GEOPHYSICAL METHODS IN EXPLORATION AND MINERAL ENVIRONMENTAL INVESTIGATIONS

by Donald B. Hoover, Douglas P. Klein, and David C. Campbell

INTRODUCTION

In the following discussion, the applicability of geophysical methods to geoenvironmental studies of ore deposits is reviewed. Details of geophysical techniques are not emphasized; these are covered in standard texts (Society of Exploration Geophysicists, 1966; 1990) and have been summarized in Hoover and others (1992).

Various geophysical methods are identified in table 1 (adapted from a chart compiled by Companie General de Geophysique, Massy, France and published with modification by Van Blaricom, 1980). The table identifies the utility of each method in airborne, ground, or borehole applications. Borehole methods are a specialized branch of geophysics that are not emphasized here. However, where ground disturbance is not prohibited, or where drillholes exist, there are a variety of useful borehole, crosshole, and borehole-surface techniques that may aid geoenvironmen tal studies (Mwenifumbo, 1993).

Table 1 also outlines physical parameters and properties, anomaly sources, and depth of investigation for each method. If a feature of geoenvironmental concern does not have an associated, measurable, physical property then geophysical investigations are not applicable. Depth of burial (of contaminant plumes, for instance) is extremely important in assessing the potential applicability of geophysics in geoenvironmental hazards identification. Geophysical responses for more deeply buried sources decrease in amplitude and increase in spatial wavelength until they disappear into geologic noise. Physical properties of cover, host rock, and mineral waste strongly influence responses of potentially hazardous material and are also important for evaluating the utility of a method in geoenvironmental investigations.

Some geophysical methods, such as gamma-ray spectrometry and remote sensing, measure surface attributes; others, such as thermal and some electrical methods are limited to detecting relatively shallow features but may help identify features at greater depth. Secondary effects of deeper features, such as geochemical haloes, can often be identified by these methods.

Geophysical modeling provides generalized and non-unique solutions to questions concerning the geometry of subsurface geologic relations. The non-uniqueness of these solutions is both a mathematical problem and one related to the multiplicity of sources that can cause geophysical anomalies. This feature is an implicit uncertainty in the discussion that follows. Environmental geophysics, like exploration geophysics, requires complimentary geophysical surveys integrated with geochemical and geologic insight.

This presentation first summarizes geophysical methods. Following the methods summary, geophysical strategies (that usually employ multi-technique approaches) for specific geoenvironmental investigations are discussed.

GRAVITY METHOD

Gravity measurements define anomalous density within the Earth; in most cases, ground-based gravimeters are used to precisely measure variations in the gravity field at different points. Gravity anomalies are computed by subtracting a regional field from the measured field, which result in gravitational anomalies that correlate with source body density variations. Positive gravity anomalies are associated with shallow high density bodies, whereas gravity lows are associated with shallow low density bodies. Thus, deposits of high-density chromite, hematite, and barite yield gravity highs, whereas deposits of low-density halite, weathered kimberlite, and diatomaceous earth yield gravity lows. The gravity method also enables a prediction of the total anomalous mass (ore tonnage) responsible for an anomaly. Gravity and magnetic (discussed below) methods detect only lateral contrasts in density or magnetization, respectively. In contrast, electrical and seismic methods can detect vertical, as well as lateral, contrasts of resistivity and velocity or reflectivity.

Applications of gravity to mineral deposit environmental considerations includes identification of lithologies, structures, and, at times, orebodies themselves (Wright, 1981). Small anomalous bodies, such as underground workings, are not easily detected by gravity surveys unless they are at shallow depth.

MAGNETIC METHOD

The magnetic method exploits small variations in magnetic mineralogy (magnetic iron and iron-titanium oxide minerals, including magnetite, titanomagnetite, titanomaghemite, and titanohematite, and some iron sulfide minerals, including pyrrhotite and greigite) among rocks. Measurements are made using fluxgate, proton-precession,

Table 1. Summary of geophysical methods and their characteristics applicable to exploration and geoenvironmental studies.
[In method column: A, airborne surveys; B, borehole surveys; and G, ground surveys]

Method	Physical parameter measured	Typical units	Relevant physical property	Typical source of anomaly	Depth of investigation
Gravity: A,B,G	Total attraction of Earth's gravity field (the vertical attraction of anomalous masses) Gradient of Earth's gravity field	Milligals or gravity unit (0.1 mGal) Eötvös unit (10^9 gal/cm)	Density	Rock density contrasts	All
Magnetic: A,B,G	Vector component, or total attraction of Earth's magnetic field Gradient of Earth's magnetic field	Nanotesla, or gammas Nanotesla/m	Magnetic susceptibility and remanent magnetization "	Magnetic susceptibility and (or) remanent magnetization contrasts "	Surface to Curie isotherm
Gamma-ray scintillometry: A,B,G Gamma-ray Spectrometry: A,B,G	Rate of gamma-ray photons received Rate of gamma-ray photons received and their energy	Counts/second Counts/second in spectral regions. If calibrated, %K and PPM equiv. U and Th	Quantity of K+U+Th and daughters Quantity of K,U,Th and daughters	K+U+Th contrasts in Earth's upper 50 cm K,U, and Th contrasts in Earth's upper 50 cm	Upper 50 cm "
Seismic refraction: B,G Seismic reflection: B,G	Seismic energy travel time "	Meters, milliseconds "	Velocity of P or S waves "	Structures or velocity layer contrasts "	All "
Thermal bore-hole or shallow hole: B Thermal remote sensing: A,G	Thermal gradient or temperature Surface temperature day and night	Degrees C/m, degrees C Degrees C	Thermal conductivity Thermal inertia	Thermal flux or conductivity variations Thermal inertia contrasts	Hole depth About 5 cm
Electrical (see text) Direct current resistivity: B,G several variations in electrode geometry	Electrode position (m), applied current (A), and electric field (mV)	Meter, amps, millivolts; typically converted to units of resistivity (Ohm-m)	Resistivity	Lateral or vertical changes in resistivity	About 2 km
Electromagnetic methods (see text): A,B,G many variations available	Dependent on method; ratio of received to applied electric and magnetic fields	Impedance (Ohms) or dimensionless ratio; units of conductivity (Siemens/m) or resistivity (Ohm-m)	Conductivity (inverse of resistivity)	Lateral or vertical changes in Earth conductivity	Shallow (10 m; VLF; 100 m, controlled source), intermediate (1 km; AMT), deep (10 km; MT)
Mise-a-la-masse: B,G	Applied DC or low frequency AC field	Millivolts	Resistivity	Conductive body	A few hundred meters
Induced polarization: B,G	Resistivity change w/ frequency (PFE) Phase angle between transmitted and received signal(ϕ) Normalized area of part of received voltage decay curve	Percent change Milliradians Milliseconds	Interface ionic polarization	Metallic luster minerals and pore water Clay and zeolite minerals	About 2 km
Self potential: B,G	Natural near-static (direct current) electric field	Millivolts	Eh/pH electronic conductor; streaming potential and thermal coupling coefficients	Vertical change in Eh/pH caused by electronic conductor; ground water flow; thermal flux	A few hundred meters
Remote sensing: A	Reflected radiation intensity (UV, VIS, IR)	Recorded as optical or digital intensity image	Spectral reflectance, Albedo	Changes in spectral reflectance and Albedo	Surface only

Overhauser, and optical absorption magnetometers. In most cases, total-magnetic field data are acquired; vector measurements are made in some instances. Magnetic rocks contain various combinations of induced and remanent magnetization that perturb the Earth's primary field (Reynolds and others, 1990). The magnitudes of both induced and remanent magnetization depend on the quantity, composition, and size of magnetic-mineral grains.

Magnetic anomalies may be related to primary igneous or sedimentary processes that establish the magnetic mineralogy, or they may be related to secondary alteration that either introduces or removes magnetic minerals. In mineral exploration and its geoenvironmental considerations, the secondary effects in rocks that host ore deposits associated with hydrothermal systems are important (Hanna, 1969; Criss and Champion, 1984) and magnetic surveys may outline zones of fossil hydrothermal activity. Because rock alteration can effect a change in bulk density as well as magnetization, magnetic anomalies, when corrected for magnetization direction, sometimes coincide with gravity anomalies.

Magnetic exploration may directly detect some iron ore deposits (magnetite or banded iron formation), and magnetic methods often are an useful for deducing subsurface lithology and structure that may indirectly aid identification of mineralized rock, patterns of effluent flow, and extent of permissive terranes and (or) favorable tracts for deposits beneath surficial cover. Geoenvironmental applications may also include identification of magnetic minerals associated with ore or waste rock from which hazardous materials may be released. Such associations permit the indirect identification of hazardous materials such as those present in many nickel-copper or serpentine-hosted asbestos deposits.

GAMMA-RAY METHODS

Gamma-ray methods (Durrance, 1986; Hoover and others, 1991) use scintillometry to identify the presence of the natural radioelements potassium, uranium, and thorium; multi-channel spectrometers can provide measures of individual radioelement abundances. Gamma-ray methods have had wide application in uranium exploration because they provide direct detection. Thorium is generally the most immobile of the three radioelements and has geochemical behavior similar to that of zirconium. Thorium content, like uranium content, tends to increase in felsic rocks and generally increases with alkalinity.

Gamma-ray spectrometry, because it can provide direct quantitative measures of the natural radioelements, provides geoenvironmental information concerning radiation dose and radon potential. Because uranium and (or) potassium are commonly enriched in or adjacent to some deposits, their presence may often be used to indirectly assess the potential for release of hazardous materials from ore or waste piles. Where sulfide minerals are present their oxidation accelerates uranium mobilization.

SEISMIC METHODS

Seismic techniques have had relatively limited utilization, due to their relatively high cost and the difficulty of acquiring and interpreting seismic data in strongly faulted and altered igneous terranes, in mineral assessments and exploration at the deposit scale. However, shallow seismic surveys employ less expensive sources and smaller surveys than are typical of regional surveys, and the cost of studying certain geoenvironmental problems in the near subsurface may not be prohibitive. Reflection seismic methods provide fine structural detail and refraction methods provide precise estimates of depth to lithologies of differing acoustic impedance. The refraction method has been used in mineral investigations to map low-velocity alluvial deposits such as those that may contain gold, tin, or sand and gravel. Applications in geoenvironmental work include studying the structure, thickness, and hydrology of tailings and extent of acid mine drainage around mineral deposits (Dave and others, 1986).

THERMAL METHODS

Two distinct techniques are included under thermal methods (table 1): (a) borehole or shallow probe methods for measuring thermal gradient, which is useful itself, and with a knowledge of the thermal conductivity provides a measure of heat flow, and (b) airborne or satellite-based measurements, which can be used to determine the Earth's surface temperature and thermal inertia of surficial materials, of thermal infrared radiation emitted at the Earth's surface. Thermal noise includes topography, variations in thermal conductivity, and intrinsic endothermic and exothermic sources.

Borehole thermal methods have been applied in geothermal exploration, but have seldom been used in mineral exploration. However, this method has potential usefulness in exploration and in geoenvironmental investigations (Ovnatanov and Tamrazyan, 1970; Brown and others, 1980; Zielinski and others, 1983; Houseman and others, 1989). Causes of heat flux anomalies include oxidizing sulfide minerals and high radioelement concentrations.

Conditions that may focus, or disperse, heat flow are hydrologic and topographic influences, as well as anomalous thermal conductivity. In geoenvironmental applications, oxidation of sulfide bodies in-place or on waste piles, if sufficiently rapid, can generate measurable thermal anomalies, which can provide a measure of the amount of metal being released to the environment. Borehole temperatures may also reflect hydrologic and hydrothermal systems that have exploration and geoenvironmental consequences. Airborne thermal infrared measurements have applications in geothermal exploration, and may have potential in mineral exploration and in geoenvironmental applications whenever ground surface temperature is anomalous due to sulfide oxidation, hydrologic conditions, or heat-flow perturbations due to structure or lithology (Strangway and Holmer, 1966).

Thermal infrared imaging methods are a specialized branch of more generalized remote sensing techniques. Images obtained in this wavelength range may be used for photogeologic interpretation or, if day and night images are available, to estimate the thermal inertia of the surface. Unconsolidated or glassy materials can be distinguished by their low thermal inertia. In places, thermal infrared images can distinguish areas of anomalous silicification (Watson and others, 1990).

ELECTRICAL METHODS

Electrical methods comprise a multiplicity of separate techniques that employ differing instruments and procedures, have variable exploration depth and lateral resolution, and are known by a large lexicon of names and acronyms describing techniques and their variants. Electrical methods can be described in five classes: (1) direct current resistivity, (2) electromagnetic, (3) mise-a-la-masse, (4) induced polarization, and (5) self potential. In spite of all the variants, measurements fundamentally are of the Earth's electrical impedance or relate to changes in impedance. Electrical methods have broad application to mineral and geoenvironmental problems: they may be used to identify sulfide minerals, are directly applicable to hydrologic investigations, and can be used to identify structures and lithologies.

Direct current resistivity method

Direct current resistivity methods measure Earth resistivity (the inverse of conductivity) using a direct or low frequency alternating current source. Rocks are electrically conductive as consequences of ionic migration in pore space water and more rarely, electronic conduction through metallic luster minerals. Because metallic luster minerals typically do not provide long continuous circuit paths for conduction in the host rock, bulk-rock resistivities are almost always controlled by water content and dissolved ionic species present. High porosity causes low resistivity in water-saturated rocks.

Direct current techniques have application to a variety of mineral exploration and geoenvironmental considerations related to various ore deposit types. Massive sulfide deposits are a direct low resistivity target, whereas clay alteration assemblages are an indirect low resistivity target within and around many hydrothermal systems. The wide range of earth material resistivities also makes the method applicable to identification of lithologies and structures that may control mineralization. Acid mine waste, because of high hydrogen ion mobility, provides a more conductive target than solutions containing equivalent concentrations of neutral salts.

Electromagnetic method

Electromagnetic measurements use alternating magnetic fields to induce measurable current in the Earth. The traditional application of electromagnetic methods in mineral exploration has been in the search for low-resistivity (high-conductivity) massive sulfide deposits. Airborne methods may be used to screen large areas and provide a multitude of targets for ground surveys. Electromagnetic methods, including airborne, are widely used to map lithologic and structural features (Palacky, 1986; Hoover and others, 1991) from which various mineral exploration and geoenvironmental inferences are possible.

Mise-a-la-masse method

The mise-a-la-masse method is a little used technique applied to conductive masses that have large resistivity contrasts with their enclosing host rock. In exploration, application of this method is principally in mapping massive sulfide deposits. This method is useful in geoenvironmental investigations of highly conductive targets; it has been applied to identify a contaminant plume emanating from an abandoned mine site (Osiensky and Donaldson, 1994).

Self potential method

Several possible natural sources generate measurable direct current or quasi-direct current, natural electrical fields or self potentials. The association of a self potential anomaly with a sulfide deposit indicates a site of ongoing oxidation and that metals are being mobilized; other self potential anomalies are due to fluxes of water or heat through the Earth (Corwin, 1990). Geoenvironmental applications include searching for zones of oxidation and paths of ground water movement.

Induced polarization method

The induced polarization method provides a measure of polarizable minerals (metallic-luster sulfide minerals, clays, and zeolites) within water-bearing pore spaces of rocks. Polarizable minerals, in order to be detected, must present an active surface to pore water. Because induced polarization responses relate to active surface areas within rocks, disseminated sulfide minerals provide a much better target for this method than massive sulfide deposits, although in practice most massive sulfide deposits have significant gangue and have measurable induced polarization. Induced polarization has found its greatest application in exploration for disseminated sulfide ore, where it may detect as little as 0.5 volume percent total metallic luster sulfide minerals (Sumner, 1976). In geoenvironmental studies, induced polarization surveys are principally used to identify sulfide minerals, but it may have other applications, such as outlining clay aquitards that can control mine effluent flow.

REMOTE SENSING METHODS

Remote sensing includes methods that utilize images obtained in the ultra-violet, visible, and near infrared bands of the electromagnetic spectrum (table 1). Thermal infrared observations, discussed previously under thermal methods, are also part of remote sensing. Remote sensing data are treated in image format, often in digital form, so that they can be processed conveniently. By comparison with known spectral responses of minerals or mineral groups, iron hydroxide minerals, silica, clay alteration, etc., can be defined over broad areas. Remote sensing can be used in geoenvironmental studies to map surface alteration patterns (Knepper, 1989) and to identify anomalous vegetation patterns in areas related to abnormal metal content in soil (Birnie and Francica, 1981).

OTHER METHODS

A number of other geophysical or quasi-geophysical methods have been used, or have potential application, in mineral exploration. Application of these methods in geoenvironmental investigations has been limited, but should not be dismissed. Some peripheral techniques that have special uses (as in archeology), whose utilization is not widely known in mineral exploration, that may directly apply to shallow geoenvironmental investigations. Examples of such techniques are ground-penetrating radar (used to image the shallow subsurface in electrically resistive rock; Davis and Annan, 1992), the piezoelectric method (used in studies of quartz veins; Volarovich and Sobolev, 1969), ultraviolet laser induced fluorescence (the Luminex method, used to identify scheelite, hydrozincite, and other fluorescent minerals; Seigel and Robbins, 1983), airborne gas sniffing (used in mercury exploration), the Russian CHIM (partial extraction of metals) electrogeochemical sampling technique, and radon sensing.

GEOPHYSICAL INVESTIGATIONS IN GEOENVIRONMENTAL STUDIES

The major geoenvironmental concerns related to investigations described below include (1) identifying abandoned and concealed mine openings, (2) tracing toxic substances, including metals or radiative species released to air and (or) water, resulting from sulfide mineral oxidation, and (3) delineating geologic structures that control the flow of potentially toxic water. Geologic relations outline the surficial distribution and concentration of potentially toxic sources. Geophysical investigations can provide limited means to trace pollutants and their sources in the subsurface without drilling or opening shafts (King, 1993; Paterson, 1995). If drilling and mine shaft operations are permissible, an additional array of geologic, geochemical and geophysical surveys, including cross-hole tomography and in-shaft techniques, become available, but these are beyond the scope of this discussion.

Abandoned mine workings

Abandoned mine workings may be an environmental hazard because of the possibility of subsidence or collapse. They can also channel contaminated ground water flow, particularly if they are located in sulfide mineral-bearing rock and contain water. Several geophysical strategies enable identification of lost mine workings. In general, the deeper and smaller such workings are, the harder they are to locate using geophysical techniques. However, deep or small workings are less likely to collapse, so it may be less important to locate them. If abandoned workings contain metallic tram rails or ventilation tubes, it may be possible to trace such installations from the surface using a magnetometer or geoelectrical device. If part of the metallic installation is accessible, the mise-a-la-masse method can be used to locate the rest of the installation. These methods only trace the metallic installation, so they will not identify workings where the installation is absent or, in the mise-a-la-masse method, where workings are disconnected from the energized installation segment. Further, the method may not map true voids; the tunnel where the metal was installed may have collapsed.

Magnetometers have been used to trace burned-out coal seams, particularly pyrite-bearing coal. During combustion, pyrite may oxidize to magnetite, which then can be traced using surface or airborne magnetic measurements. If the burned seam is still hot, geothermometry and infrared sensing methods may be used.

When the above special conditions are not met, the challenge for geophysical techniques is to find large voids, regardless of whether the voids are manmade. More reliable approaches to this challenge involve microgravity, seismic, ground-penetrating radar, geoelectric surveys, or a combination thereof. Microgravity requires measurements be made at a spacing about equal to the diameter of the workings being sought. Only shallow workings, whose tops are located at a depth less than about one opening-diameter, can be traced using microgravity.

Shallow, high-resolution seismic methods and ground penetrating radar have been used to trace caves. Both methods are applicable to identification of air- or water-filled openings. Jessop (1995) reports that ground penetrating radar returned massive, ringing reflections from the top of an air-filled cave buried about 6 m in sandstone. A large, but opposite polarity, ground penetrating radar response may result from water-filled caves; air and water filled caverns may be differentiated in this way. Ground penetrating radar signals, however, are attenuated by wet or clay soil, and are inefficient where these conditions exist in the surficial layer.

Geoelectrical work has also been successful in tracing cave systems. In the majority of reported cases, the caves were in resistive limestone strata. Direct current resistivity is particularly useful in identification of air-filled openings, though in some instances the caves were partly or completely filled with water. Electromagnetic methods, particularly at very low frequencies, are also efficient where cave floors are covered by conducting clay deposits. Guerin and Benderitter (1995) caution, however, that for caves in France that were traced, apparently successfully, using very low frequency techniques, the electromagnetic response was mainly generated by mud-filled fractures in the limestones rather than the caves themselves, which are localized along such fractures.

<u>Contaminant plumes associated with sulfide deposits</u>

Contaminant plumes, in sulfide-mineral-bearing environments, are intrinsically hazardous because they may merge with human water supplies or recreational water. *In situ* sulfide minerals near or above the water table may be actively oxidizing; the effect is likely to be greater in cases involving widely disseminated sulfide minerals because of greater surface area. Similarly, sulfide-mineral-bearing waste piles may oxidize when broken rock presents large surface area access for water and oxygen. Three geoelectrical techniques applicable to identification of sulfide-reduction/oxidation systems and their products are self potential, electromagnetic or direct current resistivity, and induced potential. In addition, ground penetrating radar may also detect the top of shallow acid water through relatively thin or resistive cover, and thermal studies have potential application in detecting oxidation centers and fluid circulation systems. Conductive materials that may cause uncertainties include clay, zeolites, sulfide minerals, and naturally saline water.

Self-potential applications: Self-potential investigations (Corwin, 1990) detect electrical potentials due to ongoing redox processes and involve measuring electrical potentials on grids of stations laid out on the surface or in boreholes. Self potential surveying is relatively inexpensive, and when used on closely spaced grids, accurately identifies redox cells in waste dumps. Self potential noise sources include electrical potentials generated by fluid movement, and natural potentials focused by topography.

Resistivity applications: Electromagnetic or direct current conductivity measurements may trace electrically conductive acid plumes (King and Pesowski, 1993). As these plumes are buffered, causing metal precipitation and neutralization of hydrogen ions, they become less conductive; resistivity surveys may be a useful monitoring method as well. Many different ground conductivity (or resistivity, the inverse of conductivity) measuring systems and survey approaches are available; each addresses different kinds of targets, target depths and dimensions, access considerations, and cultural interference problems, and has a unique range of interpretative difficulties. Conductivity data appropriate to local problems can often be collected and interpreted in rudimentary, rapid, and useful ways. Electrical conductivity maps can be useful for outlining contaminant plumes, but may also indicate anomaly highs caused by unrelated conductors (clays, for instance).

Induced polarization applications: Induced polarization is applied to detect disseminated conducting minerals, whether or not they are actively oxidizing. Flow channels carrying oxidizing fluids in high-sulfide-mineral tailings and waste dumps may have reduced induced polarization because of the formation of oxide minerals from sulfide minerals.

However, anomalies related to local sulfide mineral oxidation may be of low amplitude and difficult to resolve. Induced polarization is inefficient as an areal reconnaissance tool, but efficiently identifies disseminated mineral targets whose general location is already known. Advanced induced polarization equipment can discriminate between benign electrical conductors, like clays, and environmentally threatening ones, like heavy-metal plumes or petrochemical spills.
Other applications: Active oxidation of sulfide minerals may produce thermal anomalies that may be identified by infrared surveys or shallow heat-flow probes. Limited data are available concerning the use of thermal signatures in geoenvironmental investigations; thermal signatures may be low amplitude and overshadowed by topographic effects, thermal inertia contrasts in surrounding rocks, and heat distribution effects related to ground water circulation (Strangway and Holmer, 1966). Oxidized pyrrhotite within limited areas, for instance along fluid conduits in waste dumps, may be coincident with magnetic lows.

Argillic alteration

Argillic alteration that surrounds some sulfide deposits may be associated with resistivity lows, induced polarization highs, and moderate magnetic lows, whereas silicified rock and quartz lenses associated with sulfide deposits are associated with high resistivity, low magnetization, and increased density. Altered tracts commonly have diagnostic reflectance patterns on remote-sensing multispectral images. In addition, trace elements and alteration products may be absorbed by plants resulting in recognizable reflectance anomalies.

Thickness of waste piles

Tailings and waste pile thickness can be determined by direct current or electromagnetic resistivity soundings and seismic refraction and reflection. Uncertainties relate to the variability of waste pile properties and contrasts between waste material and country rock.

Structures controlling contaminated water flow

Numerous geologic structures that can focus ground water flow can be identified by various geophysical surveys. Aquitards can be identified by direct current or electromagnetic resistivity studies. Clay lenses are less resistive than sand- and gravel-bearing aquifers, unless contained pore water is ion rich or highly acidic, in which case the aquifers may be less resistive. Reflection seismic and ground penetrating radar may distinguish subtle velocity and resistivity changes related to distributions of aquifers and aquitards in sedimentary environments. Pore fluid with properties that vary laterally and with depth cause some uncertainties in aquitard delineation.

Lithologic boundaries and faults may be associated with porosity contrasts that may concentrate ground water flow. Porosity contrasts are associated with density, resistivity, and acoustic velocity contrasts, and some may have associated gamma-ray contrasts. In most cases, increased porosity lowers density and resistivity, the latter resulting from an increase of conductive pore fluid. In crystalline bedrock, faults and lithologic boundaries commonly have density and magnetic contrasts related to rock composition but ambiguities may result from subtle mineralogical changes in associated rocks.

Bedrock topography, including structural highs and buried channels, that influence ground water flow may contrast with overlying sedimentary and alluvial cover in having higher density, magnetization, and resistivity. These contrasts may be identified using gravity, resistivity, ground-penetrating radar, and seismic refraction and reflection. Anomalies may be small and ambiguities in defining bedrock topography or buried channels include equivalent amplitude anomalies from variable properties of both bedrock and overburden.

SUMMARY

Many geophysical methods commonly used in exploration have potential application to geoenvironmental investigations. Although these methods have mainly been used to identify pollutants and record their dispersion from mine areas, their application is not limited to studies of this sort. For instance, geophysical monitoring of pollutant activity, which requires significantly greater study, is another aspect of geoenvironmental investigations. Monitoring differs from detection chiefly in recurrent use of geophysical techniques. The effort required to extend application of geophysical techniques to naturally occurring pollutants related to mineralized, but unmined, rock or to other cultural concentrations of toxic or potentially toxic substances is minimal and could be of considerable assistance in meeting national needs for healthy environmental conditions (Henderson, 1992).

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