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Surface Geophysical Techniques for Aquifer and Wellhead Protection Area Delineation

SURFACE GEOPHYSICAL TECHNIQUES FOR AQUIFERS AND WELLHEAD PROTECTION AREA DELINEATION

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FORWARD

This document, "Surface Geophysical Techniques for Aquifer and Wellhead Protection Area Delineation," is one in a continuing series of technical reports prepared by the U. S. Environmental Protection Agency's Office of Ground-Water Protection. These publications report on miscellaneous scientific topics which may be of interest to State ground-water program managers. The methodologies described in these reports do not represent EPA policy but are intended to assist State decision-makers as well as contribute to the scientific literature. This latest report is a companion document to OGWP's "Guidelines for the Delineation of Wellhead Protection Areas."

EXECUTIVE SUMMARY

Surface geophysical techniques developed by the minerals and petroleum prospecting industries are applicable to ground-water investigations. Through measurements taken at the earth's surface, these techniques detect subsurface physical property changes which are related to hydrogeologic conditions.

The Safe Drinking Water Act Amendments (SDWAA) of 1986 establish that the States must define Wellhead Protection Areas (WHPA) for public water supply wells. The Environmental Protection Agency's (EPA) Office of Ground-Water Protection (OGWP) has developed the "Guidelines for the Delineation of Wellhead Protection Areas" which presents a variety of criteria and methodologies for delineating WHPAs.

The WHPA delineation methods are used to transfer the delineation criteria to the ground, and the spatial limits of these mapped criteria represent the WHPA. Many of the WHPA delineation methods such as the analytical flow method and the numerical modeling method require subsurface hydrogeologic data as input; however, surface geophysical techniques can also provide information which estimate subsurface hydrogeologic conditions. In many ground-water investigations, surface geophysical data are used to supplement well data, thereby reducing the need for extensive water well drilling programs. Common approaches are to use surface geophysical data to correlate between boreholes or to extrapolate borehole information into nearby areas. In these applications, surface geophysics functions as a rapid, inexpensive, supplement to test drilling.

Hydrogeologic mapping is the WHPA delineation method outlined in the Guidelines that can be used to map the flow boundary WHPA criterion. Surface geophysics is one technique within this method that can support the flow boundary criterion in unconfined aquifer systems.

The nature of the hydrogeologic setting determines the applicability of a particular geophysical method. In many ground-water studies, several different geophysical methods are applied to the same survey area. Although each method in these integrated surveys responds to different property changes, the results of each data set often support a single interpretation. In general, the selection of a geophysical technique depends on the physical nature of the survey area, the desired depth of penetration, the data resolution requirements, and the available resources.

TECHNIQUE	PARAMETER CHANGE	MEASUREMENTS	RESOLUTION	PENETRATION DEPTH	APPLICATIONS	ADVANTAGES	LIMITATIONS
Seismic Refraction	acoustic velocity	stations with ground contact	good vertical description of 3 or 4 layers	depth is limited by space on the surface; equipment dependent	depth to water table in unconfined aquifers; saturated thickness of aquifer; depth to bedrock in alluvial valleys; stratigraphic mapping	quantitative results; refined acquisition and interpretation procedures; data acquisition faster than for seismic reflection	can require explosives or long geophone spreads; noise can impair results; velocity required to increase with depth
Seismic Reflection	acoustic velocity	stations with ground contact	excellent vertical resolution	depth is equipment dependent; limited accuracy above 100 ft; probes to 1000 ft	mapping of bedrock in valley-fill aquifers; detailed stratigraphic mapping of sedimentary units	velocity not required to increase with depth; moderate geophone spreads; high resolution in areas of high water table	complex field and interpretation procedures; may require explosives; data is recorded digitally; data impaired by noise; poor resolution for shallow reflections--especially shallow water table
Electrical Resistivity	electrical resistivity	stations measurements with ground contact	good vertical resolution of 3 to 4 layers	depth is equipment dependent	depth to water table and salt-fresh water interface; delineation of clay layers or fine and coarse sediments; mapping unconfined aquifer boundaries	provides some lithologic information; interpretation is quantitative; acquisition and processing procedures are refined	limited resolution; non-uniqueness of solutions; requires large surface area for deep soundings; acquisition is slow and data is impaired by noise
Electromagnetic Induction (EMI)	electrical conductivity	continuous and station measurements; no ground contact	excellent lateral resolution; good vertical resolution of 2 layers	depth is determined by the coil spacing; common depths are from 1 to 100 feet	same as electrical resistivity	rapid and simple data acquisition--no ground contact; good resolution	data impaired by noise; depth limitations; interpretation is qualitative; can define only 2 to 3 layers; limited to simple stratigraphy
Very Low Frequency Resistivity (VLF)	electrical resistivity	continuous	same as EMI	depth is determined by the resistivity of the terrain; performs like EMI	same as electrical resistivity	rapid and simple data collection; good resolution	depth limitation; qualitative interpretation; VLF signal is intermittent; limited to simple stratigraphy
Ground Penetrating Radar (GPR)	dielectric constant	continuous with ground contact not necessary	Excellent vertical and lateral resolution	depth limited by conductivity of terrain; probes from 1 to 100 ft	map water table and shallow stratigraphy in unconfined aquifer systems	rapid data acquisition; excellent data resolution	depth of penetration severely limited in conductive terrains; complex to operate
Gravimetry	density	stations	poor	not relevant	map bedrock and thickness of alluvial sediments	economical and unaffected by cultural noise	poor resolution; care required in performing measurements; interpretational ambiguities; elevations required for each station
Magnetometry	magnetic susceptibility	continuous airbourne or land-based; land-based station measurements	poor	not relevant	map sedimentary units which contain magnetic materials; map fractures and fault zones depth of alluvium when bedrock has a measureable magnetic susceptibility	economical	poor resolution; limited to crystalline bedrock; interpretational ambiguities

Table 1: Summary of geophysical techniques considered in this document.

Table 1 summarizes the technical characteristics, applications, advantages and limitations of the geophysical techniques which have been reviewed in this document. This summary is expected to give the reader an idea of the capabilities of each technique. Seismic and electrical methods are most suited to aquifer mapping studies with the gravity and magnetic methods having only secondary applications. Recent technology advances have resulted in the development of new techniques which have ground-water applications.

The seismic refraction technique is used to estimate the water table depth, the saturated thickness and the areal extent of unconfined alluvial aquifers. With increasing target depths, data acquisition procedures become more sophisticated while the uncertainty of data accuracy remains at ten percent.

An advantage of this technique is that quantitative data interpretation procedures have been developed. Refraction data can resolve three or four layers. Disadvantages of this technique are restrictive data acquisition requirements, depth limitations, and blind zone or velocity inversion problems. Since data acquisition and processing are labor-intensive, seismic refraction can be relatively expensive.

The petroleum exploration industry has developed the seismic reflection technique for use in detailed stratigraphic mapping of sedimentary basins. Due to recent technological advancements, this technique has been used to map the hydrogeologic boundaries in shallow unconfined aquifers. As compared to seismic refraction, this technique provides greater resolution within the saturated zone, has slow but routine field operations, and does not require the acoustic velocity to increase with depth. Unfortunately, data resolution is limited to depths shallower than 100 feet, and data acquisition and processing techniques are still being refined. Thus, the refraction technique is the preferred seismic method for targets at depths less than 100 feet; but, due to technology advances, seismic reflection is gaining increased popularity in ground-water applications.

Although the seismic refraction and the electrical resistivity techniques measure different physical property changes, both techniques have similar ground-water applications. As with seismic refraction, the electrical resistivity technique can identify the water table and the alluvium/bedrock interface under certain hydrogeologic conditions. The effectiveness of each technique in these mapping studies depends on the relative strengths of subsurface earth property contrasts. In many cases, both electrical and acoustic velocity contrasts are sufficient to allow detection by both methods. In these settings, both techniques are sometimes applied to verify or complement the results of each other.

There are differences in the applicability of the electrical resistivity and the seismic refraction techniques. For example, the refraction technique is generally more accurate in delineating the water table or the alluvium/bedrock interface. The resistivity technique can identify lithologic variation within alluvial sediments. Typical resistivity surveys map the relative positions of coarse and fine sediments or clay layers. Electrical methods can also map conductivity variations within ground water. When conducting an electrical survey, it is the responsibility of the investigator to separate electrical response of lithologic and water quality variations.

Data acquisition, data processing, and data resolution characteristics are similar for the refraction and resistivity techniques. Both refraction and resistivity measurements require ground contact and are therefore labor-intensive. Similarly, both techniques utilize quantitative processing routines which can resolve three or four subsurface horizons. Since data acquisition and processing requirements are similar, survey costs are similar. Both the similarity in cost and in applications contribute to the frequency of integrated refraction/resistivity surveys.

In addition to electrical resistivity, there are many electrical techniques which have been applied to ground-water studies. This document reviews three techniques which have gained recent popularity due to technology advances. These are the electromagnetic induction (EMI), very-low-frequency resistivity (VLF), and ground penetrating radar (GPR) techniques.

The EMI technique detects subsurface changes in electrical conductivity (inverse of electrical resistivity). Although EMI measures the same quantity as the electrical resistivity technique, there are many data acquisition and resolution characterisitics which distinguish the two techniques.

EMI instruments are portable units which provide a direct measurement of subsurface conductivity. Moving the instrument along a survey traverse results in a continuous profile of subsurface conductivity. Using one or several instruments which measure subsurface conductivity variations at different depths, the investigator can generate a cross-section. In general, EMI processing and interpretational procedures can only accurately resolve two layers. These vertical resolution restrictions combined with the simplicity of data acquisition and interpretation make the EMI technique most effective as a shallow reconnaissance profiling tool.

In general, EMI measurements are more sensitive to lateral variations than electrical resistivity measurements. Likewise, the resistivity technique is more accurate at resolving vertical variations. In spite of these resolution differences, EMI and resistivity data have similar ground-water applications and are often collected over the same area.

The VLF technique is very similar to the EMI technique but instead uses low frequency radio waves as a source. The VLF instrument is a portable unit which measures subsurface electrical resistivity. The penetration depth of the instrument is dependent on the resistivity of the subsurface like the EMI technique, therefore the VLF technique is well-suited for shallow reconnaissance profiling surveys.

GPR is a reflection technique which used high-frequency radio waves to continuously map shallow hydrogeologic boundaries. GPR is a reflection technique which measures electromagnetic contrasts and can be rapidly and continuously acquired. Unlike seismic reflection, GPR is limited to shallow penetration depths. Input signal attenuation is caused by high-conductivity media such as clay-rich lithologies. The GPR technique can map shallow water table surfaces, but the success of this application is highly site-specific.

The primary advantage of the GPR technique relates to its data acquisition capabilities. The GPR instrument is mounted on wheels and pulled across the survey area. The resulting data profile can be viewed directly in the field. Thus, GPR combines continuous spatial sampling with qualitative in-field interpretation and is most effective as a reconnaissance tool.

In the gravity method, the spatial variation of surface gravity measurements are interpreted as subsurface density contrasts. Since different lithologies are characterized by different densities, the gravity method can detect lithologic changes. Unfortunately, a single gravity data set can be related to an infinite number of geologic interpretations. As a result, gravity interpretations must be constrained by other geologic or geophysical information.

The density contrast between unconsolidated alluvial sediments and bedrock is detectable by the gravity method. Since gravimeters are portable units, gravity data are often used in reconnaissance surveys of valley-fill aquifers. Gravity data can define the spatial extent of aquifer boundaries as well as locate topographic variations in the bedrock. Although these reconnaissance data can be rapidly acquired, interpretation can be tedious and inconclusive. In any case, gravity data often provide inexpensive reconnaissance information which can supplement other geophysical data in ground-water studies.

The gravity and magnetic methods measure potential field quantities at the earth's surface and relate these data to theoretical models. These methods have similar data acquisition, processing, and interpretation characteristics. Since water-bearing units are typically non-magnetic, the magnetic method has only limited applications. There are special circumstances however where the magnetic method is applicable to ground-water studies. In most of these cases, the magnetic method provides qualitative data which has poor resolution and is difficult to interpret.

In conclusion, the applicability of a particular geophysical technique depends on the subsurface geology and the available resources. Selecting a particular technique often depends on what data are already available. In most cases, geophysical data are used to supplement surface geological and well information. Thus, when delineating aquifers for WHP efforts, investigators may utilize surface geophysics as a rapid, inexpensive, companion technique to test drilling.

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CHAPTER 1

INTRODUCTION

1.1 WELLHEAD PROTECTION

1.1.1 Legislative Authority

The Safe Drinking Water Act Amendments of 1986 require the States to delineate Wellhead Protection Areas (WHPA) for all public water wells. A grant program is included to assist the States in this effort. A WHPA is defined by the Amendments as "the surface and subsurface area surrounding a water well or wellfield, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or well-field." Although the statute gives this careful legal definition of a WHPA, it does not specify WHPA delineation approaches. States are allowed maximum flexibility in designing WHPA programs. The U. S. Environmental Protection Agency's (EPA) Office of Ground-Water Protection (OGWP) has issued the technical guidance, "Guidelines for Delineation of Wellhead Protection Areas." The Guidelines outline a variety of criteria and methodologies believed most effective in establishing WHPA's.

1.1.2 Delineation Criteria and Methodologies

In general, a WHPA consists of all or part of the zone of influence (ZOI) or the zone of contribution (ZOC) around a pumping well. Figure 1 presents the ZOI and the ZOC for an unconfined aquifer system. The ZOI is the area on the earth's surface overlying the pumping well's cone of depression. The ZOC consists of the entire flow system which contributes water to the well. The hydrogeologic boundaries of the ZOC are defined by ground-water divides, surface water features, and permeability contrasts.

A WHPA is established within or including a ZOI or a ZOC according to specific conceptual standards or criteria. These criteria are determined by the protection goals of the WHP program. For example, States may conceive of a WHPA as: 1) remedial action zones which protect wells from unexpected contaminant releases, 2) attenuation zones which provide for the proper assimilation of the contaminant before it reaches the wellhead, or 3) wellfield management zones which apply land use restrictions to recharge areas.

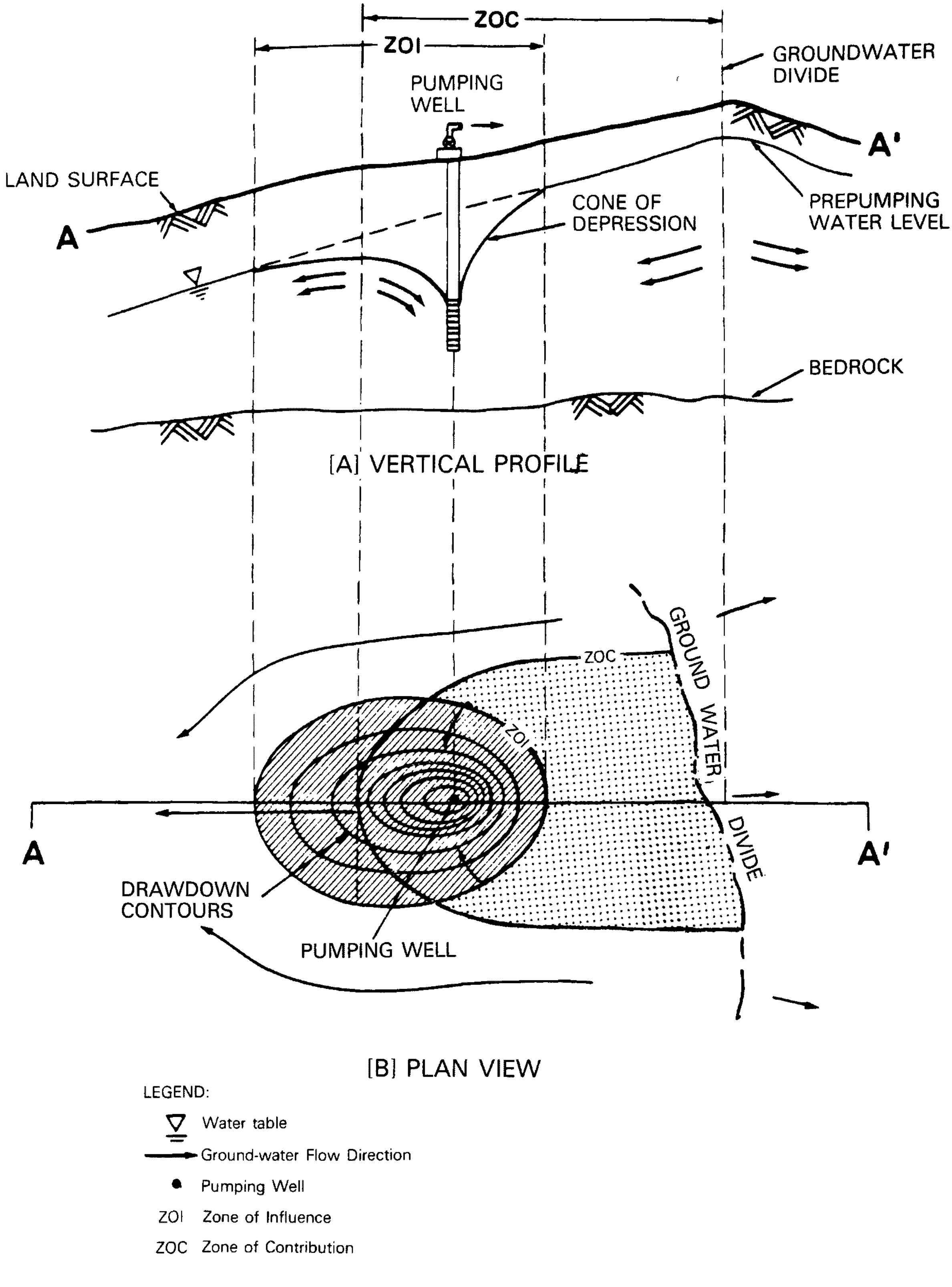

Figure 1: Terminology for WHPA delineation (after Guidelines for Delineation of Wellhead Protection Areas, U.S. EPA, 1987)

All but one of the WHPA criteria outlined in the Guidelines require subsurface data for their determination. This criterion is the distance criterion which is a simple distance measurement from the well. The hydrologically-based criteria are: drawdown, time of travel, flow boundaries, and assimilative capacity.

The delineation methods outlined in the Guidelines range in complexity from the very simple arbitrary fixed radius method which consists of drawing a circle around a well to the numerical flow model method which uses high-speed computers to predict ground-water flow. The methods of intermediate complexity are the: calculated fixed radius, simplified variable shapes, analytical flow model and hydrogeologic mapping methods. The reader should consult the Guidelines to familiarize himself with the details of the WHPA criteria and methods.

Hydrogeologic mapping is the WHPA delineation method which uses geologic, hydrologic, geophysical, and tracing observations to map the flow boundary criterion of an aquifer system. This document, "Surface Geophysical Techniques for Aquifer and Wellhead Protection Area Delineation," discusses surface geophysics as one mapping technique within the hydrogeologic mapping method. This document is designed as an auxiliary paper to EPA's technical Guidelines.

In the example of Figure 1, the flow boundary created by the ground-water divide could be selected as the upgradient limit of the WHPA. This flow boundary criterion could then be mapped to the ground by the application of one or more WHPA delineation methods. In this case, the WHPA would correspond to the ZOC outlined in Figure 1.

1.2 SURFACE GEOPHYSICAL METHODS

Surface geophysics has been developed by the mining and petroleum industries to measure subsurface physical property contrasts. More recently, geophysical techniques have been used by the environmental community to detect buried waste and waste migration (Benson et al., 1982; Olhoeft, 1986; Walther et al., 1986). These geophysical methods map the earth's response to either natural or artificially generated energy fields. The parameter changes that these methods measure are caused by subsurface elastic, density, electrical, or magnetic constrasts.

Since the earth is a complicated system, geophysical methods are interpreted using models that treat the subsurface according to simplifying assumptions. Survey data are acquired and interpreted in accordance with these assumptions, and the accuracy of these interpretations depend on how well the actual geology agrees with the assumed model. Subsurface interpretations are generally improved when information from test borings or observation wells is available to constrain the data sets.

Surface geophysical technologies are commonly applied in reconnaissance ground-water surveys that identify the major flow boundaries in unconfined aquifers. These surveys may integrate data from several field methods. For example, seismic refraction and electrical resistivity data are often collected over the same area to verify and complement the results of each other.

In addition to reconnaissance information, geophysics can also be used to obtain detailed subsurface information; typical surveys may result in a map of the hydrologic, lithologic, or salinity changes in alluvial aquifer systems. In some cases, surface geophysical studies are tailored to the geological complexities of the survey area. For example, although the magnetic method cannot generally detect changes in alluvial aquifers, it has been used to map the subsurface extent of some basaltic aquifers. In general, the applicability of a particular technique depends on the relative magnitudes of subsurface physical property changes.

1.3 DOCUMENT OBJECTIVES

In this document, the principles and methodologies are presented for some of the surface geophysical techniques which have been applied in ground-water investigations. The text is divided by section according to technique, and the level of detail in each section corresponds to the relative utility of that technique with regards to aquifer assessment as reflected in the literature.

The principal techniques used in ground-water studies have been seismic refraction and electrical resistivity. As a result, these data acquisition and processing technologies have been refined, and there is a substantial literature describing these procedures. Both seismic refraction and electrical resistivity are presented at the beginning of this document so that fundamental geophysical concepts can be introduced. It is expected that the reader will acquire a basic understanding of geophysical principles by reading these sections. These principles are relevant to the other techniques, although they are not discussed at the same level of detail. This document focuses on geophysical techniques that have found increased ground-water applications based on new technology advances (Collett and Haeni, 1987; Walther et al., 1986; Dobecki and Romig, 1985).

It is assumed that the reader of this document has a technical background in geology or engineering hydrology, and some knowledge of geophysics. This document is not a textbook on geophysical principles or a cookbook on how to perform a geophysical survey. Instead it is intended to serve as a resource document that introduces the reader to some of the ground-water applications of geophysical techniques. The reader should use this as one starting point when investigating the various aquifer delineation methods that can assist in defining Wellhead Protection Areas.

CHAPTER 2

SEISMIC METHODS

2.1 SEISMIC REFRACTION

2.1.1 Introduction

The seismic method was developed for use in petroleum and mineral exploration as well as in engineering studies. As pointed out by Haeni (1986a), recent technological developments have made the seismic refraction technique highly effective and economical for obtaining data for ground-water investigations. Seismic refraction is most often used to delineate the hydrogeological boundaries characterized by high-velocity surfaces in unconfined aquifer systems. In many of these aquifer settings, refraction data can determine: the depth to the water table, the saturated thickness of the aquifer, the alluvium/bedrock contact, and the spatial limits of the aquifer. These results often provide the information necessary for the development and implementation of a test drilling program.

2.1.2 Theory

Seismic refraction is a surface geophysical technique which attempts to obtain information about shallow subsurface geologic formations. In the seismic techniques considered in this document, geologic formations are modeled as acoustic layers. The seismic refraction technique consists of introducing seismic energy into the ground and recording the arrival of direct or refracted sound waves at various distances along the earth's surface. This seismic energy travels in each layer of the earth with a characteristic velocity as a pressure or compressional wave (see Figure 2). The speed of these compressional waves depends on the density and the compressibility of the geologic formation. Thus, by measuring compressional wave velocities and the travel times of the sound waves, scientists can infer the nature and depths of the subsurface geologic units. Usually this subsurface interpretation is dependent on other geological or geophysical information. The success of this technique in defining lithologic and hydrologic boundaries depends on how accurately the layered acoustic model simulates the actual geology.

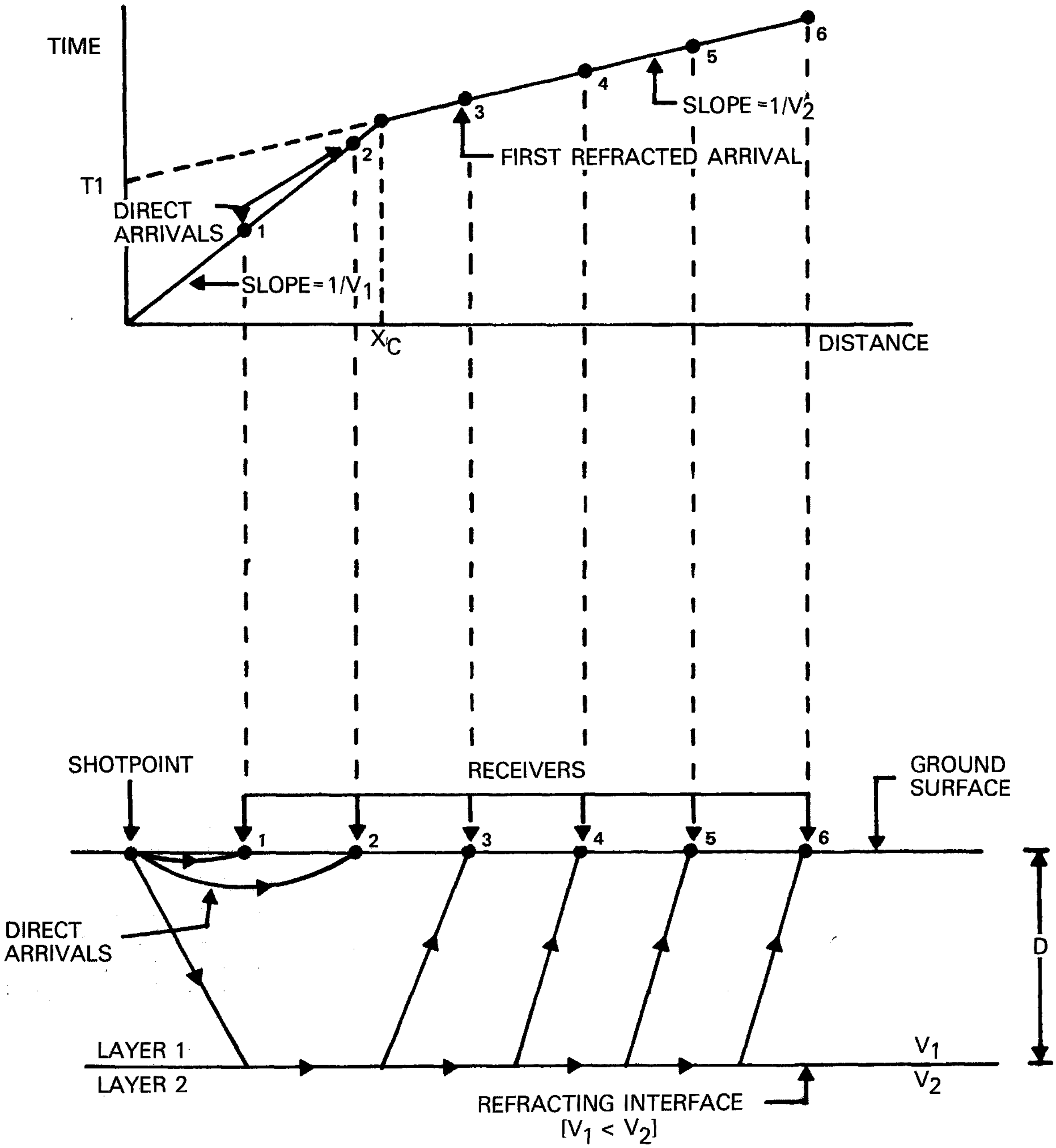

Figure 2: Schematic representation of a single interface seismic refraction experiment and the corresponding time-distance plot (after Costello, 1981)

The impulsive source which initiates the seismic energy is located at or near the earth's surface. A linear array of seismic sensors or geophones located some distance away on the earth's surface detects the arrival of these sound waves. If the compressional wave velocity of each layer increases with depth, then seismic energy is refracted along each subsurface interface. The seismic waves refracted along these interfaces continue to release energy upward into the lower velocity layers. These refracted waves are detected by the geophones on the surface.

When interpreting the recorded data, only the direct wave travelling in the surface layer and the waves refracted from deeper interfaces are considered. The reflected energy and other elastic wave components are not relevant in a refraction survey. Figure 2 represents a cross-section of a layered acoustic earth with ray paths representing the direct and refracted waves travelling from source to receiver. This linear array of receivers is connected to a multichannel field recording system. Plots of the recordings of the first arrival from each channel constitute a time-distance profile. Therefore, refraction data consists of: 1) the travel times of the direct and refracted waves from source to receivers, and 2) the associated distances between the source and the receivers. From these times and distances, lithologic thicknesses and velocities are calculated.

The relative times of arrival of the refracted and the direct waves depend on the subsurface velocity distribution and the source-receiver spacing. For a close source-receiver spacing, the first wave to arrive at the receiver is the "direct wave" travelling in the near-surface layer. The next recorded pulse is the wave which travels from the source through the first layer, refracts along the higher velocity interface, and travels up through the near surface layer to the receiver. As the source-receiver spacing is increased, the refracted wave eventually reaches the receiver at the same time as the direct wave. The distance which corresponds to the simultaneous arrival of the direct and refracted waves is known as the "cross-over distance." For all source-receiver spacings beyond this distance, x_c, the refracted wave reaches the receiver before the direct wave. At increasingly greater receiver spacings, the refracted waves from the deeper interfaces may become the successive first arrivals.

From the plot of first arrivals against their corresponding source-receiver distances, the subsurface velocity configuration can be inferred. The time-distance plot for the single interface horizontal geometry is shown in Figure 2. In this plot, the two intersecting lines represent arrivals from each of the two layers. The line passing through the origin corresponds to the direct wave which travels through the surface layer while the other line represents the arrivals which have refracted along the top of the higher velocity medium. This plot provides graphical information which allows an inference on the subsurface velocity structure. The reciprocals of the slopes of these lines are the media velocities, and their graphical point of intersection on the distance axis is the crossover distance. The crossover distance and the layer velocities lead to a calculation of the interface depth for a horizontally layered earth:

$$D = X_c/2 \cdot [(V_2 - V_1)/(V_2 + V_1)]^{1/2}$$

Thus, these refraction data can characterize the subsurface velocity configuration of this simple model. For multi-interface and dipping models, similar but more complex depth "inversion" equations can be derived. Graphical and analytical solutions for some of these more complicated models are presented by Haeni (1986b) and Dobrin (1976).

2.1.3 Methodology

In a seismic refraction survey, the acoustic energy generated by the seismic source is converted to an electrical signal by the seismic sensors. This signal is then amplified, filtered, and recorded. The specific energy source, geophone array, and recording system are chosen according to the objectives of the survey.

The type of energy source utilized in a refraction survey depends on the targeted depth of penetration. For target depths less than 100 feet, a hand-held impact hammer is commonly used. For intermediate depths between 100 and 300 feet, various explosive and non-explosive technologies are available. For depths greater than 300 feet, explosives are required.

The selection of a sound source requires both economic and scientific considerations. For instance, a hammer source can provide inexpensive shallow data in a minimum of time (see Underwood et al., 1984). In contrast, buried charges produce data at a greater cost and time commitment (Tucci and Pool, 1987). The advantages and disadvantages of the various seismic refraction sources are discussed by Haeni (1986b).

The geophones which react to the impinging seismic energy are connected by cables to the recorder. These spread cables are multiconducting with geophone "takeouts" located incrementally along their length. The geophones are arranged linearly over the target area, and their spatial arrangement with respect to the shot determines the subsurface coverage of the recorded data. This can be understood by tracing the ray paths from the source to the receivers according to Snell's law.

In a typical refraction survey, the distance between the shot and the geophones is such that the refracted wave is the primary recorded wave component. The geophone spread length is three to five times the maximum depth of interest. Usually the geophone spread is advanced along a line to obtain a profile of continuous coverage. Many times however, shots are fired in the middle of the linear array to acquire near-surface information. Deep information is obtained by "shooting" off either end of the spread. Shooting data from both directions produces forward and reverse traveltime plots. This procedure is known as reversed profiling. Reversed profiling data can be inserted in the appropriate inverse equations to search for the dip of the geologic formations. In order to achieve more accurate assessments of lateral velocity changes, reversed profiling is an absolute requirement.

The spacing between adjacent geophones determines the resolution of the data, with closer geophone spacings providing higher resolution. Common geophone spacings range between 15 and 50 feet. When a refraction survey is initiated in a new area, the geophones are usually spaced close to each other to allow construction of a highly detailed time-distance curve. This information helps to define the spread geometry necessary to map the lithologies of interest.

The recording system used in a refraction survey can contain between 1 and 24 channels. The signal transmitted by each geophone is amplified and filtered before it is recorded. The filtering of seismic data is designed to selectively eliminate the temporal frequencies associated with seismic noise. Noise is defined as any form of seismic energy which is generated by natural or cultural sources and interferes with the signal. The final output of these amplified and filtered signals is typically displayed on an oscilloscope, or recorded on heat sensitive paper or magnetic tape for later processing.

A minimum of three people are necessary to efficiently run a seismic refraction survey. Such a crew could complete three or four reversed refraction profiles in a typical work day. Usually four-wheel drive vehicles are used to carry equipment and personnel. In some surveys with deep target depths, an explosive truck and a drill rig are necessary. In general, the more complicated the field system or the deeper the target, the more experienced and numerous the field crew. The details of seismic refraction survey field procedures are outlined by Haeni (1986b).

2.1.4 Data Processing and Interpretation

Raw refraction data must be processed before a subsurface interpretation can be made. One essential processing step is the systematic elimination of travel time errors introduced by topographic variations. This procedure is known as data reduction. Once the data have been reduced, then the arrival times are plotted against source-receiver distances. Finally, the time-distance data are inverted to form a subsurface velocity structure. Well logs or core information from the survey area can insure more accurate interpretations and are highly desirable.

This entire process from data reduction to interpretation may be automated by digital seismographs and microcomputers, but an experienced geophysicist is required to insure the accuracy of these procedures. Many of these processing systems can accomplish these tasks while still in the field. The degree of automation depends on the scale of the survey. If many refraction lines are anticipated, then it may be more cost efficient to program a computer to reduce the data, pick the travel times, plot the points, fit the lines to the plotted points, and offer an interpretation. For smaller scale surveys, a programmable hand calculator is often adequate.

2.1.5 Ground-Water Applications

Seismic refraction surveys are most useful in mapping high velocity contrasts such as the water table, bedrock surfaces, and some lithologic changes. In general, any shallow geologic feature which has a velocity increase of greater than 20 percent can be detected by seismic refraction. This condition is usually satisfied in sedimentary environments or along the contact between sedimentary lithologies and basement. Haeni (1986b) discussed the effectiveness of the refraction method for many hydrogeologic settings.

Unconsolidated surficial materials commonly occur as valley-fill deposits in channeled bedrock. Such geologic features are known as buried valleys or buried channels. The contact between these alluvial materials and bedrock forms an important flow boundary; and in temperate regions, these deposits provide an extensive and valuable source of ground water.

Seismic refraction techniques are useful in defining the areal extent of channel deposits due to the considerable velocity contrast which sometimes characterizes the bedrock/alluvium interface. One approach for delineating valley-fill aquifer deposits is to complete several profiling surveys in parallel sequence. Mapping the contact for each profile and extrapolating between profiles produces an areal map which reveals the channel. Survey maps are presented as contour maps or profiles.

The literature is replete with examples concerning bedrock surface mapping as a means to delineate valley-fill aquifers. In two survey papers, Zohdy et al (1974), and Sendlein and Yazicigil (1981) describe some typical bedrock surface mapping surveys which have appeared in the literature. These mapping procedures apply identical principles although they differ in scale, equipment, available data, and specific objectives. Other interesting investigations not included in these two papers are presented by Tucci and Pool (1987), Sverdrup (1986), Underwood et al. (1984), Frohlich (1979), and Sander (1978). Also, Haeni (1986b) provides an annotated bibliography for refraction applications to ground-water investigations. In general, the literature provides information on the practicality of this technique as well as a glimpse at the available technology.

The velocity increase occurring at the interface between the saturated and unsaturated zones in an unconfined aquifer is usually detectable by refraction profiling techniques. In fact, water table refractor information is often implicit in valley-fill aquifer mapping data. Some surveys however focus primarily on obtaining water table information. The ability of refraction techniques in detecting the water table depends on the size of the velocity increase at the saturated zone. In some cases, the acoustic properties of the saturated zone are not sufficiently different from the surrounding media to allow water table detection. A more serious obstacle results when a lithologic refractor lies directly beneath the zone of saturation. When this occurs, the water table refractor does not occur as a separate branch on the time-distance curve, and the zone of saturation cannot be located. This situation commonly arises when the water table in an unconfined alluvial aquifer lies just above bedrock. The significance of the vertical separation between the two refractors becomes less critical when the lithologic acoustic contrast is less severe. Despite these obstacles, seismic refraction is an rapid and cost-effective technique for both the delineation and the areal mapping of the water table in unconfined aquifers.

Seismic refraction can also be used to define stratigraphic boundaries which often correlate with permeability or flow boundaries. These stratigraphic surveys are more ambitious than bedrock or water table mapping surveys; they generally require high resolution data and some subsurface information. Examples of these surveys are discussed by Sendlein and Yazicigil (1981).

2.1.6 Limitations

In the simplest use of the seismic refraction technique, the subsurface geologic formations are modeled as homogeneous acoustic layers whose compressional wave velocities increase with depth. These requirements are satisfied in most sedimentary environments, but deviations must be accounted for in subsequent interpretations. For example, glacial or alluvial deposits usually include sand and clay lenses or channel deposits. These geologic features must be accounted for when both collecting and interpreting the data.

The alluvium/bedrock interface as well as the unsaturated/saturated zone in unconsolidated deposits are characterized by a velocity increase. Occasionally, the geologic configuration is such that a low-velocity layer occurs beneath a high-velocity layer. This situation is known as "velocity inversion." The energy refracted from this type of interface travels downward into the subsurface and cannot be detected by the geophones. As a result, the time-distance plot leads to an incorrect determination for that layer velocity and layer depth. This situation commonly occurs when glacial till overlies finer-grained, unconsolidated glacial sediments.

The seismic refraction method also requires that the stratigraphic layers be of sufficient thickness, and that successive layers form a sufficient velocity contrast to allow their detection. Many times however, a refracting layer is too thin to be detected by the seismic method, but thick enough to cause a significant change in travel time. This undetected layer is known as a "blind zone." Blind zones are common in geologic formations which contain high-velocity limestone sequences. In many surveys areas, well logs or core information may be used to estimate velocity structure so that blind zones may be recognized and the time data corrected. Sander (1978) has provided a detailed discussion on the implications of blind zones on the interpretation of refraction data.

Haeni (1986b) and Zohdy et al. (1974) examine typical geologic settings which depart from the simplified stratified model. Among other things, they consider blind zones, velocity inversions, multi-layered media, and dipping layers. They present the time-distance plots which correspond with these geologic features. These documents are important resources which can be consulted when interpreting refraction data. In general, the refraction technique most accurately models three or four flat layers which are characterized by substantial velocity increases.

2.1.7 Summary

Seismic refraction is an effective means for mapping the subsurface hydrologic conditions of some unconfined aquifers. Refraction data can provide estimates to within ten percent on: the depth to the water table, the areal extent of the aquifer, the saturated thickness and the hydraulic gradient. Refraction data are often used to correlate between wells or to extrapolate well information into new terrain. Thus, the refraction technique provides an economical supplement to extensive test drilling programs and is well-suited for mapping the flow boundaries in WHPA programs.

2.2 SEISMIC REFLECTION

The seismic reflection technique utilizes the same principles as seismic refraction but measures the reflected instead of the refracted component of the acoustic waves (see Figure 3). Since the receivers are close to the sound source, sound waves reflected from shallow horizons and the surface waves arrive at the receivers at the same time. As a result, near-surface lithologic changes are not clearly defined in the recorded response. In general, the seismic reflection technique is most effective in mapping reflecting horizons below 100 feet. Shallower targets are usually better handled by refraction.

The primary application of seismic reflection has been in petroleum exploration where exploration targets are thousands of feet deep. The petroleum industry has developed sophisticated data acquisition and processing techniques which enhance reflection data at the expense of the near-surface response. The seismic reflection technique has not been routinely used in shallow aquifer studies, but has had some application in ground-water studies where probing depths exceed 100 feet.

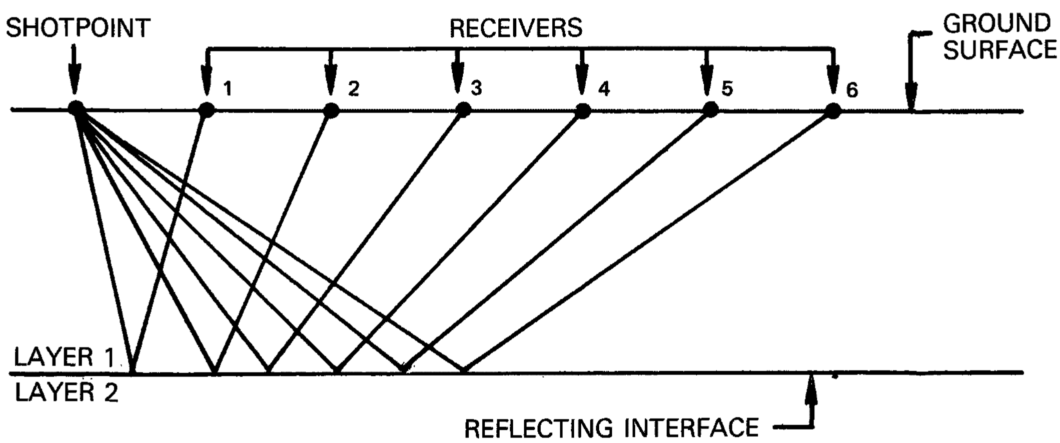

Figure 3: Schematic representation of a single interface seismic reflection experiment.

The processing and acquisition of seismic reflection data is complicated and will not be discussed here. The rudiments of reflection data acquisition and processing are discussed by Telford et al. (1976). In general, reflection data are more expensive to collect than refraction data. Spread lengths are shorter, sources are highly sophisticated, and the acquisition procedure is routine. Also, the reflection method does not require the velocity structure to increase with depth which reduces thin bed and blind zone problems.

Recent research efforts have focused on increasing the applicability of seismic reflection to shallow aquifer mapping studies. These surveys minimize the deleterious surface wave component of the seismic wave by using an optimal travel time window. Such parameters are site specific and must be determined in the field.

Shallow aquifer reflection mapping studies offer innovations in both acquisition and processing procedures. For example, Hunter et al. (1982, 1984) have used a multichannel engineering seismograph and a hammer source to acquire reflection data which they process with algorithms developed on microcomputers. Work is also being done to improve the useful frequency range of shallow reflection data (Knapp, 1986a, b). In a another related study, Haeni (1986c) has used continuous seismic reflection profiling techniques to locate hydrogeologic boundaries in formations beneath water covered areas. After reviewing these new advances in the light of conventional technologies, Dobecki and Romig (1985) predict that the reflection technique will have more widespread application.

CHAPTER 3

ELECTRICAL METHODS

3.1 ELECTRICAL RESISTIVITY

3.1.1 Introduction

The electrical resistivity technique measures variations in subsurface electrical resistivity and has been employed in both mineral exploration and ground-water investigations. In an electrical resistivity survey, separate electrode pairs are used to inject a current in the earth and measure the resulting potential difference. Varying the positions and configurations of these electrodes provides information about subsurface resistivity variations. As in seismic methods, the electrical resistivity interpretation is based on a stratified earth model. Resistivity data can be used to infer the lithologic and the hydrologic characteristics of the survey area. There are many publications discussing the rudiments of electrical resistivity. Three papers which relate resistivity techniques to ground water are presented by Senglein and Yazicigil (1981), Zohdy et al. (1974), and Bisdorf (1985).

3.1.2 Theory

Electrical resistivity is the measure of a material's resistance to the flow of an electrical current. Since most geologic materials behave as electrical insulators, surface measurements of earth resistivity are governed by the electrolytic properties of interstitial water. The subsurface distribution of water is controlled by the porosity of the formations. Thus, resistivity values generally are governed by the amount of porosity and the degree of water saturation in a geologic formation. Additionally, clay minerals are capable of conducting electricity; and as a result, geologic materials which contain significant amounts of clay minerals have relatively lower resistivities. For the most part though, it is the amount and conductivity of pore water and not the rock matrix of a formation which controls resistivity values.

The electrical resistivity technique consists of introducing an electrical current (I) into the ground and measuring a voltage response (V) along the earth's surface. The subsurface resistivity can be calculated from the injected current and the measured voltage. Conventional resistivity methods utilize four electrodes. A direct or low-frequency current is injected into the ground by a pair of current electrodes C1 and C2, and the resulting potential difference ΔV is measured by a potentiometer at a pair of potential electrodes P1 and P2 (see Figure 4). From these data, the resistivity (r) is calculated according to:

$$r = K\Delta V/I$$

where K is a geometric factor based on the relative positions of the electrodes. The calculated resistivity is the true resistivity if the geologic medium is electrically homogeneous over a volume which is large compared to the electrode spacing. This is usually not the case, and the measured resistivity is known as the apparent resistivity.

3.1.3 Methodology

Resistivity surveys are designed to independently resolve the horizontal and vertical components of subsurface resistivity variations. The horizontal profiling procedure measures lateral resistivity variations while depth soundings measure vertical resistivity variations. There are many different electrode configurations which have been developed according to different survey objectives. Three common configurations are the Wenner, Schlumberger, and dipole-dipole arrays. The specific geometric configurations and K formulas for these arrays are given in Figure 5. The Wenner and Schlumberger arrays are commonly used for vertical sounding investigations. The dipole-dipole array is often used for lateral investigations and is sometimes used for deep sounding investigations.

Vertical sounding are made by symmetrically expanding the current electrodes for the Wenner or Schlumberger arrays along a line about the array center. This procedure is based on the fact that greater and greater electrode spacings probe deeper and deeper beds. In general, the maximum electrode spacing should be three to four times the depth of investigation to allow proper penetration of the current.

Horizontal profiling is generally performed by moving a fixed-spacing array incrementally along the earth's surface and recording the apparent resistivity values. This fixed spacing is at least one to two times the depth of interest. A simple plot of these values against their spatial coordinate reveals lateral resistivity variations for a given depth. If several of these profiles are performed in a parallel sequence, then the data may be contoured to give an areal map of resistivity variations. Sounding measurements are commonly made in conjunction

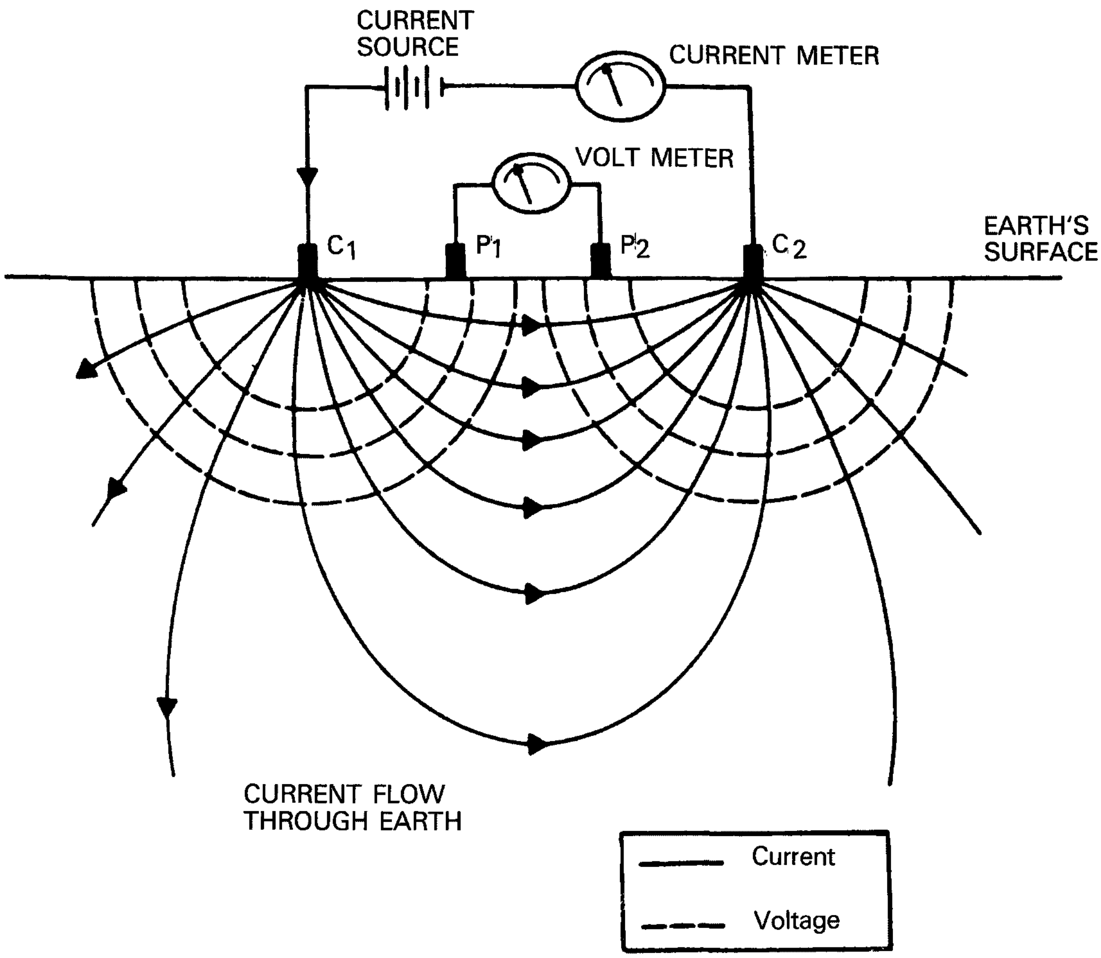

Figure 4: Typical four electrode electrical resistivity arrangement (after Benson et al., 1982).

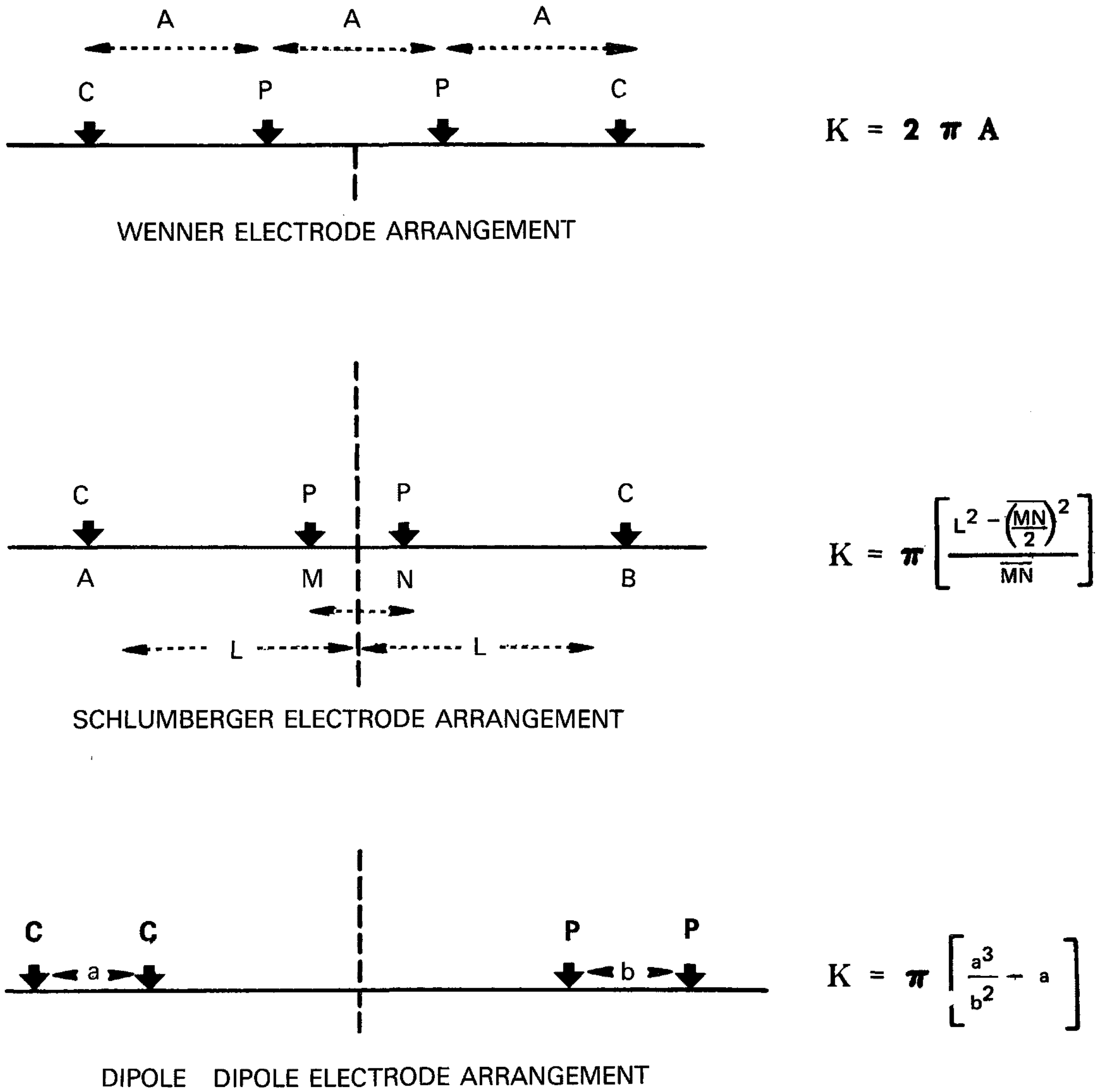

Figure 5: Electrode configurations for the various electrode arrays. P represents the potential electrodes and C the current electrodes. K is the geometric factor used to convert the measured quantities to apparent resistivity values (after Benson et al., 1982).

with profiling data in order to determine the appropriate array spacing or target depth.

A second profiling method utilizes the dipole-dipole array. In this procedure, measurements are made with one of the electrode pairs held fixed while the other is moved incrementally along a line. The fixed electrode pair is then advanced down the line, and the procedure is repeated. This process yields both lateral and depth information which can be presented as a cross-section.

Zohdy et al. (1974) have discussed these arrays. After comparing the Schlumberger array to the Wenner array, they conclude that the Schlumberger array requires less field effort, offers somewhat greater resolution, is less sensitive to noise and lateral homogeneities, and is suited to more sophisticated interpretation techniques. The Schlumberger method however requires more current to achieve the same potential difference (Fretwell and Stewart, 1981). In a more recent work, Carrington and Watson (1981) have conducted both laboratory and field experiments comparing nine different electrode configurations. Dobecki and Romig (1985) have suggested that this wide variety of electrode configurations may have hindered geophysicists by confusing the issue of the appropriate geometry for a specific field problem.

The equipment for a resistivity survey consists of electrodes, cables, a current source, and a potentiometer. The specific equipment selected for a survey depends on survey objectives and field conditions. There are many source and receiving technologies commercially available. In general, the degree of sophistication increases as the target depth increases. To probe to depths of 150 to 300 feet, portable battery-powered units are sufficient; deeper surveys require generator-powered transmitters. Most current sources provide a direct reading of the transmitted current, and some receivers have signal-enhancing circuitry.

In electrical resistivity surveys, noise is defined as any unwanted electrical current or voltage which interferes with the signal. Equipment-related sources, cultural sources, and natural sources are responsible for this noise. Equipment-related noise is generated by insufficient ground-electrode coupling, or by any of the other electrical contacts associated with the cables. Cultural noise is caused by stray currents related to such things as power lines, and metallic objects. Natural sources are caused by spontaneous potential and other earth currents. Noise can be reduced by careful field procedures and filter mechanisms. For instance, some potentiometers contain special circuitry which filter power line noise.

There are many types of electrodes used in electrical resistivity surveys. For shallow surveys, stainless steel or copper rods are often used as current electrodes. For deep surveys, buried copper screens or culverts are often used. Stainless steel rods or non-polarity electrodes (porous pots) are used to measure the potential difference. For sounding surveys, the current and potential electrodes are made of the same material. For profiling or dipole-dipole surveys, non-polarized electrodes are used. Once in place, the soil around the electrodes is sometimes soaked with water to improve electrical contact. The cables which are connected to the source electrodes carry the full input current and are well insulated. The cables connected to the potentiometer do not carry high currents and are of a lighter grade. A minimum of three field personnel are usually required to complete a resistivity survey.

3.1.4 Data Processing and Interpretation

As an initial processing step, field measurements must be converted to apparent resistivity values. This is accomplished by forming the ratio of observed potential difference to input current and weighting the result by the appropriate geometric factor. For profiling data, these values are plotted as a profile or contoured on a map. For sounding data, these resistivity values are plotted against electrode spacing in a logarithmic format. These procedures are collectively known as data reduction.

Converting geophysical sounding data to a subsurface earth model is known as inversion. In this process, the apparent resistivity plots are compared to theoretical curves which are calculated from stratified earth models (Koefoed, 1979). This comparison procedure is commonly done automatically by a computer (Zohdy, 1973). This is often an iterative process whereby the differences between the observed and the theoretical curves are progressively minimized according to established criteria such as least squares error (Anderson, 1979). The theoretical model data which correspond to the observed curve are inferred to be the subsurface resistivities and thicknesses of the discrete layers.

Before the widespread use of computers, sounding data were inverted visually by matching the actual data to a set of "master curves" which were calculated for a wide range of layer thicknesses and resistivity contrasts (see Orellana and Mooney, 1966). Curving-matching, however, requires a high level of expertise, and sounding data are generally inverted and by automated techniques.

3.1.5 Ground-Water Applications

Since the electrical resistivity values are largely controlled by the spatial and salinity distributions of interstitial water, this method is well-suited to ground-water studies. As stated above, the spatial distribution of water in these systems is controlled by lithologic or porosity changes. Superimposed on these lithologic changes are salinity variations within the water. Thus, some surveys measure lithologic or porosity variations (Poole, 1986; Heigold et al., 1984; Page, 1968) while others map the location and migration of buried waste, or the salt water/freshwater interface (Stewart et al., 1983; Sweeney, 1984; Rudy and Caoile, 1984; Gorhan, 1976). Usually, both lithology and water quality vary simultaneously which results in interpretational problems. It is the responsibility of the interpreter to assess the validity of survey assumptions.

Although the electrical resistivity and seismic refraction techniques measure different physical properties, their results may be complementary for ground-water studies. Refraction and resistivity data are often applied to the same survey area to resolve the ambiguities inherent in each data set (Tucci and Pool, 1987, Denne el al., 1984; Underwood et al., 1984; Frohlich, 1979; Wachs et al., 1979). Each technique has its own strengths or weaknesses depending on the geology of the survey area. For example, the resistivity technique is particularly useful in detecting clay layers in alluvial sequences whereas the refraction technique is often more accurate in determining the depth to the water table. In general, the applicability of each method depends on the geology of the survey area, the availability of well data, and the objectives of the survey.

Resistivity values are always site-specific, and so the reliability of subsurface interpretations depends on subsurface information. If well logs are available, then resistivity sounding data are correlated with these data. This approach can lead to accurate inversions which often incorporate lithologic information. Many resistivity surveys result in geoelectric correlations which distinguish clay from sand, coarse from fine, and saturated from unsaturated sediments. Some researchers have even concluded that resistivity measurements can be used to estimate the hydraulic properties of aquifers (Kelly and Reiter, 1984; Kosinski and Kelly, 1981).

3.1.6 Limitations

The inversion of resistivity sounding data does not produce a unique model. In general, a resistivity data set can be related to an unlimited number of stratigraphic models. For example, a thin resistive layer may create the same response as a thicker, less resistive layer. This is the "equivalence" problem. In many cases, restrictions can be placed on layer thicknesses and resistivity contrasts, based on geologic or other geophysical information such as resistivity logs. These controls can be entered as constraints in some computerized inversion routines and can lead to a more accurate inversion.

In addition to interpretative limitations imposed by the nonuniqueness of solutions, the accuracy of the resistivity method is also limited by other factors. The resistivity method is most successful when resistivity contrasts are at least twenty percent. However, extremely conductive or resistive layers can dominate the measured response and often preclude further electrical penetration. Common examples of these barriers are coal seams and the salt water/fresh water interface. In general, this method's ability to resolve resistivity contrasts decreases with increasing depth.

3.1.7 Summary

As with seismic refraction, the electrical resistivity technique is used to map hydrologic and lithologic boundaries in unconfined aquifer systems. In settings where stratigraphic units are composed of distinctly different resistivities, this technique can identify lithology. Resistivity data have successfully defined: the depth to the water table, the depth and thickness of clay layers, the relative positions of coarse and fine sediments, and the depth to the salt-water/fresh-water interface. Thus, electrical resistivity is another surface geophysical technique which can provide data for WHPA delineation programs.

3.2 ELECTROMAGNETIC INDUCTION

3.2.1 Introduction

The electromagnetic induction (EMI) method was developed for use in mineral exploration and has been applied to ground-water investigations. These applications include salt water intrusion studies (Stewart, 1982) and aquifer mapping studies (Haeni, 1986d). With the enforcement of new environmental standards, EMI surveys have also been applied to contaminate mapping investigations (Sweeney, 1984; Rudy and Caoile, 1984; Grady and Haeni, 1984). The recent popularity of the EMI method relates also to the development of new technology which provide for rapid data acquisition and interpretational procedures.

3.2.2 Theory

The electromagnetic induction method uses coils instead of electrodes to induce current into the earth without ground contact. A time-varying magnetic field is generated by the transmitting coil, and this primary field induces currents and a secondary EM field in the subsurface. This secondary EM field is measured by the receiving coil as a voltage (see Figure 6). These voltage measurements are related to the subsurface electrical conductivity (inverse electrical resistivity).

EMI conductivity measurements reflect the cumulative response of the materials stretching from the earth's surface to an approximate depth known as the "penetration depth." Surface materials contribute more to these bulk measurements than do the deep materials. Thus, the electromagnetic technique respond to the same subsurface variations as the electrical resistivity technique, even though each method weights the contributions from each subsurface region differently.

3.2.3 Methodology

Terrain conductivity meters or low induction number instruments provide direct readings of conductivity in the field. For these instruments, the penetration depth of the EM field is a function of the coil spacing, the transmitter frequency and the coil orientation. For profiling measurements, all three variables are held fixed and the coils are moved incrementally along the survey traverse. These instruments are designed for this procedure as they have fixed coil spacings and employ frequencies that are sufficiently low for the depth of penetration to be independent of frequency. In general, the sampling depth of these instruments is roughly three quarters to one and one-half times the coil spacing, depending on instrument orientation. Coil spacings range from 3 to 122 feet. In these profiling surveys, data is collected at discrete stations, and the resulting conductivity values are plotted as a function of position. The resulting pattern is a map of subsurface conductivity.

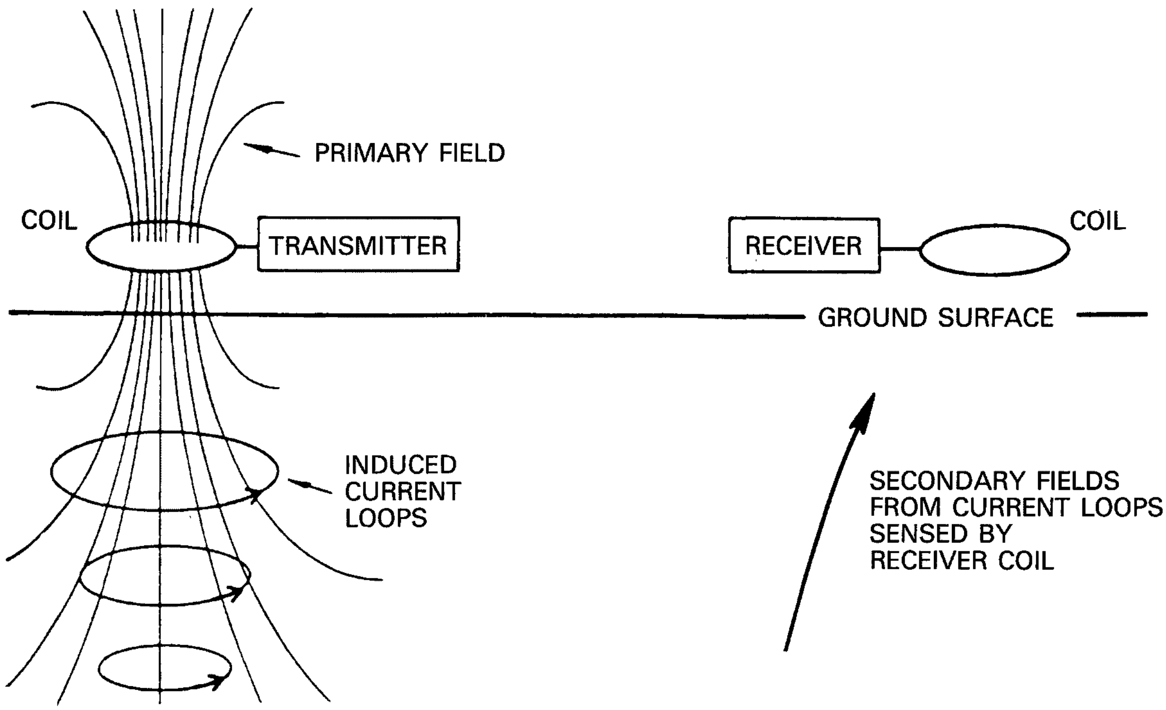

Figure 6: Schematic diagram of EMI method (after Benson et al., 1982).

EMI has also been used to collect sounding data. In these investigations, the coil orientation is held fixed while the coil separation is increased over each survey station. (For these instruments, the frequency is also changed at each spacing to keep the induction number constant.) Usually two fixed-spacing instruments are employed in an EMI sounding survey, and the resulting data requires semiquantitative analysis. Unfortunately, an experienced geophysicist is required to interpret these data, and the data are generally inadquate for resolving more than two or three layers (McNeill, 1980). Although the analysis of selected soundings can provide useful information (Grady and Haeni, 1984), the EMI method is most effective for profiling measurements.

As with all geophysical methods, the EMI technique is susceptible to cultural and subsurface noise. For example, passive metallic objects may cause actual geophysical anomalies; power lines may interfere with EMI measurements; and, radio signals may interfere with data acquisition. The interpreter must account for these cultural and physical anomalies when interpreting the data.

3.2.4 Ground-Water Applications

In many ground-water assessment studies, the EMI method is used as a reconnaissance tool since qualitative conductivity information can be acquired, mapped, and interpreted in a minimum of time. The recent popularity of EMI methods relates to instrument and data processing advances. For many instruments, ground contact is not required, and some instruments are even designed to make continuous electrical conductivity measurements.

EMI reconnaissance data may be supplemented by other surface geophysical or test hole data. Electrical resistivity data are commonly used to corroborate EMI profile data. EMI measurements are more sensitive to small-scale lateral conductivity variations. Thus, EMI data are used to map shallow lateral lithologic and water quality variations while resistivity data are used to map vertical changes or to calibrate EMI measurements.

3.2.5 Summary

The EMI conductivity method provides an efficient means for assessing subsurface conductivity anomalies, and extrapolating between wells or resistivity survey lines. The EMI method however provides only limited vertical resolution due to the limited amount of sounding data that can be acquired. EMI is most effective as a profiling tool and is often applied in reconnaissance surveys. Some investigators have used the EMI method to map lithologic changes in unconfined aquifer systems. Within their respective depth or resolution limitations, both the EMI and resistivity methods can provide estimates of hydrologic parameters and aquifer characteristics. The careful implementation of these electrical methods can reduce the costs of wellhead protection programs.

3.3 VERY-LOW-FREQUENCY RESISTIVITY

Many other electrical techniques have been developed for use in both mineral and petroleum exploration as well as ground-water studies. One technique which deserves some mention is the very-low-frequency resistivity (VLF) technique. VLF is similar to EMI but uses low frequency radio waves transmitted by naval communications stations as the source. VLF instruments consist of one EMI-type coil which measures the horizontal magnetic field, and a pair of electrodes which measure the orthogonal electric field. These portable instuments provide a direct reading of apparent resistivity values in the field. As a result, VLF data can be acquired both rapidly and inexpensively.

Since the input frequency is constant, the penetration depth of the probing radiation is solely determined by the subsurface resistivity. In resistive terrains, the penetration depth can range from 100 to 1000 feet. In conductive terrains, the penetration depth can be as little as 10 feet. VLF has been applied in both groundwater contamination studies (Grady and Haeni, 1984), and aquifer mapping studies (Haeni, 1986d). Haeni used VLF in conjunction with other geophysical techniques to delineate hydrogeologic boundaries in glacial aquifer systems. Thus, the VLF method is similar to the EMI method in both data acquisition characteristics and application potential. Both techniques are simple to use and provide information suitable for reconnaissance purposes.

3.4 GROUND PENETRATING RADAR

3.4.1 Introduction

Ground penetrating radar (GPR) is a reflection technique which uses high-frequency electromagnetic waves to continuously map subsurface parameter changes. This technique is similar to seismic reflection in that both methods measure the time required for a wave to travel from the earth's surface to a reflecting horizon and back to the surface. These travel times are used to map the distribution of hydrologic or lithologic changes. The probing electromagnetic radiation of the radar technique responds to the same property changes as the electromagnetic technique. Thus the GPR technique has acquisition similarities to seismic reflection yet measures electromagnetic instead of acoustic property changes. This technique has been available for a number of years, and recent technological advances and environmental applications have led to the technique's increased popularity. The principles and the applications of GPR are discussed by Davis et al. (1984), Coon et al. (1981), Dolphin et al. (1978), and Moffat and Puskar (1976).

3.4.2 Theory

The subsurface parameters which influence the propagation of radar waves are the dielectric permittivity and and electrical conductivity. The radar technique responds to near-surface changes in electrical conductivity and the dielectric constant. Dielectic permittivity is controlled by water content, clay content and bulk density. Clay minerals tend to increase permittivity substantially while high salinity slightly decreases permittivity. The result is that the depth of penetration of radar waves is controlled by the electrical conductivity, water content, and clay content.

3.4.3 Methodology

Ground penetrating radar devices emit electromagnetic pulses and record the travel time of the transmitted and reflected energy as the instrument is moved along the earth's surface (see Figure 7). A radar device contains a radio antenna, a signal receiver, a recorder, and electronic circuitry to coordinate the signal input and output. This equipment is highly sophisticated, yet data acquisition procedures are simple. A typical radar transducer is mounted on wheels a few inches off the ground and either pushed or pulled across the survey area. With this approach, data are collected continuously, and a large amount of data can be rapidly acquired. Many radar units are towed behind field vehicles at speeds up to five miles per hour. The resolution of the resulting data is determined in part by the rate of traverse.

Although data collection is a simple procedure, operating the radar instrumentation can be challenging since instrument parameters must be adjusted to accomodate site characteristics. For example, the bandwidth of the survey antenna must be selected so as to optimize the

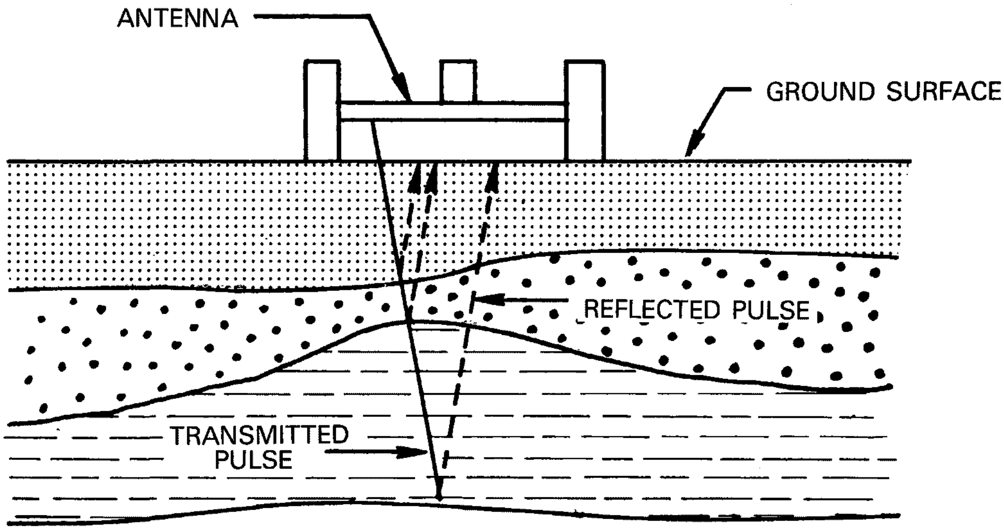

Figure 7: Schematic representation of Ground Penetrating Radar method (after Costello, 1981)

depth of penetration and the vertical resolution. Higher input frequencies favor greater resolution but are subject to increased attenuation. Penetration depth however is the primary consideration and resolution a minor factor. The estimated travel time required for the radar waves to probe the targeted depth is also an input parameter. This "time window" is based on an assessment of the subsurface geology. Thus, to effectively operate complex radar instrumentation, field personnel must have a working knowledge of geophysics and electronics.

3.4.4 Data Processing and Interpretation

Radar data are presented graphically as distance versus two-way travel time. Each graphic profile represents a direct vertical slice of the survey area which allows interpreters to associate subsurface features with surface locations. Most radar instruments contain graphic display devices which provide a "picture" record in the field. By checking display records, real-time analog processing parameters can be refined in the field.

In many surveys, the data is recorded on magnetic tape and is eventually reprocessed to reveal more detailed subsurface information. This processing utilizes digital or analog filters to eliminate background system or cultural noise. Some survey objectives may require the application of sophisticated digital processing algorithms which have been developed by the petroleum industry for reflection data. The costs of applying these processing techniques are not usually justified for radar surveys. Most radar surveys are used for the rapid reconnaissance of surficial materials.

It is often important to convert the time-distance output plots to depth-distance plots. This can only be accomplished by estimating the subsurface velocity of the radar wave. The accuracy of these estimates depends on the geologic complexity of the area and the reliability of the data. In many cases, the moisture content of the porous media varies with depth. As a result, the vertical velocity distribution has a nonlinear component which is not accounted for in time-depth conversions. This leads to the inaccurate location of reflectors.

3.4.5 Ground-Water Applications

Since water has a high dielectric constant and bedrock has a low conductivity, GPR can be used to identify the water table and the alluvium/bedrock contact in some shallow unconfined aquifer systems. This technique can also detect some small-scale stratigraphic changes in some alluvial deposits.

Since radar is a reflection technique, it is useful to compare its methodology to that of seismic reflection. The radar technique provides extremely high-resolution data; a seismic reflection survey with equivalent resolution would have geophones spaced only a few inches apart. The primary advantage of radar however relates to its data acquisition capabilities. The radar technique combines rapid continuous spatial sampling with qualitative in-field interpretation. By contrast, seismic reflection data acquisition is a complicated process which requires complex equipment and a field crew. Furthermore, processing of reflection data involves the application of sophisticated computer algorithms, but the resulting interpretations are quantitative. Both reflection techniques require experienced personnel for successful operation.

The primary difference between radar and seismic reflection is the effective depth of penetration. As mentioned above, radar waves are attenuated by the electrical conductivity of pore fluids and clay minerals. Penetration depths are highly site-specific. By contrast, engineering reflection surveys are most effective in areas with a shallow water table and an overburden which exceeds 100 feet in thickness (Haeni, 1986b). Thus, in ground-water studies, seismic reflection is used to quantitatively map deeper horizons while radar is used as a shallow reconnaissance tool due to its data aquisition capabilities.

3.4.6 Limitations

Like all surface geophysical techniques, radar has its own unique capabilities and limitations. To understand the applicability of this method, the operator must understand the characteristics of the site. In general, high subsurface conductivity results in an increased attenuation of the probing waves and a decreased depth of penetration. Highly-conductive media or clay-rich lithologies impair the penetration depth of the technique. A fine-grained, clay-rich, saline-saturated lithology can lead to a penetration depth of 3 feet. In coarse-grained sands which are either dry or saturated with fresh water, the penetration depths can be as deep as 100 feet. Thus, interstitial water influences the radar response in two ways: changes in dielectric properties produce strong reflections, and high conductivity attenuates the radar waves, thereby reducing penetration depths. The result is that the radar technique can accurately map shallow water table surfaces in some alluvial settings (Olhoeft, 1984; Wright et al., 1984).

3.4.7 Summary

The radar technique provides continuous reflection profiles of shallow dielectric interfaces. Radar is most effective as a reconnaissance tool since data can be acquired rapidly and do not require complicated processing. The radar technique is most suited to mapping the water table or bedrock surfaces in certain unconfined aquifers. This application is highly site-specific since the probing depth of the electromagnetic radiation is limited by conductive materials.

CHAPTER 4

POTENTIAL FIELD METHODS

4.1 GRAVITY

In gravimetric studies, the local vertical component of the acceleration due to gravity is measured at the earth's surface using a gravimeter. These data are processed to remove known gravitational effects (for example, local topography) and then the resulting "gravity anomalies" are presented as profiles or contour maps. The spatial variation of gravity anomalies is related to lateral subsurface density contrasts. In principle, any geologic feature which has an associated density change can be detected by the gravity method.

Gravity data cannot be directly related to a unique subsurface model. Data interpretation consists of comparing field anomaly patterns with the gravitational patterns of theoretical models. This comparison procedure can be done by simple graphical means or by computerized iterative inversion routines. The measured gravitational field is a complex function of the shape, density and depth of the subsurface features, and quite different subsurface features may give rise to rather similar anomalies. This inherent nonuniqueness of data sets is a serious problem. The use of highly-sophisticated computerized inversion algorithms cannot reduce uncertainty due to nonuniqueness factors.

In general, gravity interpretations are improved if they are constrained by additional subsurface geologic or geophysical information. This information is usually derived from well data, regional geologic mapping studies, and other geophysical data. The rudiments of gravimetric data interpretation and acquisition are discussed by Dobrin (1976), and Telford et al. (1976).

With the development of modern gravimeters, the gravity method has become an important reconnaissance tool in ground-water studies. These instruments are portable and can be operated by relatively inexperienced personnel. The gravity method has proved to be an inexpensive and rapid means of determining the large scale features of unconfined aquifer systems, at least in areas of relatively flat topography (Stewart, 1980; Carmichael and Henry, 1977; Zohdy et al., 1974; Ibrahim and Hinze, 1972; Rankin and Lavin, 1970). The success of the gravity method in these studies depends on the density contrast between the unconsolidated sediments and the underlying bedrock. In general, this density contrast is measurable, and the gravity method is often used to map bedrock topography by defining the boundaries of these aquifers. Many times these surveys focus on determining aquifer thickness.

Care must be taken in gravity data collection and processing. Results can be seriously impaired by local geologic inhomogeneities, topographic irregularities, gravity station location errors, and vibrational noise. Additionally, the resolving power of the method is limited and usually additional geophysical data are required to formulate an interpretation. The primary advantage of the gravity method is its facility in data acquisition. Processing and interpretation of these data however can be a tedious and inconclusive process. This is especially true if the data require complicated topographic corrections which can add noise that may seriously obscure the anomaly patterns of the aquifer. In any case, the gravity method can provide inexpensive reconnaissance data which can be used to supplement other geophysical data in ground-water studies.

4.2 MAGNETICS

The magnetic method detects variations in subsurface magnetic susceptibility through measurements taken on or above the earth's surface. Magnetic surveys measure either the absolute or the relative intensity of some magnetic field component. The magnetic field at any surface location is composed of the earth's primary magnetic field and the magnetic field anomalies produced by local distributions of magnetic material. The quantitative interpretation of magnetic data reveals the spatial magnetic characteristics of these materials.

Magnetic surveys range from the simple and inexpensive to the complicated and expensive. Correspondingly, magnetic field measuring devices range from primitive mechanical instruments to airborne systems. The instruments most commonly used are hand-held proton-precession magnetometers. These instruments are available in various sensitivities. The type of instrument used in a magnetic survey depends on the required level of precision, the spatial sampling, and the survey resources. Data is rapidly collected in all types of magnetic surveys and is either plotted as profiles or as contour maps.

The magnetic and gravity methods are similar in data acquisition and interpretation characteristics. Both methods sample a potential field quantity at the earth's surface and relate these observed data to theoretical models by curve-matching techniques. Nonuniqueness of data sets is also inherent in magnetic data, and experienced personnel are often required to provide accurate interpretations. The interested reader should consult Dobrin (1976), Telford et al. (1976), or Grant and West (1965) for more detailed treatments of magnetic data acquisition and analysis.

Sedimentary units are the most common water-bearing deposits but are typically nonmagnetic. Thus, the magnetic method is not generally applicable to mapping sedimentary units. (A few coarse clastics do contain magnetic minerals and have been mapped directly.) Special circumstances have made the magnetic method applicable to ground-water investigations. For instance, magnetometer surveys have been used to estimate the thickness of unconsolidated deposits overlying magnetic crystalline basement (Birch, 1984; Zohdy et al., 1974). Also, Wire et al. (1984) have used magnetic data to assist in the location of wells in bedrock formations, and Harmon (1984) used magnetics to delineate fracturing in basalts overlain by alluvium. Therefore, although the magnetic method has limited use in aquifer mapping studies, innovative surveys have been designed to reveal hydrologic boundaries which are defined by magnetic susceptibility contrasts.

The primary advantage of the magnetic method is its facility in data acquisition. Magnetic data can be rapidly collected in both surface and airborne surveys. Like gravity data, magnetic data has poor vertical resolution so that interpretations of depth parameters tend to be inaccurate. Both gravity and magnetic data, however, can give good resolution of lateral parameter changes. As a result, magnetic data is used qualitatively for reconnaissance purposes or to support other geophysical data.

CHAPTER 5

METHOD COSTS

5.1 INTRODUCTION

Aquifer delineation programs are designed according to economic and hydrogeologic constraints. Investigators often compare the production costs of the various aquifer delineation methods when designing a program. Many surface geophysical surveys are conducted in conjunction with the collection of observation well data. As a result, integrated surveys are sometimes designed according to cost analyses that consider the comparative utilities of surface and subsurface data. Often, the variability of survey costs prohibits the easy selection of one approach over the other.

In this section, cost estimates for surface geophysical surveys are presented with some of their associated operational constraints. These estimates are based on private contractor fees for penetration depths of 100 feet (where appropriate), based on limited personal communication in early 1987. Contracting costs are presented here because the capital costs of obtaining geophysical equipment can be expensive (see Table 2). Although these

Technique	Acquisition Instrument	Cost
Refraction	12 channel seismograph & acces.	$25000
Reflection	same as above & digital recorder	$32000
Resistivity	transmitter/receiver & cables	$12000
EMI	instrument	$19000
VLF	instrument	$10000
GPR	instrument	$25000
Gravity	instrument	$40000
Magnetics	instrument (hand-held)	$5000

Table 2: Capital cost estimates for geophysical instruments.

estimates are in dollar values, they should be viewed in a somewhat relative sense and not be used to plan individual surveys. One should remember that surface geophysical surveys are highly variable depending on who does the work, the details of the site, and the scope of the investigation. In this section, the cost estimates are grouped by method according to production cost similarities.

5.2 SEISMIC AND ELECTRICAL RESISTIVITY

The seismic refraction, seismic reflection and electrical resistivity techniques are labor-intensive techniques that can require complex data processing procedures. The estimated costs are presented in Table 3. In estimating survey costs, the investigator should account for field crew, equipment rental, and data processing costs. In addition to these fixed costs, one must realize that the location and the terrain of the site as well as the depth of investigation are important factors. The cost ranges in Table 3 reflect the variability in production rate and processing requirements for these techniques. Crew travel and land surveying costs are not included.

Technique	Cost
Seismic Refraction	$2.00 - $3.50/foot
Seismic Reflection	$6.00 - $9.00/foot
Resistivity Sounding	$275 - $425/location
EMI	$0.25 - $0.50/foot
VLF	$0.25 - $0.50/foot
GPR	$0.10 - $0.30/foot
Resistivity Profile	$2.00 - $3.75/foot
Gravity Profile	$0.75 - $1.25/foot
Magnetic Profile	$0.50 - $1.00/foot

Table 3: Contractor cost estimates for a depth of penetration less than 100 feet and a station spacing of 50 feet (where applicable).

5.3 GRAVITY AND MAGNETICS

Unlike the preceeding techniques, these potential methods do not require a field crew of more than one person, so equipment rental and data processing costs are relatively more significant. The costs for running a gravity survey and a magnetic survey are similar with gravity slightly more expensive due to increased labor and processing costs. The cost estimates in Table 3 for the gravity and magnetic methods consider the labor of one geophysicist, equipment rental, and data processing with travel and land surveying costs not included. (Land surveying is critical to the success of a gravity survey and represents a sizable additional expense.) The cost range presented for these methods results from variation in production rates at a constant station spacing, here assumed to be 50 feet.

5.4 EMI, VLF, and GPR

Electromagnetic induction, very-low-frequency, and ground penetrating radar are electromagnetic techniques which permit rapid and simple data collection. The processing requirements are not expensive for each of these techniques. Thus, linear foot costs for these methods are relatively inexpensive (see Table 3). Survey costs include: field crew labor, equipment rental and data processing. As before, the range in the estimated costs results from variability in rates of production.

5.5 CONCLUSIONS

Table 3 provides an estimate of private contractor survey costs. Private contractors however are not the only reliable means of collecting surface geophysical data. The U. S. Geological Survey, State geological surveys, and geology departments at many universities are currently conducting geophysical studies for municipal or State governments at somewhat different cost/timing structures. Investigators should be aware of these possibilities when designing an aquifer delineation program. Table 3 can be used as a rough guide when designing a water resources investigation. Actual survey costs can only be determined from site reconnaissance data and the accessability of the site.

CHAPTER 6

WHPA AND AQUIFER DELINEATION

6.1 INTRODUCTION

In WHPA delineation programs, surface geophysical techniques can: 1) provide aquifer information to complement well data used by some WHPA delineation methods, and 2) map the hydrogeologic flow boundary WHPA criterion. Surface geophysical techniques are most applicable for aquifers under water table or shallow confinement conditions. In geophysical surveys, the selection of a particular technique depends on the geology of the survey area, the existing hydrogeologic data, and the project resources.

6.2 AQUIFER ASSESSMENT

Except for the arbitrary fixed radius method, all WHPA delineation methods map hydrologic WHPA criteria and therefore require well data as input (see Guidelines for Delineation of Wellhead Protection Areas, 1987). In order to map a WHPA, regional or subregional hydrogeologic information are required. As an alternative to an extensive drilling program, decision-makers may wish to supplement limited well data with surface geophysical or geological data. There are many different strategies for integrating surface and well data based on economic and hydrogeologic considerations. In general, these surface geophysical surveys are designed to provide a more detailed understanding of the subsurface while limiting the cost of drilling additional exploratory water wells.

6.2.1 Reconnaissance

An important step in developing a WHPA program is the assessment of hydrogeologic conditions within a state's borders. One initial step is the review of published and unpublished hydrogeologic data on the survey areas. In many survey areas, well data provide the aquifer information required to design surface geophysical surveys.

After the preliminary work has been completed, then geophysical reconnaissance data may be collected. If, as in many cases, there are only limited well data in the survey area, then these reconnaissance measurements may provide an initial assessment of subsurface aquifer characteristics. If, however, there are extensive well data in the survey area, then geophysical reconnaissance data may be used to extrapolate this subsurface information away from or between these wells. In general, the design of a geophysical reconnaissance survey depends on the existence and the nature of previous data sets.

The selection of a particular technique used in a reconnaissance survey depends on the nature of the survey area, and the availability of equipment and skilled personnel. In reconnaissance work, the least expensive geophysical techniques are generally applied first. For example, the gravity method is an economical and rapid means for determining the gross configuration of some glacial aquifers, and this method may be applied in advance of the more expensive seismic refraction technique (Tucci and Pool, 1987; Frohlich, 1979). Similarly, the electromagnetic induction (EMI) technique is often applied in coastal settings to estimate the location of the salt-water/fresh-water encroachment zone without drilling expensive observation wells (Stewart, 1982). In these encroachment surveys, EMI data may later be supplemented by more expensive electrical resistivity data which offer improved vertical resolution. As a final example, seismic refraction and electrical resistivity reconnaissance measurements have been used to determine the saturated thickness variations of a glacial aquifer in efforts to site water wells in the area (Underwood et al., 1984).

Once reconnaissance work has been completed, more detailed investigation is required to define the flow characteristics of aquifer systems. To obtain this information, decision-makers may decide either to site new observation wells, or to perform more detailed geophysical investigation. In general, their decision is based on a comparison of the relative cost of drilling water wells against the cost and accuracy of the geophysical methods.

6.2.2 Detailed Site Investigation

In detailed geophysical surveys, the acquisition parameters are designed to allow maximum resolution. These studies generally provide detailed maps of subsurface parameter variations. As before, the selection of a particular technique depends on the hydrogeologic setting. For example, in some glacial aquifers, the ground penetrating radar (GPR) technique can be employed to map the water table and possibly to predict ground-water flow (Wright et al., 1984). Similarly, a seismic refraction survey may be designed to produce a detailed map of the alluvium/bedrock contact (Sverdrup, 1986). Also, the electrical resistivity method has been used to predict aquifer permeability and transmissivity values (Kosinski and Kelly, 1981); these aquifer parameters may serve as the input to analytical ground-water modeling routines.

The final example discussed here was an integrated survey conducted by Tucci and Pool (1987) in the alluvial basins of Arizona. This investigation used the strategy of collecting reconnaissance data first and later conducting more detailed site investigation. The gravity method was used as the reconnaissance tool to delineate the basin margins and estimate the depth to bedrock. Although the accuracy of these data are estimated to be only within plus or minus 30 percent, they do provide a rapid and relatively inexpensive first approximation.

This reconnaissance work was followed by a detailed refraction/resistivity survey. The refraction survey identified the depth to bedrock and the water table as well as provided more detailed stratigraphic and structural information on such features as buried faults. The resistivity survey verified the structural and stratigraphic interpretations of the seismic method and also provided information on the location of fine-grained deposits. The resistivity technique was unsuccessful in locating the water table due to the heterogeneity of the deposits. Therefore, this integrated survey provided a variety of basin information that could be used to guide further ground-water flow investigation.

In addition to these cited examples, there are other published reports which discuss detailed aquifer assessment surveys. Most of these studies are focused on ground-water resource evalution and are directly applicable to WHPA delineation efforts.

6.3 WHPA DELINEATION

In the above examples, surface geophysical techniques are an economical means for recovering subsurface information related to ground-water flow. These geophysical data supplement well data which are used for mapping WHPA delineation criteria. As mentioned above, geophysical reconnaissance surveys often map the margins of alluvial aquifers. In some of these settings, the aquifer margins correspond to the aquifer recharge zone and therefore form one flow boundary of the WHPA. In the hypothetical valley aquifer shown in Figure 8, surface geophysical techniques are used to map the upgradient limit of the aquifer materials. This lithology change is designated as one WHPA boundary. Therefore, surface geophysics, as one set of techniques within the hydrogeologic mapping WHPA delineation method outlined in the Guidelines, may be used to directly map the flow boundaries WHPA criterion.

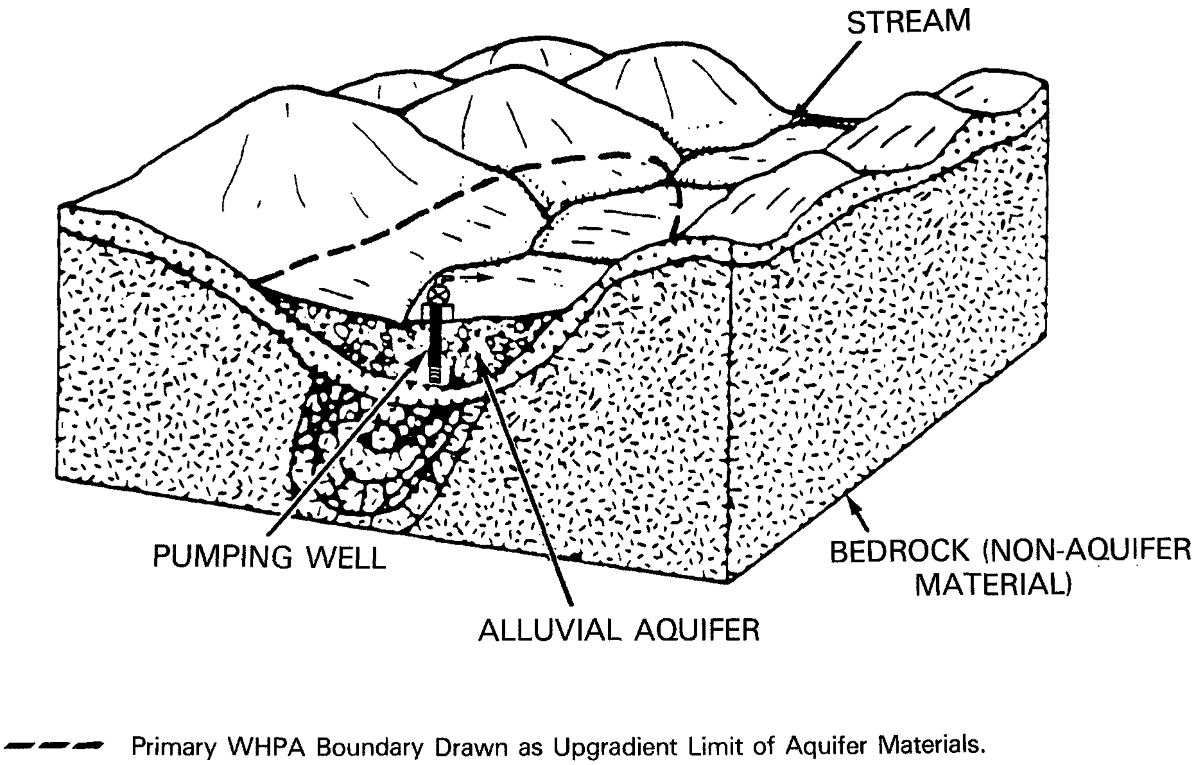

Figure 8: WHPA "flow boundary" criterion is mapped using surface geophysical techniques.

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