the technological slope referred to above, but it has certainly lessened it to the point that we no longer think of ourselves as the poor cousins of the larger and richer oil and mining industries. Adaptations of mining electromagnetic instrumentation for environmental applications have been very successful. Good software has been written specifically for the presentation and visualization of environmental data. And in ground-penetrating radar (GPR) environmental and geotechnical geophysicists have a technology they can truthfully call their own.

In the mining industry environmentalism and exploration are often cast as adversaries. Geophysicists, like geologists, are found on both sides of these battles. This symposium is primarily concerned with mining exploration but mine wastes and their drainage products, typically metal rich and conductive, are good targets for geophysical methods and constitute a small but growing market.

King (1994) and Paterson *et al.* (1994) have ably described the applications of geophysics to problems of mine wastes and these reports form a starting point for any study of the field. These authors point out that such applications are not new. Examples of geophysical surveys for mine

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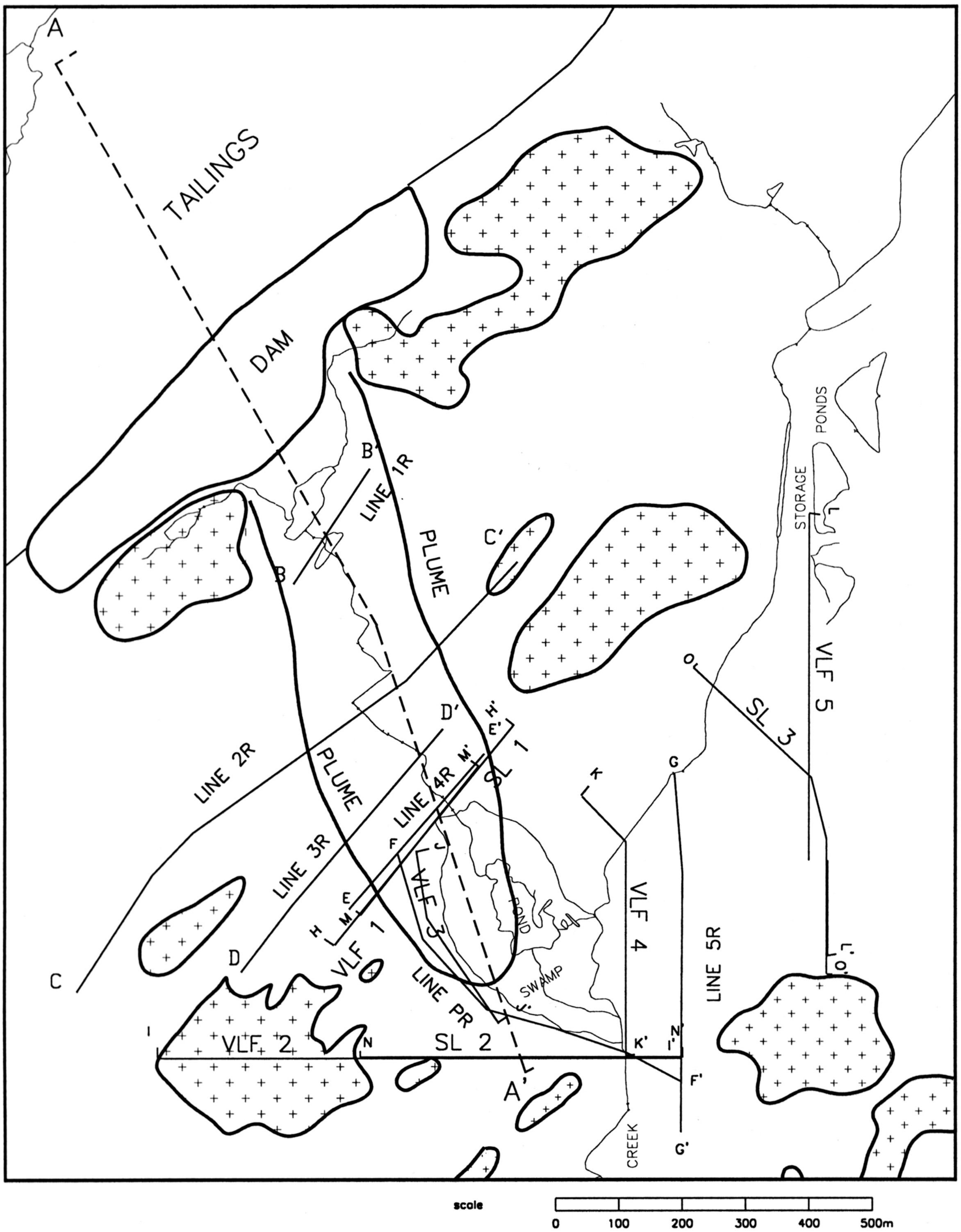

Figure 1: *The study area, showing locations of geophysical cross sections and plume extent.*

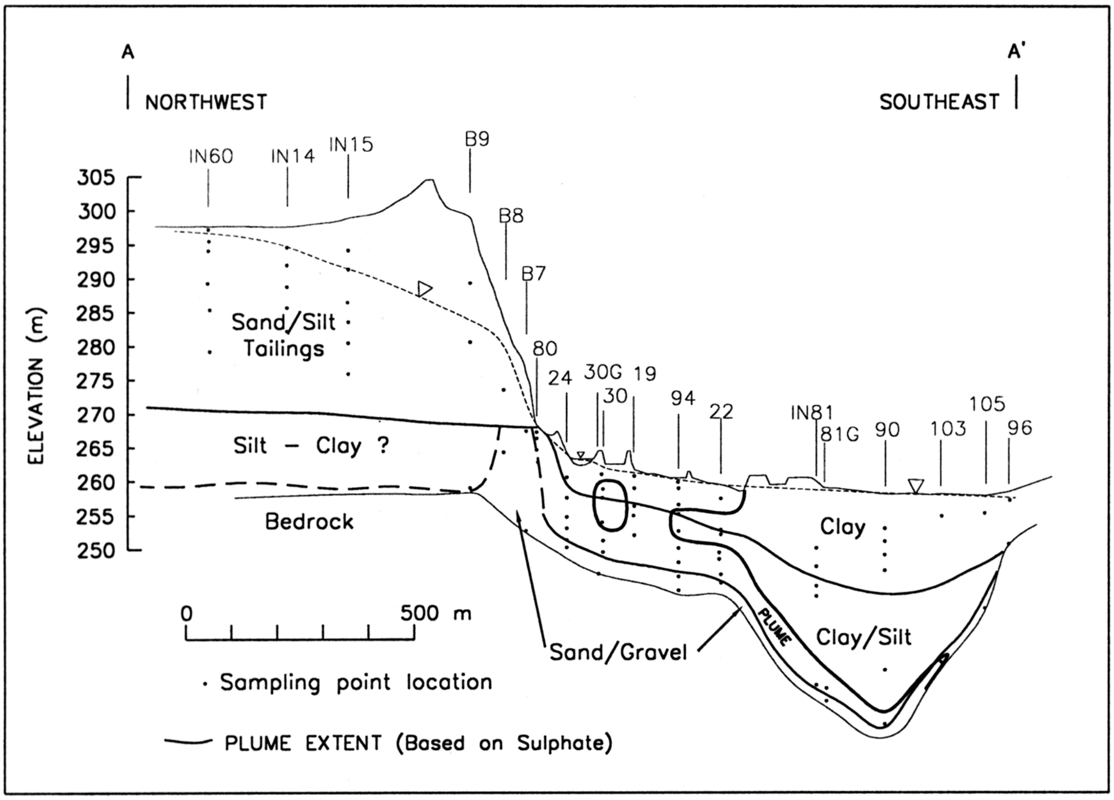

Figure 2: *Cross-section A–A' from Figure 1, showing stratigraphic units and plume boundaries as of September, 1994.*

wastes, particularly electrical resistivity surveys, have been carried out for decades. What is new in the past decade is the growth in the number of these surveys, and the context of environmental awareness in which the geophysicist now works.

Paterson (1997, this volume) has further summarised this material, and described the methodologies and instrumentation in current practice. The proceedings of the annual SAGEEP meetings (*see* SAGEEP in references) are also a good source of current practice (although these conferences tend to emphasise successful rather than typical results). Papers by Freeman *et al.* (1997), Campbell *et al.* (1997), Carlson and Zonge (1997) and Kristiansen *et al.* (1997) describe applications that include fine-scale IP measurements of tailings pile using push (piezocone) technologies, an IP and GPR survey of a river bed which has been used for transported tailing materials, and detecting leakage from tailings ponds.

In this paper we present two short case histories involving geophysical surveys for groundwater contamination caused by mine wastes. One is a research project participated by several universities and institutions including ours, and is characterised by the availability of relatively abundant time and resources. This study seems typical of the research interests of the mid-1990s, and it required a close working relationship between geophysicists and hydrogeologists.

The second case history is more typical of the short, time and budget limited consulting jobs that are far more common than the first example. Here the geophysics is carried out quickly, in relative isolation from other studies, and often with less detail than the problem really requires. Competition for these jobs is high, budgets are small and there is little latitude available to the contractor to deviate from the survey plan in light of the data obtained.

The ultimate goal of geophysical surveys in acid mine drainage environments such as these is to provide a rapid, inexpensive tool that can be used to identify potential zones of tailings-derived water and to determine the extent of migration of tailings-area drainage. The advantages of geophysical techniques over conventional groundwater monitoring techniques are the relative ease of data collection and the large quantity of data that can be collected over a short period of time. Used in conjunction with a conventional groundwater monitoring program, geophysical techniques should result in savings of time and money and assist in the optimal placement of sampling wells.

CASE HISTORIES

Case 1: Copper Cliff Mine tailings

Some sediments underlying the Pistol Dam of the INCO, Copper Cliff P area tailings are permeable and a plume of high electrical conductivity tailings-derived water is emanating from between two bedrock outcrops to the south of the dam (Figure 1). The sediments south of the dam consist of bedrock overlain by a thin layer of glaciofluvial sand overlain by

5 to 33 m of glaciolacustrine silt and clay (Figure 2). Geochemical and hydrogeological data describing this plume of water DeVos (1995) have been used to evaluate the potential advantages of geophysical investigations, and to assess a variety of geophysical techniques. The geochemical data is essentially more reliable than the geophysical data; however, it is also much more localized and site specific. Blowes (1997, this volume) describes the geochemical issues and the environmental effects of mine waste. Background data on the Copper Cliff tailings is presented in Jambor (1994), McGregor (1994), and Robertson and Blowes (1992).

Earth resistivity, induced polarization (IP), electromagnetics (EM), airborne EM, seismic refraction and piezocone technology (Campanella *et al.*, 1993) were all implemented at this site with varying degrees of success. Other related geophysical activities on the site include geophysical borehole logging and an IP survey conducted on the tailings surface (Oldenburg, 1995; Yuval and Oldenburg, 1996).

Galvanic resistivity

A series of galvanic resistivity readings at several locations, using a Wenner array (described in DeVos, 1992, and DeVos, 1995) were taken over the Pistol Dam study area to determine the distribution of high electrical conductivity tailings-derived water and to determine possible depressions in the bedrock topography. The results from these studies indicate that in the near-dam sediments it was possible to define the lateral extent of the plume water due to the high conductivity contrast between the plume water at depth and the upper higher resistivity sediments that were not affected by plume water. Further to the south and east it was not possible to define the plume of high conductivity water due to the presence of thick deposits of high electrical conductivity, silt and clay material on top of the electrically conductive tailings-derived water; however, the resistivity contrast between the bedrock and the sediments within the bedrock valley made possible the estimation of depth to bedrock between borehole locations. Figures 3 presents interpreted resistivity sections from lines R1, R2, and R3 (after DeVos, 1992).

VLF resistivity

A VLF resistivity survey was conducted in the study area to define trends in bedrock topography. VLF is quick to run, requires only one person, and makes an excellent reconnaissance tool. Apparent resistivity, and phase angle were determined for five lines south of the Pistol Dam (Figure 1), and the product of conductivity and thickness of the conductive deposits overlying an assumed non-conducting bedrock determined. The conductivity-thickness product provides an indication of the relative variation in depth to bedrock along the line. Low phase angle dominates throughout the swamp area indicating the presence of an upper layer of lower resistivity than the lower unit (McNeill, 1980). This result is consistent with drill logs from auger drilling which indicate an upper layer of silt and clay. Plots of apparent resistivity vs. distance along the line are presented in Figure 4.

Seismic refraction

Three seismic lines were positioned to determine topographic bedrock lows which may be acting as conduits for groundwater flow (Figure 1). In the study area the upper layer seismic velocity ranged from

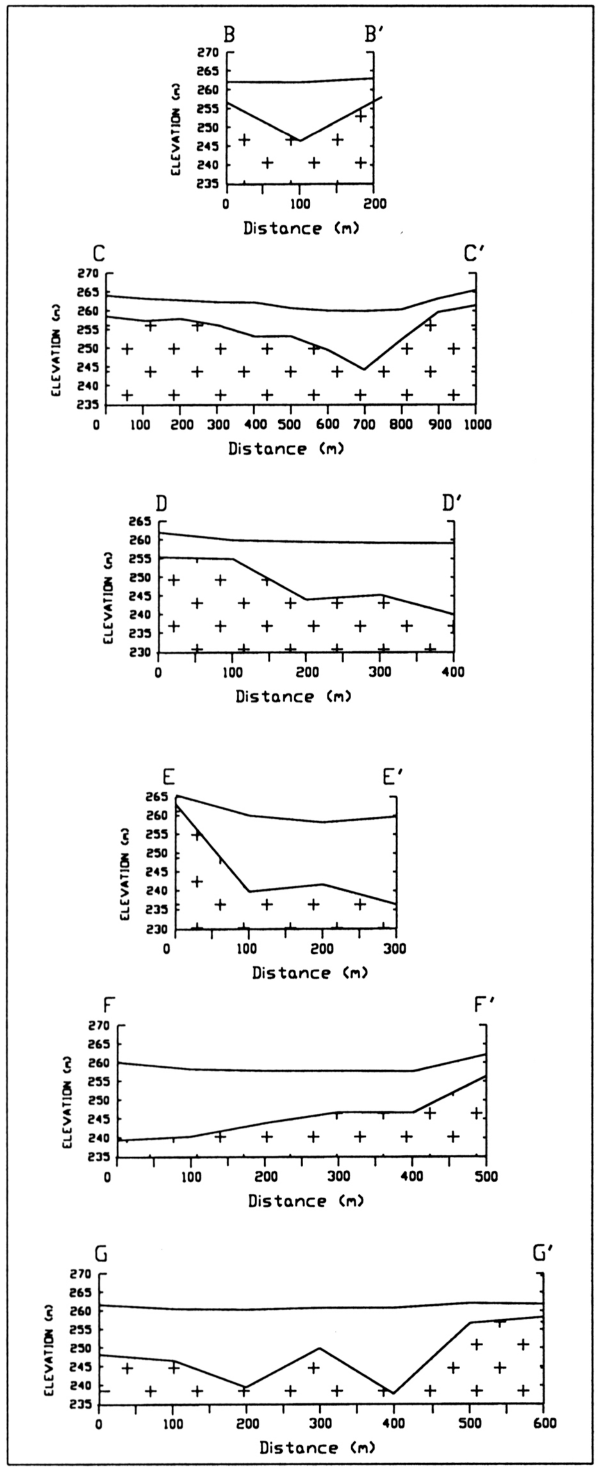

Figure 3: *Cross-sections based on galvanic resistivity soundings showing interpreted depth to bedrock.*

1800 m/s under saturated conditions to 500 m/s under unsaturated conditions and the bedrock seismic velocity was approximately 5000 m/s. Results were analysed using VIEWSEIS (Kassenar, 1992).

The seismic survey identified three possible bedrock channels which may be acting as groundwater conduits. The first is along seismic line (SL) 1 where a large bedrock depression can be observed (Figure 5a). It is through this depression that the groundwater is entering the basin. A possible bedrock opening was located along SL2 in bedrock depression between SL2 350 to SL2 450 (Figure 5b). This depression has been confirmed through the placement of a piezometer, IN95, 30 m north of the line. The piezometer depth was greater than that found by seismic refraction possibly due to error in the interpretation of the seismic data owing to steepness of the dipping refractor, and because the piezometer was located 30 m north of the seismic line. Groundwater probably exits the basin through this opening. Another depression in the bedrock was located at the northern end of SL3 (Figure 5c). This location was drilled (IN92) and hydraulic gradients have identified this as a possible mine water impacted groundwater input into the study area.

Time Domain EM

An EM-47 survey designed to investigate deep conductors was completed over the swamp the south of Highway 17 in the winter of 1993. The results contoured for one of the channels (Channel 8, 0.04 msecs) are shown in Figure 6. The aerial view clearly outlines the highly conductive sediments of the swamp area, and the low conductivity bedrock bounding it to the west. The data from a single channel does not, however, discriminate between conductive water and conductive sediments. Interpretation of the complete data set by King (1994) tentatively identified a zone of anomalously high conductivity material at depth south of IN29, which suggests the possibility of plume water at depth here, or that high conductivity clay sediments also exist at depth in these sediments. King (1994) concluded, however, that the thin conductive plume under 20 to 30 m of conductive overburden is a difficult target in a complex environment and that results of the surface EM techniques employed should be considered typical in this type of environment.

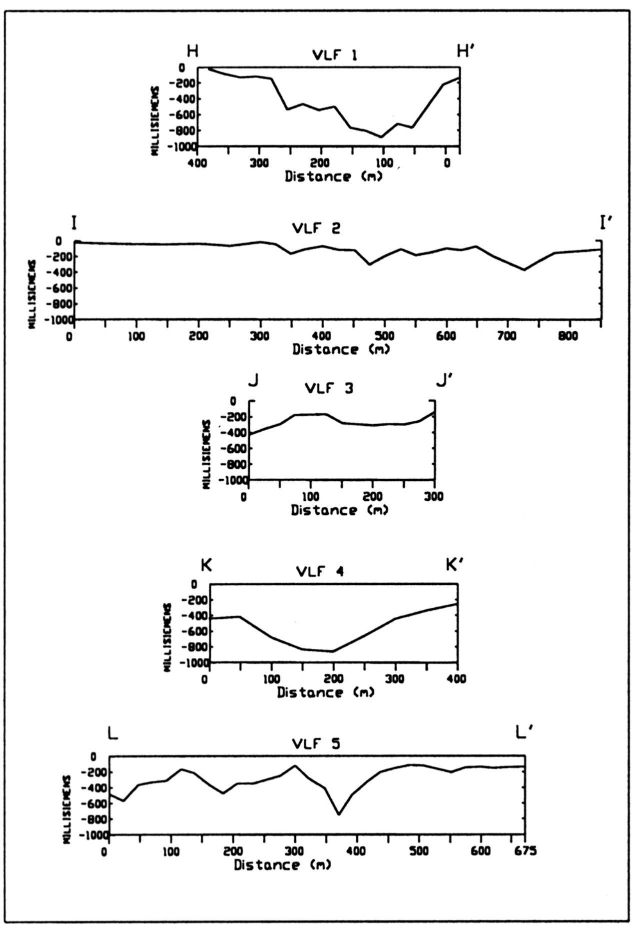

Figure 4: *Cross-sections based on VLF resistivity showing resistivity plotted in negative (for relative comparison purposes).*

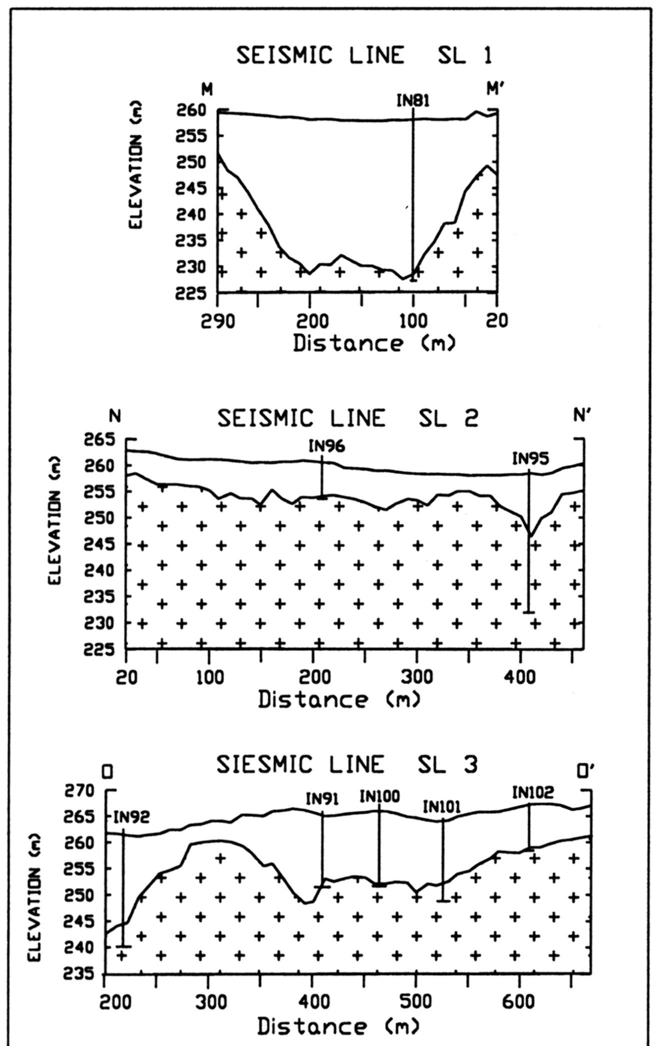

Figure 5: *Cross-sections based on seismic refraction data showing interpreted depth to bedrock.*

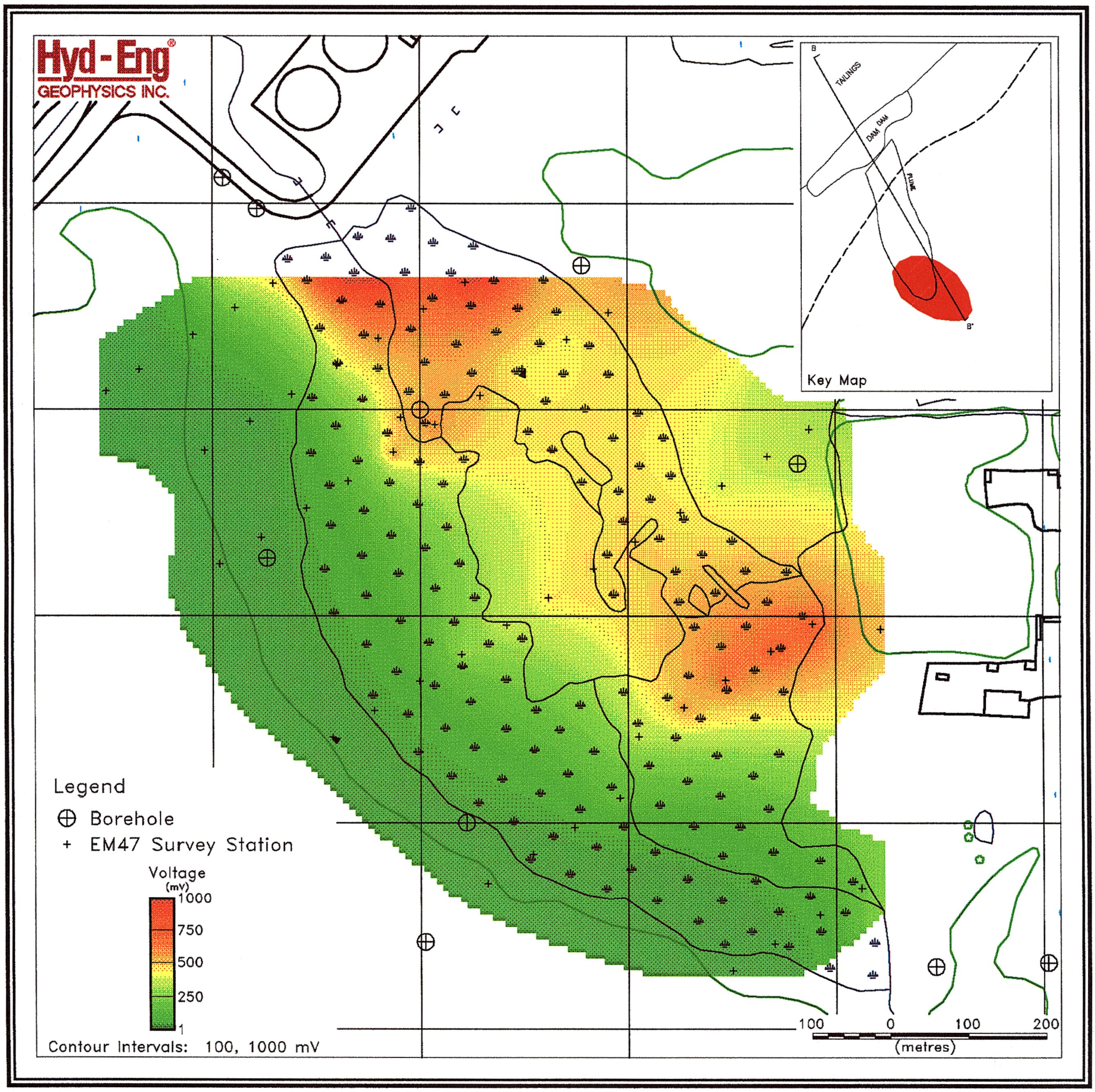

Figure 6: *Time domain EM data, Pistol Dam Project (Channel 8, data in millivolts).*

Other geophysical studies

A number of electromagnetic (EM) earth conductivity measuring devices including EM-31, EM-34, airborne electromagnetics and borehole EM were used by Inco Ltd. to map the subsurface conductivity throughout the Pistol Dam area. Details of their investigations are available in King (1994).

The INCO surface EM-31 and EM-34 surveys indicate a zone of high conductivity associated with sediments of the upper few meters extending south of Pistol Dam approximately 350 m to near borehole IN22. This zone of high conductivity may be the result of surface run off from the tailings impoundment. A zone of high conductivity material near surface at one location may be due to salt seeping from a Ministry of Transportation warehouse, or from road salt.

The INCO surveys indicated elevated conductivity values at depth south of the Pistol Dam to a distance of 200 m (IN19). South of this point the method was unable to discern conductivity variations at depth due to the thickness of the overburden and the relatively thin character of the plume at depth. A borehole conductivity log conducted at IN81G located a 3 m thick zone with a bulk electrical conductivity of approximately 60 ms/cm (30 to 40 ms/cm higher than the clays above). This zone occurs below IN81-29 at a depth of 30 to 33 m below ground surface, just above the bedrock.

Overall usefulness of geophysical techniques in the Pistol Dam area

This fairly comprehensive geophysical survey at the foot of a major tailings pile well illustrates the strengths and weaknesses of geophysics for these problems. Geophysics was able to delineate the topography of the bedrock which controls the direction of groundwater flow in the study area as was confirmed through a hydrogeological study. To some extent the geophysical studies were able to describe the general characteristics of the plume; however, a hydrogeochemical investigation was required to confirm and describe the nature of the contaminant. Of the geophysical methods employed, seismic was most useful in the delineation of the bedrock topography. VLF resistivity was useful in determining trends in depth to bedrock between borehole locations. Based on the geophysical and borehole data a bedrock contour map was constructed (Figure 7).

In terms of detecting porewater conductivity, galvanic resistivity was useful near the dam where boreholes provided preliminary data with which to calibrate interpretations. The high conductivity of the plume water in the basal aquifer and the relatively shallow depth to bedrock near the dam made it possible to trace the tailings-derived water in the basal aquifer. Further away from the dam, high conductivity clay sediments with thickness exceeding 20 m lead to difficulties in the interpretation of VLF, EM, TDEM and galvanic resistivity results in terms of groundwater conductivity. Even if these methods have difficulty in discriminating between conductive porewater and clays, however, the aerial views they afford are very useful for indicating the best locations for piezometer installation in a study area. They certainly indicate, for example, where high conductivities of any kind are likely to be absent.

Preliminary results from the group at the University of British Columbia investigating piezocone technology suggest that this technique may be useful in investigating conductors at depth. At locations IN22, IN21, and IN27 the high conductivity zones obtained by the piezocone device closely match the zones defined by geochemical methods (Campanella *et al.*, 1993).

Costs

The true costs of these investigations off the Pistol Dam area are difficult to access. The project was undertaken as a research study, combining efforts of many investigators from different educational institutions, government and commercial enterprises. A reasonable estimate of the time spent collecting and analysing just the geophysical data would be 40 to 50 man-days. If a cost of $400 per man day is combined with approximations for equipment and other expenses, the mean geophysical costs of this investigation would be upwards of $160,000 if conducted commercially.

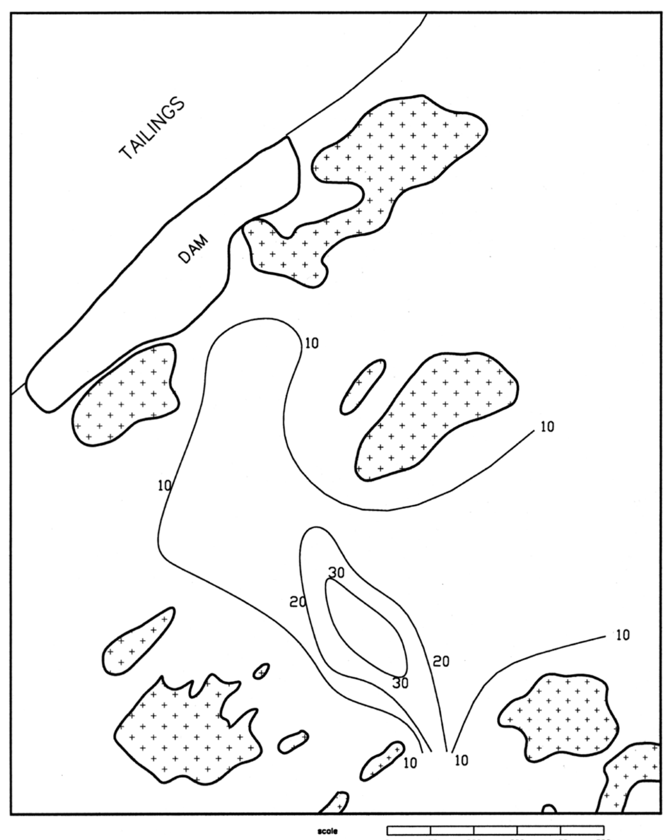

Figure 7: *Map of estimated depth to bedrock (m) in the study area based on geophysical, borehole and piezometer data.*

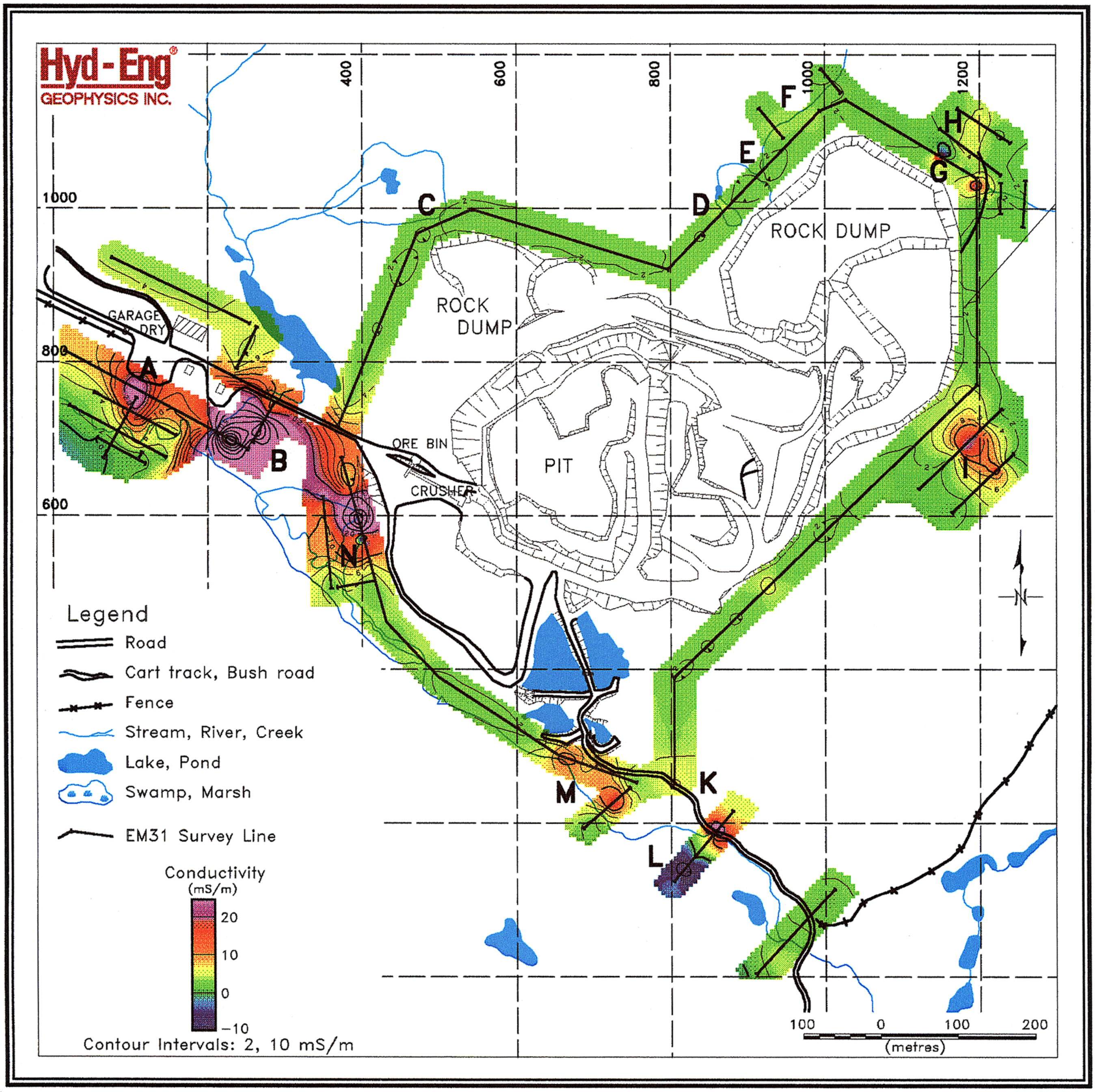

Figure 8: *EM-31 data, Northern Ontario mine site.*

Case 2: Another Northern Ontario mine site

In contrast to the study at Pistol Dam where considerable time and resources were available to study the problem, this section describes a short consulting job that is much more typical of geophysical mine waste surveys as a whole. The mine site includes a number of open pits and rock dumps. A request for proposal was submitted that specified the geophysical surveys to investigate the possibility that runoff from these wastes were contaminating the groundwater. The mine site is shown in Figure 8. It is characterised by fairly rugged topography, and is surrounded by bush. The geology consists of a thin veneer of overburden over crystalline basement. Low lying areas surrounding the rock piles tended to be wet and potentially had increased overburden thickness.

The survey

The survey specifications called for a traverse around the site perimeter. The survey was expanded by the consultant by adding additional data lines in areas where field interpretation of the data indicated a potential anomaly. A Geonics EM-31 was used in both horizontal and vertical coil modes and at ground level in the vertical mode at waist level. Readings were taken at 10 m intervals. Although only the quadrature phase was specified in the RFP both quadrature and inphase were measured. The 3 measurements at each point allow some discrimination of the vertical distribution of electrical conductivity but the results in Figure 8 can be considered simply as an average ground conductivity of a roughly hemispherical volume of about 5 m radius.

Results

The data are plotted as colour-coded apparent conductivity in Figure 8. The perimeter survey has identified several zones of anomalously high or low conductivity. These probably result either from elevated porewater conductivities, ground mineralization or cultural interference. An follow-up EM-34 had been considered in the RFP; however, that requirement was abandoned by the client.

Cost

The geophysical survey at this mine site required five man days to complete including fieldwork and data processing. The total cost was $6,000.

The overall usefulness of geophysics at this site

The limitations of access and budget have resulted in a less than ideal response to the problem. Instead of a proper aerial coverage of the potential contamination source and its surroundings the interpretation must be based on a thin "fence" around the target. Because anomalies on this fence are essentially one-dimensional, the consultant has had to perform at least a few step-out lines to determine if these features extend away from the perimeter.

From the perspective of return on investment the information provided by the geophysical survey provided a guide to the *degree* of the problem at a minimal cost. This information served as a base for follow-up drilling and geochemical investigations. A collection and treatment system to contain contaminated seepage was ultimately implemented by the client.

DISCUSSION

The two case studies described here do not cover the range of applications for geophysics applied to groundwater contamination caused by acid wastes. They perhaps exemplify two extremes of a spectrum of geophysical activity that characterizes these problems in this particular period of time. We are heartened by the fact that geophysical activity in this whole area has grown substantially during the past decade, and we are optimistic that geophysicists will rise to the technical challenges presented as they have always done in the past. Research programs like the one at Copper Cliff will clearly help to make that happen. Nevertheless, in our experience. the great majority of contract geophysics carried out for problems related to mine wastes resembles the second of our examples rather much more than the first.

We can lament the lack of completeness of the second study but, like it or not, this is usually just a fact of the environmental geophysicist's life. More complete areal coverage of the site would almost certainly have paid its way in terms of the information obtained. That extra information must now be gained by drilling and sampling, which will probably prove to be more expensive. Nor is it be reasonable to place all the blame for this on the client; their shareholders demand that they spend as little as possible on what are viewed as non-productive aspects of the mine.

In day-to-day practice then—here and in other environmental areas—there is some reason for concern that competition for work and the modern preoccupation with efficiency will limit the geophysicist to the role of anomaly hunter. Short, quick and minimal surveys such as the second one presented here do not always show geophysics in its best light or make efficient use of its potential for solving these problems. The most cost-effective application of geophysics always comes from an interactive, multidisciplinary approach, one that allows the survey parameters to be refined as the data are collected. This should be our goal, and we can hope that the coming decade will see progress towards it.

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