ANNOTATED BIBLIOGRAPHY OF GEOPHYSICAL METHODS FOR CHARACTERIZING MINE WASTE, LATE-1994 THROUGH EARLY-2000

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SUMMARY

In recent years, a variety of geophysical methods have been tested for characterizing mine waste. Of these, the geoelectrical techniques (those which measure the electrical conductivity of the ground) generally have met with the most success. This success is probably due to the fact that, for pH values less than about 5, the pH and electrical conductivity of leachate waters inversely correlate with one another (Campbell and others, 1999). For studies of acid mine drainage (AMD), therefore, electrical conductivity may be a surrogate for pH. Our search of recent (post 1994) literature shows that electromagnetic induction (EMI) methods have proven most effective for tracing AMD plumes outside of mine waste piles; direct-current (DC) and controlled source audiofrequency magnetotelluric (CSAMT) methods are preferable for mapping the bottoms and edges of mine piles; and time-domain electromagnetic (TEM) methods work well for mapping deeper water tables within such piles. These techniques are described more fully by Campbell and Fitterman (2000), who review published reports describing their application in mine waste and landfill studies. Tables 1-3 summarize the geophysical community's present experience using geophysical methods for characterizing mine waste, and the appendix contains an annotated bibliography to support and expand the generalizations made in those tables.

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

Method	Measures	Caused by	Best Mine Waste Application
EM or EMI, Electromagnetics	Electrical Conductivity, mS/m	Ground water, lithology	Tracing AMD plumes (many references in bibliography)
DC, Direct Current	Electrical Resistivity, Ohm-m	Ground water, lithology	Shallow (<10m) water tables in, and bottoms of, shallow (<20 m) waste piles (Buselli and others, 1998)
TEM, time-domain electromagnetic	Electrical Conductivity, mS/m	Ground water, lithology	Deeper (10-30 m) water tables in mine piles (Buselli and others, 1998)
CSAMT, controlled source audio-magnetotellurics	Electrical Resistivity, Ohm-m	Ground water, lithology	Deeper (10-50 m) bottoms of mine waste piles (Carlson and Zonge, 1997)
IP, Induced Polarization	Electrical Chargeability, mV-sec/V; other measures are also commonly used.	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	Monitoring plume remediation. (Patterson, 1997)
Magnetics	Magnetic field, nT	Magnetization	Ferrous debris in mine piles. Other mine pile applications unproven. (Campbell and others, 1999)
Seismic	Acoustic wave velocity, m/s	Compaction and ground water content	Tracing bottoms and edges of waste piles (Lanz and others (1997), basement under plume areas (DeVos and others, 1997). All mine waste applications are still in experimental stages.

Table 2. Mine dump characterization problems, expected geophysical signature, and suggested methods to use. Less sure methods have ? prefix.

Characterization Problem	Expected Signature	Suggested Geophysical Methods
pile thickness	host rock with higher resistivity than pile	<10 m: DC resistivity, ?multi-frequency EMI >10 m: CSAMT, TEM, ?DC resistivity
lateral extent	host rock with higher resistivity than pile	EMI, DC resistivity
water table location	saturated material below water table has much higher conductivity than unsaturated material above	<10 m and low conductivity ground water: DC resistivity > 10 m, low conductivity ground water: ?DC resistivity > 10 m, conductive ground water: TEM
sulfide concentrations inside pile	high polarization and high conductivity	IP ?Possibly SP
location of metallic junk	extreme magnetic highs or lows	Magnetics
hydrologic pathways	conductive fractures and fissures	in bedrock: ?VLF <10 m: EMI >10m: ?TEM
pore water motion	streaming potential	?SP
mapping of AMD plume	conductive zone	EMI, ?GPR, ?DC resistivity

Table 3. Summary of advantages (pros) and disadvantages (cons) of selected geophysical methods for mine waste investigations.

METHOD	*PROS*	*CONS*	*NET*
Magnetics	Can pick out ferric oxidation (biogenic?) Magnetic structures that channel plumes.		Useful only in VERY special cases.
EMI	Fast & cheap. Very good for tracing plumes.	Depth determinations fuzzy to nonexistent. Can't tell active from passive plumes.	USE THIS to screen for AMD plumes.
TEM	Good for finding water tables.	Slower than EM to collect, process. Shallow depths it gives may be poor.	Good for sounding into deeper dumps.
CSAMT	Good for finding bottoms of dumps.	Slower than EM to collect, process. Shallow depths it gives may be poor.	Good for sounding into deeper dumps.
DC	Can show acid-generating potential (pH<5). Useful for both dumps & plumes. Results similar to EM, better depth estimates.	Slower than EM to collect, process. Deeper depths it gives may be poor. Best to use modern (multi-electrode) gear.	Good for finding details in shallow dumps.
GPR	Immediate results. Very accurate for shallow plumes. Can help study fluvial mine tailings.	Limited depth penetration (< ~5m). Can't see thru evaporative crusts. May only work on WET dumps.	Best use is to monitor remediation of shallow plumes in soil.
IP	Shows sulfides vs. oxides in dumps. Gets DC as an automatic by-product.	Expensive gear, slow field operations. Takes much processing & interpreting.	Excellent for mapping dump details sulfide pods.
Borehole	Excellent vertical info, both dumps and plumes. Can check and calibrate geophysical work.	Takes special gear & crew. Electrical logs require uncased or PVC-cased drillholes.	Use as adjunct to, and check of, other geophysics.

Appendix: Annotated Bibliography (emphasizing recent publications, about 1994 to early 2000)

General geophysical references and overviews

Benson, Richard, Glaccum, R.A., and Noel, M.R., 1984, Geophysical techniques for sensing buried wastes and waste migration: National Ground Water Association, 6375 Riverside Dr., Dublin OH 43107, 236 p. [An older treatment, written for hydrologists. Not specific to mine waste problems.]

Conyers, L.B., and Goodman, Dean, 1997, Ground-penetrating radar: Walnut Creek, California, Altamira Press, 232 p. [A good introduction to GPR methods.]

Corwin, R.F., 1990, The self-potential method for environmental and engineering applications, *in* Ward, S.H., *ed.*, Geotechnical and Environmental Geophysics, v. I: Tulsa, Oklahoma, Society of Exploration Geophysicists, p. 127-146. [Information about, and examples of, SP methods.]

Greenhouse, John, Pheme, Peeter, Coulter, David, and Yarie, Quentin, 1998, Trends in geophysical site characterization: in Roberston, P.K., and Mayne, P.W., eds., Geotechnical site characterization--proceedings of the first international conference, Atlanta, Georgia, 19-22 April, 1998, p. 23-34. [Excellent review of recent trends in geophysical site characterization, with many examples. Not specific to mine waste work.]

McNeill, J.D., 1990, Use of electromagnetic methods for groundwater studies, *in* Ward, S.H., *ed.*, Geotechnical and Environmental Geophysics, v. I: Tulsa, Oklahoma, Society of Exploration Geophysicists, p. 191-218. [A good introduction to EM methods.]

Ward, S.H., 1990, Resistivity and induced polarization methods, *in* Ward, S.H., *ed.*, Geotechnical and Environmental Geophysics, v. I: Tulsa, Oklahoma, Society of Exploration Geophysicists, p. 147-190. [A good introduction to DC and IP methods.]

Direct push and borehole methods

Bell, R.S., Powers, M.H., and Larson Timothy, eds., 1998, Proceedings of the Symposium on the Application of Geophysics to Environmental and Engineering Problems, March 22-26, 1998, Chicago IL: Environmental and Engineering Geophysics Society, 10200 W.44th Avenue, Wheat Ridge CO, 1110 pps. [Contains a section with many papers on direct push technologies, p. 1-100. Not specific to mine waste problems.]

Keys, W.S., 1997, A practical guide to borehole geophysics in environmental investigations, Boca Raton, Florida: CRC Press, 176 p. [Good text on standard geophysical logging of boreholes.]

Robertson, P.K., Lunne, T., and Powell, J.J.M., 1998, Geo-environmental applications of penetration testing, in Robertson, P.K., and Mayne, P.W., eds., 1998, Geotechnical site characterization--proceedings of the first international conference, Atlanta, Georgia, 19-22 April, 1998, p. 35-48. [Keynote paper at a symposium emphasizing direct push technology. Excellent overview.]

Robertson, P.K., and Mayne, P.W., eds., 1998, Geotechnical site characterization--proceedings of the first international conference, Atlanta, Georgia, 19-22 April, 1998, 1496 pp., 2 vols. [Both volumes have many papers on direct push methods. Not specific to mine waste work.]

Overviews on using geophysics for mine waste applications

Blowes, D.W., 1997, The environmental effects of mine wastes, *in* Gubins, A.G., *ed.*, Proceedings of Exploration '97, Fourth Decennial International Conference on Mineral Exploration: Prospectors and Developers Association of Canada, Toronto, ON, p. 887-892. [Useful overview of geochemical, mineralogical, and hydrological processes in mine waste piles. Minor geophysics discussion.]

Campbell, D.L, and Fitterman, D.V., 2000, Geoelectrical methods for investigating mine dumps: ICARD2000—Proceedings from the Fifth International Conference on Acid Rock Drainage; Littleton CO, Society for Mining, Metallurgy, and Exploration, Inc., p. 1513-1523. [An expanded version of the present paper, but without detailed tables or annotations on the bibliographic citations.]

Campbell, D.L., Horton, R.J., Bisdorf, R.J., Fey, D.L., Powers, M.H., and Fitterman, D.V., 1999, Some geophysical methods for tailings/mine waste work: Tailings and Mine Waste '99, Proceedings of the Sixth International Conference, Fort Collins, Colorado, January 24-27, 1999; Rotterdam, A.A. Balkema, p. 35-43. [DC, EM, IP, Mag, and GPR work done on and near mine dumps by US Geological Survey.]

Custis, Kit, 1994, Application of geophysics to acid mine drainage investigations, volume I -- literature review and theoretical background, MS 09-06: California Department of Conservation, Office of Mine Reclamation, 801 K Street, Sacramento CA 95814-3529, 100p. [The standard older treatment of surface geophysical methods that can be applied to AMD problems. Includes literature review through about 1993.]

Custis, Kit, 1994, Application of geophysics to acid mine drainage investigations, volume II – site investigations, MS 09-06: California Department of Conservation, Office of Mine Reclamation, 801 K Street, Sacramento CA 95814-3529, 100p. [The standard older treatment of surface geophysical methods that can be applied to AMD problems. Includes examples from several Western U.S. mine waste piles.]

King, Alan, and Pesowski, M.S., 1993, Environmental applications of surface and airborne geophysics in mining: CIM Bulletin, v. 86, no. 966, p. 58-67. [Review of geophysical methods applicable to mining environmental issues, with many examples from Canada.]

Paterson, Norman, 1997, Remote mapping of mine wastes, *in* Gubins, A.G., *ed.*, Proceedings of Exploration '97, Fourth Decennial International Conference on Mineral Exploration: Prospectors and Developers Association of Canada, Toronto, ON, p. 905-916. [A very useful overview of geophysical methods, including spectral remote sensing techniques, that are being used for all types of mine waste work. Several case histories from Canada, evaluation of lessons learned, good bibliography.]

Paterson, Norman, and Stanton-Gray, R., 1995, Application of remote sensing and geophysics to the detection and monitoring of acid mine drainage: CANMET Proceedings for Sudbury '95 - Mining and the Environment, Sudbury, Canada, May 28 - June 1, 1995, v. III, p. 955-967. [Geophysical methods in use in Canada for AMD studies, with predictions of possible future directions.]

Schueck, Joseph, 2000, Investigating abandoned mine reclamation sites using geophysical techniques: Proceedings, 22nd Annual National Association of Abandoned Mine Land Programs Conference, Steamboat Springs, Colorado, September 24-27, 2000, p. 395-410. [A nice set of examples of using EM, VLF, and magnetics in abandoned coal mine workings in Pennsylvania. VLF used to locate fissures where surface water was flowing into underground mine workings, to emerge down gradient as AMD. Elsewhere, EM units were used to trace edges of coal mine backfill and AMD from backfill. Magnetics used to find buried tipple refuse, a source of AMD, as well as lost tanks and drums.]

Smith, B.D., McCafferty, A.E., and McDougal, R.R., 2000, Utilization of airborne magnetic, electromagnetic and radiometric data in abandoned mine land investigations: Fifth International Conference on Acid Rock Drainage, May 21-24, 2000, Denver, Colorado, p. 1525-1530. [A case history showing how to integrate various airborne geophysical methods to survey abandoned mine lands in the Boulder, Montana, and Animas, Colorado, watersheds.]

<u>Case histories using geophysics to trace AMD plumes</u>

Benson, A.K., 1998, Integrating hydrogeology, geochemistry, and geophysics to map acid mine drainage: in Schultz and Sidhartan, eds., Proceedings of the 33rd symposium on engineering geology and engineering technology, March 25-27, 1998, Reno, Nevada: Exploration and Mining Geology, v. 4, p.

411-419. [This paper summarizes geochemistry of mine waters over an area with many mines. Includes an example where many DC Wenner soundings scattered throughout an area mapped out a plume.]

Benson, A.K., and Addams, C.L., 1998, Detecting the presence of acid mine drainage using hydrogeological, geochemical, and geophysical data: applications to contrasting conditions at mine sites in Little Cottonwood and American Fork Canyons, Utah: Environmental Geosciences, v. 5, n. 1, p. 17-27. [Repeats the material in the previous reference and includes a second example using areal DC soundings.]

Buselli, G., and Hwang, H.S., 1996, Electrical and electromagnetic surveys of a mine tailings dam at Brukunga, SA: CSIRO Exploration and Mining Report 277F, 55 p. [Successfully used DC.]

Buselli, G., Hwang, H.S., and Lu, K., 1998, Minesite groundwater contamination mapping: Exploration Geophysics, v. 29. p. 296-300. [Used DC to detect a particular plume.]

Buselli, G. and Lu, K., 1999, Applications of some new techniques to detect groundwater contamination at mine tailings dams: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, March 14-18, 1999, Oakland, California, p. 507-516. [Helicopter TEM data covering a large tailings dam and vicinity was inverted to give maps of conductivity at different depths. The maps clearly show a shallow conductivity high over the tailings area, and another nearby high that probably reflects geology. Both highs disappear below 50 m depth. The maps show no obvious AMD plume, however. The authors also made ground SP and IP surveys in an attempt to locate the plume, but these appear to be inconclusive. They think that drainage may be taking place along a fault in the electrically resistive (10^3-10^5 ohm-m) gneissic bedrock and they show thin linear conductivity highs in both section and plan views that appear to follow this fault.]

Campbell, D.L., Horton, R.J., Bisdorf, R.J., Fey, D.L., Powers, M.H., and Fitterman, D.V., 1999, Some geophysical methods for tailings/mine waste work: Tailings and Mine Waste '99, Proceedings of the Sixth International Conference, Fort Collins, Colorado, January 24-27, 1999; Rotterdam, A.A Balkema, p. 35-43. [Includes an example of EM over a fossil plume.]

Campbell, D.L., Wynn, J.C., Box, S.E., Bookstrom, A.A., and Horton, R.J., 1997, Tests of ground penetrating radar and induced polarization for mapping fluvial mine tailings on the floor of Coeur d'Alene River, Idaho: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, March 23-26, 1997, Reno, Nevada, p. 81-87. [Used IP and GPR to look for fluvially-redistributed mine tailings on the bed of the Coeur d'Alene River, Idaho. IP highs probably reflected concentrations of such tailings, whereas the GPR profile showed the stratigraphic structures in which the tailings collected.]

DeVos, K.J., Pehme, P., and Greenhouse, J.P., 1997, Ground geophysical surveys for mine wastes, *in* Gubins, A.G., *ed.*, Proceedings of Exploration '97, Fourth Decennial International Conference on Mineral Exploration: Prospectors and Developers Association of Canada, Toronto, ON, p. 917-926. [Compares DC sounding, VLF, seismic refraction, and TEM methods for tracing an AMD plume below a tailings dam in Canada. The plume was in soil containing many clay lenses, which complicated the interpretations. DC, VLF, and seismic refraction were good at mapping bedrock at 4-25 m depth, but the plume was ambiguous. Of these, VLF was far the fastest and cheapest. TEM did map the plume fairly well, but follow-up drilling was necessary to resolve the issues.]

Ebraheem, A.M., Hamburger, M.W., Bayless, E.R., and Krothke, N.C., 1990, A study of acid mine drainage using earth resistivity measurements: Ground Water, v. 28, p. 361-368. [Successfully used DC.]

Gamey, T.J., 1998, Acid mine drainage in northern Ontario, *in* Gibson R.I., and Milligan, P.S., *eds.*, Geologic applications of gravity and magnetics: case histories: SEG Geophysical Reference Series, no. 8, and AAPG Studies in Geology, no.43, Tulsa OK: Society of Exploration Geophysicists, p.112-113. [Used a helicopter-borne 3-frequency system to map a plume extending over 2000 ft from a tailings pond. The sensor was slung 30 to 45 m above the ground and survey lines were spaced 200 m apart. The plume had conductivity of ~5mS/m in a background of ~1mS/m. The size of the plume made it economical to use airborne, rather than ground, EM methods to trace it.]

Gudjurgis, P., Katsube, T.J., and Gingerich, J., 1997, Complex resistivity characteristics of pyrite and clays altered by acid-mine-drainage contaminants: implications for monitoring of advancing contamination fronts: Expanded Abstracts With Biographies, Society of Exploration Geophysicists International Exposition and Sixty-Seventh Annual Meeting, November 2-7, 1997, Dallas TX, v. 1, p. 434-437. [A laboratory study to predict IP signatures of AMD plumes. The main IP effects were at higher frequencies than are commonly used by present-day IP gear.]

King, A.R., and Hynes, T., 1994, Applications of geophysical methods for monitoring acid mine drainage: Proceedings of the International Land reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acid Drainage, U.S. Bureau of Mines Special Publication SP 06A-94, v. 1, p. 317-326. [Review of geophysical methods for tracing AMD.]

McDougal, R.M., Smith, B.D., Cannon, M.R., and Fey, D.L., 2000, Integrated geophysical, geochemical, and hydrological study of the Buckeye mine tailings, Boulder watershed, Montana: Proceedings, 22nd Annual National Association of Abandoned Mine Land Programs Conference, Steamboat Springs, Colorado, September 24-27, 2000, p.411-428. [EM units were used to trace shallower (EM-31) and deeper (EM-34) parts of a plume migrating from tailings deposit towards a nearby stream.]

Merkel, R.H., 1972, The use of resistivity techniques to delineate acid mine drainage in ground water: Ground Water, v. 10, p. 38-42. [Successfully used DC.]

Paterson, Norman, 1997, Remote mapping of mine wastes, *in* Gubins, A.G., *ed.*, Proceedings of Exploration '97, Fourth Decennial International Conference on Mineral Exploration: Prospectors and Developers Association of Canada, Toronto, ON, p. 905-916. [Includes two particularly instructive examples involving repeat geophysical surveys to monitor evolution of plumes. The first, made with an EM-34™ system, showed up a new lobe of the plume that had developed between surveys. The second showed the GPR profiles reproduced here in Figure 6. This paper also reports an attempt to trace an AMD plume using SP. The results were strongly affected by near-surface conditions and were inconclusive.]

Phillips, G., and Maathuis, H., 1997, Surface and downhole EM investigations at potash mine sites in Saskatchewan, Canada: case histories: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, March 23-26, 1997, Reno, Nevada, p. 97-106. [Authors relate their practical experience using geophysics to trace plumes from potash mines. Their plumes were briney, rather than acidic, but also very electrically conductive. They state they have found EM cheaper than DC for their application, and compare many commercial EM instruments, giving useful discussions of the strengths and weaknesses of each.]

Schueck, Joseph, 2000, Investigating abandoned mine reclamation sites using geophysical techniques: Proceedings, 22nd Annual National Association of Abandoned Mine Land Programs Conference, Steamboat Springs, Colorado, September 24-27, 2000, p. 395-410. [VLF used to locate fissures where surface water was flowing into underground mine workings, to emerge down gradient as AMD. Elsewhere, EM units were used to trace AMD from coal mine backfill.]

Sinha, A.K., 1994, Ground electromagnetic surveys for environmental investigations a the Heath Steele mines area, New Brunswick: Current Research 1994-E; Geological Survey of Canada, p. 219-225. [Used EM-31™ and EM-34™ at two sites. At the first, the AMD plume was in soil, and EM easily found it. At the second, drainage appeared to be via fractures in the bedrock. There EM failed to see the plume.]

Yuval and Oldenberg, D.W., 1996, DC resistivity and IP methods in acid mine drainage problems: results from the Copper Cliff mine tailings impoundments: Journal of Applied Geophysics, v. 34, p. 187-198.

[Authors were trying out IP, but made the necessary concomitant DC profiles. DC showed the AMD plume well, whereas IP was inconclusive.]

<u>Examples using geophysics at mine waste piles</u>

Buselli, G., Hwang, H.S., and Lu, K., 1998, Minesite groundwater contamination mapping: Exploration Geophysics, v. 29. p. 296-300. [Compares DC and TEM methods in a study of a tailings pond, now mostly filled, at an abandoned pyrite mine in South Australia. Concludes that DC works best for shallow investigations, TEM for deeper ones (see fig 5). Also reports on SP work done on the property.]

Butts, R.A., and Hague, P.R., 1998, Locating dangerous historic mine workings in the Cresson open-pit mine with the aid of ground penetrating radar: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, March 22-26, 1998, Chicago, Illinois, p. 511-520. [GPR is being used at a new open pit gold mine near Cripple Creek, Colorado, to systematically survey ahead of its excavation machinery. The GPR work warns of potential hazards from old mine openings.]

Campbell, D.L., Fitterman, D.V., Hein, A.S., and Jones, D.P., 1998, Spectral induced polarization studies of mine dumps near Silverton, Colorado: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, March 22-26, 1998, Chicago, Illinois, p. 761-769. [This paper contrasts two mine dumps in Colorado, one with a low and even IP response (<12 milliRadian phase shift) and a second with local highs in its IP response (>40 mR phase shifts). IP highs did not particularly correlate with conductivity highs. Analyses of composite geochemical samples from the first dump showed <1 wt% sulfides, and about 6 wt% sulfides in the second (Steve Sutley, written commun., 1998), a result that supported the geophysical interpretation.]

Carlson, N.R., and Zonge, K.L., 1997, Case histories of electrical and electromagnetic geophysics for environmental applications at active mines: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, March 23-26, 1997, Reno, Nevada, p. 73-80. [A report on using both TEM and CSAMT at several active leach dumps in the southwestern U.S. They give an example from a copper leach dump, where the 10 ohm-m contour on their cross sections closely coincides with pre-dump topography, now buried as much as 150 ft deep. They state that CSAMT works better than TEM for such an application and depths.]

Frangos, W., 1997, Electrical detection of leaks in lined waste disposal ponds: Geophysics, v. 62, no.6, p. 1737-44. [Permanent electrode arrays were emplaced under a liner to monitor for leaks.]

Freeman, K., Wright, J., and Phillips, N., 1997, Practical geophysical applications for everyday operational and engineering problems at Newmont Gold Company: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, March 23-26, 1997, Reno, Nevada, p. 53-56. [Gives an example of monitoring for leaks in a tailings pond by combining a mise-a-la-masse source in the pond with permanent electrode arrays under its liner.]

Jansen, John, Haddad, Bassem, Fassbender, Wayne, and Jurcek, Patrick, 1992, Frequency domain electromagnetic induction sounding surveys for landfill site characterization studies: Ground Water Monitoring Review, v. 12, no. 4, p. 103-109. [FDEM data was inverted to get details of dump structure.]

McDougal, R.M., Smith, B.D., Cannon, M.R., and Fey, D.L., 2000, Integrated geophysical, geochemical, and hydrological study of the Buckeye mine tailings, Boulder watershed, Montana: Proceedings, 22nd Annual National Association of Abandoned Mine Lands Programs Conference, Steamboat Springs, Colorado, September 24-27, 2000, p.411-428. [EM-31 and EM-34, DC, and magnetics were used to investigate a deposit of mill tailings. The EM units gave shallower (EM-31) and deeper (EM-34) details on tailings units, and on a plume migrating towards a nearby stream. DC gave depth to bedrock, and mag showed ferrous metal junk.]

Monier-Williams, M., Maxwell, M., and Schneider, G., 1997, Preparing for waste: geophysics in geotechnical and environmental assessments of proposed mine waste facilities, *in* Gubins, A.G., *ed.*, Proceedings of Exploration '97, Fourth Decennial International Conference on Mineral Exploration: Prospectors and Developers Association of Canada, Toronto, ON, p. 893-904. [Describes integrated GPR, EM, seismic reflection, and borehole geophysical work done by their firm to investigate basements and damsites prior to siting new tailings empoundment areas in Canada. One part of this report tells of SASW (spectral analysis of surface waves) work done to help determine mechanical properties of a tailings pile in Ontario. Geophones, which were wetted and allowed to freeze into place, were used to record seismic waves generated by weight drops and sledgehammer blows. Spectral analyses of these wavetrains were then used to model vertical distributions (soundings) of shear strength under the source points. The models extended to about 20 m depth. Such methods presumably could be used to find depths to water table and base of the tailings, as well as shear strength.]

Painter, M.A., Laverty, B., Stoertz. M.W., and Green, D.H., 2000, Resistivity imaging of a partially reclaimed coal tailings pile: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, February 20-24, 2000, Arlington, Virginia, p. 679-687. [A dipole-dipole resistivity survey did an excellent job of outlining the bottom of a coal tailings pile in southern Ohio. Coal tailings with AMD had resistivity of <20 ohm-m; unconsolidated clays, silts, and sands fell in the range 20 to 50 ohm-m; and sandstone bedrock was >50 ohm-m.]

Schueck, Joseph, 2000, Investigating abandoned mine reclamation sites using geophysical techniques: Proceedings, 22nd Annual National Association of Abandoned Mine Land Programs Conference, Steamboat Springs, Colorado, September 24-27, 2000, p. 395-410. [A nice set of examples of using EM, VLF, and magnetics in abandoned coal mine workings in Pennsylvania. VLF used to locate fissures where surface water was flowing into underground mine workings, to emerge down gradient as AMD. Elsewhere, EM units were used to trace edges of coal mine backfill and AMD from backfill. Magnetics used to find buried tipple refuse, a source of AMD, as well as lost tanks and drums.]

Wardlaw, S., and Wagner, R., 1994, Development of waste rock sampling protocol using induced polarization: CANMET-MSL Div., Nat. Resour. Can., Ottawa, LR, 777-071, Final Rep. [An IP survey of a tailings/rock pile near Sudbury, Ontario, successfully identified high sulfide concentrations therein. Authors consequently propose that IP work could be part of protocols to estimate the sulfide contents of such sites.]

Yuval and Oldenberg, D.W., 1996, DC resistivity and IP methods in acid mine drainage problems: results from the Copper Cliff mine tailings impoundments: Journal of Applied Geophysics, v. 34, p. 187-198. [IP work at several mine dumps near Sudbury, Canada, found likely sulfide pods, although there were no boreholes or other information to confirm the interpretations. Metallic junk in the mine dumps gave extreme IP signatures that complicated the interpretations. At Sudbury, high IP values generally correlated with high conductivity values.]

Examples using geophysics at landfills, possibly relevant to mine work

Bauman, P.D., Lockhard, M., Sharma, A., and Kellett, R., 1997, Case studies of 2D resistivity surveying for soils, waste management, geotechnical, and groundwater contaminant investigations: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, March 23-26, 1997, Reno, Nevada, p. 261-270. [Practical case histories demonstrating use of multiple-electrode DC arrays.]

Draskovits, P., 1994, Application of induced polarization methods in integrated studies of ground water exploration and characterization of subsurface contamination: The John S. Sumner Memorial International Workshop on Induced Polarization (IP) in Mining and The Environment, Dept. Min. Geol., Univ. Arizona, Tucson AZ. [Work on a high-chloride plume in Hungary showed IP response peaked at places where total dissolved solid content in the plume was moderate, but decreased again for higher amounts of TDS.]

Frangos, W., and Andrezal, T., 1994, IP measurements at contaminant and toxic waste sites in Slovakia: The John S. Sumner Memorial International Workshop on Induced Polarization (IP) in Mining and The Environment, Dept. Min. Geol., Univ. Arizona, Tucson AZ. [DC and IP studies of a Czech landfill and its plume. Both outlined the edges and depth of the landfill. DC saw the plume; IP did not.]

Frohlich, R.K., Urish, D.W., Fuller, James, and O'Reilly, Mary, 1994, Use of geoelectrical methods in groundwater pollution surveys in a coastal environment: Journal of Applied Geophysics, v. 32, p. 139-154. [Schlumberger DC soundings, Wenner DC profiling, and borehole geoelectric work were done to map a plume from a landfill on Cape Cod. There was an *increase* in formation factor (the ratio of the overall electrical resistivity of a geological unit to that of its pore water alone) as the plume moves through an unconsolidated sand. The authors speculate that residues from the landfill were clogging pores and that iron-oxidizing bacteria were precipitating dissolved iron so as to cause the observed increases.]

Lanz, E.B., Maurer, H., and Green, A.G., 1997, Characterization of a composite landfill: a multidisciplinary approach: Expanded Abstracts With Biographies, Society of Exploration Geophysicists International Exposition and Sixty-Seventh Annual Meeting, November 2-7, 1997, Dallas TX, v. 1, p. 776-779. [Seismic tomography to investigate a landfill in Switzerland. Geophones spaced 2 m apart on the surface recorded P-waves from multiple shots. The data, inverted using a tomographic inversion scheme, show the shape of the bottom of the landfill, which is up to 18 m deep. It also shows some internal structure of the landfill. Dump material had a P-wave velocity of about 1400 m/s, and that of the underlying unconsolidated gravel into which the landfill had been emplaced was about 1800 m/s. This seismic tomographic method should work for mine dumps as well as for landfills.]

Lemke, S.R., and Young, C.T., 1998, Leachate plume investigations using mise-a-la-masse resistivity: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, March 22-26, 1998, Chicago, Illinois, p. 839-847. [Describes mise-a-la-masse investigations to trace contaminant plumes from landfills in Michigan. The method should also work for tracing AMD plumes.]

Park, Stephen, 1998, Fluid migration in the vadose zone from 3-D inversion of resistivity monitoring data: Geophysics, v. 63, no. 1, p. 41-51. [An example of electrical resistivity tomography, ERT, to trace fluid plumes.]

Tezkan, B., Goldman, M., Greinwald, S., Hördt, A., Müller, I., Neubauer, F.M., and Zacher, G., 1996, A joint application of radiomagnetotellurics and transient electromagnetics to the investigation of a waste deposit in Cologne (Germany): Journal of Applied Geophysics, v. 34, p. 199-212. [CSAMT and TEM surveys at an abandoned gravel pit which now serves as a municipal waste dump. The dump is full to overflowing, so that the locations of the original edges of the gravel pit are lost. Reflection seismic, DC geoelectric, and VLF surveys were also used there. All the electrical conductivity methods found the buried pit edges; like most mine dumps, relatively conductive inside and resistive outside.]

White, C.C, and Barker, R.D., 1997, Electrical leak detection system for landfill liners: a case history: Ground Water Monitoring and Remediation, Summer, 1997, p. 153-159. [A system of electrodes emplaced below a landfill liner was subsequently monitored, giving early warning of the presence and location of leaks.]

Zonge Engineering, 1999, Down in the dumps: landfill characterization with an extremely fast IP method: workshop notes from the Symposium on the Application of Geophysics to Engineering and Environmental Problems, March 15, 1999, Oakland, California. [Demonstrates a multi-electrode DC/IP system that was fast and effective at locating trash pockets under a 17ft-thick soil cap.]