Remote Mapping of Mine Wastes

Paterson, N.[1]

1. Paterson, Grant and Watson Ltd., Toronto, Ontario, Canada

ABSTRACT

Non-geophysical and geophysical remote sensing techniques are applicable to the detection and monitoring of the most common and troublesome mine waste — namely acid mine drainage (AMD). Repeat surveys using the same technique in the same area provide a temporal parameter that is valuable in assessing both the onset and spread of a leakage plume as well as the success and extent of a remedial program.

Ground spectroradiometer studies can establish the important parameters for programs of satellite and airborne thematic mapping and multi-spectral imaging in areas of active or past mining activity. Recent developments in narrow-band spectral imaging allow the direct recognition of a variety of secondary minerals in a leachate plume, as well as the by-products: vegetation stress, morbidity, die-off, ponding etc.

Satellite-borne sensors are expected to improve in resolution to 2–5 m over the next two years, thus improving their applicability to the mapping of mine wastes.

Conditions amenable to direct geophysical detection include sulphide wastes (dumps and tailings), active oxidation (tailings), AMD plumes, fluid flow and direction (dam leakage) and radioelement-rich surface seepage.

Electromagnetic (EM) methods are best suited to most of these problems, starting with the popular ground conductivity metres, followed in complexity, depth-penetration, sounding capability and cost by multi-frequency EM, time domain EM and, recently, portable controlled-source audio magneto-tellurics (CSAMT). All of these devices sense the enhanced electrical conductivity associated with nearly all mine effluents. Ground penetrating radar (GPR) shows major promise in AMD applications both in mapping and in monitoring remedial work.

Airborne EM is a fast and effective method for mapping AMD and for spotting areas where ground work should be concentrated. Both remote sensing and geophysics are used indirectly to determine the geological parameters that control migration of mine wastes. Major advances are expected in the areas of data enhancement and interpretation. Hopefully, one of these will be the ability to correlate multi-parameter images to provide a dynamic model of the process of mine waste spread and remediation.

INTRODUCTION

In 1993–94, the writer and Roberta Stanton-Gray of Geomatics International Inc., Burlington, Ontario, made an in-depth review of the application of remote sensing and geophysics to the detection and monitoring of acid mine drainage (AMD). The results are available (Paterson *et al.*, 1994) as a handbook, published by the Mine Environment Neutral Drainage (MEND) Secretariat of CANMET, Ottawa, Ontario.

Research on this project led inevitably into much broader areas than AMD since it was found, not surprisingly, that the problem is similar in most of its aspects to other, common problems of industrial contamination. Leaving aside organic pollutants such as petrochemicals and pulp and paper effluents, it was found that most effluents are both toxic to normal plant life and electrically conductive by virtue of dissolved ions of metals, salts, acids, bases etc. The toxicity induces stress in vegetation, which can be sensed by a variety of remote sensing methods; the enhanced conductivity, spreading to the groundwater regime, lends itself to detection by the electrical and electromagnetic (EM) methods of geophysical exploration.

Indirect sensing methods are also applicable equally, in most cases, to mining and other industrial contamination problems. These include methods of mapping the architecture of the containment and seepage systems, such as bedrock topography, sedimentary layering and surface erosion. Methods of sensing fluid movement are also applicable to mining and other industrial seepage problems.

Certain properties are unique to the mining environment, such as those associated with the active oxidation of metallic sulphides and the migration of radioactive elements. These may be detected directly by

In "Proceedings of Exploration 97: Fourth Decennial International Conference on Mineral Exploration" *edited by* A.G. Gubins, 1997, p. 905–916

thermal, gamma-ray spectrometer, self-potential, induced polarization, or (sometimes) magnetic methods.

This paper draws examples, where necessary, from non-mining applications in order to identify methods that can assist in the increasingly serious environmental problems facing the mining industry. Discussion is limited to non-intrusive methods, so borehole geophysics is not covered.

MINE CONTAMINATION

AMD is by far the largest source of troublesome mine contamination and is common to nearly all metallic and some non-metallic mines. By-products of the mining process include dumps of coarse waste-rock; tailing ponds of finer, crushed and usually chemically treated waste-rock; and liquid effluents that originate in one or other of the above sources and find their way by seepage into the surrounding groundwater regime. Nearly all metallic and most coal mines contain pyrite or other sulphides that oxidize when exposed to the surface environment, generating both sulfuric acid and secondary minerals (Nordstrom, 1982) such as copiapite, jarosite, goethite and hematite. The sulphate and metal ions contribute to greatly enhanced electrical conductivity (Figure 1), as was first demonstrated by hydrological studies at the Nordic Mine near Elliot Lake (Blair *et al.*, 1980). In fact, in contrast to the normal range of lake, river and groundwater conductivities of 1 to 20 mS/m (milli-Seimens per metre), groundwater sampled at the base of the Copper Cliff, Sudbury, tailings dam (King, 1994), for example, had an anomalous conductivity of 100 mS/m. The enhanced conductivity is due in part to ion mobility (McNeill, 1980) and both H^+ and SO_4 have high mobilities, leading to typical conductivities for soil saturated with mine seepages of 15–35 mS/m (Kalin and Pawlowski, 1994). These are usually sufficiently higher than those associated with local uncontaminated soil that they can be detected and mapped geophysically.

The acid contaminant and associated heavy metals are toxic to most forms of vegetation, leading to stress and morbidity, die-off and encroachment, followed eventually by changes in surface erosion. These phenomena may be monitored by a variety of remote sensing methods.

Mine dumps and tailings ponds, themselves sources of contamination, may be overgrown or buried and undetectable visually but may be located and mapped by remote sensing and geophysical methods.

Uranium mine seepage at surface can be mapped by gamma-ray spectrometer, the daughter products normally carrying significant radioactivity. Of greater importance, however, is the acid by-product of the normally pyrite-rich waste rock, which can be detected by geophysical methods at considerable depth (Pehme, 1981; Koch, 1996).

REMOTE SENSING APPLICATIONS

Remote sensing is the science and art of obtaining information about an object, area or phenomena through the analysis of data acquired by a device from a distance. Devices common to "traditional", non-geophysical remote sensing include instruments based on film, multi-spectral imaging, video and radar. Aerial photography, the backbone of remote sensing for well over 60 years, is the predominant method for acquiring remotely sensed data. Satellite and airborne multi-spectral imagers have been available since the early 1970s and have been used as a means of

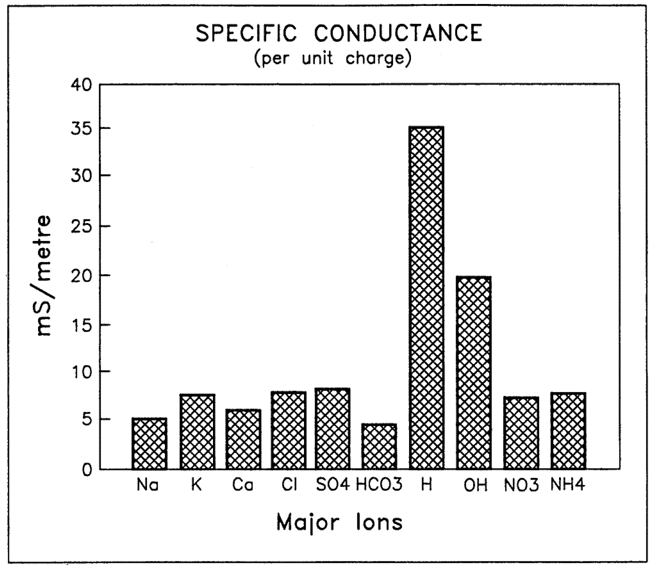

Figure 1: *Conductivity contribution of specific groundwater ions. (After King, 1994).*

acquiring image data in several wavelengths for a variety of disciplines including the detection and monitoring of mine waste.

Three criteria have been identified (Intera Kenting, 1992) that could be used for monitoring uranium tailings. These criteria are also applicable to the detection and monitoring of other mine drainage and include:

VEGETATION	MOISTURE	SOIL/ROCK
encroachment	drainage	dam failure
die off	ponding	surface erosion
stress and morbidity	seepage	sub-aqueous erosion
coverage and type	diversion channel silting/erosion	waste rock/open pits

A fourth criterion, namely the pyrite and secondary minerals associated with the oxidation-weathering process, has become a practical reality (Watson, 1996) with improvements in high-resolution imaging spectrometry.

Mapping of vegetation encroachment, die-off, stress and morbidity, as well as percentage and distribution of ground cover and type are effective techniques in monitoring the impacts of AMD seepage and any remediation of such conditions. Multi-spectral data with information on the visible and near infrared is required. Although both satellite (Landsat and SPOT) and airborne multi-spectral data can be used, one must consider the size and extent of the area being monitored. Satellite data has been successfully used to monitor the effects of AMD in reclaimable mining areas such as strip coal mining and in areas with abundant mining waste (Spahn, 1983) and to locate abandoned mine sites in northern Ontario with concomitant AMD problems (Robitaille *et al.*, 1991). Gross changes can be monitored on an annual basis in addition to identifying targets sites requiring detailed follow-up with airborne information. In addition, because satellite data has been available since 1972, archived information can be acquired providing an historical record of mining

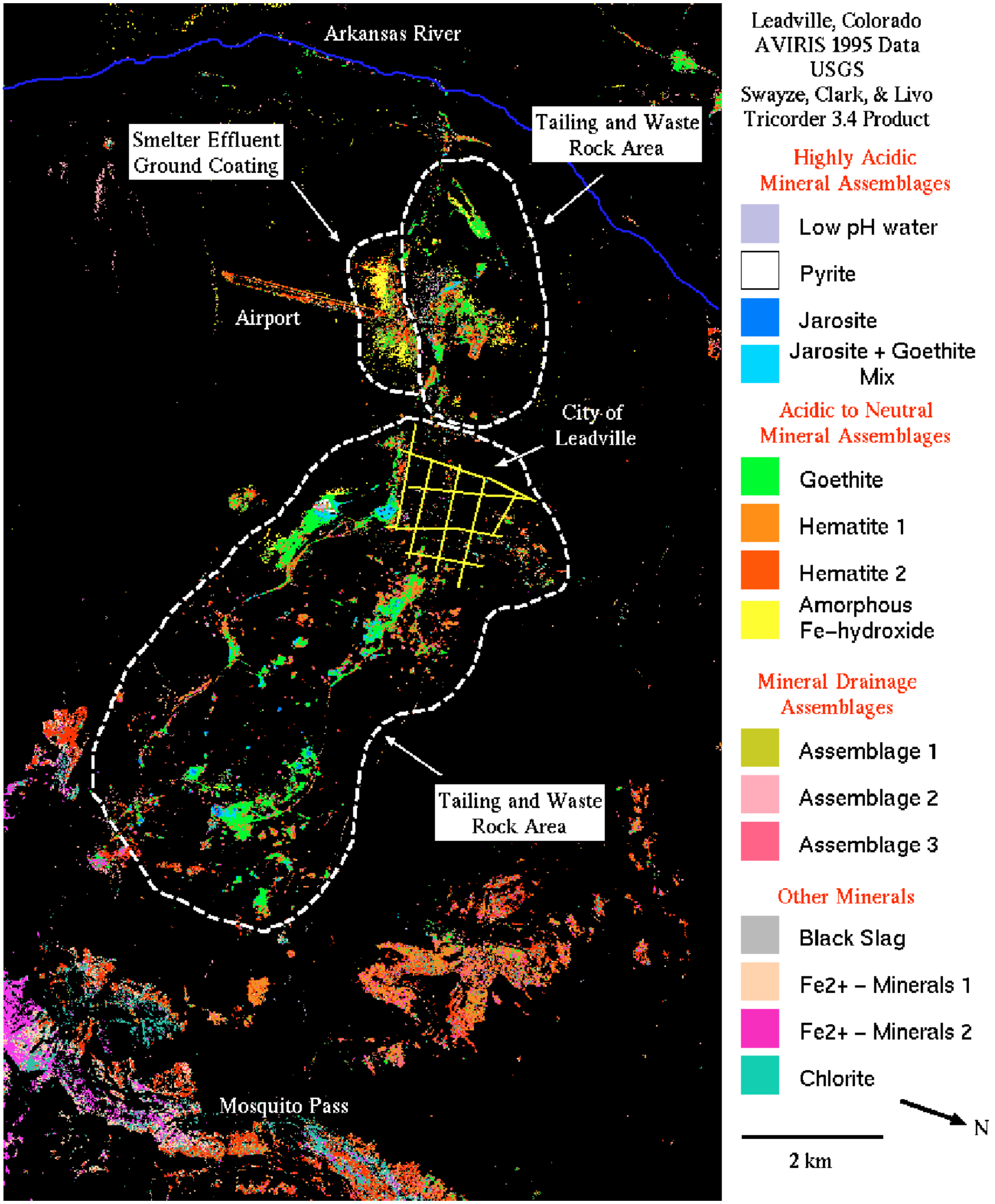

Figure 2: *Map of mineral distribution in waste-rock and tailings piles at the California Gulch Superfund site near Leadville, Colorado. Produced by the USGS using NASA/Jet Propulsion Laboratory Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). Each colour identifies iron-bearing minerals in each 17 x 17m square area on the ground. Blue colour shows minerals which cause AMD high in dissolved minerals like cadmium, zinc and lead. Areas in green have minerals that are more neutral but are still of concern. Other colours are minerals not contributing to water contamination. No iron-bearing minerals were found in areas shown in black. Area shown is 10.5km wide and 17km long. (After Swayze et al, 1996).*

activities, related AMD and remediation. Airborne multi-spectral imaging is recommended for site specific projects and can be used both for the identification of vegetation stress and the direct spectral detection of pyrite and derived secondary minerals (Swayze *et al.*, 1996). Figure 2 shows an example of this application at Leadville, Colorado.

The direct detection and effective mapping of surface moisture from seepage, ponding, and drainage patterns, uses the traditional techniques of air photos for generation of three-dimensional terrain or drainage mapping, and satellite and airborne multi-spectral data for mapping of ponds and detection of surface penetrating seepage (Jupp *et al.*, 1990). Detection of sub-surface moisture uses thermal infrared techniques or the indirect method of monitoring stress and vigour patterns in the vegetation and ground cover. Other indicators may be found in mapping open pit mines, diversion channel silting, dam failure and changing conditions leading to imminent dam failure, all of which can be detected using combinations of air photo, multi-spectral and infrared monitoring. It should also be noted that iron-oxide stained river banks and river beds, indicative of acidic surface water, can be identified using colour infrared photos (Johnson and Willson, 1972; Standberg, 1964).

While traditional remote sensing methods, with the possible exception of near-infrared measurements, are generally considered to be limited to the direct detection of very shallow seepage conditions, the use of multi-spectral techniques, both satellite and airborne, provides an ability to detect changes in the vegetation or ground cover that are indicative of sub surface acid mine drainage problems. The development of these techniques have been quite recent and research in this area is ongoing. The USGS has been particularly active in using narrow spectral channels (≅10nm) to study geological and biological processes. Examples of these can be seen on the Internet at http://speclab.cr.usgs.gov.

Table 1: *Popularity of Various EM Techniques for AMD-Related Applications*

Technique	Respondents	
Fixed-wing airborne transient	12	17%
Fixed-wing frequency domain	6	8%
Helicopter airborne transient	6	8%
Helicopter airborne frequency domain	17	24%
Ground fixed loop transient	23	32%
Ground fixed loop frequency domain	17	24%
Ground moving coil transient	21	29%
Ground moving coil frequency domain	36	50%
EM31	39	54%
EM34	35	49%
MAXMIN	14	19%
Other	9	12%
Borehole	23	32%
One or more EM techniques	71	87%

The use of spectroradiometers is a relatively new field that is growing rapidly. The collection of reference spectral signatures has become an important component for site characterization for environmental remediation. In addition, geologists are starting to use spectroradiometers for mineral exploration in arid and semi-arid environments and for characterizing mine tailings and waste rock.

The real strengths of these methodologies are to be found, not so much in the raw data, but in the ability to analyse and integrate this data with other data sources, homing in on the actual realities contained in a series of integrated data sets. It is the image analysis and GIS (geographic information systems) systems that make this possible. The monitoring of mine wastes is an application where this ability to integrate is crucial. Because the necessary sources of information are quite diverse, not only do the multiple remote sensing data sets have to be properly analysed and integrated, but a wide range of geophysical data must also be incorporated into, and analysed through, this process. Work at the Kam Kotia mine in northern Ontario (Mussakowski *et al.*, 1993) illustrates the data integration process applied to an AMD environment.

REMOTE SENSING METHODOLOGY

Satellite-born sensors provide a relatively inexpensive, repetitive data set that can be used independently or to augment ground-based monitoring programs. More than a dozen multi-spectral, radar and film satellites are now in operation, including Canada's Radarsat, launched in 1995. Current resolution of about 10 m is expected to improve to 2–5 m within a few years (Watson, 1996).

Optical scanners carried by aircraft provide a logistic freedom that allows data acquisition at user specified wavelengths, spatial and spectral resolutions, and acquisition dates. The mine waste application requires high spatial precision that can be achieved (Watson, 1996) by using (for example) SPOT 10 m images to compensate for the pitch and yaw that is unavailable even at the high (~24 km) survey altitudes.

Direct identification of contamination by imaging spectroscopy is a relatively new development (Swayze *et al.*, 1996). Information on this methodology and other applications of the NASA sensor AVIRIS can be found on the Internet at http://jpl.nasa.gov.

Digital frame cameras (DFCs), consisting of solid-state arrays with more than 1024 × 1024 photo sites have virtually replaced airborne videography (King, 1993) for large-scale, site-specific applications. Unlike line scanners DFCs produce stable two-dimensional digital images that resolve aircraft motion and can be incorporated simply, along with GPS, laser profiling and radar etc., into a GIS for further analysis.

Spectrometers are becoming increasingly popular as commercial image analysis software is enabling analysts to use collected reference signatures (or spectral libraries) to interpret both satellite and airborne multi-spectral data.

Active systems such as radar are able to penetrate a limited thickness of soil cover and might be effective (Intera Kenting, 1992) in monitoring for sub-aqueous erosion. In remote, cloud covered regions radar data is becoming a useful tool for a variety of applications, including distinguishing broad cover types such as vegetation, bare soil, ponded water and waste rock (Gregory Geoscience, 1975). A newly developed radar system with forward and rear viewing sensors can provide both topographic and reflectance information (Lawrence, 1996).

Standard airborne photography, though providing higher spatial resolution than digital formats, lacks the spectral resolution necessary for mine waste studies and is more difficult to integrate in a GIS with other digital data sets.

GEOPHYSICAL APPLICATIONS

Geophysical methods have been applied to civil engineering and environmental problems since the 1940s in such applications as groundwater exploration, dam site investigations and transportation/pipeline planning. The earliest published references to mine waste applications appear in the late 1960s and 1970s (e.g., Chewning and Merkel, 1972) on the use of resistivity techniques to delineate acid contamination plumes. There are a great many references, however, to the effective application of geophysical methods to problems similar to those of mine contamination. Review papers by McNeill (1989, 1990), Monier-Williams *et al.* (1990), Greenhouse *et al.* (1989), Henderson (1992) and Mwenifumbo (1993) describe a wide variety of applications such as contaminant leakage from industrial waste and landfill sites. Many of these present the same technical problems as AMD and can be solved by the same geophysical strategy.

King (1994) identified three areas where geophysics can be used effectively on problems of mine waste:

1. sulphides, which are the source of AMD
2. areas of active chemical oxidation
3. acid mine drainage itself

Possibly a fourth category should have been added, namely the movement of contaminated groundwater, which has been shown by Corwin (1990) and others, to be detectable by the self-potential SP method. Radioactive wastes and leachate form another category of problems, specific to uranium mining operations.

All of the above conditions are amenable to direct detection and monitoring by one or more geophysical techniques. In addition, there are many indirect applications of geophysics that can benefit studies of mine waste.

Sulphides

Mapping these materials may be necessary as part of an overall investigation of an abandoned mine site or the planning of a cleanup of an existing operation. Induced polarization (IP) methods lend themselves ideally to this problem (King, 1994; Clarke, 1991), though the normally very high conductivity of the overlying acidic layer can cause complications. If the sulphides contain appreciable pyrrhotite, the magnetic method (Roberts, 1989) can be used to map the sulphide boundaries.

Areas of active chemical oxidation

The sulphide-oxide interface is critical to the generation of acid leachate; and its configuration has been shown (King, 1994; Clarke, 1991) to have an important influence on the migration of fluids. A combination of IP and resistivity methods has been effective in mapping this interface in the Sudbury area. EM methods are generally too high in frequency for work in tailings areas, but transient EM (TEM) techniques (Pawlowski and Kalin, 1997) have been applied successfully, though with limited depth of penetration.

Airborne EM (AEM) methods are, of course, effective in mapping the boundaries of tailings deposits (King, 1994) and are capable of providing some measure of the thickness of the more conductive layer.

King (1994) tested the SP methods on the Copper Cliff tailings area, expecting to find a large SP difference between the top of the tailings (oxidizing) and the base (reducing). The results, however, appear to be too strongly influenced by topography and near-surface conditions to be truly diagnostic.

Acid Mine Drainage (AMD)

AMD, by virtue of its enhanced electrical conductivity, makes an ideal target for both EM and resistivity methods. Only in areas of clay deposits are the host materials sufficiently conductive that leakage plumes may be undetectable. Recent references to AMD detection and mapping by EM methods include King (1994), Kalin and Pawlowski (1994) and Koch (1996). By far the largest proportion of this work has been done with the frequency EM (FEM) EM-31 and EM-34 "ground conductivity metres" by Geonics. "Difference" maps such as Figure 3 are an exciting new application of geophysics in the dynamic mode. Shallow seepage from the mill pond at the South Bay Mine towards Confederation Lake, Ontario, was monitored in March 1992 and again in February 1995 by EM-31 and EM-34 (Kalin and Pawlowski, 1994). Apparent conductivities in the depth range 1–6 m around the demolished mill, shaft and mine buildings were found to vary from 15 to > 35 mS/m. In the period 1992-1995 the pattern improved to the west but migrated generally northward. Figure 3 shows a serious danger spot on Line 300 E and a high conductivity area to the north, towards Mud Lake.

Ground conductivity metres provide valuable conductivity estimates in the depth range 0–20m, but give little information on the vertical distribution. To obtain information in the third dimension recourse is made either to down-hole EM or resistivity or to multi-frequency FEM (frequency EM), multi-channel TEM or resistivity surveys. Koch (1996) found the Max Min 1-8S FEM system very effective for studying leakage from the Claude waste rock pile at the Cluff Lake Mine, Sask. Though no depth inversion was carried out, the apparent conductivities derived by best fit to a horizontal layer provided reasonable and consistent results. Commercial software (e.g., EMIX-MM and GIPSI GEMINV) can be used to invert Max Min data to conductivity depth sections.

TEM surveys are reported by King (1994), Pawloski and Kalin (1997) and Koch (1996) for vertical sounding (and profiling) in AMD applications. Figure 4 is an EM-47 pseudo-section in the AMD seepage area of Mud Lake, near the South Bay Mine, showing clearly both the plume and the approximate bedrock profile. Again, inversion by software such as Interpex TEMIX or CSIRO Grendl could be used to produce a vertical conductivity section.

Resistivity profiling and sounding have been used for AMD leakage detection for many years (Chewning and Merkel, 1972). Recent applications by Koch (1997) at Cluff Lake (Figures 5 and 6) show the method to provide useful information in the vertical dimension, particularly when the data are inverted using Interpex RESIX plus (sounding) or Campus Geophysics RES2DECO software (profiling). The method is capable of virtually unlimited depth penetration and provides good resolution of shallow, resistive layers. The pros and cons of EM versus resistivity are

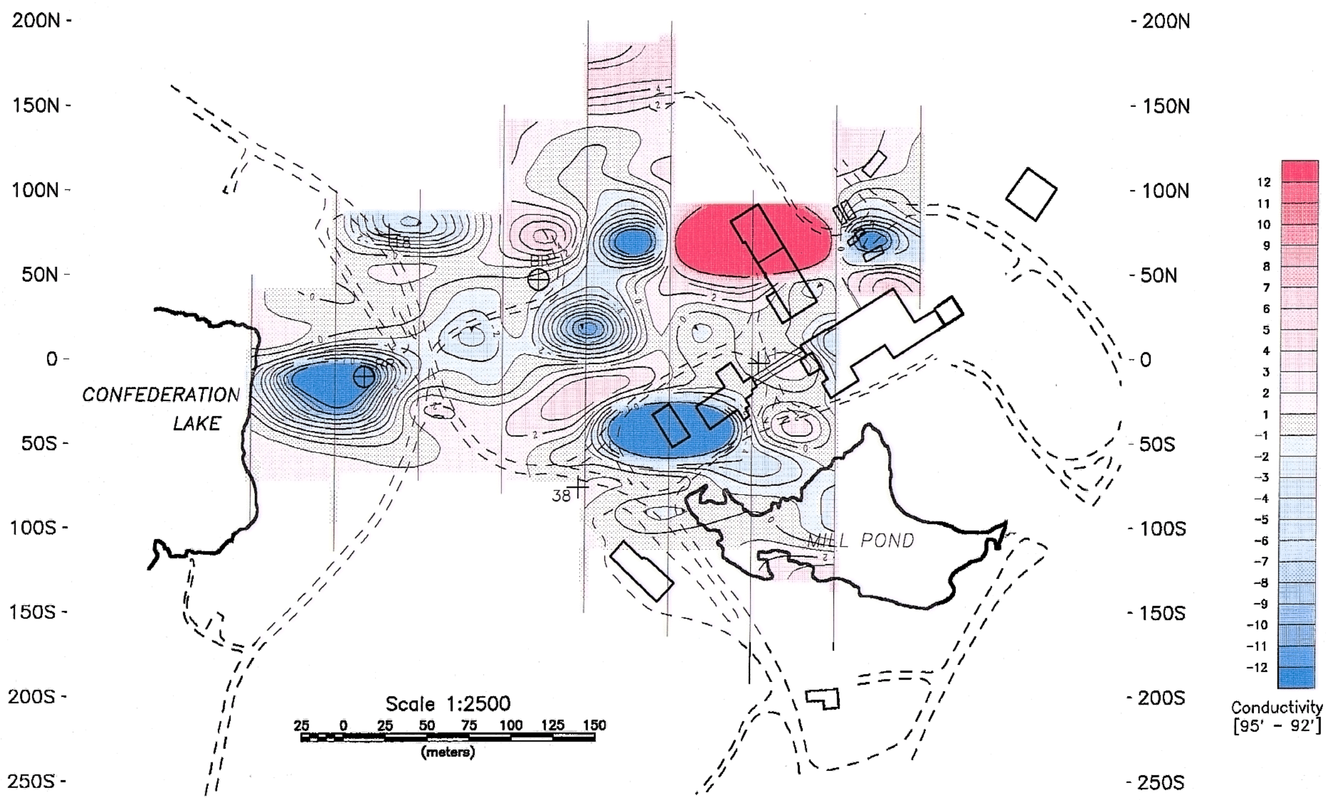

Figure 3: *Difference in mS/m of two EM 34-3 surveys conducted in 1992 and 1995 at the South Bay Mine, Ontario. Leakage from the mill pond, initially towards Confederation Lake, has now migrated northward towards Mud Lake (See Figure 4).*

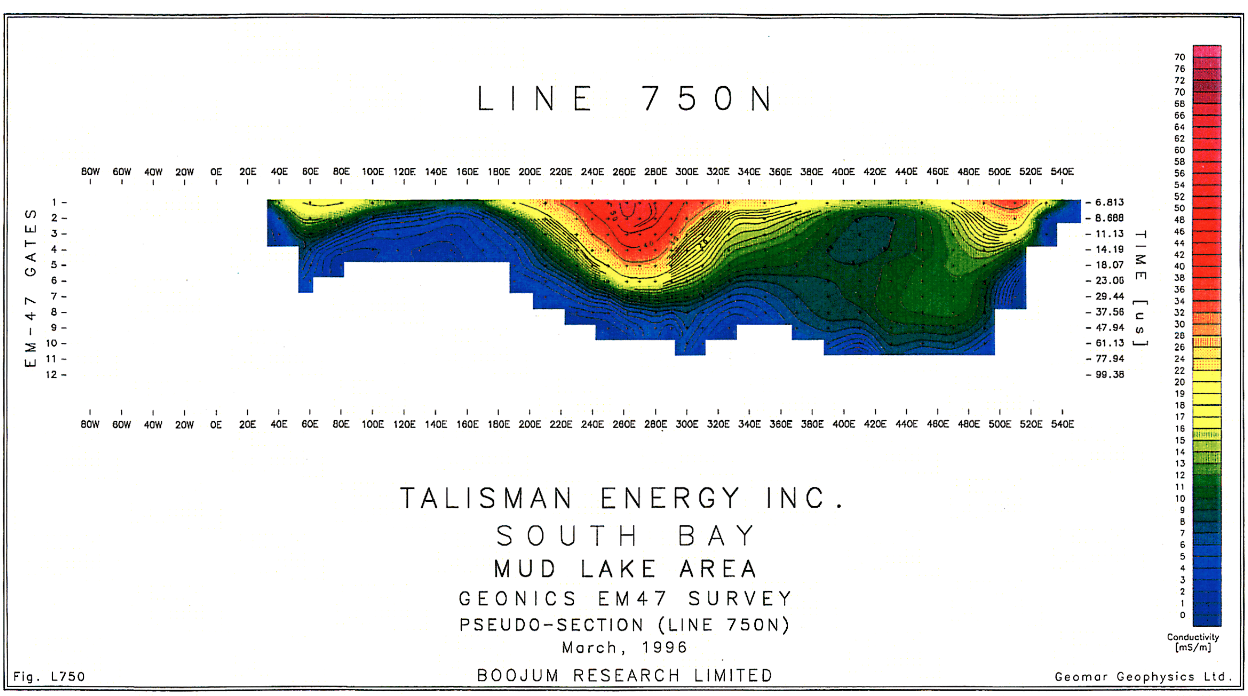

Figure 4: *EM 47 pseudo-section profile north end of Mud Lake near South Bay Mine shows acid plume overlying till and bedrock. (After Pawlowski and Kalin, 1997).*

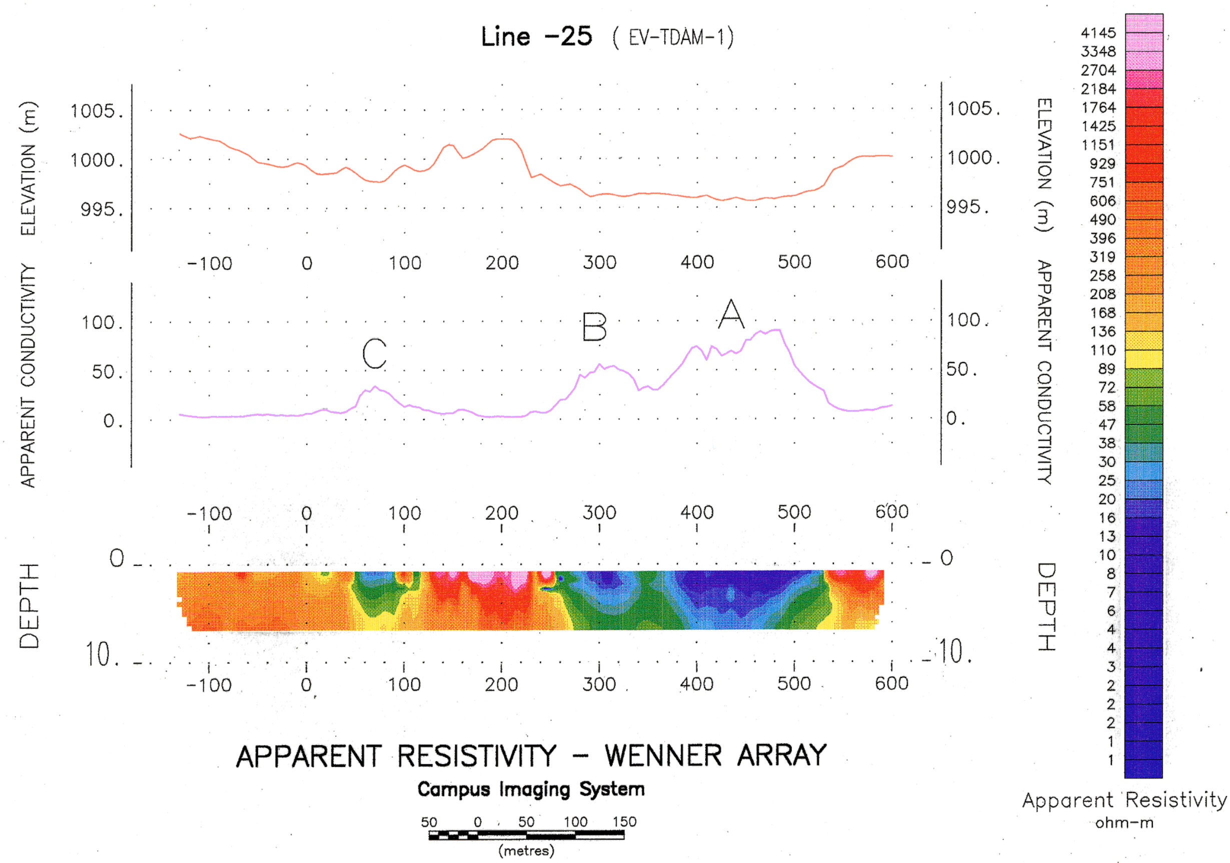

Figure 5: *DC resistivity survey: profile of apparent conductivity and vertical resistivity section adjacent to Claude waste rock pile, Cluff Lake Mine. Inversion by RES2DECO of Campus Geophysics. (After Koch, 1996).*

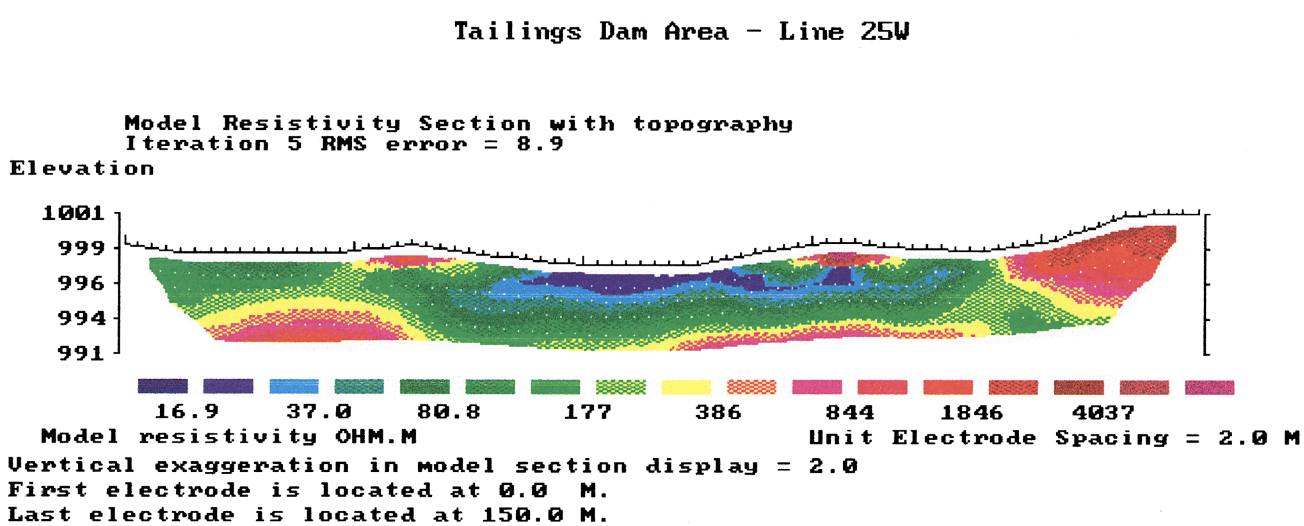

Figure 6: *DC resistivity survey: vertical resistivity section, Cluff Lake Mine area. Inversion by Interpex RESIX plus sounding software. (After Koch, 1996)*

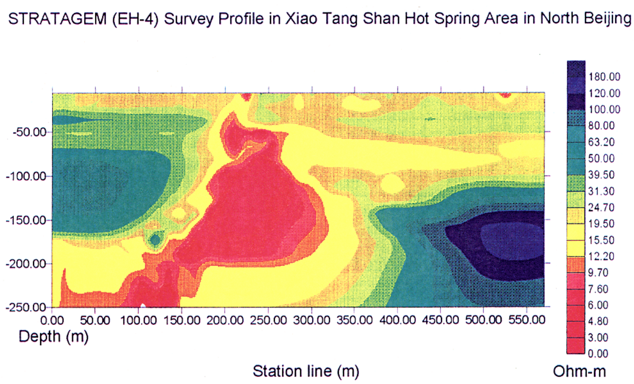

Figure 7: *Stratagem (EH-4) survey profile in Xiao Tang Shan hot spring area in North Beijing. (Courtesy Geometrics)*

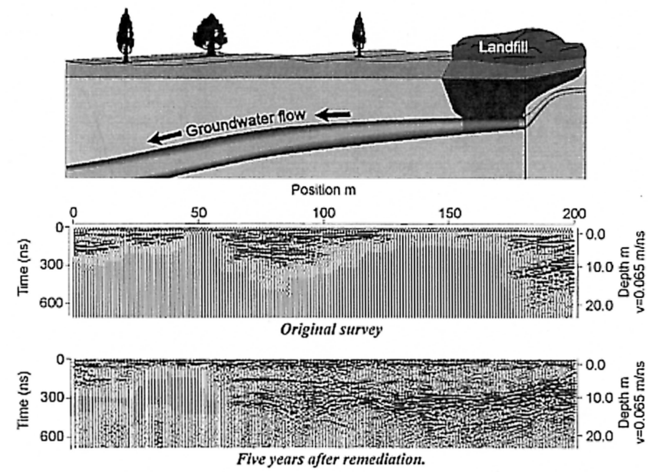

Figure 8: *Pulse EKKO GPR surveys adjacent to a municipal landfill site in Ontario. Blank areas are contaminated by acidic seepage from landfill. Repeat surveys show the effectiveness of remediation measures. (Courtesy Sensors & Software Inc.)*

discussed by the writer (Paterson *et al.*, 1994). For first-pass shallow AMD detection EM is a clear winner because of its much greater speed and simplicity.

Other methods of directly detecting AMD include controlled source audio magneto-tellurics (CSAMT) and ground penetrating radar (GPR). Conventional CSAMT is capable of extremely deep penetration and has been used widely for deep groundwater exploration (Nichols *et al.*, 1994). The Geometrics-EMI Instruments Stratagem is a modified version that has quite good resolution in the 10 to 250 m range (Figure 7) and is relatively portable and simple to operate.

GPR becomes virtually opaque to ground over about 20 mS/m in conductivity. At 50 MHZ it can be used to map very accurately the upper boundary of conductive plumes, including those of AMD. Figure 8 shows two GPR profiles of a conductive plume recorded five years apart, showing the extent of the remedial process. The method, which is fast and simple, is clearly a very powerful one in the appropriate geological circumstances. Lack of penetration through clayey ground does not inhibit this method any more than it does EM or resistivity since there is little conductivity contrast seepage between clay and acid seepage in any event.

AEM methods are ideally suited to the rapid detection and mapping of AMD, as has been demonstrated at Sudbury (King, 1994). Figure 9 demonstrates this very clearly. AEM has excellent depth penetration and is capable, using one of the commercially available inversion techniques such as the SENGPIEL section and GIPSI AEMINV, of providing a crude conductivity–depth section (Figure 10). AEM data, available in the public domain over many mining areas, can provide inexpensive information on the danger spots where more detailed ground studies need to be undertaken.

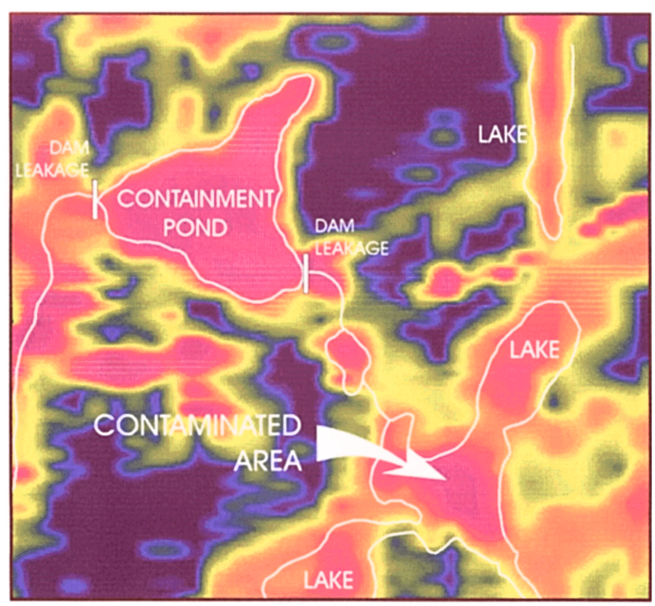

Figure 9: *Contaminant mapping using airborne EM conductivity in part of the Sudbury area, Ontario. A rapid and effective means to locate areas of containment ponds breaches and contamination plumes.. (Courtesy Dighem* 1-Power)*

Movement of acid leachate

Corwin (1990) demonstrated that the SP method can be used to distinguish between a static and a dynamic leakage problem as it responds not only to changes to pH but also to the movement of ions. The method has been used (e.g., Butler and Llopis, 1990) to detect and monitor leakage from reservoirs. King's (King, 1994) SP trials on the Copper Cliff, Ontario, tailings demonstrated that surface SP measurements are strongly affected by near-surface ground conditions. Static arrays and down-hole SP logs could be used to overcome some of these problems.

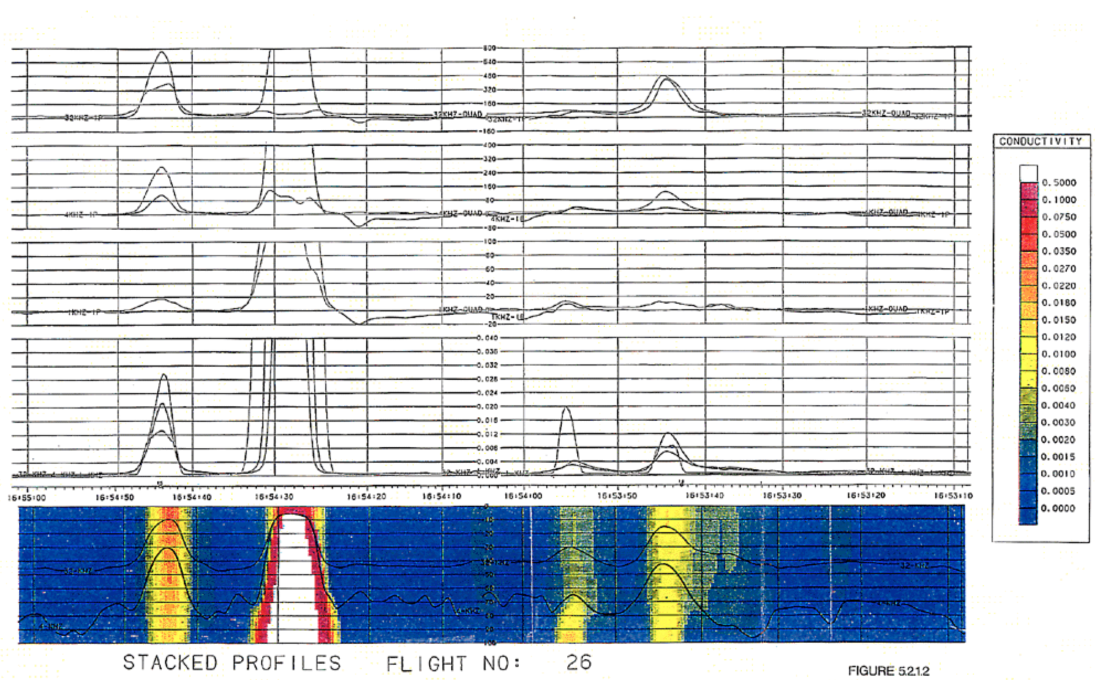

Figure 10: *Helicopter EM profiles at 900 4000 and 33000 Hz inverted to Sengpiel vertical conductivity section. Profile across part of Sudbury basin. Anomaly in centre is Inco tailings pile; smaller anomaly at left in groundwater plume. (After King, 1994).*

Radioactive wastes

Radioactive contamination can be spotted easily by airborne or ground gamma-ray spectrometer, methods that have been used widely to detect solid, liquid and gaseous wastes in the vicinity of refineries and nuclear power plants. The methods are limited to materials in the top 1 m of the ground. The same methods were used at the Stanleigh Mine, Ontario (King and Pesowski, 1993) to detect radioactive materials up to 2km from the mine. However, the most troublesome of the uranium mine wastes is groundwater contaminated by leachate from waste rock piles and tailings, which is both acidic and radioactive. Although gamma-ray spectrometry would be effective in tracing the migration of radioelement solutes at surface, this method would not trace the acidic leachate or dissolve daughter products that move to the groundwater table (Koch, 1997). EM, resistivity and GPR remain the preferred techniques for this purpose.

discussed by the writer (Paterson *et al.*, 1994). For first-pass shallow AMD detection EM is a clear winner because of its much greater speed and simplicity.

Other methods of directly detecting AMD include controlled source audio magneto-tellurics (CSAMT) and ground penetrating radar (GPR). Conventional CSAMT is capable of extremely deep penetration and has been used widely for deep groundwater exploration (Nichols *et al.*, 1994). The Geometrics-EMI Instruments Stratagem is a modified version that has quite good resolution in the 10 to 250 m range (Figure 7) and is relatively portable and simple to operate.

GPR becomes virtually opaque to ground over about 20 mS/m in conductivity. At 50 MHZ it can be used to map very accurately the upper boundary of conductive plumes, including those of AMD. Figure 8 shows two GPR profiles of a conductive plume recorded five years apart, showing the extent of the remedial process. The method, which is fast and simple, is clearly a very powerful one in the appropriate geological circumstances. Lack of penetration through clayey ground does not inhibit this method any more than it does EM or resistivity since there is little conductivity contrast seepage between clay and acid seepage in any event.

AEM methods are ideally suited to the rapid detection and mapping of AMD, as has been demonstrated at Sudbury (King, 1994). Figure 9 demonstrates this very clearly. AEM has excellent depth penetration and is capable, using one of the commercially available inversion techniques such as the SENGPIEL section and GIPSI AEMINV, of providing a crude conductivity–depth section (Figure 10). AEM data, available in the public domain over many mining areas, can provide inexpensive information on the danger spots where more detailed ground studies need to be undertaken.

Movement of acid leachate

Corwin (1990) demonstrated that the SP method can be used to distinguish between a static and a dynamic leakage problem as it responds not only to changes to pH but also to the movement of ions. The method has been used (e.g., Butler and Llopis, 1990) to detect and monitor leakage from reservoirs. King's (King, 1994) SP trials on the Copper Cliff, Ontario, tailings demonstrated that surface SP measurements are strongly affected by near-surface ground conditions. Static arrays and down-hole SP logs could be used to overcome some of these problems.

Radioactive wastes

Radioactive contamination can be spotted easily by airborne or ground gamma-ray spectrometer, methods that have been used widely to detect solid, liquid and gaseous wastes in the vicinity of refineries and nuclear power plants. The methods are limited to materials in the top 1 m of the ground. The same methods were used at the Stanleigh Mine, Ontario (King and Pesowski, 1993) to detect radioactive materials up to 2km from the mine. However, the most troublesome of the uranium mine wastes is groundwater contaminated by leachate from waste rock piles and tailings, which is both acidic and radioactive. Although gamma-ray spectrometry would be effective in tracing the migration of radioelement solutes at surface, this method would not trace the acidic leachate or dissolve daughter products that move to the groundwater table (Koch, 1997). EM, resistivity and GPR remain the preferred techniques for this purpose.

Structure and stratigraphy

Geophysical methods can aid indirectly in the study of leachate migration pathways through the 3-D mapping of stratigraphy and structure. Dave *et al.*, (1986), Pehme (1981), Roberts (1989), Hanson *et al.*, (1993), Snodgrass and Lepper (1993) and Clark (1991) describe geophysical surveys with a variety of methods aimed at solving the architecture of the ground as opposed to directly locating acid drainage. This information, which might include thickness of a tailings pile, the location and relief of buried river channels, the existence and depth of an aquitard such as a clay layer, or a bedrock ridge that might effect seepage flow, can very definitely benefit both the AMD assessment and an appropriate program of monitoring and remedial action.

Methods used for these studies may include seismic, GPR, gravity, resistivity or EM, sometimes in combination, depending mainly on the geology.

Bedrock profiling is the most common indirect study tool since the bedrock configuration frequently controls the leakage flow pattern. For this purpose the seismic refraction method is commonly preferred, providing good resolution to almost unlimited depths. Seismic reflection is effective also below a few tens of metres. Resistivity, gravity and EM provide less accurate information but can be used where adequate seismic velocity contrasts are lacking.

The GPR method is ideal for these problems, subject to the restrictions in depth which are compounded if the target layer is below the acid plume.

GEOPHYSICAL METHODOLOGY

Paterson *et al.* (1994) discussed in some detail the availability and relative merits of geophysical equipment suitable for AMD detection and monitoring (both direct and indirect). Interested parties can access that publication via E-mail at swalker@nrcan.gc.ca, or by writing to the MEND Secretariat, 555 Booth St., Ottawa, Canada. The following summary aims at highlighting new developments and issues surrounding their application to mine waste detection.

The EM method senses directly the enhanced ground conductivity caused by the presence of acid contaminants. Its major advantage over DC resistivity lies in its speed and portability, particularly in the airborne mode, rendering its much less expensive per km of profile recorded. Another advantage is its ability to make parametric soundings, as well as geometric, thereby improving lateral resolution. The literature records both the pros and cons of the EM-DC resistivity debate, King and Pesowski (1993) and Greenfield and Stoyer (1976) being among the strongest EM advocates; Jansen *et al.* (1993) and Stierman (1984) supporting the DC resistivity method, particularly for defining shallow, resistive layers.

Industry has overwhelmingly adopted the frequency domain "ground conductivity metre" as its favourite shallow mapping tool, as shown in Figure 12 taken from Paterson *et al.* (1994).

The EM-31 and EM-34 series instruments developed and manufactured by Geonics (McNeill, 1980, 1990) are currently the industry standard for basic conductivity mapping. The new MAXMIN 1-85 and MAXMIN 1-10 horizontal loop system of APEX Parametrics have clear advantages in respect to depth penetration and the ability to do soundings and 2-D conductivity imaging, but industry has not yet accepted these as necessary primary survey requirements.

Indeed, debate continues as to the necessity of geophysical tools that provide information on the vertical dimension. McNeill (1996) comments as follows:

> *Once the lateral extent of the plume is recognized from a cheap surface EM survey, appropriately located monitoring wells are installed, based on the EM survey data, and then borehole conductivity (logs) will be used to accurately determine the vertical extent of the plume so as to properly locate the screened portion of the plastic casing. Chemical analysis will be used from then on.*

The author accepts that this is current practice but points to the advantage of knowing the approximate 3-D distribution of the plume at an early stage in order to understand the migration pathway and estimate its seriousness. Using multi-frequency or multi-channel EM such information can now be obtained at the field site (Figure 5), at an additional cost that may be offset by an overall improvement in efficiency.

New on the scene since 1994 is the Geometrics Stratagem EH4 portable CSAMT system, which combines the advantages of both electrical and magnetic field measurements, and sounding capability (Figure 8), at some sacrifice as to economy and speed.

Airborne electromagnetics, particularly helicopter EM has been shown (King, 1994) to be a very powerful technique for mapping both surface and underground acid leachate plumes. Ancillary devices on the helicopter platform produce useful information of an indirect nature. AEM surveys cover large areas at a relatively low unit cost and are therefore well suited to the primary identification of contaminated areas (Figure 10) around existing mines. Inversion programs can extend their usefulness into the vertical dimension.

The DC resistivity method has been applied successfully to a wide variety of environmental problems including AMD (e.g., Ebraheem *et al.*, 1990, and Koch, 1996). Limitations of speed/cost and lateral resolution (particularly at depth), compared to ground EM (see above), will probably result in decreasing popularity except where used in conjunction with IP for 2-D tailings studies conductivity imaging, possible with PC-based programs such as RES2DECO greatly enhance the value of resistivity profiling, producing cross-sections (Figures 6 and 7) that closely resemble the sub-surface stratigraphy/hydrogeology.

The GPR method has been under development since the late 1970s (Davis and Annan, 1992) but most of the major developments have taken place since about 1986. Lightweight, portable systems are capable of surveying at a rate of 2 km per day at a measurement interval of 1 m.

Penetration in conductive ground is obtained, at the expense of portability, by lowering the frequency from (typically) 100 or 200 MHZ to as low a 12.5MHz.

Standard exploration magnetometers are adequate for mapping pyrrhotite-rich waste and for detecting buried artifacts. Vertical magnetic gradiometers have some advantages in the latter application.

IP/resistivity methods, useful for mapping sulphide-rich waste dumps and tailings, employ standard equipment operating in either the time or frequency domain. Experience (e.g., King, 1994) has shown that ground conditions around mine sites tend to be complex and, although depth penetration requirements are not severe, high transmitter power may be necessary. For example:

1. a resistivity surface layer of dry sand limits transmitter current;
2. highly conductive, saturated tailings at depth reduce the measured voltage;
3. man-made interference and artifacts such as power lines and buildings add noise to the system.

The seismic method is useful in an indirect role. For refraction studies standard engineering type 12- and 24-channel equipment with small dynamite or shot-gun charges can be used effectively for most problems. In the reflection made most operators prefer 48 channels with 16-24–bit resolution and a repeatable source such as the weight drop or, with some loss of stacking effectiveness the shot-gun. Off-line data enhancement may be necessary to unravel the usual complexities of the mine environment.

The SP method has considerable potential in AMD studies and is probably the simplest of all the electrical methods. Equipment consists essentially of a high-impedance voltmeter together with non-polarizing electrodes, and surveys are commonly carried out with standard laboratory instruments. SP can also be measured by most commercial resistivity and IP/resistivity systems.

No mention has been made in this paper of VLF EM and VLF resistivity methods. VLF EM can produce rapidly and inexpensively a rough profile of apparent resistivity, but would not appear to have the resolution of the FEM ground conductivity metres. VLF resistivity adds a useful depth parameter but is slower than either the DC resistivity or FEM methods. Standard exploration VLF equipment may be employed for either technique.

Gamma-ray spectrometers have limited usefulness other than to detect surface dumps of radioactive waste. For this purpose simple hand-held total count or 3-channel instruments are adequate. To detect plumes of radioelement-bearing acid seepage the electrical and EM methods are clearly superior.

CONCLUSIONS

The problems associated with mine wastes are being taken more seriously by environmentalists, and funds are finding their way into both remote sensing and geophysical research. In addition, mine contamination studies are benefiting from advances in technology made with other resource (and military) applications in mind.

Improvements in satellite sensing resolution are opening this tool to mine-scale applications. Advances in imaging spectrometry now permit the identification of certain minerals in a seepage plume, as well as vegetation stress, morbidity and die-off. Ground spectroradiometers are gathering data on the spectral signatures of waste plumes.

Airborne and ground geophysical methods are increasing in popularity as engineers and hydrologists become familiar with their strengths and limitations. Advances in both hardware and software are making it possible, even at an early stage in a mine waste study, to obtain vertical, as well as lateral images of acid contamination.

Rapid advances in data processing and interpretation may be expected to impact favourably on the use of geophysical and remote sensing in the detection and mapping of mine wastes. One of the most important developments will be improvements in joint inversion of multi-parameter images. On the practical level, tools need to be reprogrammed to provide outputs more directly useful (and comprehensible) to the hydrologists and engineers who are responsible for the mine waste cleanup.

ACKNOWLEDGEMENTS

The author acknowledges the major contribution by Roberta Stanton-Gray (Geomatics) in the remote sensing portion of this paper. In response to a call for help, useful information was also provided by Ken Watson (USGS), Duncan McNeill (Geonics), Margarete Kalin (Boojum Research), Jerzy Pawlowski (Geomar Geophysics), Doug Groom (Geometrics), Peter Annan (Sensors & Software) and Greg Street (World Geoscience).

REFERENCES

Blair, R.D., Cherry, J.A., Lim, T.P., and Vivyurka, A.J., 1989, Groundwater monitoring and contamination occurrence at an abandoned tailing area, Elliot Lake, Ontario: Presented at the First Internat Conference on Uranium Waste Disposal, Am. Inst. Mining Eng.

Butler, D.K., and Llopis, J.L., 1990, Assessment of anomalous seepage conditions: Geotec and Env. Geophys., **2**, Environmental and Groundwater, Ward, S.H., ed., Soc. Expl. Geophys. 153-173.

Chewning, J.R., and Merkel, R.H., 1972, The use of resistivity to define aquifers polluted from acid mine drainage: Abstract, Eos (Am. Geophys. Union, Trans), **53**, .368.

Clarke, M.A., 1991, Locating fluid migration pathways in a high sulphide tailing pond using non-invasive methods, B.Sc. Thesis, McMaster University, Canada.

Corwin, R.F., 1990, The self-potential method for environmental and engineering applications. Geotech and Env Geophys **1**. Environmental and Groundwater, Ward, S.H., ed., Soc. Expl. Geophys. 127-145.

Dave, N. K., Lim, T.P., and Siwik, R.S., 1986, Geophysical and biohydrogeochemical investigations of an inactive sulphide tailings basin, Noranda, Québec. National Symposium on Mining, Hydrology, Sedimentology and Reclamation, Univ. of Kentucky, 13-19.

Davis, J.L., and Annan, A.P., 1992, Applications of ground penetrating radar to mining, groundwater and geotechnical projects: Selected Case Histories, Geological Survey of Canada, Paper No. 90-04, 49-55.

Ebraheem, A.M., Hamburger, M.W., Bayless, E.R., and Krothe, N.C., 1990, A study of acid mine drainage using earth resistivity measurements, Groundwater, **28**, 361-368.

Greenfield, R.F., and Stoyer, C.H., 1976, Monitoring groundwater contamination with geophysical methods: *in* Am. Institute of Mining, Metallurgical and Petroleum Engineers—Soc. of Mining Engineers of AIME, **260**, 20-23.

Greenhouse, J.P., Monier-Williams, M.E., Ellert, N., and Slaine., D.D., 1989, Geophysical methods in groundwater contamination studies: Ontario Geological Survey Special Vol. **3**, Proceedings of Exploration '87, 666-667.

Gregory Geoscience, 1975, An assessment of the potential use of remote sensing technology for monitoring mine waste dumps: **1**, Development of Techniques, Gregory Geoscience, Ottawa, Canada.

Hanson, J.C., Tweeton, D. R., Friedel, M.J., 1993, A geophysical field experiment for detecting and monitoring conductive fluids, The Leading Edge. Pub. of the Soc. of Expl. Geophys., 930-937.

Henderson, R.J., 1992, Urban geophysics—a review: Exploration Geophysics, Australian Soc. Expl. Geophys. **23**, 531-542.

Intera Kenting., 1992, Remote sensing to monitoring uranium trailing sites—a review: research report prepared for the Atomic Energy Control Board, Ottawa, Canada. 73 p. + Appendices.

Jansen, J., Pencak, M., Gnat, R., and Haddad, B., 1993, Some application of frequency domain electromagnetic induction surveys for landfill characterization studies, *in* Symp. on Applications of Geophys to Engineering and Environmental Problems, SAGEEP '93 Proceedings, **1**, 259-271.

Johnson, G., and Willson, R., 1972, A colour and colour infrared study of mine acid drainage in Rich Run of Jackson County, Ohio: ASP-ACSM Fall Meeting, Proceedings, 300-318.

Jupp, D.L.B., Walker J., Kalma, J.D., and McVicar, T., 1990, Using thermal remote sensing to monitor land degradation and salinization in the Murray-Darling basin of Australia: 23rd International Symposium of remote sensing of the environment, Proceedings, **2**, 10011-10021.

Kalin, M., and Pawlowski, J., 1994, Electromagnetic surveys in acid-generating waste management areas: *in* International Symposium on Extraction and Processing for the Treatment and Minimization of Waste, Proceedings, 727-736.

King, D.J., 1993, Digital frame cameras: the next generation of low cost remote sensors: ASPRS Biennial Workshop on Photography and Videography in the Plant Sciences, Proceedings, 10.

King, A., 1994, Application of geophysical methods for monitoring acid mine drainage: MEND Project #4.6.1, CANMET Library, 562 Booth St. Ottawa, Ont.

King, A., and Pesowski, M., 1993, Environmental applications of surface and airborne geophysics in mining: CIM Bulletin, **86,** 58-67.

Koch, R.L., 1996, Environmental monitoring of uranium mining wastes using geophysical techniques Phase 1-A comparison and evaluation of conductivity and resistivity methods to monitor acid mine drainage from uranium waste rock piles and tailings areas: A report for the Atomic Energy Control Board, Cogema Resources Inc., Regina, Saskatchewan.

Lawrence, G., 1997, Intera Information Technologies Corp., Ottawa, Ontario, pers. comm.

McNeill, J.D., 1996, Geonics Ltd., Mississauga, Ontario, Canada, pers. comm.

McNeill, J.D., 1980, Electrical conductivity of soils and rocks: Technical Note TN-5, Geonics Ltd., Mississauga, Ontario, Canada.

McNeill, J.D., and Merkel, R. H., 1972, Advances in electromagnetic methods for groundwater studies: Ontario Geological Survey Special, Vol. **3**, Proceedings of Exploration '87, 678-702.

McNeill, J.D., 1990, Use of electromagnetic methods for groundwater studies: Geotech and Env Geophys, **1**, Environmental and Groundwater, Ward, S.H., ed., Soc. Expl. Geophys. 191-218.

Monier-Williams, M.E., Greenhouse, J.P., Mendes J.M., and Ellert, N., 1990, Terrain conductivity mapping and topographic corrections at three waste disposal sites in Brazil: Geotec and Env. Geophys, **2**, Environmental and Groundwater, Ward, S.H., ed., Soc. Expl. Geophys. 41-45.

Mussakowski, R., Chan, P., and Chan Goba, N., 1993, Spatial modelling of abandoned mine tailings for environmental assessment—The Kam Kotia test site: Ontario Ministry of Natural Resources Geographic Information Seminar, 8.

Mwenifumbo, C.J., 1993, Borehole geophysics in environmental application, Expl. and the Environment, Abstract, CIM Bulletin, **86**, 43-49.

Nichols, E.M., Morrison, H.F., and Lees, S., 1994, Controlled source magnetotelluries for groundwater: 56th Ann. Mtg. Soc. Expl. Geophys., Expanded Abstract.

Nordstrom, D.K., 1982, Aqueous pyrite oxidation and the consequent formation of secondary ion minerals: *in* Acid Sulfate Weathering, Kittrick, J.S., et al., eds., Soil Society of America, 37-56.

Paterson, N., Robertson, D., Hearst, R., Stanton-Gray, R., Miller, E., and Silverthorn, S., 1994, Application of remote sensing and geophysics to the detection and monitoring of acid mine drainage: MEND Project #4.6.3, CANMET Library, 562 Booth St. Ottawa, Ont. 116 p

Pawlowski, J., and Kalin, M., 1997, The use of non-intrusive methods of defining bedrock in AMD ground water discharge zones: *in* International Symposium on Extraction and Processing for the Treatment and Minimization of Waste, Poster paper.

Pehme, P.E., 1981, Geophysical survey of the Nordic contamination plume: B.Sc. Thesis, University of Waterloo.

Roberts, R.L., 1989, A multi-technique geophysical approach to the study of land-fills and potential groundwater contamination, Master's Thesis, Purdue Univ.

Robitaille, R., Dempsey, D., and Gallie, A., 1991, The use of landsat TM imagery in the detection of mine sites and mine wastes in the Sudbury, Ontario region: Eight Thematic Conference on Geologic Remote Sensing, Proceedings, 955-958.

Snodgrass, J.J., and Lepper, C.M., 1993, Geophysical characterization of mineral waste sites: Symposium on the Application of Geophysics to Engineering and Environmental Problems, SAGEEP '93, Abstracts **2**, 433

Spahn, J.L., 1983, A land cover classification of a portion of the Western Kentucky Coal Field utilizing multi-temporal thematic mapper simulator data: ACSM-ASP Fall Convention Proceedings, 367-377.

Standberg, C.H., 1964, An aerial water quality reconnaissance system: Photogrammetric Engineering, **30**.

Stierman, D.J., 1984, Electrical methods of detecting contaminated groundwater at the Stringfellow waste disposal site, Riverside County: California Environmental and Water Sciences, **6**, 11-20.

Swayze, G.A., Clark, R.N., Pearson, R.M., and Livo, K.E., 1996, Mapping acid-generating minerals of the California Gulch Superfund Site in Leadville, Colorado using imaging spectroscopy: *in* Summaries of the 6th Annual JPL Airborne Earth Science Workshop, 4-8.

Watson, K., 1996, USGS, Denver, Colorado, pers. comm.