Preparing for Waste: Geophysics in Geotechnical and Environmental Assessments of Proposed Mine Waste Facilities

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ABSTRACT

In today's mine development environment, two essential components of a successful venture are the feasibility study and the environmental assessment. Geophysical surveys can provide invaluable information for the planning, design and construction of mine infrastructure and, in particular, mine waste facilities. The use of geophysical methods aids in optimization of solutions for geotechnical and environmental issues. We highlight specific examples of geotechnical and environmental applications of geophysical techniques that are effective for preparing for mine waste. We note that there have been significant advances in geophysical methods in available hardware and interpretive software. It is our experience that geophysical information spans the geotechnical and environmental aspects of mine development. Geophysical applications producing data used by both camps may act as an external catalyst to bind these two areas and provide a more integrated final product.

Components of geotechnical design include tailings basin selection, dam site selection, borrow material supply, pipeline/linear infrastructure routing, and infrastucture siting. For these geotechnical aspects, geophysical methods can be applied to profile and map depth to bedrock, overburden stratigraphy, basin bathymetry, basin soft sediment thickness, bedrock geology, faulting in the bedrock, in situ material/engineering properties, permafrost and massive ground ice. In addition, most of these data are useful for planning to mitigate future environmental impacts. The geophysical data provide critical information for environmental planning including hydrogeological modeling to aid design and to predict groundwater flow and contaminant transport.

INTRODUCTION

Two essential components of developing a mine are the feasibility study and the environmental assessment. These two broad and encompassing aspects of mine development include a spectrum of considerations for mine, mill and tailings disposal site development, operations and closure options of a required cradle-to-grave mine plan. The feasibility study determines if the required engineering is possible and the associated costs, together with the ore reserve calculations and marketing details, are geared to producing a bankable document to determine if there is a net profit in the ground. The environmental assessment determines if the potential for damage to the environment falls within acceptable parameters and is geared towards obtaining permits from the regulatory agencies. The feasibility study drives the environmental assessment but the environmental assessment may control the feasibility study by limiting options for mine site and mine infrastructure development (Figure 1). In the extreme, findings of the environmental assessment may stop the entire project regardless of profitability.

It is for the requirements of both the feasibility study and the environmental assessment process that geophysical methods present a rapidly growing service industry.

The Role of Geophysics

Application of geophysical methods provides interpreted data which can be used to interpolate between and extrapolate beyond points where factual data exist. Factual data may consist of information derived from LandSAT images and air photos, boreholes and test pits, and land surface examination inclusive of geological and geographic mapping. In this framework, geophysics is, as it has always been, a tool to aid in improving the overall understanding of a site and serves to put perceived key aspects of factual data into perspective. Today's geophysicist working on mine development must be more than a data gatherer and number cruncher. This person must have an understanding of the feasibility study and environmental assessment process as well as the geotechnical

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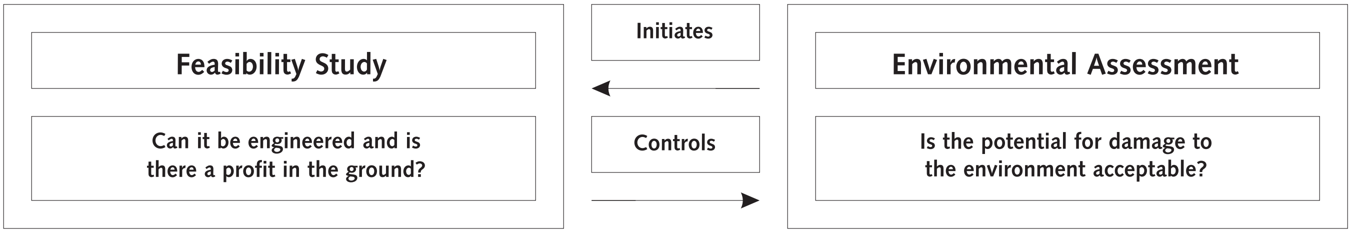

Figure 1: *The interrelationship between the feasibility study and the environmental assessment. Both are driven by economics, environmental concerns and socio-political considerations.*

and environmental considerations. Typically, of the team of scientists and engineers working on a mine development project, few understand the full nature of the problem. It generally falls to a senior engineer to put the pieces together. However, one of the key members of the design team should be the geophysicist who has walked the site (metre by laborious metre) and has spent considerable time looking forward to interpreting the data and wondering how to present the results as a simple expedient model which encompasses all of the inherent detail and uncertainty. Presentation of these results has to be useful to the geotechnical engineer designing dam alignments for the tailings basin, the planner working on the mill layout and pipeline routing, the hydrogeologist calculating pump rates for mine de-watering, the modeler simulating groundwater flow and contaminant transport and the environmental scientist considering potential for environmental impact.

Modern geophysical methods, equipment and interpretive aids provide interpretation for investigations that were not possible ten years ago. Within this paper, we will highlight a number of mine waste facility design considerations, list a range of geophysical methods which are routinely applied for mine waste planning issues and provide brief examples of geophysical applications we have used in the process of preparing for mine waste.

Typically, the cost for a mine feasibility study is on the order of \$250,000 to \$5,000,000 depending on the size of the project, physical setting and existing infrastructure. An environmental assessment may double or triple this amount after the legal and public scrutiny issues have been dealt with. The cost of the geophysical component may be on the order of \$20,000 to \$200,000. Weighed against the cost of mine site construction and operation (a few hundred million dollars or more) these numbers are not large. Yet the geophysical survey can provide a significant amount of information and level of comfort, which together with the factual data, can make or break a mine project.

WASTE FEASIBILITY DESIGN CONSIDERATIONS

Typically, most mines will have a tailings basin or interim storage facility as in the case of using the mine itself as a final repository for the tailings. The key aspects of a tailings basin for a feasibility study or environmental assessment are:

- minimize construction costs
- maximize basin efficiency
- minimize environmental impact

Figure 2 is a schematic figure presenting the main components of a mine site. These include the mine itself, the mill and associated infrastructure, process water storage ponds and the tailings basin. These components all provide potential for on or off-site migration of contaminated groundwater. In addition, there must be transport of materials from the mine site to the mill, from the mine site to the waste rock pile, from the mill to the tailings basin and to and from the process water storage ponds. All these aspects require geotechnical engineering. The key areas requiring geotechnical engineering for the feasibility study in preparing for mine waste are:

- basin selection,
- dam site selection,
- borrow material supply, and
- pipeline access and routing.

The environmental aspects for geophysical surveys typically involve determination of the overburden and bedrock hydrophysical properties which may include information pertaining to overburden thickness and composition, water table depth, areal distribution of groundwater quality and structure within the bedrock. These data play a key role for groundwater flow and contaminant transport modeling which relates back to tailings basin or storage facility design. The results of a groundwater flow and contaminant transport model may be key in satisfying permitting for the environmental assessment.

The following sections provide brief examples of highly successful geophysical surveys carried out for both design and environmental permitting.

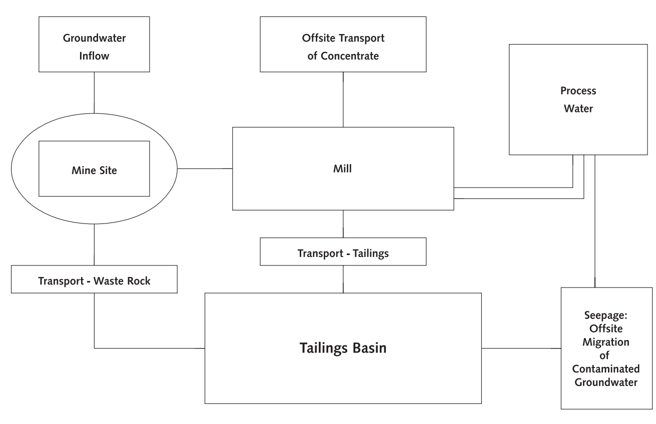

Figure 2: *Schematic of the components of a mine site.*

GEOPHYSICAL APPLICATIONS

Basin Selection

Key issues for tailings basin selection include the available volume, overburden thickness and overburden type within the basin. During the feasibility study for the mine site, calculations for ore reserves inclusive of the expected volume of tailings will be completed. In addition to selecting a tailings basin with sufficient volume, there may be requirements for disposal of the tailings slurry as well as the waste rock which may include sub-aqueous deposition, sub-grade materials with low hydraulic conductivity and an available source of organic material.

Geophysical techniques typically applied for basin volume and stratigraphy consist of marine or terrestrial seismic reflection and refraction and ground penetrating radar. In some cases, time domain electromagnetic induction methods have also been applied for these investigations. In particular, marine ground penetrating radar and seismic reflection techniques are ideal for rapid delineation of sediments and underlying bedrock in fresh and salt water situations.

Ground Penetrating Radar in Northern Lakes for Basin Volume and Soft Sediment Thickness

For a proposed mine site in Northern Canada, there was a requirement for sub-aqueous disposal of sulfide bearing waste rock. In addition, it was determined that it would be preferable to deposit the waste in a lake with a natural source of organic material (Gyttja). The combination of sub-aqueous and sub-organic deposition of the waste was considered to be ideal for reducing the available oxygen and, hence, acid leachate generation. The object of the geophysical survey was to locate a lake (natural basin) with sufficient volume and an *in situ* source of Gyttja.

Ground penetrating radar surveys were carried out during the winter on the ice over a number of lakes about the proposed mine site. A detailed description of the ground penetrating radar technique is provided by Annan, 1993. The measurements were made using 50 and 100 MHz antennas depending on the depth of the water and thickness of the underlying soft sediments. The ground penetrating radar system was mounted on a sled and towed behind a skidoo to facilitate rapid reconnaissance work. Readings were recorded on the move with a sampling rate of 800 picoseconds, time windows up to 2000 nanoseconds and stacked up to 32 times. This enabled data acquisition at an interval of 2 m at a slow walking pace. Fiducial marks were recorded at staked intervals instead of taking readings at stepped intervals.

The results from one ground penetrating radar section (50 MHz) are shown on Figure 3. The section depicts the data recorded along a 500 m line across a frozen lake. The measured ice thickness was on the order of 1 m. These data clearly resolve the water depth beneath the ice, the thickness and lateral extent of the Gyttja/fine sand and silt layers and the underlying till/bedrock interface. On some of the sections it was also possible to differentiate the till and bedrock interface. Overall, the survey was very successful in profiling the lake bottom at depths in excess of 20 m with an additional 10 m of sub-bottom profiling. Multiple profiles on some of the lakes surveyed were used to provide volume estimates.

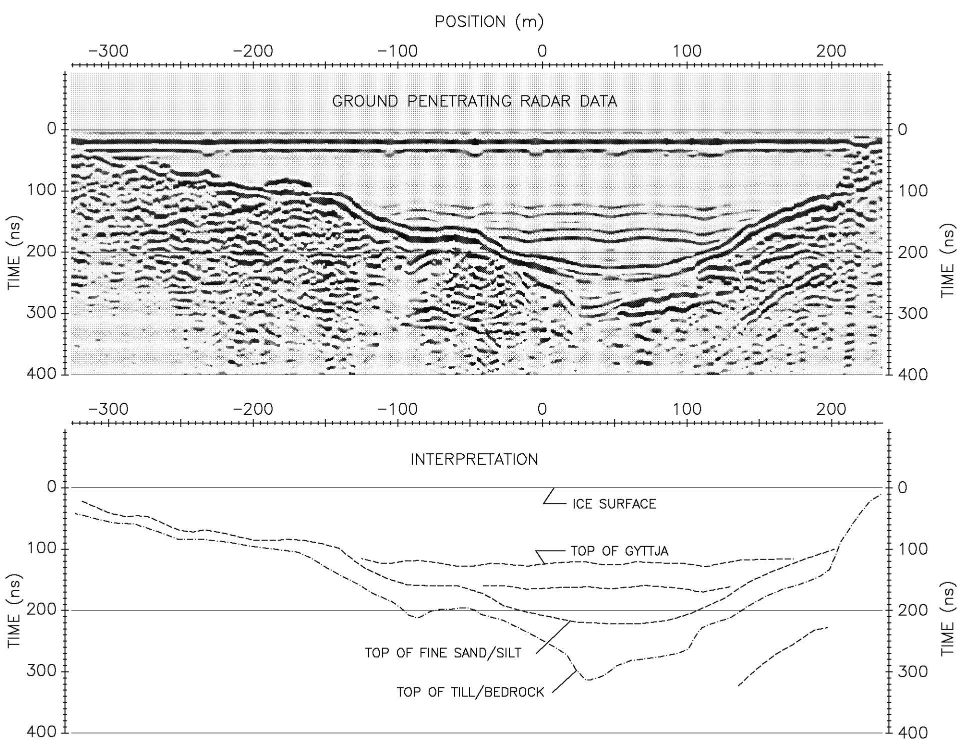

Figure 3: *Ground penetrating radar profile over a frozen lake in Northern Canada. The interpretation has been presented as a time section because of the different velocities between the ice (0.16 m/ns), water (0.03 m/ns) and soft sediments (Gyttja and fine sand and silt - 0.07 m/ns). The ice was a fairly uniform 1 m (3 ft) thick.*

Marine Reflection in Northern Lakes for Bedrock Delineation and Volume Estimates (BHP-Diamet)

Development of kimberlite pipes requires knowledge of stripping volumes for design of removal and storage systems. Marine seismic reflection surveys were carried out over kimberlite pipes in small lakes in the Northwest Territories. Low frequency single channel seismic reflection systems were based on a small boat platform with differential global positioning navigation to rapidly survey small lakes. A sub-bottom profiling unit with 3.5 kHz transducer and a 400 to 1000 Hz Datasonics Bubble Pulser system were used to profile lake bottoms. The reflection techniques delineated soft sediment, coarser sediment and bedrock (below sediment thickness up to 30 m). Borehole data was used to calibrate the geophysical interpretations. Volume estimates using standard software packages were made based on the much greater geophysical coverage and provided to development engineers.

In the development of some basins for tailings deposition, it is important to know the thickness of covering sediment and bedrock depth for volume estimates, dredging estimates and total available volume. Marine seismic reflection was carried out on a lake in Northern Ontario close to a proposed mine site using the same marine reflection systems. An example of a portion of the marine seismic profile coverage is shown on Figure 4. Volume estimates and borehole calibration were again used to provide data to development engineers.

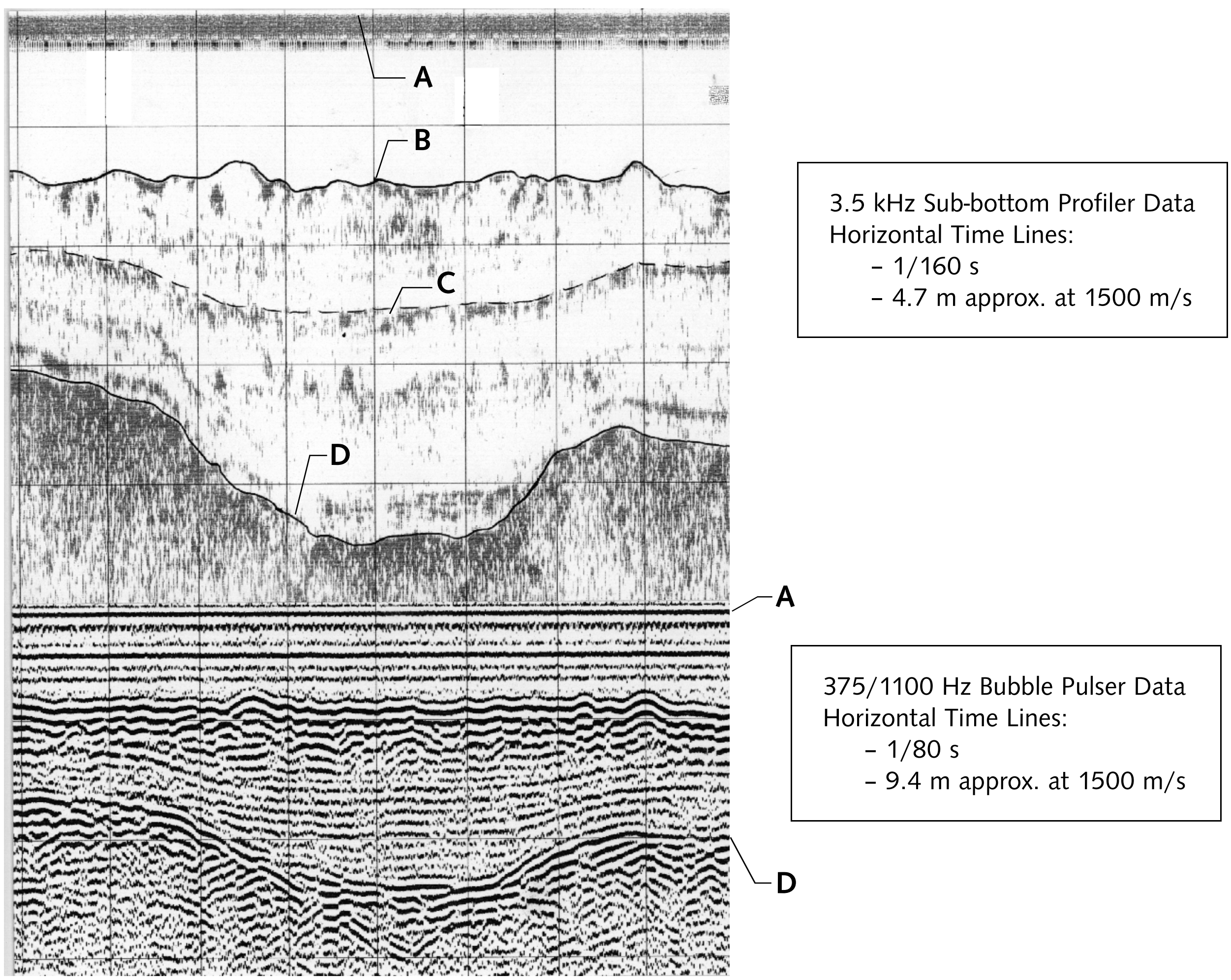

Figure 4: *Marine geophysical data from a mine site in Northern Ontario. The interval between the vertical time lines was 15 seconds which corresponds to an approximate distance of 27 m. The time lines were date and time stamped to a differential global positioning system for survey control at better than ± 3 m. For sets of data, the letters A, B, C and D refer to the water surface, water bottom, an interface within the soft sediments and the bedrock surface respectively.*

Dam Foundations

Dam foundation design requires knowledge of the overburden statigraphy, depth to bedrock, faulting within the bedrock, permafrost, massive ground ice and sources of local borrow material. Geophysical methods that we have applied to investigate these conditions include seismic reflection and refraction, ground penetrating radar and frequency domain electromagnetic induction.

Ground Penetrating Radar Results at a Site in Eastern Canada

Ground penetrating radar profiles were recorded along a number of proposed dam alignments for a tailings basin site selection process carried out at a mine site in Eastern Canada. The bedrock valleys in the area of the proposed mine site were formed by glaciation and provided for natural basins with excellent opportunities for dam closure. Surficial deposits associated with the glaciation were limited to the depressions and lower slopes of bedrock ridges. The till and glaciofluvial outwash deposits were described as consisting primarily of dense sands with varying admixtures of clay, silt, gravel, cobbles and boulders. It had been determined that the clay sized component of the till was not a mineral clay. The area was ideal for conducting ground penetrating radar surveys to profile overburden stratigraphy, depth to bedrock and some structure within the bedrock.

A section of one ground penetrating radar profile form the survey is shown on Figure 5. The data was collected with 100 MHz antennas, a 500 picosecond sampling interval, 400 nanosecond time window and with readings at a stepped interval of 0.5 m. Processing for the section included high pass (dewow) and low pass (125 MHz cut off) filtering and topographic correction. For the interpretation, a velocity of 0.11 m per nanosecond was used to derive the elevation scale. This velocity was consistent with results from common mid-point soundings completed along the profile.

Interpretation of the ground penetrating radar data in conjunction with borehole results have provided a high resolution image of the subsurface conditions along the profile indicating both the depth to bedrock and the location of fractures within the rock mass. These data were useful for both the dam construction design and hydrogeological modeling for groundwater flow.

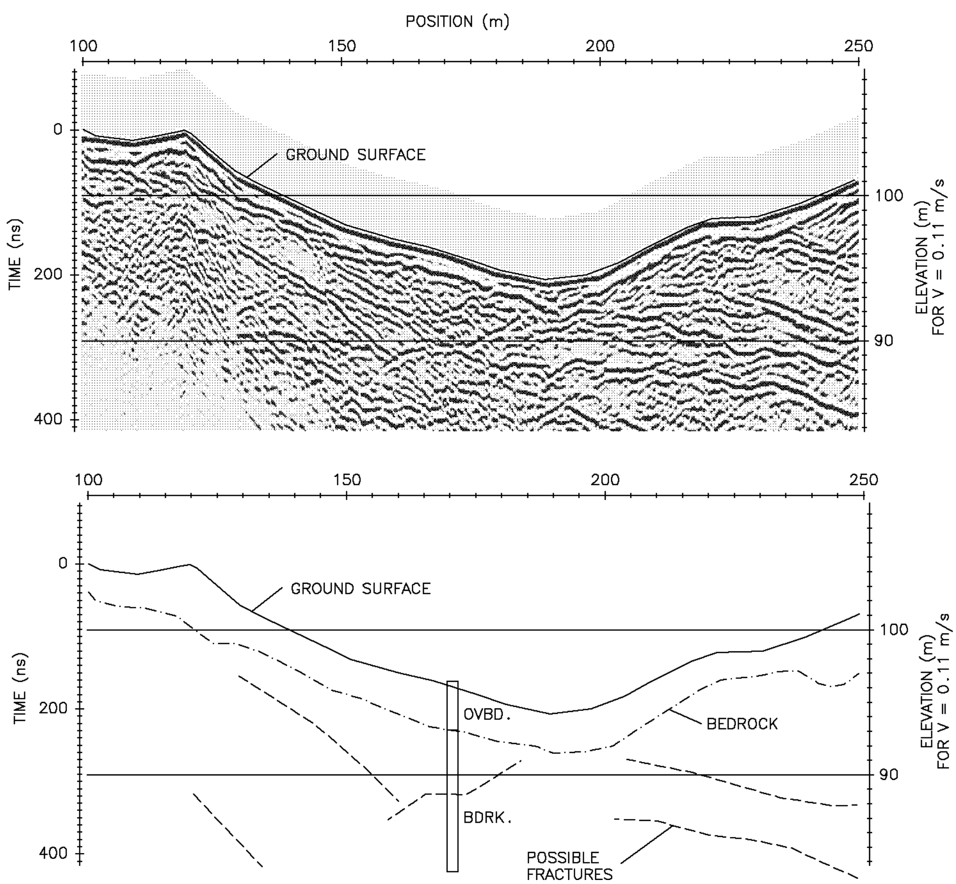

Figure 5: *Ground penetrating radar data and interpreted section along a proposed dam alignment at a mine site in Eastern Canada. The data was recorded with 100 MHz antennas. The elevation for the interpreted section was based on topographic data and a calculated ground penetrating radar velocity of 0.11 m/ns to a depth of 5 m. The borehole result (schematic) was overlaid on the section subsequent to the processing of the radar data.*

Fault Delineation, Bedrock Profiling and Massive Ice Mapping at the Kubaka Project (Omolon Gold/Cyprus Amax)

Tailings dam siting work at the Kubaka Gold Project in Far East Russia was optimized using geophysical techniques to help direct drilling programs for site characterization. Regulatory agencies also required fault delineation because of seismic stability and leakage issues. Our approach included air photo and remote sensing investigation in conjunction with ground-based geophysics. Possible approaches for fault location include electromagnetic and magnetic techniques with GPR and seismic being appropriate in certain situations. As is often the case, once at site, a wealth of exploration data was available. VLF, VLF Resistivity, and Magnetic mapping had been carried out across the areas of the potential tailings dam. Many of the fault and geological structures had been located and it remained to delineate these for drill investigation.

The problem at the site was that it was necessary to determine whether potential thaw of faults would result in leakage from the tailings dam and that dam structures would not be located over faults. The VLF conditions were poor during the spring site visit, however, EM34 profiling proved very successful at fault location using 10, 20, and 40 m separations to give penetration to nominally 15, 30, and 60 m respectively. Measurement spacing was determined by expected depth to bedrock and ranged from 5–10 m. We profiled quickly using skis over the 1–2 m deep snow. In spite of frozen conditions, the principal structures were observed as conductivity highs (Figure 6). Subsequent drilling of the anomalies delineated geological structure changes and clay-filled faults. The structures were principally steeply-dipping and in most cases the dip could be interpreted from data asymmetries. The shallower structures (less than 10 m of overburden) were imaged using GPR.

EM34 and GPR profiles (100 MHz antenna) along proposed tailings dam footprints indicated only localized massive ice conditions, however, the GPR successfully delineated bedrock along proposed dam footprints. In addition, with drill confirmation, the GPR data was utilized to delineate weathered and non-weathered bedrock. The success of the GPR profiling resulted in a subsequent detailed survey program (500 and 100 MHz antennas) to aid in location of additional proposed paste tailing dams. Again, weathered and non-weathered conditions were clearly delineated and confirmed using test pit logs.

Stratigraphic mapping for hydrogeologic considerations

Shallow Seismic Reflection (SSR) at the Adam's Mine, Northern Ontario

The Adam's mine site near Kirkland Lake, Ontario is now decommissioned and the open pits are proposed as the location of a landfill for municipal waste from Metropolitan Toronto. As part of the assessment of the potential environmental impacts of this, a shallow seismic reflection (SSR) survey was carried out to map thickness of drift on four east-west lines across the Misema River Valley and on the west flank of the Munro Esker, hydraulically down-gradient from the site. For details on the SSR technique the reader is referred to Hunter *et al.* (1982), Steeples and Knapp (1986a/b) and Yilmaz (1987).

In this survey, 96 geophones (50 Hz) were deployed at 3 m intervals and connected by a roll box to a 24 channel engineering seismograph. A 12 gauge seismic shotgun was used as an energy source at 6 m intervals along the line. The range of source-geophone offsets used for each com-

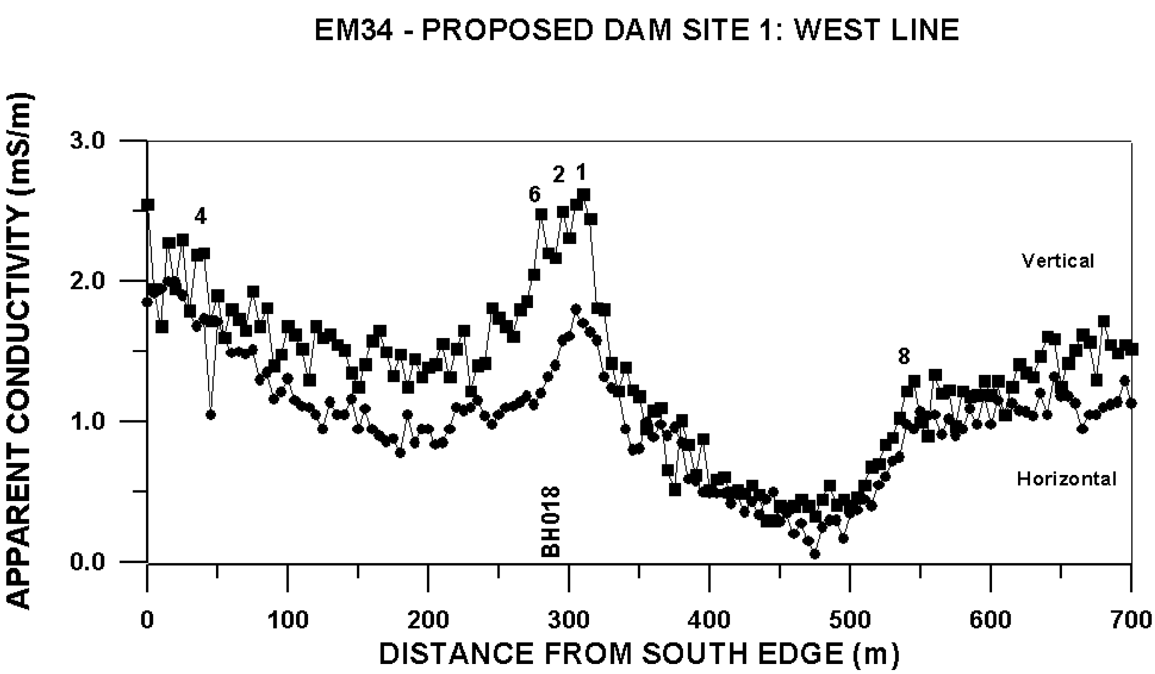

Figure 6: *EM34 vertical and horizontal data—West Tailings Dam Line (B). Apparent conductivity data is from 10 m coil spacing survey along a 700 m line over deep permafrost. The numbers identify the faults and geological structures delineated by regional geophysics. Borehol es located at the EM34 apparent conductivity highs encountered clay-filled faults and geological structural changes.*

mon shot gather was 12–81 m, producing 6-fold common mid-point (CMP) coverage at 1.5 m intervals. The survey successfully mapped drift thickness on all of the lines surveyed. It showed that the Munro Esker occurs east of the Misema River down-gradient of the site, and that there is a bedrock high on the east bank of the river which acts as a divide to groundwater flow from the site to the west. These findings were critical to the development of a conceptual groundwater model for the site. A portion of the depth-migrated CMP-stacked section on Line 2 is shown on Figure 7, where the bedrock surface is interpreted to gently dip from west (40 m deep) to east (50 m deep) at the western flank of the Munro Esker.

In Situ material elastic properties

Stiffness of soils is an important parameter in geotechnical design of tailings dams and other infrastructure at a mine site. *In situ* geophysical methods are playing an increasing role in determining these properties as opposed to drilling and sampling of materials. In particular, shear modulus determinations are critical in assessment of slope stability and the effect of vibration and seismicity on soils and engineered earth structures.

Shear wave velocity is intrinsically linked to shear modulus; shear wave refraction, spectral analysis of surface waves (SASW), and cross-hole, down-hole and up-hole seismic techniques can be used to determine shear wave velocity structure of the subsurface. A summary of the techniques along with some of their inherent advantages and limitations are shown in Table 1. An example of the SASW technique is described in the following section.

Spectral Analysis of Surface Waves (SASW) at a Tailings Stack in Northern Ontario

The SASW technique was utilized as part of a geotechnical and long term groundwater monitoring investigation carried out at a raised tailings stack in Northern Ontario. A total of 8 SASW tests were carried out on top of the stack to aid in determination of geotechnical properties of the tailings material. A description of the SASW technique can be found in Stokoe *et al.* (1994).

The SASW testing equipment was comprised of a microcomputer equipped with a data acquisition card, two 1 Hz resonant frequency geophones, a preamplifier/control unit linking the geophones to the acquisition card and impact energy sources. The energy sources used were a sliding 45 kg weight drop connected to a 60 by 60 cm base-plate and a 6 kg sledgehammer and steel plate. The two geophones were deployed at a number of separations and coupled by wetting the geophone bases and allowing them to freeze to the ground surface. For each geophone spacing and source separation, five impacts were recorded and summed in the frequency domain. A dispersion curve of surface wave velocity versus frequency for each test location was assembled by combining the data for all source and receiver separations. The measured dispersion curve was then matched to a model dispersion curve for a layered earth. In the model, Poisson's ratio was assumed to be 0.3 and the mass density of the soil was assumed to be 1.90 g/cc. The resulting models of shear wave velocity versus depth for four of the tests are shown on Figure 8. The tests showed that the shear strength of the tailings increases with depth and decreases towards the edge of the stack.

Permafrost and massive ice conditions

Ground Penetrating Radar for lake basin volume and glacier ice thickness and volume, Kumtor Gold Project (Kumtor/Cameco)

The Kumtor Gold Project required tailings basin investigation, aggregate mapping, and infrastructure siting. The high altitude and extreme weather conditions of the Kumtor site contributed to permafrost conditions, and a situation existed for the ore-body which is becoming less unique as mines are pushed into remote areas; it had a sig-

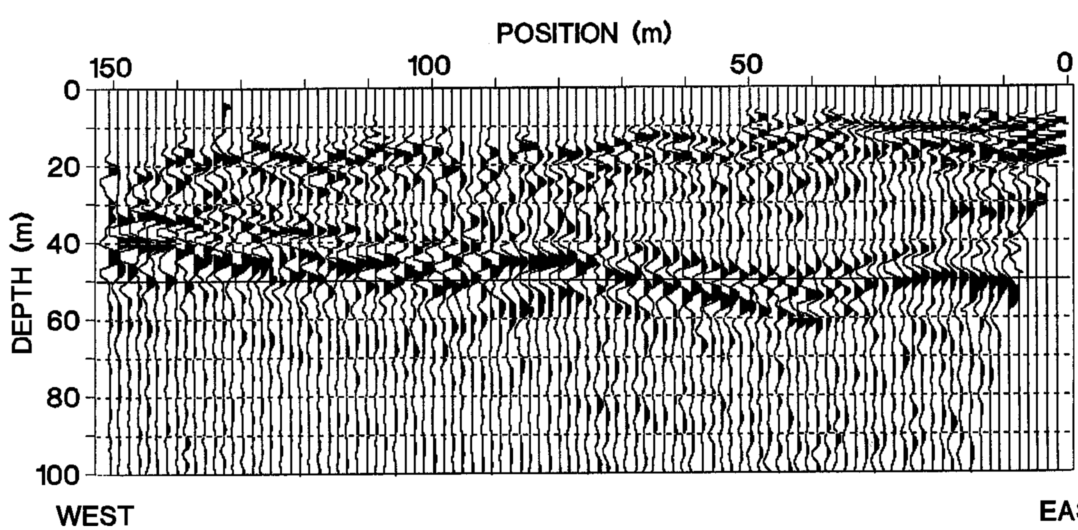

Figure 7: *Depth-migrated common mid-point (CMP) stacked shallow seismic reflection (SSR) section at the Adam's Mine site, Kirkland Lake, Ontario.*

Table 1: ***Geophysical methods to determine shear wave velocity in the subsurface.***

Method	Advantages	Limitations
Shear wave refraction	Non-invasive, survey is rapid, data reduction is straightforward, can provide continuous coverage along lines, doesn't assume horizontal layering.	Shear wave velocity must increase with depth, does not provide continuous coverage along lines.
SASW	Non-invasive, survey is rapid, shear wave velocity does not have to increase with depth.	Vertical resolution decreases with depth, data reduction is complex, assumes horizontal layering, does not provide continuous coverage along lines.
Cross-hole seismic testing	Shear wave velocity is determined by direct cross-hole travel times.	Requires two boreholes at each investigation, requires a down-hole shear wave source and receiver, does not provide continuous coverage along lines.
Down-hole seismic testing	Requires only one borehole, layer thickness for data reduction are constrained by soil borehole logs, shear wave velocity does not have to increase with depth.	Requires a down-hole shear wave receiver, simple data reduction assumes straight rays, does not provide continuous coverage along lines.
Up-hole seismic testing	Requires only one borehole, does not require a down-hole shear wave receiver, layer thickness for data reduction are constrained by soil borehole logs, shear wave velocity does not have to increase with depth.	Simple data reduction assumes straight rays, does not provide continuous coverage along lines.

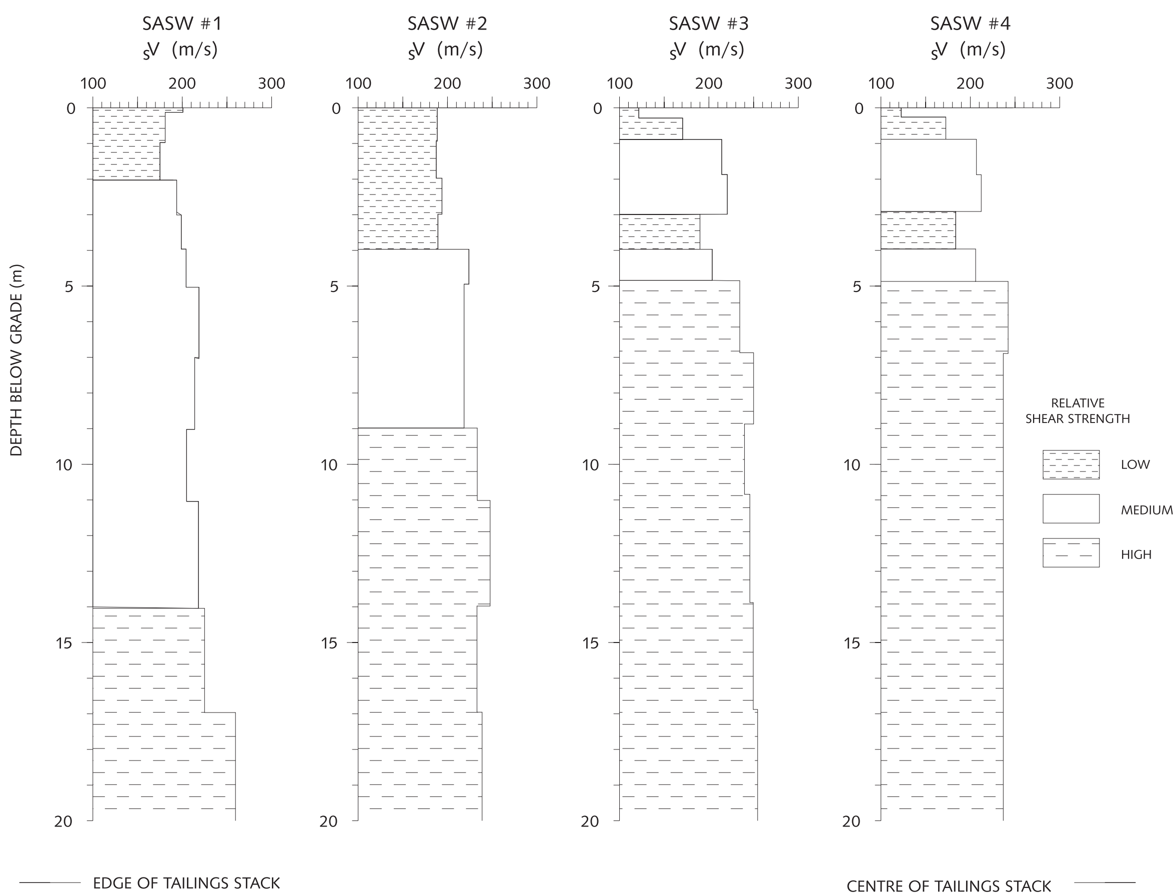

Figure 8: *Relative shear strength derived from four spectral analysis of surface wave (SASW) tests at a tailings stack in Northern Ontario. Of note is that the shear strength decreases with depth towards the edge of the tailings stack.*

nificant part covered by glacier ice. We used standard geophysical techniques and specialized snow and ice geophysics to provide valuable data input to the planning and construction of waste systems.

The proposed tailings dam and tailings basin and proposed areas for infrastructure were profiled using GPR and Geonics EM34 ground conductivity meter to delineate subsurface stratigraphy and in particular, massive ice conditions. Areas of massive ice were highlighted based on conductivity lows (Figure 9) and the multiple reflections that are observed in GPR data.

In addition, contoured bathymetry maps of an existing lake were produced using GPR data measured over the frozen ice surface and shear wave refraction measurements were carried out in the tailings dam and proposed mill site areas to obtain engineering parameters of the soils.

The unique glacier situation required ice volumes to be calculated. We utilized custom ice radar to map the sub-glacier bed for estimating waste ice volume. In addition, ice flow was modeled based on available information, including short term ice velocity measurements, to assist in designing the pit walls which are partly ice. Because of the restrictions of ice cover, the best solution for waste rock (non-acid producing) was to place it on ice. Glacier flow and ice radar depth measurements were used to model glacier flow of the proposed glacier to aid in evaluation and design of waste rock dumps onto a nearby glacier. The dumps are now in successful operation.

Bedrock permeability for hydrogeological assessment

Borehole hydrogeophysical logging at the Adam's Mine, Northern Ontario

At the abandoned Adam's Mine site, one proposed plan for disposal of municipal waste from Toronto, Ontario is to fill the open pit mine workings. The overburden in the vicinity of the pit is thin (0 to less than 10 m) and the exposed bedrock appears to be highly fractured in places. As part of the hydrogeological investigation, a program of borehole drilling and *in situ* bulk permeability testing was required in 9 boreholes about the main pit. The boreholes were angled and placed about the pit to intersect the main structural features identified from geological mapping. A program of packer testing was proposed to acquire factual data regarding the overall bulk permeability of the rock mass. Packer tests involve sealing off a portion of the borehole with inflatable packers and then monitoring the fluid response to an externally applied pressure in the test interval. Preliminary information indicated that the rock mass would have low permeability and that packer tests could be difficult and time-consuming to run. A program of geophysical logging was proposed to pre-screen the boreholes to identify fractures and fracture zones with potential for high flow.

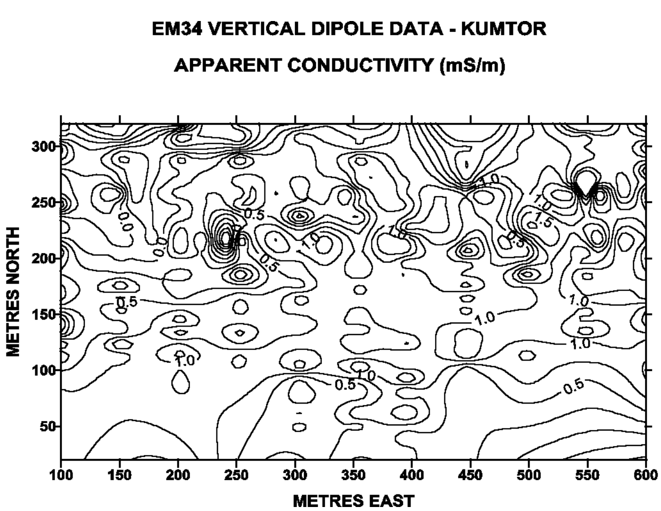

Figure 9: *EM34 vertical dipole data—Kumtor Project. Apparent conductivity data from the 20 m spaced coil configuration was recorded over permafrost to locate massive ice zones. Drilling in the low conductivity areas (less than 0.2 mS/m) encountered thick massive ice bodies.*

The geophysical (hydrogeophysical) log suite consisted of borehole video-camera inspection, caliper, fluid temperature and fluid resistivity. The procedure for logging consisted of:

- logging the borehole for background fluid temperature and fluid resistivity response,
- replacing the borehole fluid with an equivalent volume of saline or fresh water with a higher temperature (5°C or more),
- re-logging the borehole for fluid temperature and fluid resistivity response,
- stressing the static fluid conditions within the borehole (if necessary) by pumping from the top of the borehole,
- re-logging the borehole for fluid temperature and fluid resistivity response,
- acquiring a caliper log to measure variations in borehole diameter indicative of open fractures, and finally
- acquire a borehole video camera log to assess the aperture and openness of any fractures.

This procedure was determined to be highly successful for delineating relative high hydraulic conductivity zones (10^{-5} to 10^{-6} cm per second) within a low hydraulic conductivity rock mass (10^{-8} to 10^{-9} cm per second). An example of the results from logging one of the boreholes is shown on Figure 10. The packer test results are shown together with the staged fluid temperature and fluid resistivity logs, the caliper log, results from the borehole camera log and an interpretation of possible permeable zones. Interpretation of potential low hydraulic conductivity zones was based on deflections on the fluid logs that correlated with caliper anomalies and fractures identified on the borehole camera logs.

The results of the hydrophysical logging produced a qualitative analysis for the location of relative low hydraulic conductivity fractures and fracture zones within the rock mass. These results helped to streamline the packer testing program and significantly reduced the amount of time required to complete the borehole testing. The interpreted results correlated well with the results from the packer tests.

SUMMARY AND DISCUSSION

The geotechnical requirements of mine development, and particularly preparation for waste, must address the principal aspects of minimization of construction costs, minimization of environmental impact, and maximization of efficiency of all systems including those that are waste-related. It has been our experience in numerous mine development investigations such as those discussed above, that geophysics contributes to all of these aspects. The geophysics alone is not the important factor, but it is the integration of the geophysical and factual data by engineers and geoscientists to improve the design of the mining systems.

Geophysical data and factual data are complementary and provide the advantages of extensive coverage at reasonable costs in minimum time with good comfort level. Experienced engineers and geophysicists can determine the appropriate mix of non-invasive geophysics and invasive investigations to provide optimized information. Relatively small front-end geophysical expenditures have provided critical information that has saved large amounts of money when considered on the length of a mine's life.

We have discussed only a surface exposure of the massive body of successful geophysical investigations of waste-related mining development. The future is more exciting with the improvement of hardware and software providing additional tools for geophysical characterizations. Interpretation routines utilizing inverse theory are improving the resolution of sub-surface features. Development of new borehole and marine systems, and GPR advancements have all expanded geophysical capabilities.

The greatest potential of all, however, to improve mining preparation for waste is the use of geophysical methods to improve the efficiency of delineation of underground and surface mining ore. New probes and geophysical techniques are reducing the amount of waste by improving ore characterization.

However, there will always be mine waste and there will always be optimal approaches that utilize geophysical methods to prepare for the disposal. These geophysical methods will continue to provide data that can span the geotechnical and environmental requirements of mine development. It is up to geophysicists to ensure that they provide development engineers and geoscientists with the information and the knowledge that encourages them to consider the geophysical solution.

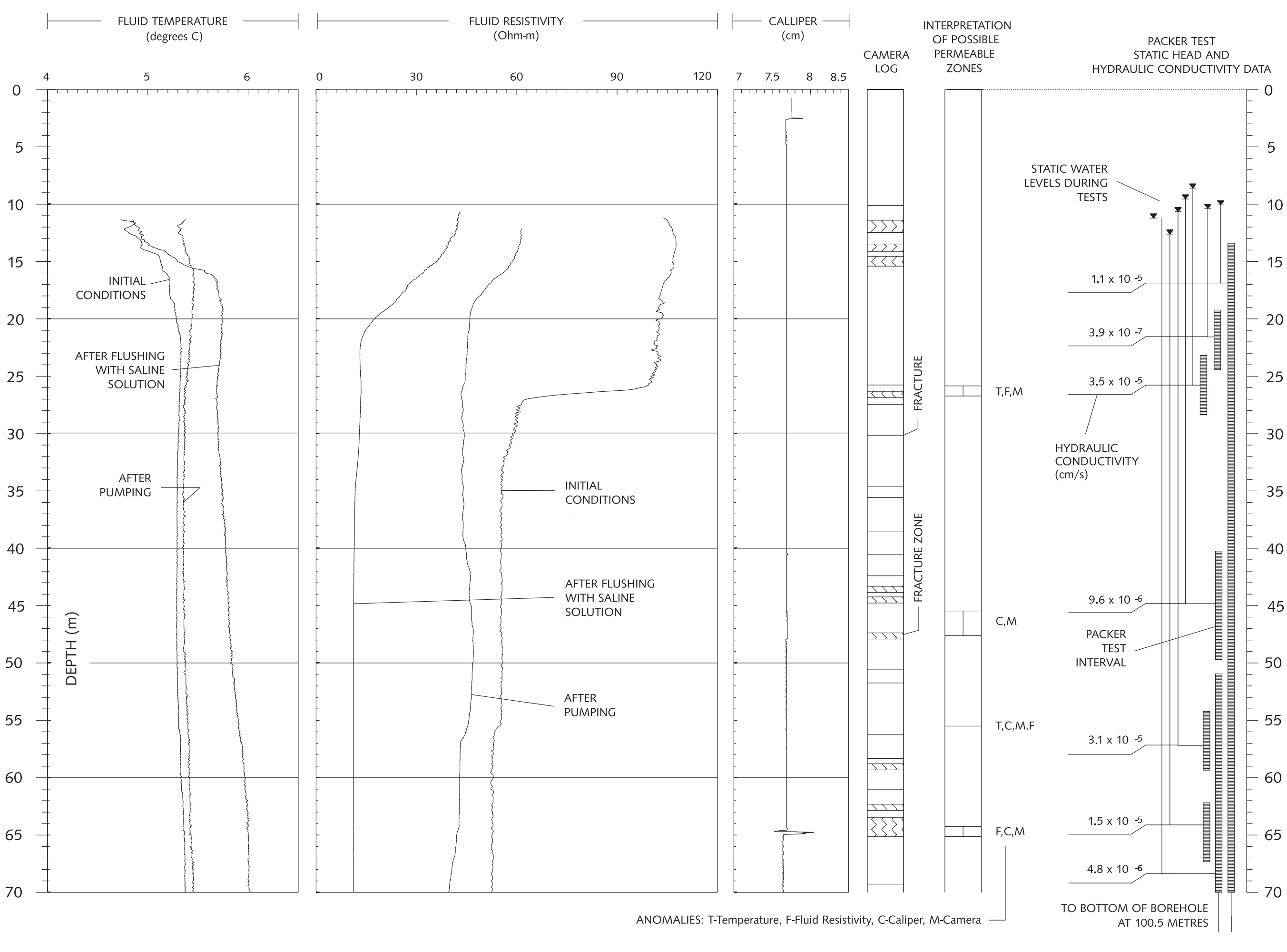

Figure 10: *Results from geophysical logging of borehole hydrophysical properties—hydrogeophysical logging. Anomalous results from staged recordings of fluid temperature and fluid resistivity were compared to caliper and borehole video-camera logs to locate fractures or fracture zones within the borehole to streamline a follow-up program of packer testing for hydraulic conductivity determinations.*

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