

# Geoelectrical Methods for Investigating Mine Dumps

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## ABSTRACT

We've used direct current resistivity (DC), electromagnetic (EM), induced polarization (IP), and ground-penetrating radar (GPR) geoelectrical methods to study mine dumps. The results reflect lithology, pore water saturation, and dissolved solids in the pore water. If the pore water has a pH less than 5, conductivity maps can indicate acid generating potential. IP measurements can help distinguish mineralogy in mine dumps, especially concentrations of sulfide minerals. EM and DC can help locate acidic/high TDS groundwater associated with mine dumps. GPR methods failed at the sites we studied in the West. Our own conclusions are augmented by those from the recent literature.

## OVERVIEW

A standard general reference on mine waste geophysics is the work of Custis (1994). Other references on mine waste geophysics, containing many instructive examples and good bibliographies, are by King and Pesowski (1993), Patterson (1997), and Campbell et al. (1999). A standard reference on using geophysics for landfills (not necessarily mine dumps, though much of the advice given therein applies to mine dump problems) is by Benson et al. (1983), with a good recent update by Greenhouse et al. (1998).

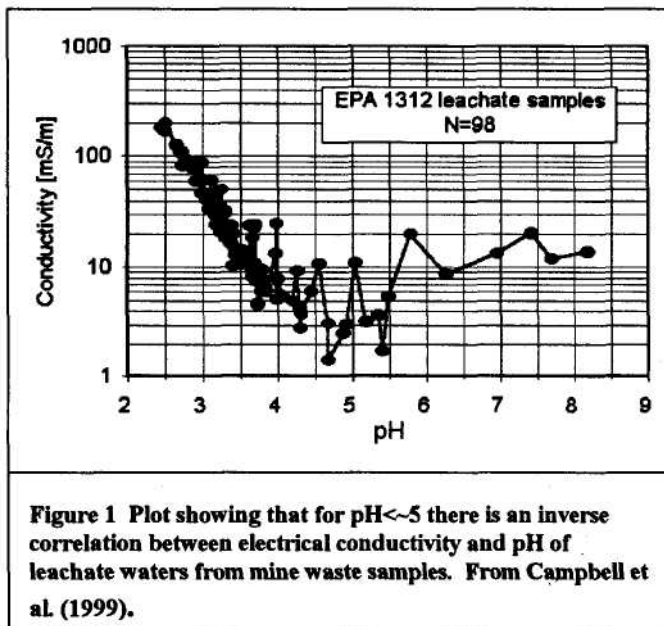
Over the past three years, our group at the US Geological Survey has used direct current resistivity (DC), electromagnetic (EM), induced polarization (IP), and ground-penetrating radar (GPR) geoelectrical methods to study mine dumps. We have also reviewed post-1994 literature on the subject. This report summarizes what we have learned, and is intended as an update to the manual by Custis (1994).

## BRIEF DESCRIPTIONS OF SOME GEOELECTRICAL METHODS

Table 1 lists some major geophysical methods, the physical properties they measure, and their optimal application for mine waste studies. In this report we focus on geoelectrical methods, those that measure electrical conductivity or resistivity. We do so because mine dump material is typically more conductive than host material, and because ground containing effluents with high amounts of total dissolved solids (TDS) and/or acid mine drainage (AMD) is more conductive than ground containing normal pore waters. The conductivity of a geologic unit, in general, reflects its lithology, its porosity, and the saturation and conductivity of its pore water. A unit containing conductive minerals, such as clays (e.g. montmorillonite) or sulfides (e.g. pyrite) will be more conductive than one consisting of silicate minerals. A unit consisting of crushed rock (e.g., most mine dumps) will have higher porosity than uncrushed host rock; this means potentially higher pore water content to carry electrical currents through the unit. The moister a formation is, the higher its conductivity is likely to be. Similarly, increased amounts of dissolved solids and of acid in its pore water will also increase the conductivity of a formation. Figure 1 illustrates the effect of acid, showing that for pH values less than about 5, the conductivity of mine *leachate* waters is inversely proportional to pH. Usually the conductivities of leachate waters and pore waters are similar. To move from pore water conductivity to formation conductivity, measured geoelectrically, one must divide by a so-called formation factor that depends on the lithology of the formation. Typical formation factors fall in the range from 5 to 20. This suggests that in dumps that are fairly uniform and generally moist, and as long as the pH of the pore water is 5 or less, a conductivity map might help

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### Direct Current Resistivity

Typical DC and IP surveys (Ward, 1990) are done by injecting current into the ground via transmitter electrodes, and measuring the resulting voltages at receiver electrodes. The results are usually reported as resistivity in units of ohm-m. Such surveys may be set up to detect electrical structures vertically under the station ("sounding"), or they may move across the surface to detect lateral changes in resistivity ("profiles"). To some extent, the traditional 4-electrode sounding and profiling methods are being replaced nowadays by multi-electrode methods that do simultaneous sounding and profiling (Bauman et al., 1997; Park, 1998; Zonge Engineering, 1999). An old DC method now being tried for tracing acid mine drainage (AMD) plumes (Freeman et al., 1997) is "mise-a-la-masse," a type of surveying used to trace an electrically conducting body away from its exposure in a borehole or outcrop. Electrical current is injected into the exposure and voltages are then measured at different stations on the surface to infer the body's extent.

### Electromagnetic Induction

Typical electromagnetic surveys (McNeill, 1990) use loops of wire as transmitter and receiver antennas; these need not touch ground, and may be deployed in aircraft. Such instruments are so widely used throughout the engineering community that they are often designated by their particular trade names<sup>2</sup>. Conventional EM instruments simultaneously transmit and receive signals at one or a few specified frequencies. Some trade names are EM-31, EM-34, Max-Min, GEM-2, and GEM-300. Systems that alternately transmit and receive signals, which typically include a broad band of frequencies, are called time-domain, or TEM. Some trade names are GEOTEM, SIROTEM, PROTEM, and EM-47. Magnetotelluric (MT) equipment picks up low frequency EM fields from natural sources, conventional audiomagnetotelluric (AMT) equipment picks up natural EM fields in the audiofrequency ranges, and AMT systems that use transmitters controlled by the survey crew are called controlled-source audiomagnetotellurics (CSAMT). VLF equipment specifically tunes in naval navigation transmitters (trade name EM-16R). EM results are usually reported as conductivity in units of milli-siemens/meter (mS/m). Conductivity in siemens/m is the numerical reciprocal of resistivity in ohm-m.

<sup>2</sup> Trade names are cited here for more complete description. Such citation does not constitute endorsement by the U.S. government.

indicate places where acid is being generated or stored.

Geoelectrical methods include direct current resistivity (DC), induced polarization (IP), and a wide variety of electromagnetic methods. Because they are sensitive to electrical conductivity as well as to other physical properties, both induced polarization (IP) and ground penetrating radar (GPR) are usually also considered to be geoelectrical methods. The electromagnetic methods include 2-loop frequency-domain induction methods (herein designated EM), time-domain electromagnetic (TEM or TDEM), controlled source audiomagnetotelluric (CSAMT), and very low frequency (VLF) methods, among others. Lists of suppliers of commercial geophysical equipment and of contractors who provide geophysical services are published annually by the Society of Exploration Geophysicists, Tulsa, Oklahoma, in the May issue of *The Leading Edge*.

Induced Polarization (IP) methods (Fink et al., 1990) measure the rates with which electrical charges build up in the ground due to applied voltages, and with which they re-equilibrate after such voltages are removed. Common sources of the effect are charge polarization on individual grains, charge buildup within clay layers, and electrochemical interactions at grain surfaces. Because the IP effect results from currents passing through the ground, IP surveys always measure resistivity in addition to some index of polarization. The polarization index that is reported is different for different IP equipment; it may be chargeability in mV-sec/V, percent frequency effect (a dimensionless percentage), or phase shift in milliradians (mR) between transmitted and received signals.

IP methods traditionally have been used in prospecting for porphyry copper deposits, and are often good at locating sulfide concentrations in mine dumps (Wardlaw and Wagner, 1994; Yuval and Oldenberg, 1996; Campbell et al., 1998; Fig. 2). Case studies (Draskovits, 1994; Frangos and Andrezal, 1994; Yuval and Oldenberg, 1996; Buselli and Lu, 1999) suggest that contaminant plumes have negligible IP response. A laboratory study by Gudjurgis et al. (1997) simulated acid drainage through different mixtures of sand, clay, and pyrite. Their work showed that there were definite IP effects, but they mainly occurred in a frequency range ( $10^3$  -  $10^4$  Hz) that is not covered by conventional IP equipment.

## Ground-Penetrating Radar

Ground-penetrating radar (GPR; Conyers and Goodman, 1997) measures the speed of radar waves through the ground, usually a large fraction of the speed of light, 30 cm/ns. This wave speed is principally affected by the dielectric constant of geologic materials. Water has a high dielectric constant, so that radar waves travel more slowly in water-saturated ground. The propagation of radar waves is also affected by electrical conductivity, which acts to absorb them. It is well known that GPR waves cannot propagate well into media with electrical conductivity above some 20-30 mS/m. In particular, this includes most mineralogical clays. Note, though, that the word "clay" is sometimes used to designate any sufficiently fine-grained material, which may not be a "clay" in the mineralogical sense. GPR can often be used successfully in such "engineering clays."

The consensus of work to date is that GPR waves usually will not propagate into mine waste materials (Campbell et al., 1999). Even in ordinary ground, GPR typically does not penetrate deeper than 5-10 m. GPR can show shallow fluvial, glacial, or aeolian stratigraphy, and so help search for traps that might have caught reworked mine waste (Campbell et al., 1997), but mine waste as such has no clear GPR signature. GPR profiles are likely to have blank sections over effluent plumes. GPR may be used to monitor mitigation of plumes — when the blank sections clear up and the GPR shows stratigraphy once again, the plume has probably gone (Patterson, 1997; Fig 3).

### Spontaneous Potential

Spontaneous potential (SP) refers to electrical potentials, typically of the order of tens to hundreds of millivolts, that may be caused by electrochemical reactions or ion-stripping by moving ground water, among other things (Corwin, 1990). Mining exploration experience (Sato and Mooney, 1960) is that strong SP anomalies can occur over sulfide concentrations that are actively oxidizing, usually at or near the water table. Therefore, SP surveys ought to be of help in locating concentrations of sulfides that are actively oxidizing in mine dumps. Because SP anomalies also can reflect movement of ground water, SP sounds like a promising way to address two of the most common mine waste problems. However, SP anomalies can also be caused by lithologic variations, roughness of topography, thermal stresses, wind on vegetation, and many other causes. As a result, it is hard to sort out which mechanism is causing any particular SP response (Patterson, 1997). No clear successes have been reported to date in using SP for mine waste work (note attempts by Buselli et al., 1998, and Buselli and Lu, 1999).

## OTHER USEFUL, NON-GEOELECTRICAL, GEOPHYSICAL METHODS

## Magnetics

Magnetometers measure magnetic fields, in nanoteslas (nT), generated by magnetized bodies. They usually give noisy responses in mine dumps due to ferrous junk left there, either on the surface or buried. If ferrous metal is sparse, though, magnetics can help locate pods of pyrrhotite and magnetite — either as native minerals that were mined there or as a biogenic product of microbial actions. In either case, such pods can represent strong acid producing locales. The expected signatures of such pods is only a few nanoteslas (nT), compared to hundreds of nT for ferrous junk. A sensitive instrument (such as a cesium vapor magnetometer with 0.1 nT sensitivity) with the sensor scanning at a uniform distance above the surface would be needed to

## **Exploration Seismic Methods**

The seismic geophysical methods involve generating waves in the ground via explosions, hammer blows, weight drops, or the like. The resulting seismic waves are reflected and refracted at interfaces in the ground, and their travel times are recorded using arrays of geophones. Because mine waste piles usually consist of fragmented material, the seismic velocities therein are typically slower than those in the more consolidated material at their bases or along their sides. Furthermore the velocities of seismic P-waves are greater in saturated than in unsaturated ground. Seismic work, therefore, has promise for locating bottoms and edges of mine dumps, and water tables within them. Lanz et al. (1997) have illustrated the technique in a landfill, whereas Monier-Williams et al. (1997) discuss the use of seismic methods, together with other complementary geophysical surveying, to investigate basements and dam sites prior to emplacing new tailings empondments. A possible drawback of using seismic methods for mapping mine dumps is that they may be slower or more expensive than geoelectrical methods. Depending of the particular problem(s) to be addressed, however, they could well be the method of choice, particularly for a group who already has an in-house seismic surveying capability.

## **Direct Push Methods**

Recent years have seen the rapid development of direct push methods, a variety of new techniques that are being widely used for sampling landfills and other environmentally sensitive sites. All of these methods involve pushing, pounding, or vibrating sensors into the ground that must be evaluated. The hole may be left to cave or squeeze closed, possibly with sensors and wire leads still in place to facilitate monitoring measurements, or it may be cased (typically, with 1 -2 inch PVC pipe) for further access and sampling. Direct push sampling of mine dumps can be both fast and cheap, and should always be considered as an adjunct to, and check of, other geophysical work. Robertson et al. (1998) give a good overview of direct push methods. Papers discussing specific sensors and particular sites, although few of these are mine sites, may be found in sections on direct push technologies in various proceedings volumes, such as those edited by Robertson and Mayne (1998) and Bell et al. (1998). Geophysical measurements that are made in direct-push holes are the same in principle as those made in boreholes. A good text on standard borehole geophysics is that by Keys (1997).

## **TRACING PLUMES OUTSIDE WASTE PILES**

For reasons given above, ground containing effluents is almost always more electrically conductive than nearby ground containing less contaminated pore water. Thus, any method that detects conductors should work to trace effluent plumes. The choice of an optimal method is therefore a matter of fitting the capabilities of the particular geoelectric instrumentation to the size and depth of the target plume, at cheapest cost.

DC methods have been used successfully by many investigators, both to trace AMD (Merkel, 1972; Ebraheem et al., 1990; Yuval and Oldenberg, 1996; Busselli and Huang., 1996; Busselli et al., 1998; Benson and Addams, 1998) and to trace other kinds of effluents at landfills (Frohlich et al., 1994; Park, 1998; Bisdorf and Lucius, 1999). Freeman et al. (1997) used a misse-a-la-masse DC method to trace leaks from a settling pond, whereas Lemke and Young, 1998) used it to trace contaminant plumes from landfills. Other workers (e.g., Frangos, 1997; White and Barker, 1997; King and Pesowski, 1993) have used arrays of electrodes to detect liner leaks in settling ponds. In cases where the main objective is simply to test for the existence of possible plumes, however, DC work can be overkill. Phillips and Maathius (1997) state that they have found EM methods to be cheaper than traditional 4-electrode DC surveying for tracing briney plumes at a potash mine, and they compare several commercial EM instruments, giving strengths and weaknesses of each. DeVos et al. (1997) likewise compare seismic, DC, TEM, and VLF for tracing AMD below a tailings dam, and recommend VLF as by far the fastest and cheapest.

Many successes using EM instruments for plume detection have been reported. EM-31 units usually work well to detect relatively shallow (less than ~3m depth) plumes in unconsolidated soil (King and Pesowski, 1993; Sinha, 1994; Wynn, 1996; Bisdorf and Lucius, 1999; Bruce D. Smith, USGS, 1999, unpublished data; Brent Lewis, BLM, 1999, unpublished data). A similar success using a GEM-300 unit was reported by Wynn (1999, unpublished data). For deeper (to perhaps 15 m depth) plumes in unconsolidated soil, one must use deeper-seeing units such as the EM-34 (Patterson, 1997, Sinha, 1994) or EM-16R (King and Pesowski, 1993; DeVos et al., 1997). As the area to screen for plumes gets larger, the cost of covering the ground with surface-deployed EM units goes up, and airborne electromagnetic methods become economical (King and Pesowski, 1993; Gamey, 1998; Busselli and Lu, 1999). In such cases, one presumably would follow up the airborne survey using surface-deployed units to more precisely locate the plume edges.

There are some instances where geoelectric methods might fail, or where their results can be ambiguous. DeVos et al. (1997) tell of a case where AMD drained into a glaciated terrain containing many small pockets of electrically conducting clays. Li that place it was hard to separate conductivity highs due to the plume from those due to clay. Sinha (1994) and Busselli and Lu (1999) report instances where drainage appeared to be via fractures in shallow bedrock. In both places geoelectric surveys failed to find the plume. In general, attempts to use geophysics of any kind to delineate fluid-filled fractures may fail, because the physical properties of the large masses of country rock tend to mask those of the (volumetrically minor) fractures (cf, Emerson and Yang, 1999).

In tracing plumes, one must remember that plumes may change with time in response to changing fluid heads at the source. (For an example documenting this kind of behavior with plumes of a gasoline spill, see Campbell et al., 1996). Patterson (1997) cites an instance where an EM survey of an AMD plume was repeated, finding a new lobe of the plume that had grown between surveys. Note, furthermore, that a film of pore water may coat grains that are situated well above the local water table. This leads to the possibility that high conductivities may be seen *over fossil* plumes — AMD plumes that have largely dried up, but have left conductive pore waters behind (Campbell et al., 1999).

## GEOPHYSICAL CHARACTERIZATION OF MINE WASTE PILES

For reasons given above, material within mine waste piles is likely to be more electrically conducting than material making up their flanks or bases. When this is so, geoelectric methods can be useful for delineating waste pile boundaries. Geoelectric methods may also help to map features inside the piles, such as the water table or compositional variations.

Choice of an optimal geoelectric method to investigate any particular mine pile will hinge on its depth and character. If the objective is merely to delineate the dump edges, it may be possible to hemstitch back and forth along its border with a EM system, dropping flags where the conductivity changes, just as one would do to map shallow plumes. Tezkan et al. (1996) used VLF in this way at a municipal landfill. To look for relatively horizontal boundaries, such as the water table or the base of a shallow waste pile, DC soundings (King and Pesowski, 1993) or multifrequency EM soundings (APEX Max-Min; Jansen et al., 1992) have been employed. In such cases, the individual soundings are separately interpreted using an appropriate computer program to give a layered structure at each site, and the results are then interpolated between sounding sites. In principle, it is possible to similarly interpret continuous multifrequency EM profiles, but efficient software to do so is only now becoming available.

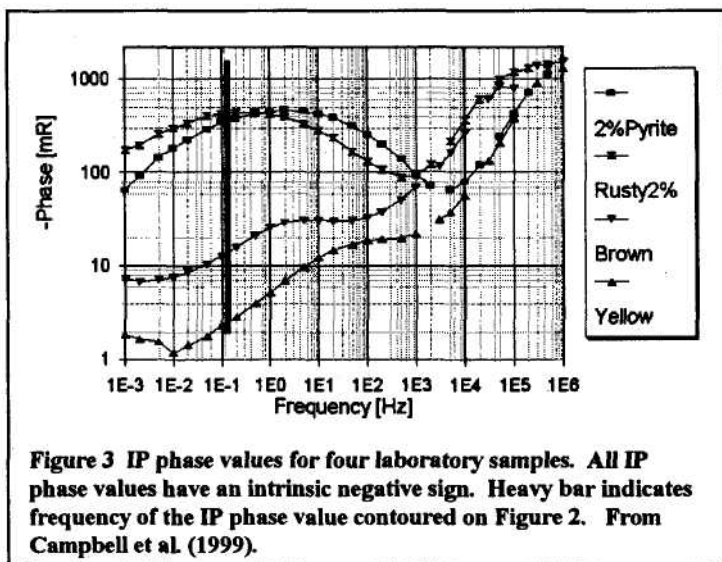
Limitations of the different geoelectric methods also play a role. General geophysical experience is that the DC and CSAMT methods are better at detecting extremely resistive layers, whereas multifrequency EM and especially TEM methods are better at detecting extremely conductive layers. This generalization fades, however, for units with only moderate electrical contrasts. The water table, for example, is usually somewhat more conductive than overlying unsaturated material. In the case of fresh ground water, it often happens that the water table is most readily detected by DC resistivity. Typical fresh water tables may be poor targets for EM methods because of the inability of these methods to differentiate between relatively high resistivity materials. However, when AMD is present or when the ground water contains high amounts of TDS, the water table can be a very conductive target that can be readily mapped by TEM or EM methods. Hence, one might choose DC or CSAMT if the primary objective were to find the (resistive) base of a dump, but multifrequency EM or TEM to accurately map the (conductive) water table within a dump. Carlson and Zonge (1997) emphasize the former point, clearly demonstrating that CSAMT is far better than TEM at mapping pre-dump topography now buried as much as 50 m deep. Tezkan et al. (1996) reach a similar conclusion in their study of a municipal landfill. This generalization is only a matter of degree, however. For practical applications, one probably could choose either method and use its interpreted depths for both water table and dump bottoms.

Both CSAMT and conventional ground TEM methods are designed to focus well below the surface, so that they give poor resolution of very shallow geoelectrical features. Hence, one might use DC or multifrequency EM methods to investigate shallow dumps, and CSAMT or TEM to investigate deeper ones. Because well-calibrated multifrequency EM systems and good interpretation packages for them may be hard to locate, present-day practice dominantly uses the more readily-available DC systems to find both shallow resistive and conductive layers. Buselli et al. (1998; their Fig. 5) used 10 m as their crossover depth in choosing between DC and TEM to map water table depth in an Australian tailings deposit.

IP methods can be useful for detailing makeup and mineralogy of mine dumps. Figure 2 (in the color appendix at the end of the book) shows interpreted conductivity (top) and IP phase (bottom) at the Yukon and May Day mine dumps, near Silverton, Colorado (also see Yaeger and Stanton, this volume). IP phase shift between transmitted and

received signals is a measure of IP effect. The particular IP phase value contoured is that at 0.125 Hz, and represents one of several we measured in the field. Coordinates are in feet. The Yukon survey used 10-ft dipoles and the May Day survey used 5-ft dipoles; both measured S in-line receiver dipoles for each transmitter dipole. Both surveys were made on free dump faces having an angle of repose of about 35°; consequently, these sections look vertically into the faces at a median slant angle of some 55° from the horizontal. Note that the interpreted values shown represent conductivity and phase values for large blocks of ground and that the resolution of the interpretation becomes poorer with depth. The interpreted conductivity values at both dumps vary from approximately zero to more than 100 mS/m. The higher conductivity regions on these sections probably represent places in the dumps either where there are conductive minerals or where the pore waters have low pH, high TDS, or both (cf. Fig. 1). Waters draining from both dumps have pH values less than 3.0. Because such pore waters are probably in chemical equilibrium with nearby grains of dump material, these regions accordingly may reflect places where acid is being generated in the dumps. The interpreted IP phase values (bottom, Fig. 2) are very different at these two mine dumps. At the Yukon dump, there are local regions with phase values of more than 50 mR. By contrast, at the May Day dump, phase values are low everywhere, generally less than 10 mR. The likely reason for this difference is illustrated in Figure 3, a plot of phase measurements made in the laboratory. Results are shown for four samples: two samples containing 1.96% pyrite ("2% Pyrite" and "Rusty 2%"), and two samples of May Day dump material ("Brown" and "Yellow", indicating color). X-ray diffraction analysis of the latter two samples showed they contained jarosite (a sulfate mineral), but negligible sulfides. The heavy vertical bar indicates the frequency of the raw IP phase value that was measured in the field and contoured in Figure 2 (see color section at the end of the book). From Figure 3, we might expect pyrite-bearing material to have high IP phase values. This is in line with general geophysical experience that metallic sulfides (e.g., pyrite, chalcopyrite, galena, but not sphalerite) give strong IP responses. It seems likely, therefore, that the high IP phase regions in the Yukon Mine dump may contain concentrations of sulfides, whereas the lack of such high IP phase regions in the May Day Mine dump argues against polarizable sulfide concentrations there.

We conclude that areas on Figure 2 having both high conductivity and high IP response may represent concentrations of *sulfide* minerals. Areas with high conductivity but low IP response may represent areas with *sulfate* minerals — also possible acid producers. Finally, areas with low conductivity but high IP response may represent mine junk. In particular, the area of the Yukon Mine dump at X = -85, Z = -10 was excavated and found to be rusting rebar in a crumbling cement block. The presence of the ferrous mine junk (rebar) had also been predicted by a magnetometer survey (not shown).



## SUMMARY AND CONSENSUS FINDINGS

- Most mine dump material is electrically conductive relative to host materials forming dump edges and bottoms. Most ground containing AMD plumes is electrically conductive relative to ground containing uncontaminated ground water. Therefore, the geophysical methods of choice for investigating most mine dumps and AMD plumes are *Geoelectrical*.
- EM methods are fast and cheap for screening for shallow AMD plumes in soil. They can fail when drainage is via fractures in bedrock, and their results can be ambiguous when the contaminated soil contains other electrical conductors such as clay lenses. Most commonly-used EM methods give only qualitative indications of depth to the plume. Repeat surveys of plumes are a good idea, in order to catch new lobes of evolving plumes.

- CSAMT methods usually yield somewhat better determinations of depths to horizons that are very *resistive*. Similarly, TEM methods give somewhat better depths to very *conducting* horizons. Water in mine dumps and AMD plumes is typically much more conducting than ordinary ground water. Thus CSAMT is better for finding the *bottoms* of dumps, whereas TEM is better for finding deeper, conductive *water tables* within them.
- DC soundings are good for finding electrical horizons at shallow depths, whereas TEM and CSAMT are designed to focus below the surface. Buselli et al. (1998; Fig. S) use 10 m as their crossover depth in choosing between the former and latter methods. Resolution of all three methods decreases with depth. Multifrequency EM systems hold promise to determine depths in lower resistivity materials such as mine waste piles, but to date they have not been used for this application.
- Induced polarization (IP) work is likely to help distinguish mineralogy, especially sulfides vs. sulfates.
- Magnetic measurements are mostly useful for locating ferrous junk in waste piles. No clear successes have yet been reported using magnetics in mine waste piles to map iron-fixing by microbes.
- Ground-penetrating radar (GPR) is likely to be unsuccessful anywhere in the arid West. That is because mine dump material in the West is typically quite electrically conductive, leading to poor penetration of GPR waves.
- No clear successes have yet been reported using spontaneous potential (SP) geoelectric voltages in mine waste work.

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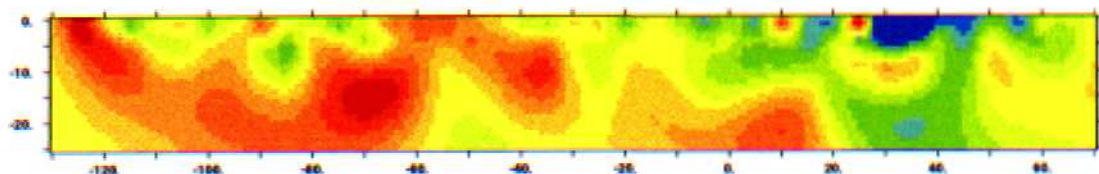
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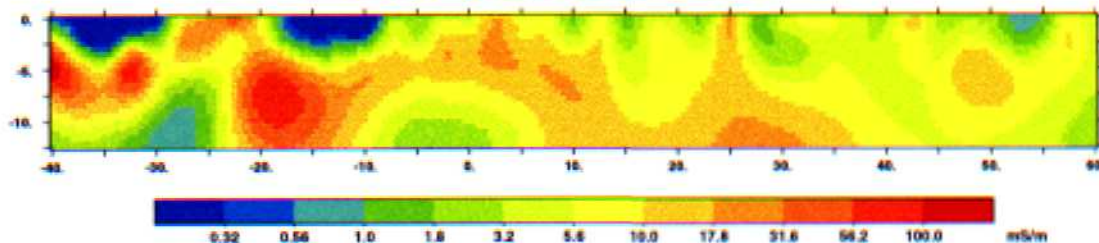
**Table 1 Geophysical methods used, or potentially useful, in mine waste studies.**

| Method                                          | Measures                                                           | Caused by                                   | Best Mine Waste Application                                                                                                                                                     |
|-------------------------------------------------|--------------------------------------------------------------------|---------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| EM, frequency-domain Electromagnetics           | Electrical Conductivity, mS/m                                      | Ground water, lithology                     | Tracing AMD plumes (many references in bibliography)                                                                                                                            |
| DC, Direct Current Resistivity                  | Electrical Resistivity, ohm-m                                      | Ground water, lithology                     | Shallow (<10 m) water tables in, and bottoms of, shallow (<20 m) waste piles (Buselli et al., 1998)                                                                             |
| TEM, time-domain Electromagnetic                | Electrical Conductivity, mS/m                                      | Ground water, lithology                     | Deeper (10-30 m) water tables in mine piles (Buselli et al., 1998)                                                                                                              |
| CSAMT, controlled source audio-magnetotellurics | Electrical Resistivity, Ohm-m                                      | Ground water, lithology                     | Deeper (10-50m) bottoms of mine waste piles (Carlson and Zonge, 1997)                                                                                                           |
| IP, Induced Polarization                        | Electrical Chargeability, mV-sec/V; or others as described in text | Electrochemical reactions at grain surfaces | Concentrations of sulfides in mine piles. (Yuval and Oldenberg, 1996)                                                                                                           |
| SP, Spontaneous Polarization                    | Ground voltages, mV                                                | Redox and streaming potentials              | Experimental. No proven successes.                                                                                                                                              |
| GPR, Ground-penetrating radar                   | Speed of electromagnetic radiation, cm/ns                          | Ground textures and included pore water     | Possibly, monitoring plume remediation. (Patterson, 1997)                                                                                                                       |
| Magnetics (Campbell et al., 1999)               | Magnetic field, nT                                                 | Magnetization                               | Ferrous junk in mine piles. Other mine pile applications unproven.                                                                                                              |
| Seismic                                         | Acoustic wave velocity, m/s                                        | Compaction and ground water content         | Tracing bottoms and edges of waste piles (Lanz et al., 1997), basement under plume areas (DeVos et al., 1997).<br>All mine waste applications are still in experimental stages. |

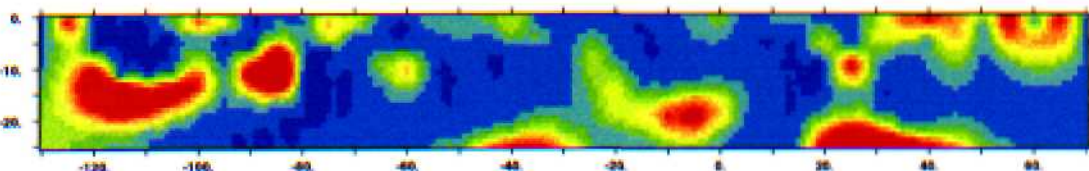
Electrical Conductivity - Yukon Mine dump face



Electrical Conductivity - MayDay Mine dump face



IP Phase - Yukon Mine dump face



IP Phase - MayDay Mine dump face

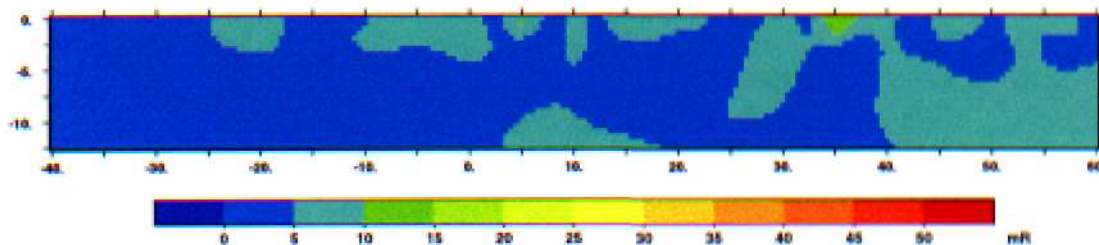


Figure 2 Interpreted conductivity (top) and IP phase (an index of IP effect; bottom) at Yukon and May Day Mine dumps, near Silverton, Colorado. On these sections, areas with high conductivity may represent places within dumps where AMD is being generated. Areas with both high conductivity and high IP effect (Yukon) may represent areas of *sulfide* minerals. Areas with high conductivities but low IP effect (May Day) may represent areas with *sulfate* minerals, also possible AMD producers. Areas with low conductivity but high IP effect may represent mine junk.