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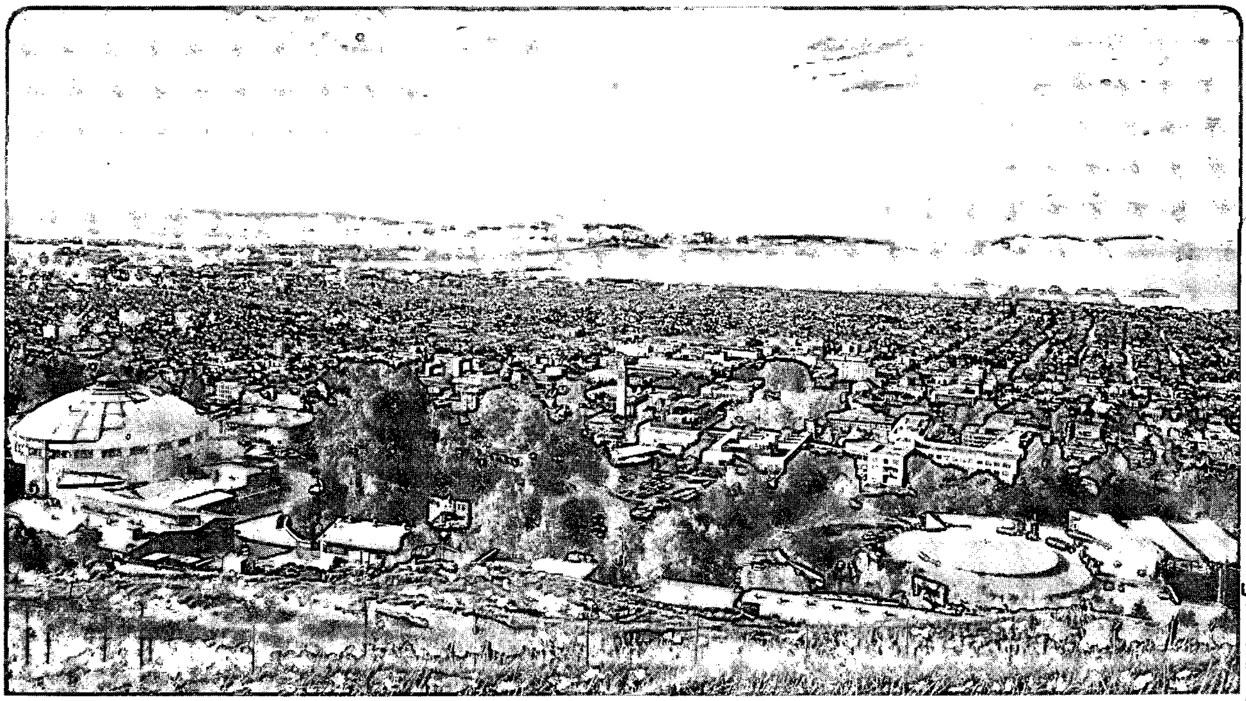

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Geophysical Methods for Fracture Characterization in and Around Potential Sites for Nuclear Waste Disposal

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Abstract

Historically, geophysical methods have been used extensively to successfully explore the subsurface for petroleum, gas, mineral, and geothermal resources. Their application, however, for site characterization, and monitoring the performance of near surface waste sites or repositories has been somewhat limited. Presented here is an overview of the geophysical methods that could contribute to defining the subsurface heterogeneity and extrapolating point measurements at the surface and in boreholes to volumetric descriptions in a fractured rock. In addition to site characterization a significant application of geophysical methods may be in performance assessment and in monitoring the repository to determine if the performance is as expected.

Introduction

The complexity of the hazardous waste problem transcends the already challenging problems associated with groundwater and petroleum detection and utilization. Hydrologists and petroleum reservoir engineers have studied the flow of water, oil, and gas in porous permeable rocks and unconsolidated sediments for many years. They have developed first order methods of analysis that are remarkably successful in assessing the potential of an aquifer or reservoir to supply a given fluid or gas for some period of time. However, these analyses seem almost trivial compared to the task of successfully isolating nuclear waste in a fractured rock.

Nuclear contaminants may be particles, chemicals that dissolve in water, or liquids or gases that are only partially soluble in water at all. Under certain conditions some contaminants may move through unsaturated soils and rocks as vapor. Contaminants can interact strongly with the minerals in the ground; clays may absorb some contaminants, some may form chemical complexes with other groundwater chemicals, immiscible dense liquids may settle vertically, and some may even become nutrients for microbes that are present naturally or have been introduced.

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The solution to the problem of disposing of nuclear waste or containments can be stated quite broadly. First, the processes and properties that control the movement of water and contaminants through earth materials must be understood and quantified. Next the distribution of the physical, chemical, and biological properties that are involved in these processes must be determined. These two steps permit the creation of a model which will describe the movement of the contaminants from either the initial injection or from any time at which the distribution of contaminants is known. In practice this simple scenario is difficult to realize, heterogeneity, anisotropy, and processes that are time dependent all combine to complicate the system "model".

The three inputs to the system model are:

1) the three-dimensional distribution of the physical, chemical, and biological properties.

2) the fundamental physical, chemical, and biological processes that control water and contaminant movement.

3) the distribution and state of the properties and processes at a given time which sets an "initial condition" for the problem.

Rapid advances are being made in laboratory and field studies in understanding the basic processes involved but much work remains to be done. This review will address the problems associated with determining the spatial distribution of the relevant physical properties and to a limited extent spatial distribution of contaminants. Techniques that determine these properties in a volumetric sense will be emphasized. This is not to reduce the importance of point measurements, but for purposes of 3-D distribution of properties, volumetric measurements are desired.

Site Characterization and Geophysics

A simple definition of site characterization is mapping the distribution of contaminant sources and effluents as well as the physical, chemical, and biological properties of the ground that control their distribution and movement. Some of the physical properties required are lithology, porosity, permeability, grain size, and fluid saturation. Rock or soil types, mineralogy and distribution and types of clay minerals are needed to model chemical processes. Chemical state, temperature, fluid saturation, and other factors that affect the presence and amount of nutrients are also needed to determine the biological properties.

Site characterization as defined here is the essential first-step toward containment, but all too often the term is used only to describe the extent (usually only over an isolated area) of the contamination itself. As a result, site characterization efforts are often limited to trying to determine the nature and extent of the toxic materials and not to defining the whole regime in which they are traveling. The limited definition may be useful in small scale sites where the solution is excavation, but it is only half the story at thousands of larger scale sites.

This additional concept that the distribution of properties and processes should also be characterized is just now being incorporated into idealized or conceptual models of hypothetical sites in anticipation of the day when actual site data will permit simulation of contaminant transport, and post closure. Unfortunately, very little work is being done on how to measure the spatial distribution of the properties of actual sites to utilize the models quantitatively. The most direct approach to site characterization is by drilling on a sufficiently dense grid of points. Direct sampling of the soils and rocks in the subsurface can be done with rotary and core drilling, and analyses of groundwaters can be made. Also, limited measurements of in-situ permeability can be made from pumping tests and interference tests between wells. Drilling provides unequivocal point measurements of the contaminants at the site of the drill. If the subsurface were uniform, or even uniformly layered, tests such as these performed in a loose grid of holes would probably suffice to characterize the site. Unfortunately, the subsurface is generally very inhomogeneous, and a program based on drill hole samples and measurements would provide incomplete or, WORSE, MISLEADING INFORMATION!

For inhomogeneous media the problem with drilling the subsurface is one of sampling and, for the measurement of properties, the fact that measurements on a core sample may not be correct for modeling larger scale phenomena — the so-called scaling problem. In principle, holes could be drilled arbitrarily close together so that at some hole density the subsurface would be sampled adequately at all scales. Not only would this approach become prohibitively expensive but much more importantly, extensive drilling could open new pathways for contaminant transport and actually increase the problem. Since the models that will be used to describe the site depend on the complete spatial description of the subsurface properties the problem becomes one of extrapolating point properties from infrequent drill holes to the volume between the holes. The difficulty in relying solely on drill hole studies is illustrated by the problem of a channel of high permeability sand that has been missed by a drill pattern. There is no way to reliably predict the fast-path properties of this channel from the drill hole measurements, and yet this channel would be the dominant feature of the site in terms of contaminant transport.

Geophysical methods can provide the spatial distribution of certain physical properties which are essential for site characterization, and can actually map the distribution of some contaminants. Indeed, a useful definition of applied geophysics is that it is the science of using physical measurements or experiments on the surface or in boreholes to determine the physical properties in the subsurface. Applied geophysics has been developed for site characterization but its major applications, and successes, have been in mineral and petroleum exploration.

Geophysics is ideally suited for extrapolating measurements made in a borehole to the large scale volume away from the hole. In this application geophysical measurements made on the surface or between holes can be used to assess the continuity and homogeneity of the intervening material. Geophysics can also serve to map the subsurface in the absence of boreholes and can be used to detect the unexpected, e.g. a fracture zone or channel not revealed in surface geologic mapping. Failure to be aware of such gross inhomogeneities would have a major impact on hydrologic flow models and on fluid transport. Finally, geophysical methods can accurately delineate some contaminants themselves either because the waste containers produce a geophysical anomaly or because leaking liquid waste alters the properties of the medium.

In the cases where the waste containers and/or the leaking wastes produce a discrete geophysical anomaly, geophysics provides direct information for site characterization. For example, plumes of liquid wastes have been directly mapped by means of electromagnetism because those waste liquids sometimes have a much higher ionic conductivity then the natural groundwater.

Direct geophysical detection does not give information on waste chemistry except in the case where radionuclides present can be inferred from X-ray spectrometry. There are many cases where geophysics provides only indirect information for site characterization. For example, geophysics may not be able to answer whether canisters are leaking, but geophysics may be useful for mapping the subsurface in preparation for a drilling/sampling effort. Highly toxic chemicals present a hazard when their concentrations are far too low to affect the physical properties of the medium, and yet their path through the ground is controlled by gross properties that are measurable indirectly from the surface. For the simple model of a buried channel it does not require elaborate reasoning to realize that minute quantities of a soluble heavy metal ion will travel preferentially in the high permeability channel. In fact if the channel were confined by clays it is quite possible that the only heavy metal concentrations of concern are those in the channel; those leaving might be absorbed and immobilized by the clays.

An important and related application of geophysics is in monitoring the processes that are implemented to contain the contaminants or waste. Once a site has been characterized and modeled, it is necessary to know how well the containment system (natural or engineered) is working. This stage is usually referred to as performance assessment or performance confirmation. Geophysical methods are ideally suited to this task since it is often easier to monitor changes in some portion of the subsurface than it is to uniquely determine the subsurface properties themselves.

Some of the information provided by geophysical methods is indirect, but the parameters measured can be related to the rock properties needed. For example the distribution of electrical conductivity is not a parameter that is directly useful in hydrological modeling, but when conductivity is used to obtain information on porosity, saturation, pore fluid salinity and clay content then it becomes a vital parameter needed for characterization. The relationship between the properties measured with geophysics and the hydrologic or mineralogic properties will in most cases be site specific and to be effective site characterization will require close integration of the geologic, hydrologic, chemical and geophysical data.

Geophysical Methods for Site Characterization and Monitoring of Subsurface Processes

The geophysical methods most directly applicable to the characterization of nuclear waste sites in fractured rock are: seismic; electrical and electromagnetic; gravity, tilt, and magnetic. The well logging applications are considered here as point measurements and will not be included in the detailed discussions that follow. This is not to imply that well logging should not be included in any geophysical program. The opposite is true, just as like geology, well logging is so fundamental to all data bases it should be the rule not the exception.

Seismic methods are used to measure the distribution of seismic wave velocity and attenuation in the ground. Seismic velocity depends on porosity, mechanical compressibility, shear strength, fracture content, density, fluid saturation and clay content. Some of these parameters are directly related to important hydrologic properties (porosity, fluid saturation) and others are used to map the distribution of soil and rock types. The most important use of seismic methods is mapping interfaces between materials of different velocities and providing high resolution images of the location of the main flow channels and soil types. The power of cross hole seismic tomography for petroleum reservoir characterization is now recognized, and will be equally important in hazardous waste site characterization.

Electrical and electromagnetic methods are used to measure the distribution of electrical conductivity and dielectric constant in the ground. Electrical conductivity of soils and rocks depends entirely on the conduction paths afforded by fluids in the pore spaces. It is determined by porosity, saturation, pore fluid salinity, and clay content. In certain cases where the contaminants are ionic solutions the electrical conductivity directly maps the distribution of the contaminant, but in most cases the conductivity will be used to extrapolate hydrologic measurements made in drill holes. The presence of clays, so important in fluid flow and chemical absorption models, brings about a distinctive frequency dependent conductivity — the induced polarization effect.

A separate electrical property of soils and rock is the streaming potential effect. Fluid flow in a porous medium generates an electric field. The field depends on the driving pressure, rock permeability, electrical conductivity of the fluid, and the electrical properties of the mineral surfaces past which the fluid flows. Natural flow along faults and fractures give rise to measurable electric fields on the surface. Often faults in unconsolidated material which are difficult to see in trenches or in surface geology have distinctive streaming potential anomalies. This phenomena also has great potential in monitoring — changes in pore fluid chemistry and flow rate produce distinctive changes in surface fields.

Streaming potentials are but one aspect of a whole class of interactions called coupled flow phenomena. Basically, driving forces of temperature gradients, hydraulic pressure gradients, chemical potentials, and voltage gradients produce flows of heat, fluid, chemicals, and electric current. These flows are coupled in the ground in the sense that not only does a pressure gradient produce a fluid flow but it also produces a current flow — the streaming potential. Similarly, temperature gradients drive currents to produce thermoelectric effects. Another cross coupling term of immense potential in contaminant studies is the electro-osmosis effect, a flow of fluid produced by a voltage gradient. This phenomena has been used in geotechnical engineering applications to stabilize embankments and assist in pile driving. It could very practically be used to alter subsurface flow patterns by directing a particular contaminant plume to an extraction or treatment region. Since the effect depends on fluid conductivity, rock permeability and the configuration of the imposed voltage gradients, the site must be well characterized in the first two properties before the design of a practical system could be implemented.

High accuracy measurements of gravity over the surface of the earth (microgravity surveys) yield a measure of the subsurface density distribution which in turn depends on distribution of porosity, water content and rock type. Borehole gravity measurements yield direct bulk volume values of density. Similarly high accuracy measurements of magnetic field may be used to infer the distribution of magnetic minerals, usually magnetite, which in turn is related to rock type and to certain sedimentary depositional environments where heavy minerals settle out of fluid flows.

Tilt measurements have recently been used to measure deformation associated with fluid withdrawal and injection. A new "twist" to the tilt measurements is that by monitoring the rate of tilt or deformation one may be able to infer the rate of fluid movement and obtain an average permeability for the formation.

The interpretation of geophysical data has traditionally involved iterative or trial-and-error fitting of simple models to the observations. In typical sedimentary sections seismic profiles of travel times to reflecting interfaces yield remarkably good cross sections of geologic structure. Recently new challenges in mineral and petroleum exploration have brought about dramatic new improvements in interpretation and in the ability of all the methods to define subsurface properties. New methods are being developed to produce direct images of the subsurface properties. Seismic tomography has opened up new levels of quantitative mapping between boreholes, and similar techniques have been demonstrated for radar, low frequency electromagnetic and even direct current methods.

Like the hydrologic studies that they are designed to assist, the geophysical methods need considerable development to meet the challenges presented by nuclear waste applications. The scale of study is smaller than that normally encountered for these methods. Radar methods are applicable at depths of one or two meters, but from this depth down to about 20 or 30 meters there is very little instrumentation now available for accurate electrical, electromagnetic, or seismic measurements. The quantitative demands of nuclear waste site characterization will also require some advances in the imaging techniques, so that uncertainties and resolution can be defined for regulatory and legal purposes.

All these methods are readily adaptable to site characterization and some equipment is suitable for immediate application. Some have already been used to detect gross contaminant concentrations, but their full potential in contaminant mapping and site characterization has not yet been recognized let alone utilized.

Specific Methods

Parameters that can be measured by geophysical methods that have an indirect or interpretable relationship to the required parameters are:

(1) electric streaming potentials
(2) microgravity/tilt
(3) seismic wave velocity and attenuation
(4) electrical conductivity
(5) magnetic properties

Of all the methods that can be used in characterization and monitoring, seismic and electrical methods appear to have the most potential and to have received the least consideration. Both are known to be sensitive to the fluid content and distribution as well as to changes in the deformation of rock conditions, and to fluid saturation.

Common sense, or perhaps simple curiosity, suggests that detailed characterization prior to, and possibly during waste disposal or storage, is a prudent activity, especially if it is of reasonable cost, easy to implement for in the future, and poses no threat to the integrity of the waste containment process. The major parameters of critical interest in characterization and monitoring are lithology, rock type, porosity, mineralogy, fluid content, stress, displacement, pore pressure, groundwater velocity and permeability (fluid and gas).

Seismic Methods

The seismic methods can be divided into the active and passive methods. The passive methods involve "listening" to seismic energy being created by stress changes or natural seismicity such as microearthquakes or acoustic emissions (AE) near the boreholes or underground openings. AE for purposes described here will probably be of use. Active methods involve introducing energy into the ground and observing how the seismic waveforms change due to inhomogeneities or anisotropy in the subsurface. Both the direct and reflected arrivals of seismic waves can be used for this process. Seismic reflection methods are used extensively in the petroleum industry for structural delineation. The utility of seismic techniques will depend upon the resolution obtainable in a given soil or rock type. For this reason this discussion will be mainly directed towards the seismic methods that have the highest resolution. The goal of seismic surveys is to describe or map the velocity and attenuation of seismic waves through the volume of interest. In general, this process is referred to as imaging although the extent to which a complete or 3-dimensional image can be formed depends on the availability of a suitable distribution of source-receiver combinations and the frequency content of the seismic waves. When a cross section of seismic parameters can be determined the process is also referred to as tomography.

Seismic imaging could play very important roles in site characterization, "performance confirmation" and monitoring tasks. It can be used to estimate and extrapolate the extent and shape of rock property distributions that are measured only at discrete points in-situ. It can also be used very effectively to detect features not mapped in the exploratory or initial phase of site characterization, and it can be used to monitor changes in properties in the site area from measurements made entirely outside the critical volume.

It is difficult to measure changes in the rock surrounding boreholes, and an extensive and costly program of drilling and measurements are often proposed for each site. The nature of these borehole measurements is such that they can be made only at a limited number of points in the rock mass. The most informative predictive models provide information about these changes throughout the subsurface, but the comparison between experimental observations and predictive calculations, however, must be made on a point by point basis. This is less than satisfactory, because the only extensive information is that provided by the theoretical models. Just as numerical models that show the complete geometry of these changes are greatly more informative and useful than even large tables of point values, so would field observations providing a continuous geometrical description be vastly more informative than any number of point measurements, let alone the limited numbers that are proposed. Point measurements are, however, still useful to provide precise values for comparison with theoretical prediction and tomographic observation. Most of the current in-situ test plans recognize the potential value of geophysical methods and include some seismic and electrical surveys. However, none of the plans incorporates the full observational power of proper tomography.

The transmission and attenuation of seismic waves through the subsurface depends upon the elastic parameters, which depend upon, among other things, the state of stress and strain, porosity, clay content, grain size, and fluid saturation. As recent research shows (Schoenberg, 1980; Pyrak-Nolte, et al., 1990a, 1990b), high-frequency seismic wave propagation is also very sensitive to fractures and discontinuities in the media. Seismic tomography can, therefore, be used to detect changes in the condition of the rock column, to locate major preexisting and new features as well as to measure overall changes in the apertures of these features. The methods that can be used for these studies use either sources on the surface and detectors in a borehole (referred to as Vertical Seismic Profiling, VSP), or in a cross-hole configurations with both sources and receivers in boreholes.

In a monitoring application it is also important to note the effect that water has on the propagation of seismic waves. As a soil is saturated, or dried, velocity changes of 20 to 30 percent are seen in relatively unconfined samples, Mochizuki (1982). A dramatic rise in compressional wave velocity occurs during the very last stages of saturation; there is little dependence on saturation up to about 90%. This is in marked contrast to the effect of saturation on electrical conductivity that we will discuss below. However, the attenuation of both compressional and shear waves is strongly affected by saturation, reported by Ito et al. (1986). The attenuation is most pronounced at low confining stress. In soil on loosely consolidated materials, the effect is even more pronounced, order of magnitude changes from partial to full saturation are obtainable (Anderson and Hampton 1980, 1980a). There is a very different relationship between Q and saturation than between velocity and saturation. This illustrates the need to study attenuation as well as velocity in any seismic experiment to determine the fluid content in the subsurface. Also, water plays a crucial role in the generation of pore pressure changes which will significantly affect the rate and generation of AE/microseismic events, especially in the presence of thermal loading.

The success of using seismic wave propagation as a monitoring tool will depend upon the resolution obtainable. One usually thinks of the resolution of the seismic methods in terms of 1/4 to 1/2 wavelengths. For frequencies of 1000 to 2000 hz. this translates to a maximum resolution of 0.5 to 1.0 meters. However, recent theoretical and laboratory work shows that a single discontinuity, (bedding boundary, lens structure, etc.) can significantly affect the propagation of seismic waves with wavelengths much larger than the discontinuity width. This is due to slippage across the discontinuity or along the discontinuity as a seismic wave passes through it. It is not so much the width of the feature that affects the seismic wave as the "stiffness" or compliance of the feature. The implication of this "stiffness theory" is that very thin discontinuities can have significant effect upon the propagation of an elastic wave. Usually one thinks of seismic resolution in terms of wavelength compared to the thickness and lateral extent of a bed or other feature. In the stiffness theory the lateral extent is still important, but the thickness of the features can be much less than the seismic wavelength.

The basic predictions of stiffness theory has been confirmed for wave propagation through fractures with laboratory measurements on individual fractures in rock cores (Pyrak-Nolte, et al., 1990a, 1990b). The stiffness is first derived from static stress-strain measurements under compressive loads across the feature, in this case a fracture. These values are then substituted in the theoretical expressions for the transmission coefficient and compared to actual measured transmission coefficients on the same sample.

This stiffness theory is also attractive from several other points of view. It has been shown that the ratio of the velocity of a seismic wave perpendicular and parallel to a set of stiffness discontinuities is a function of the spacing of the discontinuities as well as the stiffness. Thus, given the stiffness and the velocity anisotropy, one could determine the average spacing or density. Or, alternatively, given independent information on density of packing, one could determine the stiffness and relate this stiffness to actual properties such as those discriminating between filled and fluid filled or partially saturated media. In any case, there is sufficient reason to expect lithology and fluid saturation to be reflected in the velocity, amplitude, and polarization of the shear and compressional waves. In a monitoring mode one would look for changes in wave propagation characteristics as a function of time rather than absolute values. Depending upon travel paths, soil types, and frequency content, a change of just a few percent in the velocity of a zone with a distance of a few meters would be detectable. Thus, changes in the lithology and/or water content of the soil horizon and changes due to inflooding or thermal loading (i.e., either drying or resaturation) would be detectable.

Vertical seismic profiling (VSP) techniques have been mainly used for elucidating subsurface structures and determining velocities. In addition to the more conventional uses of VSP, we have been investigating the use of three-component VSP's for detection and characterization of fine scale features. Characterization and detection using both compressional (P) and shear (S) waves depends on the anisotropy, which is in turn the result of the effect of compliance or elasticity of the soil in response to a propagating wave (Majer, et al., 1988). We have carried out field exercises with this technique and have confirmed the theoretical predictions that bedding systems introduce a significant anisotropy in seismic wave velocities.

In addition to describing structure and anisotropy content it seems possible to relate the seismic response of the rock mass to the hydrologic response. The idea is to tomographically map the variation in the P and S wave properties and relate the resulting anomalies to the actual density, orientation, and spacing of the lithologic features.

In summary, field and modeling studies have shown that such features as anisotropy, fluid content and heterogeneity have a measurable effect on the propagation of seismic waves. It appears possible to use shear wave anisotropy and 3-D tomography to map the orientation, density, and spacing of these features in the field and to be able to give the hydrologist/reservoir engineer useful information on the fluid flow regime. A few percent change in properties produces effects that are easily detectable. These seismic methods would be particularly informative if used in conjunction with the electrical methods discussed below.

Electrical and Electromagnetic Methods

Electrical methods seem particularly promising in mapping and monitoring the groundwater regime of a site since the electrical conductivity of subsurface depends almost entirely on the fluid saturation, salinity and its distribution. Electrical and electromagnetic (em) methods have traditionally been used to simply detect the presence of good electrical conductors (e.g., sulfide orebodies) or to determine the electrical layering in groundwater or petroleum exploration. Quantitative interpretation in terms of rock properties or even accurate mapping of the subsurface distribution of electrical conductivity (imaging), is not as advanced as that being done seismologically. Only recently have numerical and theoretical studies advanced to the point where quantitative imaging complementary to seismic imaging may be expected.

The electrical conductivity of rocks and unconsolidated sediments in the upper part of the earth's crust is governed by the water content and the nature of the water paths through the rock. Electrical current is carried by ions in the water and so the bulk resistivity will depend on the ionic concentration, ionic mobility, as well as the saturation and the degree of connected pores. Conductivity is also temperature and pressure dependent due to the increase in ion mobility with increasing temperature and the effect of pressure on the apertures of the conduction paths.

Most studies on the electrical conductivity of rocks and soils have been on sedimentary rocks because of their importance in petroleum and groundwater exploration. Archie (1942, 1947) established an empirical relationship between the pore fluid resistivity, ρ_p (inverse of conductivity), the porosity ϕ, and the formation resistivity, ρ_f which is now referred to as Archie's Law:

$$\rho_f = a\rho_p\phi^{-m}$$

where a and m are constants for a given rock type. For a very wide range of sedimentary rocks and for some volcanic and intrusive rocks as well, the constant, a, is close to unity and m is close to 2.0.

Fluid saturation has a very dramatic effect on the conductivity of fractured materials. As water is withdrawn from a saturated rock, the large fractures empty first but, since the resistivity is mainly controlled by the small water passageways, the bulk resistivity increases slowly: the dependence is roughly proportional to one over saturation squared. As desaturation progresses a critical saturation is reached at which there is no longer any water to conduct along some fractures. This breaking of conduction paths leads to a much more rapid increase in resistivity, roughly proportional to one over saturation to the fourth power. The critical saturation depends on the rock type (the nature of the porosity) and may depend strongly on the role of "fast paths" that are present, i.e. fractures. Combined with seismic velocity and attenuation the electrical measurements would be very valuable for monitoring the progress of resaturation at a site.

An important and little studied aspect of earth materials conductivity is the role of "fast paths" on the resultant bulk properties. Laboratory studies concentrate on small intact samples which almost by definition do not include open voids or joints. Field studies using surface resistivity measuring arrays are usually too strongly influenced by the inhomogeneous nature of the near surface to allow any distinction between voids and pore porosity of a particular rock unit. With the increased measurement accuracy and resolution provided by subsurface techniques, and the interest in monitoring time changes in resistivity, it is now possible to investigate more closely the role of porosity on the electrical conductivity of large masses.

It is well known that the hydraulic conductivity or permeability is strongly influenced by the mean aperture, orientation and spatial distribution of the fluid paths. Also, as noted in the preceding section seismic velocities are strongly affected by discontinuities. It remains to develop expressions for the electrical conductivity of such material, and to take advantage of this valuable physical property for characterizing and monitoring large subsurface volumes of rock.

The simplest model of a material which is dominated by channeling or heterogeneous flow is one in which the features are parallel thin layers of conductivity σ_1 in a rock with matrix conductivity σ_2. Analysis of this model reveals that a very small effective porosity of the channel can have a dramatic effect on the conductivity of the rock, i.e., as small as porosity is in the range 0 to 2%. In tight or low porosity soils the channel porosity may equal the bulk porosity.

That channeling plays an important role in rock resistivity is practically demonstrated in the work by Brace and Orange (1968a, 1968b). Their work on the effects of confining pressure on the resistivity of a water-saturated granite showed that at low pressures the resistivity increases as the confining pressure increases and they attribute this effect to the closure of fracture porosity. A resistivity increase of a factor of 10 as the pressure increases could easily be explained by the disappearance of only 0.1% fracture porosity in a granite of 1.0% pore porosity.

The electrical conductivity of the ground can be measured in two ways. In the first, referred to as the dc resistivity method, current is injected into the ground through pairs of electrodes and the resulting voltage drops are measured in the vicinity with other pairs of electrodes. Any or all of the electrodes can be placed in the subsurface, although traditionally surface arrays have been employed. Measurements of voltage and current for different electrode geometries are then used to infer the subsurface distribution of conductivity. These methods are indirect but ideally suited to measure the properties of a region for which it is impossible to gain direct access. The resulting interpretation of the conductivity distribution is not unique, nor does it provide high resolution of subsurface features. In many applications this latter property is to our advantage since the measurements yield bulk average values of the conductivity which often includes features that are not included in hand samples or borehole logging measurements.

The electrical conductivity can also be measured inductively. Instead of injecting a dc current into the ground, currents can be induced to flow by a changing magnetic field. The source of the changing magnetic field could be a loop of wire carrying alternating current, a long, grounded wire carrying alternating rather than direct current or the earth's natural electromagnetic field. The currents induced in the ground are measured either by detecting the magnetic fields they produce or by measuring the voltage drops in pairs of electrodes. Sources and receivers can be on the surface, below the ground, or a combination of both.

In these inductive or electromagnetic (em) methods the interpretation depends both on transmitter-receiver geometry and frequency used. In principle, the interpretation should be more definitive than with the dc resistivity methods. Rigorous confirmation of this statement in inhomogeneous media awaits the development and evaluation of inversion and imaging techniques such as the wavefield transform technique (Lee and Xie, 1992) for em methods.

The em methods offer some proven advantages over the dc methods. Measurements can be made without contacting the ground; measurements are insensitive to high resistivity zones; depth of investigation can be controlled by the frequency of operation so that large transmitter-receiver spacings are not required; and because of the transmitter source field fall-off, the methods are not sensitive to conductivity inhomogeneities far from the zone of interest. Our experience in field studies and numerical modeling has been that the resolution of subsurface features is limited by the fact that the frequencies that are low enough to penetrate to the desired depth cannot have a wave-length short enough to define, or image, structural features. The problem is compounded by the surface layers which are invariably conductive, highly variable in thickness and which often act like shields to the subsurface. In overcoming these problems, borehole em methods are very promising. Measurements of magnetic or electric fields are made in a borehole at various depths, and the transmitter may be placed on the surface (surface to borehole), in the same borehole (single hole) or in another borehole (cross hole).

Pulsed borehole radar is an example of an em technique that uses very high frequencies. If the ground conductivity is sufficiently low, megahertz radar waves can penetrate up to 100 m and can respond to dielectric contrasts within the rock mass as well as conductivity anomalies. Radar has been used very successfully at some toxic waste sites to map buried objects and determine fine scale structural features. However, the requirement of very low conductivity soil limits radar to a very limited range and depth of sites.

In more conductive rocks the frequency of the em fields must be reduced to achieve significant penetration but then the resolution, or the ability to observe direct reflection images as in seismic methods, decreases as the fields become diffusive in nature. The traditional low-frequency implementation of em methods (less than a few kilo hertz) for ore prospecting relies on quasi-static magnetic induction theory, and basically ignores the wave propagation properties of the fields. In subsurface applications, especially in single hole and cross-hole modes, there are exciting possibilities for em methods in the frequency band between the prospecting and radar frequencies. We will refer to this band as the mid-frequency band.

Finally, there have been dramatic developments in natural electromagnetic field methods, particularly magnetotellurics (MT). Although MT may not have the resolution for fine scale studies it is mentioned here for completeness. In MT the impedance of the ground, the ratio of the electric to magnetic field at the surface is measured as a function of frequency. This impedance function is then interpreted in terms of a model of the earth.

MT has been plagued traditionally with problems in data quality and interpretation when the simple layered models used are inadequate. The data quality problem can be solved by using the remote reference method developed by Goubau, et al. (1978) and using improved in instrumentation (sensors and high dynamic range acquisition systems now permit high accuracy surveys that were previously not possible). We have field evidence that shows data errors of less than 1% in some frequency bands (Nichols et al., 1985). Interpretation has been a problem because the impedance has simply not been sampled at adequate intervals on the surface. The electric fields change rapidly in response to near surface resistivity variations and bias the impedances which, in effect, masks the deep structure that is sought. This can be treated either by very dense station sampling or by the use of larger lines for the electric field measurements or, preferably, both. In principle the electric fields could be measured over a grid on the surface, with magnetic fields measured at the grid nodes, and the conductivity distribution recovered accurately and unambiguously. Equipment is now available for such surveys but they have not yet been tried.

In magnetic surveys the distribution of the magnetization of the earth is measured from the surface (usually for metallic buried objects, or depth to basement) but these methods usually lack resolution for detailed studies of the subsurface. Bore hole magnetometers are now being used to supplement more conventional well logging tools to search for lithologic changes and chemicals/minerals that cause magnetization to change.

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Summary

Despite the fact that geophysics has been used successfully for many years in mineral, petroleum, and geothermal exploration it has not been used effectively in the characterization, monitoring, and performance assessment of waste repositories. By and large the examples of geophysics applied to these problems that have appeared in the literature are primitive and display a level of application that characterized geophysics 15 - 20 years ago. The exciting new developments in geophysics, especially new methods of borehole imaging the subsurface properties, seem to have been completely ignored or missed in waste studies. Perhaps hydrologists and geochemists have been unaware of the power of geophysical methods to map important properties of the ground, or perhaps geophysicists have been so preoccupied with the exploration for petroleum and minerals that they have failed to address groundwater applications and have not demonstrated the applicability of their methods in this important field. Whatever the reason, it is now important to incorporate geophysical mapping of subsurface properties into programs of not only site characterization, but in monitoring the performance of repositories before, during, and after waste emplacement.

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