REVIEW OF GEOPHYSICAL METHODS FOR SITE CHARACTERIZATION OF NUCLEAR WASTE DISPOSAL SITES

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EXECUTIVE SUMMARY

Characterization of potential geological sites for nuclear waste disposal is generally required to develop a repository design adequate to ensure safety and waste isolation to meet regulatory requirements. Site characterization techniques vary widely and depend on the specific geological setting of the area under consideration and the intended role of geologic versus engineered barrier systems in waste isolation. The applicability of specific characterization techniques may be limited due to access or safety considerations or potential for compromising site integrity through site characterization (e.g., by excavating test pits or trenches, or by drilling boreholes).

Geologic conditions of interest vary according to nuclear waste disposal site location and may include factors such as seismic and fault slip hazards, volcanic hazards, and groundwater flow, as well as stability during construction, waste emplacement, and closure. Noninvasive geophysical methods can, in many cases, effectively assess geological site conditions without compromising the integrity of the subsurface.

Understanding the capabilities and limitations of geophysical methodologies and subsequent data analysis techniques is important when assessing candidate geologic sites for disposal of nuclear waste so that proper site characterization planning and implementation can be executed. Recent rapid advances in geophysical characterization technologies provide the opportunity to formulate new strategies for characterization of future disposal sites and to set expectations and regulatory requirements for future site selection.

This report explores various geophysical methods, limitations in their use, types of data that can be expected based on different environments, and the methodologies relevant to basic site characterization for assessing the safety and performance of candidate disposal sites as well as surface and near-surface facilities associated with the nuclear fuel cycle. Geophysical investigations from Yucca Mountain characterization activities are used to illustrate concepts.

In addition, this document provides a basis for identifying opportunities to (i) tailor acquisition, data processing, and inversion techniques for site characterization of potential nuclear waste disposal sites and (ii) assess their efficacy in meeting regulatory requirements for nuclear waste disposal site characterization.

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT DATA

DATA: No CNWRA-generated original data are contained in this report. Sources of other data should be consulted for determining the level of quality of those data.

ANALYSES AND CODES: No CNWRA-generated code runs or results are included in this report. Other sources of analyses and codes are described and the referenced sources should be consulted for determining the level of quality of those analyses and codes.

1 INTRODUCTION

Properly utilized, geophysical methods can provide valuable information in nuclear waste disposal site characterization. The nonintrusive nature of geophysical investigations is consistent with the concept of preserving the integrity of a proposed waste disposal site, minimizing intrusive characterization methods such as drilling, trenching, and other exploratory excavation that can potentially compromise the integrity of the disposal site. Although intrusive methods are typically necessary to provide "ground truthing" information, geophysical investigations can provide useful guidance to further limit disruption of the subsurface caused by intrusive characterization methods.

Evaluation of candidate sites for geologic disposal of nuclear waste requires extensive assessment and characterization of the geological environment. Site properties and attributes, such as hydrogeology, water chemistry, and geologic structure, and geologic integrity issues, such as volcanic hazards, earthquake hazards, thermal stability, and structural stability, are key components to site characterization. Geophysical methods can provide information related to these key components of site characterization.

It is often desirable and beneficial to conduct geophysical surveys in a phased approach. In initial or regional evaluations, surface geologic mapping can be combined with regional geophysical studies to develop a geologic framework of the candidate site. Local-scale features identified during the regional evaluations can then be investigated with detailed surface geological mapping supplemented with focused geophysical investigations. In general, geophysics is most useful when applied in a dynamic and iterative fashion, where new information generates new investigations, ultimately leading to a sufficient knowledge basis for comprehensive site characterization.

2 CURRENT UNDERSTANDING AND RELEVANCE OF GEOPHYSICAL TECHNIQUES TO CHARACTERIZE NUCLEAR WASTE DISPOSAL SITES

Geophysics has been historically categorized into the subdisciplines of *solid-earth geophysics* and *applied geophysics* (Tables 2-1 and 2-2). *Solid-earth geophysics* generally refers to the study of the gross structure of the Earth and its natural dynamics (e.g., plate tectonics). Traditionally, these methods target earthquake seismology, heat flow, magnetics, and gravity, but can be expanded somewhat as shown in Table 2-1. *Applied geophysics* generally refers to methodologies employing geophysical methods for specific applications, such as resource exploration (e.g., hydrocarbon reserves, metals, geothermal resources; often termed *exploration geophysics*) and environmental investigations (e.g., buried waste, groundwater contamination, water supply; often termed *environmental geophysics*). *Applied geophysics* methods include those shown in Table 2-2; these are currently used more for *environmental geophysics* compared with resource evaluation.

Karasaki, et al. (2007) discuss the commonality in site characterization approaches in various international nuclear waste disposal programs, including the United States, Japan, Canada, Finland, and Sweden. This commonality addresses the various candidate nuclear waste disposal sites, even though the sites are located in different rock types under different geologic, tectonic, and environmental conditions. For example, the Yucca Mountain site is in unsaturated tuff, whereas the Swedish sites are situated in saturated granite. Karasaki, et al. (2007) identifies a number of important common features and parameters among the sites, which include (i) fault properties, (ii) fracture–matrix interaction, (iii) groundwater flux, (iv) boundary conditions, and (v) the permeability and porosity of the materials.

Application of geophysical techniques to characterize nuclear waste disposal sites may differ somewhat from conventional applications of geophysics; however, the techniques used at nuclear waste disposal sites can be generally classified as geological/hydrogeological methodologies. As such, it is necessary to understand the relationship between physical property variation and the objectives of the characterization to determine which geophysical technique would be appropriate and to specify survey design.

Geophysical surveys can be relevant when sufficient physical property contrast exists to achieve characterization objectives. Different geophysical methodologies can have varying responses to a physical property distribution, due to factors such as geometric effects, the physics of the specific measurements, and cultural and instrument noise. For sites where physical property variation does not coincide with the objective, geophysical methods that address this specific physical properties may not be helpful or appropriate. Therefore, it is necessary to carefully analyze physical properties relevant to the specific site characterization objective being addressed.

Tables 2-1 and 2-2 outline physical-property-based approaches to geophysical site characterization; Table 2-1 is a solid-earth physical properties approach, and Table 2-2 is an environmental-geophysics approach. These approaches are different than method-based approaches commonly cited in the technical literature (Table 2-3). Method-based approaches are not considered effective in nuclear waste disposal site characterization, because most site characterization is controlled by geological and hydrogeological mapping, which is defined by physical properties. In addition, a physical-property approach can minimize limitations related to availability of modeling software, personnel expertise, and bias in analysis results.

Table 2-1. Solid-Earth Geophysics Approach		
Physical Property	**Examples of Application**	**Geophysical Method**
Magnetic susceptibility magnetic permeability Remnant magnetization [*k* (emu/cm^3, SI, or cgs)]	Lithologic mapping, buried lava flows Paleomagnetism (age dating, tectonic reconstruction), sea-floor spreading rates	Magnetic, paleomagnetics Magnetic, paleomagnetics (magnetometer gradiometer)
Electrical conductivity, resistivity [*σ* (mS/m) *r* (W-m)]	Basin structure, shallow magma chambers, lithologic mapping	Magnetotellurics Controlled-source electromagnetics
Acoustic velocity (speed of sound) [V_p, V_s (m/s)]	Gross earth structure, crustal thickness, Magma chambers, earthquake hazards	Earthquake seismology Seismic (acoustic) tomography
Thermal conductivity Temperature, geothermal gradient [*q*(W/m °C), T(°C), (°C/km)]	Tectonic provinces, tectonic processes, Mantle convection	Heat flow
Density [*r* (g/cm^3)]	Isostacy, lithologic mapping, basin structure, Structure (fault offset)	Gravity (gravimeter)
Natural radioactivity	Geochronology	Isotopic (radiometric) age dating

Table 2-2. Environmental-Geophysics Approach		
Physical Property	**Examples of Application**	**Geophysical Method**
Magnetic susceptibility Remnant magnetization [*k*(emu/cm^3, SI, or cgs)]	Buried ferrous metal (detect hazardous waste drums, septic tanks, utility lines, ordinance)	Magnetics (magnetometer, gradiometer)
Electrical conductivity Resistivity, induced polarization [*σ*(mS/m), *r*(Ω-m), M(mV-s/V), m, PFE, phase (mR)]	Buried metal, conductive groundwater contaminant plumes, stratigraphy, trenches, hydrogeologic boundaries (e.g., bedrock depth, continuity of clay units, aquifer geometry), paleochannels, preferential flow pathways, bedrock fractures, leaks in lagoon liners, dam seepage, geology, salinity, total dissolved solids, karst	Electromagnetics Resistivity, ERT, SP, VLF, induced polarization, transient electomagnetics, time domain electromagnietcs, induction logging, terrain conductivity, spectral induced polarization, complex resistivity, phase induced polarization
Dielectric permittivity [ε(farad/m)]	Buried objects, groundwater surface (saturated zone), free-phase hydrocarbons	Ground-penetrating radar
Natural radioactivity [g(counts/s)]	Lithologic variation, hydrogeologic confining units	Borehole natural gamma-ray Logging
Acoustic velocity (speed of sound) [V_p, V_s (ft/s, m/s)]	Bedrock surface, lithologic boundaries, groundwater surface	Seismic refraction, seismic reflection, side-scan sonar, acoustic well logging (sonic log), shear wave studies
Thermal conductivity, temperature [*q*(**W**/m °C), T(°C)]	Groundwater flow, hydrologic framework, fracture zones	Temperature logging, thermal prospecting
Density [*ρ*(g/cm^3)]	Bedrock topography, buried valleys, tunnels, karst	Gravity (gravimeter)
Fluorescence/reflectivity	Direct detection of inorganic contamination in soils	X-ray fluorescence
Nuclear magnetic resonance	Direct detection of water saturation	NMR

Table 2-3. Selection of Geophysical Methods for Common Applications (ASTM D 6429-99).*
Black Box Is Primary Method and Grey Box Is Secondary Method.

	Seismic		Electrical		Electromagnetic							
	Refraction	Reflection	DC Resistivity	SP	Frequency Domain	Time Domain	VLF	Pipe/Cable Locator	Metal Detectors	Ground-Penetrating Radar	Magnetics	Gravity
Natural geologic and hydrologic conditions												
Soil/unconsolidated layers	■	▒	■		▒	■	▒			■		
Rock layers	▒	■	▒			▒				▒		
Depth to bedrock	■	■	▒		▒	▒	▒			■		▒
Depth to water table	■	■	▒			▒	▒			■		
Fractures and fault zones	▒	▒	▒			▒	■			▒	▒	▒
Voids and sinkholes	▒	▒	▒			▒				■		■
Soil and rock properties	■		■									
Dam and lagoon leakage			▒							▒		
Inorganic contaminants												
Landfill leachate			■			■	▒			▒		
Saltwater intrusion			■			■	▒			▒		
Soil salinity			■									
Organic contaminants												
Light, nonaqueous phase liquids	▒		▒		▒	▒				▒		
Dissolved phase												
Dense nonaqueous phase liquids												
Manmade burial objects												
Utilities					▒			■	▒	■		
Drums and USTs					■			■	■	■	■	
UXO									■	▒	■	
Abandoned wells					▒			▒	▒		■	
Landfill and trench boundaries	▒		▒		■	▒				■		
Forensics			▒		■			▒	▒	■	▒	
Archeological features	▒	▒	▒		■					■	■	▒

*ASTM International. "Standard Guide for Selecting Surface Geophysical Methods." ASTM D6429–99, Philadelphia, Pennsylvania: American Society for Testing and Materials. 2006.

2.1 Relationships Between Physical Properties and Nuclear Waste Disposal Site Characterization

The geologic complexity of a candidate waste disposal site is addressed as part of an initial site characterization. Candidate sites are generally identified based upon their potential to provide long-term integrity to the waste facility and their ability to isolate waste. A preliminary task when assessing the integrity of a candidate site is to map the area geology to shed light on its long-term climate, tectonics, hydrogeology, and general stability. Tectonic processes, lithology, structure, and hydrogeology are the most common geologic features that need to be understood and mapped during site characterization. Mapping these physical properties using geophysical methods is consistent with maintaining the integrity of the candidate site due to the nonintrusive nature of the survey technique. Similarly, the physical property volume-averaging measurement capability of geophysical surveys actually accommodates hydrogeological and geological characterization better than point measurements.

2.1.1 Tectonic Processes

Structural stability of a nuclear waste disposal site depends on tectonic stability (i.e., earthquake seismicity and heat flow) as well as stability and suitability of subsurface structural features (i.e., faults, buried valleys, and basin geometry). Tectonic features have different physical property values, such as lower acoustic velocity, density, and resistivity (Telford, et al., 1976), when compared with competent rock. Geophysical methods can effectively measure physical properties associated with tectonic processes. Measurement scale (regional versus local), geophysical method complexity, availability of adequate computer modeling software for meaningful and accurate interpretation, and availability of personnel with sufficient expertise are elements that determine.

- The type or types of geophysical methods used
- The potential success of the selected geophysical methods
- How well the results are integrated into the overall site characterization process

Evaluation of regional tectonics can be resolved by compiling historical geologic data and analyzing seismic/tectonic/volcanic stability and related regional tectonic processes.

2.1.2 Lithology

Lithologic mapping is a primary objective in nuclear waste disposal site evaluation, and the continuity of lithologic units is of primary concern. Geophysical methods can be used to laterally and vertically extend and enhance surficial and downhole lithologic mapping. Variations in physical properties, such as density, magnetic susceptibility, acoustic velocity, and electrical resistivity, create geophysical responses that in turn provide a measure of geologic continuity and integrity of a candidate site. In this regard, geophysical methods are best related to a broad context of structure (i.e., the geometry and continuity of units and the related concepts of soil/overburden thickness and depth to bedrock).

2.1.3 Hydrogeology

Hydrogeological mapping and characterization of variations in water saturation, salinity, porosity, and permeability can be effectively enhanced using geophysical methods to help to predict potential outflows of contaminants. In fact, so much work has and is being done in this field that recently a new geophysical discipline has been coined; namely, "hydrogeophysics." Hydrogeophysics is defined as the use of geophysical measurements for mapping subsurface features, estimating properties, and monitoring processes that are important to hydrological studies, such as those associated with water resources, contaminant transport, and ecological and climate investigations (Rubin and Hubbard, 1995).

When applied to characterization of the hydrogeology of nuclear waste disposal sites, geophysical surveys can potentially map the water table, aquifer geometry, and aquifer properties. Of special significance to nuclear waste disposal site characterization is the use of geophysics to assist in the hydrologic characterization of faults. Many candidate hazardous and nuclear waste disposal sites are located in either igneous or metamorphic crystalline rocks that have low primary porosity and permeability. Therefore, a primary flow pathway for contaminants within these lithic units would be through secondary porosity features, such as faults and fractures.

Water-Table Mapping

Geophysical methods can be a viable option to map the water table in areas where there are no physical controls, such as wells, streams, or lakes. The interface between the unsaturated and saturated zones in the subsurface is characterized by physical property contrasts, such as density (due to the density contrast among water, air, sediments, and rock), electrical resistivity (due to contrasts between the relatively high electrolytic conductivity of pore water versus the very low conductivity of the rock/sediment matrix), dielectric permittivity (water versus rock), and acoustic velocity (water versus rock). As an example, Sandberg (2000) and Farrell, et al. (2001, 2000) demonstrated how the water table could be ascertained using electrical resistivity values determined from direct current resistivity, induced polarization, and transient electromagnetic soundings along a transect near Yucca Mountain, Nevada.

Aquifer Mapping

Geophysical surveys can effectively determine the geometry of aquifers. Physical property contrasts useful in this mapping include resistivity (lower resistivity values in clay versus sand in unconsolidated aquifers), induced polarization effect (higher response in clays due to membrane polarization), and seismic velocity. As will be discussed next, integrated surveys can effectively use multiple methodologies to map aquifers [e.g., resistivity and induced polarization soundings, seismic refraction and reflection surveys, and existing well information (Sandberg and Hall, 1990)].

Aquifer Property Characterization

Aquifer properties can be mapped and extended from established property values using geophysical methods. An example is the use of geophysics to extrapolate point measurements of water quality [e.g., salinity, total dissolved solids (TDS)] to determine the extent of an aquifer domain. Geophysical measurement of pore-water salinity is possible due to the relationship between resistivity and salinity of pore water, which results from electrolytic conduction. Electrolytic conduction is related to the number of charge carriers, (i) ionic content of pore water (salinity of pore water), (ii) the valence of the ions in solution (type of salinity), (iii) porosity (void space available for pore water),and (iv) permeability (related to the tortuosity of the pore paths through the silicate rock matrix, or fine-scale structure). Geophysical surveys can successfully exploit the geophysical contrast between seawater and freshwater to produce salt/freshwater interface maps in water-supply applications (e.g., Sandberg, 1987; Fitterman and Deszcz-Pan, 1998).

A second example of aquifer property characterization is the use of surficial geophysical surveys to extrapolate subsurface point measurements to determine hydraulic conductivity. Recent, significant progress has been made in the ability of surficial geophysical methods to measure hydraulic conductivity. Because most shallow electrical conduction in the Earth is electrolytic, this ability relies on the relationship between ionic (electrical current) and hydraulic flow (groundwater movement) (Slater, 2007). Slater and Lesmes (2002) measured laboratory-scale electrical and hydrologic flow through both natural sediments and artificial sand/clay mixtures to establish this relationship. Field-scale-induced polarization (Sandberg, et al., 2000) and audio-frequency magnetotelluric (AMT) (Karasaki, et al., 2008) surveys were conducted to test this concept.

Hydrologic Characterization of Faults

Fracture and fault zone characterization is critical to nuclear waste disposal site assessment because these features can provide preferential paths for contaminant flow and transport. This is particularly true in crystalline (e.g., igneous or metamorphic) rocks where the host rock has minimal primary porosity and permeability.

Karasaki, et al. (2008) used AMT and seismic reflection techniques to map fault zone properties, fracture–matrix interaction, and the permeability and porosity of fault zones. Geophysical surveys can effectively map where faults juxtapose stratigraphic units provided the juxtaposed units have sufficient property contrast that is discernable at the surface. Also, the physical properties of the fault zone itself may be discernable at the surface if these zones have sufficiently anomalous property values. The electrical properties of fault zones are typically the property most discernable at the surface. These electrical properties are a function of electrolytic conduction and surface conduction. Surface conduction is a mechanism that is more efficient in conveying electricity than electrolytic conduction. Fault zones can exhibit brittle deformation where porosity and permeability are enhanced, and hence the electrical conductivity is increased. Alternatively to brittle fracture, fault zones can be remineralized, decreasing in porosity and permeability. This type of fault zone evolution leads to surface conduction. Consequently, clay alteration within a fault zone could lead to a much more enhanced electrical conductivity (as compared to the host silicate rocks, which are electrical insulators) than from an increase in permeability alone.

2.2 State of the Art of Geophysical Techniques: Examples for Nuclear Waste Disposal Site Characterization

The geological attributes of a nuclear waste disposal site are important to sustainability of the waste facility because long-lived radioactive isotopes are on the same time scale as many geological processes. Geophysical methods provide a means to understand, map, and quantify these geological processes.

Geophysical methods that measure gravity, magnetics (aeromagnetics and ground magnetics), airborne electromagnetics, and magnetotellurics are amenable to regional-scale investigations due to their relatively low cost when implemented at large scales. An example of a regional-scale geophysical survey would be a gravity survey conducted to discern the density difference between Paleozoic bedrock and overlying Cenozoic sedimentary and volcanic rock at Yucca Flat, Nevada (Ferguson, et al., 1988). Three-dimensional gravity models of the Paleozoic-Cenozoic contact are accurate to within about 15 percent of actual depth, based on borehole drilling results.

Phelps, et al. (1999) demonstrated that improvement to the depth-to-bedrock model can be achieved by improving the modeling algorithm, technological advances in presentation (e.g., color-shaded relief maps), smoothly varying density functions, and increasing the number of wells for ground truthing. Other geophysical methods are more applicable to local-scale studies than regional methods. Local-scale methods can produce higher resolution if data are acquired at increased spatial density and if advanced interpretive methodologies are used. Advanced interpretive methods include developing subsurface fault mapping, tracing lithologic units below surficial sediments/soils and away from outcrop areas (e.g., La Femina, et al., 2002), characterizing faults (physical properties related to permeability/porosity), and mapping buried volcanic vents and lava flows.

3 GENERAL WORKFLOW FOR ASSESSING GEOPHYSICAL FIELD TECHNIQUES AND THEIR POTENTIAL APPLICATION

In general, geophysics is most useful when dynamically applied, where new information generates new investigations and ultimately leads to sufficient knowledge for representative site characterization (Figure 3-1). This dynamic approach, when coupled with other geological/hydrological methods, ensures the ensuing synergy among all facets of site characterization, including geophysics, and yields a more complete understanding of the significant and critical characteristics of a nuclear waste disposal site. In addition, due to the extremely variable character of a geological environment, insights gained from preliminary evaluations, and experience acquired at the site of investigation, a significant applied research component should be part of a nuclear waste disposal site characterization. This research component helps ensure that new concepts and new technologies are used so that optimal site characterization is achieved. Conversely, employing a "standard cookbook" approach to geophysical surveys for site characterization is not likely to be effective. Much of the detail of previous site characterization efforts would not necessarily become usefully incorporated into ongoing site characterization actions if assessments use a cookbook approach.

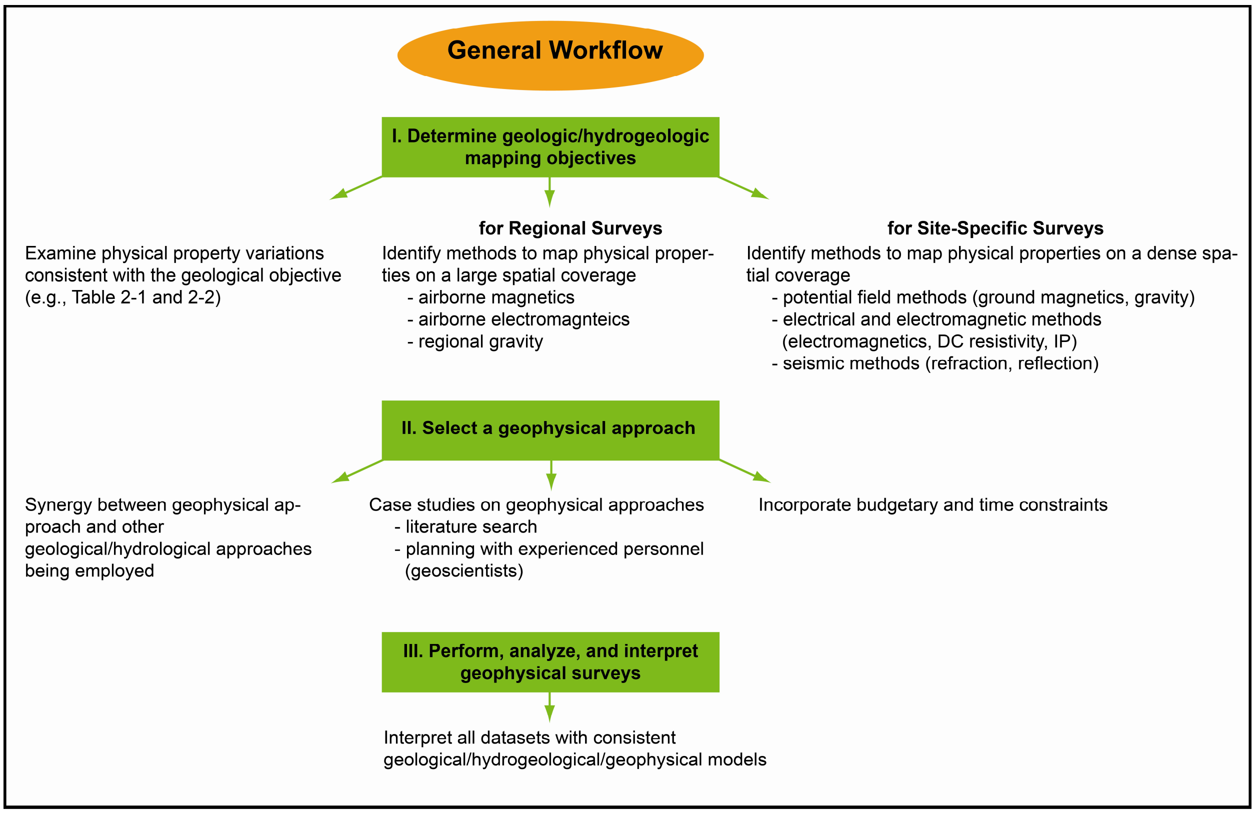

Figure 3-1. General Workflow for Assessing Geophysical Field Techniques

4 IMPACT OF CULTURAL NOISE

Site characterization can be negatively affected by man-made (commonly referred to as cultural) features that introduce interference into geophysical surveys. In this situation, special considerations in survey design, implementation, and data interpretation are required. Sources of interference are typically related to the physical property being measured. For example, traditional gravity meters are sensitive to vibrational noise of certain bandwidths that can interfere with the internal mechanism of the instrument. Similarly, metallic debris grounded with the subsurface can interfere with electrical and electromagnetic fields (i.e., from overhead or buried power lines) and interfere with electromagnetic surveys. Because of problems presented by cultural noise, “noisy” environments should be avoided when possible or alternative techniques employed that are less sensitive to the cultural noise. There are occasions and locations where and when cultural noise is present but unknown or not detected. In these situations, data manipulation or interpretation may be used to remove the effect of the noise from the data. In some situations, however, it may not be feasible to extract a meaningful interpretation from data irrevocably tainted by cultural noise. At a minimum, it is imperative to recognize when a geophysical measurement is the product of the objective being measured versus cultural interference and noise. Otherwise, cultural noise may be misinterpreted as a physical attribute of the site being characterized.

It is preferable to assess the impact of cultural noise on survey data prior to data acquisition; however, due primarily to the cost of data acquisition, cultural noise is not typically assessed prior to conducting the survey. Cultural noise that is investigated prior to the survey allows for survey acquisition guidance and constraints (i.e., distance required between survey points and the source of cultural noise) to be incorporated into the survey design. In some surveys, access limitations or the location of survey targets necessitates that geophysical data be collected at locations where cultural features cause interference. Figure 4-1 provides a workflow to be followed for sites with limited accessibility. In surveys limited by access, it is imperative to understand the effect of the interference on the acquired data as well as the type of interference or noise encountered. Cultural noise sources may affect different geophysical methods differently. Finding the optimum approach between spatial limitations and sources of noise in the data requires experience and proper analysis of cultural interference or noise. Only by knowing this information is it possible to mitigate the impact of the interference from the survey data. In the absence of this underlying information, it is difficult to appropriately evaluate survey data.

Additional information on noise and several case studies can be found in the Appendix.

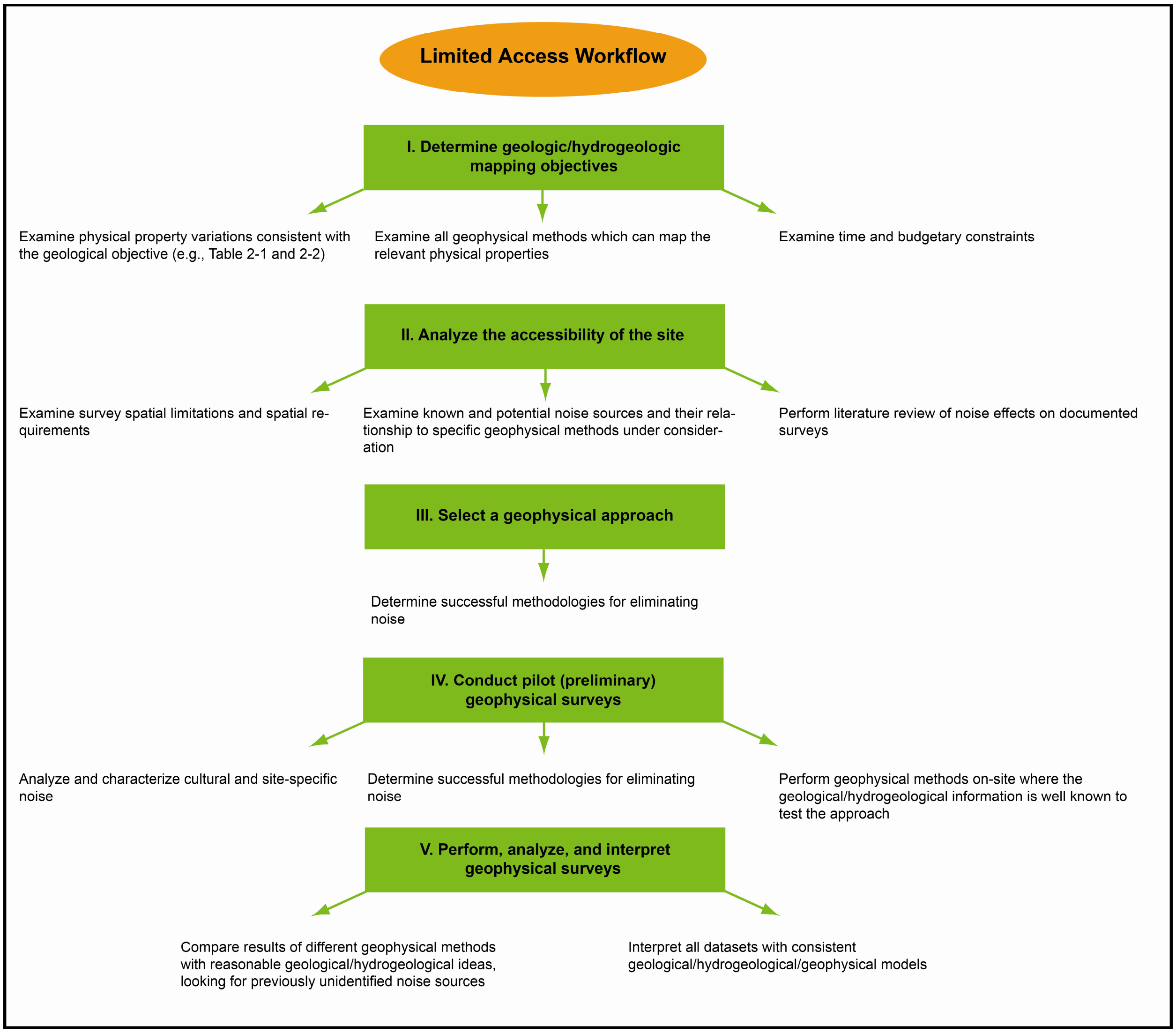

Figure 4-1. Workflow for Sites With Limited Accessibility

5 DEPTH OF INVESTIGATION AND RESOLUTION OF DATA

There is a relationship between geophysical survey geometry, depth of investigation, and the resolution of the survey. For example, direct current resistivity soundings have a depth of investigation related to the distance between current and potential electrodes [e.g., the depth of penetration for the Schlumberger array is approximately one-eight of the distance separating the outside current electrodes (Roy and Apparo, 1971)]. In the case of a resistivity sounding and subsurface imaging, the design of electrode array geometry can be optimized by taking into account accessibility of the site and the geometry, depth, property value contrast, and size of the survey target (Dahlin and Zhou, 2001; Danielsen, et al., 2005).

The size of the survey site can occasionally limit which geophysical methods are possible. Determination of specific physical properties of the site may be beneficial to characterization; however, spatial constraints may dictate which geophysical methods can be applied to the targeted site. For example, lithologic and structural boundaries (e.g., the unconsolidated soil/bedrock interface) may exhibit distinct resistivity contrasts, but limited available survey space may dictate that an electromagnetic method be used versus a DC resistivity method.

The specific application of geophysical methods has a significant effect on the resolution achieved during site characterization. Resolution is more a function of geometrical models of physical properties than simply applying geophysical methods to extend information derived from outcrop mapping or direct subsurface sampling into the subsurface. Geometrical models and subsurface properties dictate how resolution degrades with depth and distance from the location of measurements. For example, down-hole physical property measurements for rock exposed in the well bore obtained by geophysical borehole/well logging are much higher resolution compared with measurements farther into the formation.

There is a mathematical correlation between the magnitude in a geophysical response of a physical property and the geometrical distribution of the acquired data. One limitation to geophysical surveying is when a given data set can be represented with multiple geological subsurface models, a condition referred to as nonuniqueness. Increased information derived from independent physical evidence can narrow the range of subsurface model possibilities. It is desirable to employ all available data, such as surficial geological mapping, drill-hole-derived lithology and well log data, hydrogeological models, and geophysical survey results, to minimize model ambiguity. For example, relatively well-defined geological sites can be characterized with accepted ranges of physical property values (e.g., magnetic susceptibility, density, resistivity, acoustic velocity). Inverse modeling of the measured data from a geophysical survey should result in modeled physical properties that fall within these accepted ranges. If a geophysical model developed with the inverse models is inconsistent or incompatible with the accepted ranges of physical property values, then the conceptual model on which the model is based is probably in error.

The thin-layer equivalence problem in electrical geophysical methods is another example of nonuniqueness in geophysical data. In this case, only the product of resistivity and thickness of a thin layer in a one-dimensional (layered) Earth model can be uniquely determined from resistivity sounding data. Neither the thickness nor the resistivity of the layer can be independently determined. A second geophysical method, such as seismic refraction, could be employed to provide layer thickness information that would then allow for a unique determination of the layer resistivity. Improvement in the resolution of the intrinsic resistivity of a specific layer (such as an aquifer) can then lead to determination of the salinity/TDS/water quality of the pore water, for example.

A specific geologic target may exhibit anomalous values of a physical property measured using a specific geophysical technique. This dilemma can be resolved by using different geophysical methods to measure the physical property that has anomalous values and improve the resolution of the target feature or structure. Common examples are combining resistivity and induced polarization measurements to resolve the same one-dimensional layered Earth model (Sandberg, 1993) or combining gravity and magnetic data to identify the same subsurface structure (e.g., Ponce, et al., 2003).

Spatial aliasing can also negatively impact geophysical survey results. Sufficient geophysical data density is required to identify limited size subsurface features. Subsurface features or structures of limited size can go undetected when there is insufficient survey coverage. Lack of detection or misinterpretation of a target due to insufficient data density can be caused by aliasing. For example, a highly permeable fracture beneath soil cover may have a relatively small spatial footprint. Geophysical data collection has to be sufficiently dense to acquire a geophysical response of the fracture, otherwise the fracture may not be detected. Another facet of aliasing is when a feature is detected, but the ensuing interpretation is biased or skewed because of insufficient data density. An example of this would be when the response of a narrow conductor detected with a coil–coil electromagnetic system (i.e., slingram configuration) is spread out to the width of the coil separation of the system. In this case, a data collection interval of less than half the distance of the coil separation is needed to recover the correct position of the fracture. When the effects of noise are included, an even finer data collection interval may be necessary to recover the correct location and characteristics of the survey target.

6 INTEGRATED GEOPHYSICAL METHOD APPROACH

An integrated survey utilizing multiple geophysical methods can enhance the potential for comprehensive site characterization compared with singular method surveys. Integrated surveys can be especially effective if survey methods target more than one physical property. Associated with this characterization approach, joint modeling of differing geophysical datasets can mathematically improve resolution of resultant images. In addition, the synergy and resolution improvement achieved by utilizing multidisciplinary geoscience methods (i.e., geological, hydrogeological, and geophysical) in site characterization need to be recognized.

Geophysical methods generally consist of measuring a physical field, such as an electromagnetic, electric, or gravitational field. Resolution of a physical property has been shown to improve when that physical property is calculated by modeling data from two or more fields that are responding to that same physical property. For example, intrinsic resistivity and the geometry of a resistivity distribution can be modeled from both DC resistivity measurements (scattered electric field) and electromagnetic measurements (scattered time-varying magnetic field). When data from these two geophysical measurements are simultaneously modeled for the same resistivity distribution, resolution of both the intrinsic resistivity and its geometrical distribution is improved (Gustafson and McEuen, 1987; Raiche, et al., 1985; Sandberg, 1993; Vozoff and Jupp, 1975).

As an example, Asch, et al. (2008) used electrical geophysical surveys (AMT, DC resistivity) in combination with ground magnetic surveys (vertical gradient) to produce high-resolution fault geometry of the geologic structures in the northern Yucca Flat basin, Nevada, that were not readily apparent from surface geological mapping, potential field geophysical data (gravity), or surface-effects fracture maps.

Other examples of integrated geophysics surveys include an investigation of basaltic lava flows and vents beneath surficial sediments to support a probabilistic analysis of volcanism in the Yucca Mountain area (Connor, et al., 1997; Stamatakos, et al., 1997). Basaltic units were mapped using airborne and surface magnetic surveys as well as resistivity surveys. Elsewhere near Yucca Mountain, Sandberg, et al. (2001) used mise-a-la-masse, horizontal loop electromagnetic (terrain conductivity), very low frequency electromagnetics, spontaneous polarization, TEM, magnetometric resistivity, and ground magnetics to investigate the geometry and genesis of a sinkhole in the Amargosa desert downgradient from the Yucca Mountain area. This comprehensive integrated survey demonstrated the relative strengths and limitations of a broad range of geophysical methods to characterize a near-surface geological feature.

7 SUMMARY

Candidate sites for geologic disposal of nuclear waste (e.g., underground vault, deep borehole) need to be thoroughly characterized from a geoscientific focus to understand basic site conditions necessary for repository design and ensure safety and waste isolation to meet regulatory requirements. The long-term performance of a disposal site depends on conditions such as seismic and fault slip hazards, volcanic hazards, and groundwater flow, as well as stability during construction, waste emplacement, and closure. This report summarizes geophysical methods, limitations of their use, types of data that can be expected based on different environments, and the methodologies that are relevant to basic site characterization for geologic disposal of nuclear waste.

In addition we (i) evaluated the current understanding and relevance of geophysical techniques to characterize nuclear waste disposal sites; (ii) developed a general workflow for assessing geophysical field techniques and their potential application to nuclear waste disposal sites; (iii) developed a specific workflow for sites of limited accessibility or those not amenable to geophysical characterization (e.g., sites with excessive infrastructure, development limitations, electrical interference, or ground disruption); and (iv) outlined methods by which multiple techniques can be integrated or modified to enhance site characterization as it relates to design, safety, and performance evaluation

This document provides a basis for identifying opportunities to (i) tailor acquisition, data processing, and inversion techniques for site characterization of potential nuclear waste disposal sites and (ii) assess their efficacy in meeting regulatory requirements for nuclear waste disposal site characterization. While this report has focused on waste disposal, these concepts would also be applied to surface and near-surface sites associated with the nuclear fuel cycle.

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APPENDIX
ADDITIONAL INFORMATION ON CULTURAL NOISE

APPENDIX—ADDITIONAL INFORMATION ON CULTURAL NOISE

Cultural noise sources can be categorized into two types: those which produce a signal that interferes with the geophysical signal of interest in a geophysical survey, and those which produce a geophysical response that can dominate or appear similar to a geological target of interest.

Active Noise Sources

Active cultural noise sources, such as active overhead and underground power lines, should always be avoided, if possible, due to their radiated electromagnetic fields which generate signals that cause interference with electrical and electromagnetic geophysical measurements. Ground vibrations near industrial facilities, highways, and other acoustic noise sources can interfere with gravity (mentioned previously) and seismic measurements (seismic signals are in fact small ground vibrations). Figure 1 shows an example of this type of noise in a seismic survey. The noise (channels) at the right of this figure was created by trees that amplified the wind at the surface.

Noise in magnetotelluric (MT) data has been documented for a survey at the Nevada Test Site by Williams, et al. (2007). In that paper, they describe that "… noise from a number of small power lines and small moving vehicles was negligible at distances greater than 0.4 km [0.25 mi] from the noise source. Power-line signal levels were measured at each site and typically were less than 20 percent of the maximum recordable signals. Noise from larger power lines, power generators, pipelines, and trains was negligible at distances greater than 5 km [3.11 mi]. Local lightning, wind, and rainstorms may also degrade data quality. Burying the magnetic induction coils and the electric dipole wires minimized wind noise."

Electrical noise, such as power lines, power generators, and moving vehicles and trains, can affect MT data quality. All of these local disturbances can produce incoherent noise that mostly will affect data with frequencies above 1 Hz. Other electrical noise, such as direct-current (DC) electric trains and active cathodic protection of pipelines, produces coherent electromagnetic signals that mostly affect frequencies below 1 Hz. Padua, et al. (2002) present another example in which MT noise was characterized resulting from a DC electrified railway. They found that noise cancellation using a remote reference or a robust single station technique produced about the same results. However, they note that the remote reference site must be carefully selected, which one would expect.

Deep resistivity/induced polarization surveys require long electrode dipoles, which record background telluric signals whose magnitude is of the order of the signal at the receiver. Halverson (1990) describes the effective use of telluric cancellation in these data with impressive examples of improvement in data quality. Although these types of surveys have been more commonly used in mining exploration, geological mapping in waste site characterization (such as aquifer/confining unit characterization) is a definite application of the method (e.g., Sandberg, 1993).

The most densely populated U.S. state is New Jersey. Sandberg, et al. (1996) describe very simple noise reduction methods in a magnetics survey, with the objective of mapping the buried extension of the Palisades sill (basalt) in New Jersey. These data were collected in an urban setting, and the procedure consisted of collecting several readings spaced a couple of meters apart, averaging them, and then running a three-point smoothing operator along the traverse of

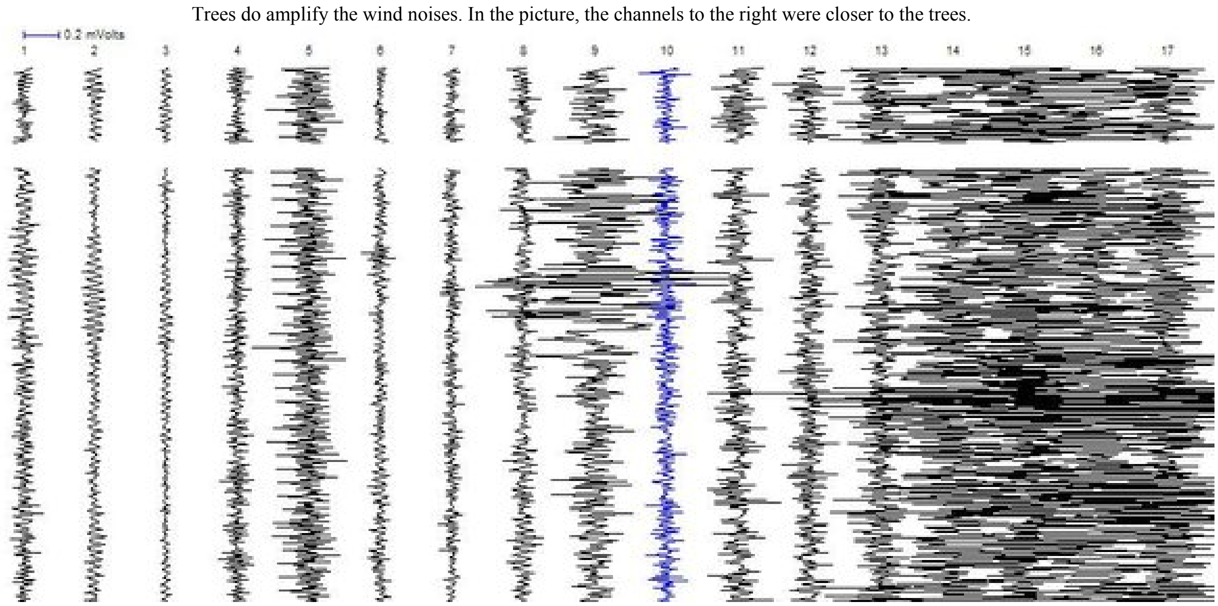

Figure 1. Seismic Survey Showing Noise Due to Surface Features
(http://forum.detectation.com/viewtopic.php?f=2&t=812&p=1948&hilit=noise#p1948)

averaged values. The resulting 2 ½ dimensional modeling fit well with gravity, seismic, and resistivity/induced polarization soundings along their sections.

Time-domain electromagnetic (TEM) data acquisition is usually designed with repetitive waveforms using polarity reversals in alternate half-cycles at a frequency that is an even fraction of the power line frequency. This eliminates the power line primary frequency, and digital integration (stacking) increases the signal-to-noise ratios. Macnae, et al. (1984) discuss noise processing techniques in TEM, specifically for the UTEM 3 system; however, these are applicable to all TEM systems.

Although noise has been documented in the literature (e.g., previous examples), noise in geophysical surveys is most often merely avoided, rather than quantitatively analyzed. Site-specific analysis of noise may become more of an integral part of geophysical surveys in industrial, suburban, or other areas with limited access.

Passive Noise Sources

Passive noise sources are those that produce a geophysical response which can either dominate or appear similar to that from geological sources. For example, strong geophysical responses occur from metallic objects (e.g., fences, buildings, pipelines) in electrical and electromagnetic geophysical methods due to the metallic conduction mechanism whose magnitude dominates geological signals that predominantly occur due to an electrolytic conduction mechanism. Knowing how far away from high-tension overhead power lines (a long linear conductor) one must locate an electromagnetic sounding, or an electromagnetic survey in general, is not entirely obvious. An example is the following electromagnetic survey {Geonics EM31, slingram configuration, terrain conductivity instrument, coil separation 3.7 m [12.1 ft], 9.8 kHz operating frequency).

Figure 2 shows data from an EM31 conductivity survey that was collected close to a standard (low voltage) overhead electrical power line that was 6 to 8 m [20 to 25 ft] above the ground surface. Results from this survey show that conductivity data have higher values in proximity to the line. The data were collected along lines parallel to the power line.

From the previous example and with the data ranges contoured, the extent of interference from the power line appears to be approximately 16 m [50 ft]. However, the proper way to evaluate the noise contribution would be to look at actual instrument response in a crossplot of data versus position traversing away from the noise source or, preferentially, to look at the electromagnetic fields themselves in relation to the response of the instrument. Our search found no good examples of this in the literature.

Geological/Hydrogeological Noise Sources

Lithologic variability inherent in dynamic geological environments (e.g., facies changes) can result in a more complex geophysical response than what was initially planned. The adage of the difference between an engineer's and a geologist's expectation of the subsurface emphasizes the often-experienced unexpected and expected variability in excavations, respectively. Engineers tend to think of geologic units as comprising regions or blocks of homogeneous material, where each block can be different from the others. Geologists tend to think of a "unit" (such as the classical definition of a formation) as a suite of material that is genetically related, more in terms of perhaps depositional processes than actual discrete physical properties. Geophysicists often lean toward the engineer's view, and when geophysical results show more complexity, this added information is considered noise; in this case "geological noise." Where there is a "huge" physical property contrast, such as the density contrast between alluvial deposits versus volcanic, metamorphic, or other "crystalline" bedrock, minor variability within these two extremes in physical properties (density, in this case) is not significant to the interpretation. However, in hazard waste site characterization, geophysical objectives often coincide with overall geological mapping of the subsurface, which can mean that physical property contrasts are not "huge." This is where a different type of thinking is required of those who merge geophysical, geological, and hydrogeological datasets. In this way of thinking, there really is no "geological noise."

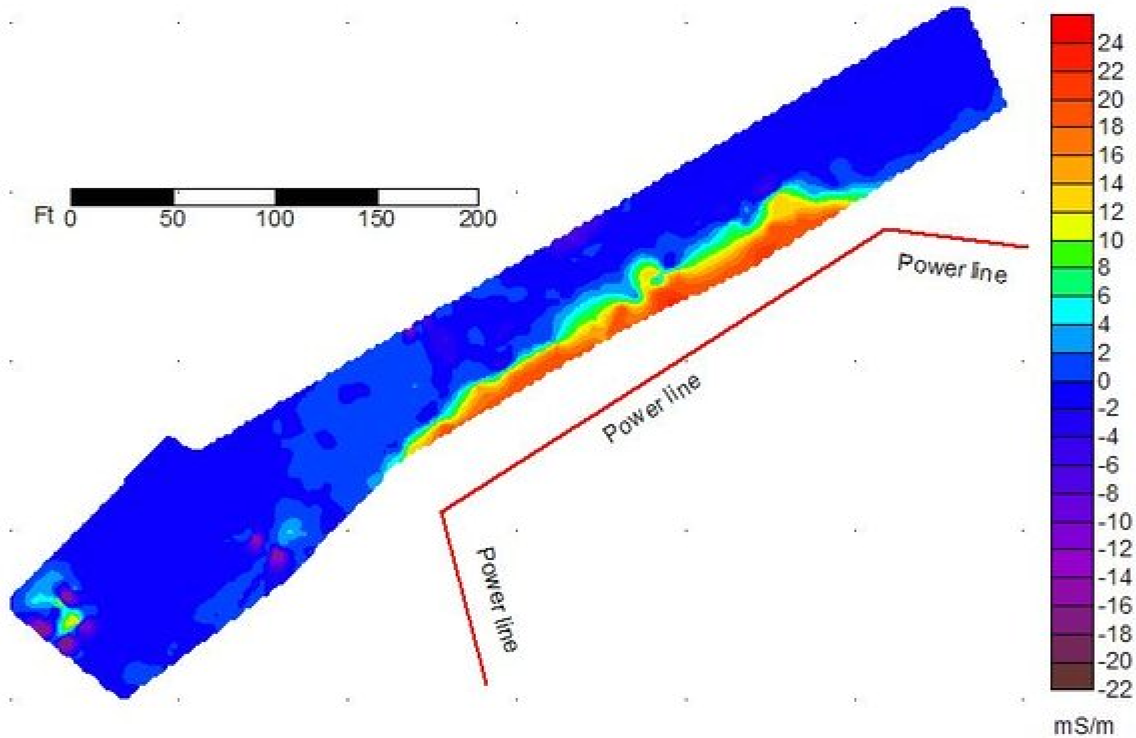

Figure 2. EM 31 Ground Conductivity Survey Collected in Proximity to a Power Line

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