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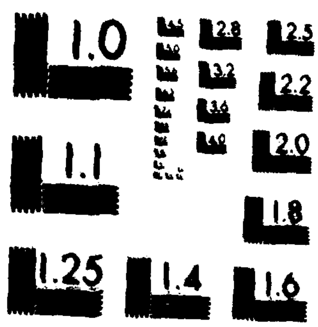

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Identification and Description of Geophysical Techniques

ROBERT L. COSTELLO
D'APPOLONIA CONSULTING ENGINEERS, INC.
10 DUFF ROAD
PITTSBURGH, PA 15235

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18. SUPPLEMENTARY NOTES

This is the first of two reports. The results of Phase I will be reviewed and geophysical techniques will be implemented in Phase 2. Phase 2 will consist of planning, executing, and interpreting a geophysical field survey.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Installation Restoration, Geophysical Techniques, Shallow Geologic and Aquifer Analysis, Hazardous Wastes, Groundwater Contamination, Pollutants

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of the Phase I study to identify and describe geophysical techniques which can be advantageously applied to shallow geologic and aquifer analysis. For clarification, "shallow" is defined to mean depths less than 300 feet. With the exception of radar, however, none of the identified techniques are inherently limited to this range.

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Included in the report is a discussion of the geologic features and conditions which affect or control groundwater movement. Following this discussion is an identification of traditional and developmental surface and borehole geophysical techniques, not to include multispectral imagery or aerial photography, which can be employed to qualify and quantify these features and conditions.

Also included is a description of each applicable geophysical technique consisting of field procedures, equipment, and data processing. Additionally, an evaluation of each technique in terms of effectiveness and cost is provided.

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1.0 INTRODUCTION

This report presents the results of the Phase I study to identify and describe geophysical techniques which can be advantageously applied to shallow geologic and aquifer analysis. This study has been conducted under Government Contract No. DAAK11-80-C-0029 entitled "Development of Geophysical Techniques for Installation Restoration" and represents the initial effort in an overall program to develop geophysical techniques for installation restoration.

1.1 BACKGROUND

The United States Army Toxic and Hazardous Materials Agency (USATHAMA) has been assigned responsibility to identify and contain or eliminate all toxic and hazardous materials which are migrating or may be migrating in groundwater at specific Department of Defense installations. Existing subsurface data are limited to borehole information. In order to expand the subsurface data base in a cost-effective manner, a decision has been reached to investigate the feasibility of using various geophysical techniques for this purpose. The additional data would be used as input to the decision-making plans for abating contamination problems.

The program to investigate the feasibility of using geophysical techniques to expand the subsurface data base is divided into two phases. Phase I consists of identifying and describing geophysical techniques that can be advantageously applied to shallow geologic and aquifer analysis. The results of Phase I will be reviewed and techniques will be recommended for implementation in Phase II. Phase II consists of planning, executing, and interpreting field surveys at the Volunteer Army Ammunition Plant in Chattanooga, Tennessee to provide actual field data for evaluating the application of geophysical techniques to installation restoration. Following completion of these activities, the field data will be evaluated, conclusions will be determined and recommendations for future use of various geophysical techniques will be made.

1.2 SCOPE AND CONTENT

The identification and description of geophysical techniques which can be advantageously applied to shallow geologic and aquifer analysis encompasses traditional and developmental surface and borehole geophysical techniques, not to include multispectral imagery or aerial photography. To provide clarification, "shallow" has been defined to mean depths less than 300 feet. With the exception of radar, however, none of the identified techniques is inherently limited to this range. Additionally, assumptions concerning the extent of field geophysical surveys have been made to assist in estimating costs. For surface techniques, it has been assumed that less than five miles of survey will be run during any one site investigation. For borehole techniques, the extent of logging for any one site investigation has been assumed to be less than 1,000 feet of logging. These limits do not imply extensive cost changes for surveys of greater extent. A detailed breakdown of costs is provided in Chapter 4.0.

Identification of potentially useful geophysical techniques is presented in Chapter 2.0. The identification consists of a determination of the features and conditions which affect and control groundwater movement, the geophysical expressions of these features and conditions, and the geophysical techniques which are sensitive to the physical expressions. Chapter 3.0 contains a description of the identified techniques to include basic theory, field procedures, data format, equipment, data processing, prerequisites, calibration of equipment, personnel qualification, verification and review, and documentation and record requirements. Chapter 4.0 contains an evaluation of each identified geophysical technique to include capabilities, range of application, and cost. Chapter 5.0 provides a limited discussion of additional geophysical techniques in the developmental stage or with limited application. Chapter 6.0 is a summary.

2.0 IDENTIFICATION OF GEOPHYSICAL TECHNIQUES

One of the most important considerations in the transmission of pollutants in the geologic environment is groundwater. Groundwater behavior and movement can be understood only with an understanding of the features and conditions which affect and control its movement. Such understanding will also provide an indication of the geophysical properties (acoustic, electrical, density, and magnetic) that are related to these features and conditions which can be detected and/or measured by geophysical techniques for the purpose of shallow geologic and aquifer analyses.

The following sections provide a discussion of the features and conditions which affect and control groundwater movement, the geophysical properties related to these features and conditions, and the geophysical techniques which are useful for defining these features and conditions both in a qualitative and quantitative sense. For convenience, the pertinent features and conditions have been organized into three categories as follows:

- Stratigraphy
- Geologic structure
- Aquifer properties

2.1 DEFINITION OF STRATIGRAPHY

Within the category of stratigraphy, the following features and conditions are of major importance in the analysis of shallow geology and aquifers:

- Lithology
- Lithologic correlation
- Surficial Materials

Lithology is an important feature as it indirectly suggests chemical properties of rocks which determine the potential for reaction with groundwater and pollutants. Shales and clays, for example, have the potential for concentrating certain ions by the processes of ion exchange and adsorption. Further, limestones may dissolve when the groundwater is acidic. Knowledge of lithology is also important because certain properties can be inferred for certain lithologies. For example, low permeability can almost always be assumed within an unweathered, unfractured shale unit. Geophysical expression of lithology can include acoustic velocity, electrical resistivity, spontaneous potential, density, gamma emission, gamma absorption, and neutron absorption.

Lithologic correlation is important because it provides knowledge of the lateral continuity and thickness of formations and indicates the potential for groundwater movement in three dimensions. Correlation also provides information concerning facies changes and unconformities which may inhibit or redirect groundwater flow. Finally, the validity of interpolating hydrologic properties (e.g., porosity and permeability) across an area depends directly on lithologic uniformity which can be determined by correlation. Since correlation is the study of lithologic interrelationships across an area, the geophysical expressions which are useful in studying correlation are the same for lithology with the qualification that applicable geophysical techniques should have the ability to provide lateral or profile type information.

Surficial material (soil, alluvium, weathered rock, talus, etc.) can affect groundwater behavior and movement in three ways. Firstly, the surficial material can act directly as a pathway for groundwater movement, particularly when overlying relatively impermeable formations. Secondly, the nature of surficial material can quantitatively and qualitatively control the percolation of pollutants from the surface into the groundwater regime. Finally, the nature of surficial material can control the rate of aquifer recharge which in turn can control the flow and dilution of pollutants. The surficial material can be studied from the standpoint of lithology in which case the geophysical expressions are the same as discussed specifically for lithology or from the standpoint of thickness and lateral extent in which case the comments concerning lithologic correlation are pertinent.

Based on the previous discussions the surface geophysical techniques which are useful for stratigraphic resolution on the basis of associated geophysical expression are:

- Seismic refraction
- Seismic reflection
- Resistivity
- Gravity
- Magnetics
- Radar

The geophysical borehole logging techniques which are likewise useful are:

- Spontaneous potential
- Resistance
- Natural gamma radiation
- Gamma-gamma
- Neutron

2.2 DEFINITION OF GEOLOGIC STRUCTURE

Within the category of geologic structure, the following features and conditions are of major importance for shallow geologic and aquifer analysis:

- Folding
- Faulting
- Fracturing
- Dissolution features
- Buried drainage and topography
- Igneous features (dikes and sills)

Folding impacts the movement of groundwater in two ways. The first and most obvious way is the control of flow direction. In the absence of other pertubating factors, groundwater will preferentially flow down dip. The second way in which folding can control groundwater movement is by ponding along the axes of folds, particularly synclines; groundwater may flow down one limb of the fold, but not have the gradient to flow up the other limb. The geophysical expression of folding is the warping of acoustic, electrical, density, and magnetic interfaces. Often these interfaces correspond to formation boundaries.

Faulting may provide pathways along which groundwater may migrate depending on the intensity of associated fracturing and the occurrence of recementation. Faulting can also produce permeability barriers when movement brings permeable and impermeable units into contact or when the fault zone is recemented. The geophysical expression of faulting is offset of the same types of interfaces discussed above for folding. Additionally, the zone of fracturing associated with faulting can have direct expression as a low resistivity zone when infilled with mineralized groundwater.

Fracturing can also provide pathways along which groundwater migrates. In this context, both the intensity and orientation of fracturing are important. The intensity of fracturing impacts the flow rate directly while the orientation can control preferred direction of flow. Often, fracturing is the only form of permeability which exists in crystalline rock. The geophysical expressions of fracturing can include changes in acoustic velocity, electrical resistivity, gamma ray absorption, neutron absorption, and dielectric constant.

Dissolution features such as cavities and vugs are important because they can provide pathways for pollutants to percolate from the surface to the groundwater regime or may provide pathways for the flow of groundwater itself. Additionally, dissolution features may effectively create reservoirs for the storage of groundwater and pollutants or may provide discharge pathways for groundwater to the surface. The geophysical expressions of dissolution features are acoustic velocity, density, electrical resistivity, dielectric constant, gamma ray absorption, and neutron absorption.

Buried drainage is important primarily because it represents possible pathways for migration of groundwater. Also, it may act as a storage reservoir. The geophysical expressions of buried drainage are acoustic velocity, density, electrical resistivity, and magnetic susceptibility (when incised into magnetic terrains or infilled with magnetic material).

Another feature which can control or affect groundwater movement is buried topography. For the case where the buried topographic surface has a lower permeability than the surficial materials, percolating groundwater will flow along the buried interface in a manner analagous to surficial runoff. Buried topographic surfaces can also cause ponding of groundwater in low spots. The geophysical expressions of buried topography are the same as for buried drainage.

Igneous features such as dikes and sills can also control groundwater movement, particularly in igneous and metamorphic terrains. In such terrains, the predominant form of groundwater movement is through fractures or joints. Emplacement of dikes and sills can impede groundwater flow due to the low permeability of intrusives. The geophysical expressions of igneous features are the same as for buried drainage.

The previous discussions indicate that all of the surface geophysical techniques identified as potentially useful for defining stratigraphy are also potentially useful for defining geologic structure. Similar comment applies to geophysical borehole logging techniques with the addition of the caliper and sonic logging methods.

2.3 DEFINITION OF AQUIFER PROPERTIES

The aquifer properties of greatest importance to the task of containing or eliminating the spread of pollutants in groundwater are:

- Porosity and permeability
- Potentiometric surface
- Flow direction and rate
- Temperature
- Water chemistry

Porosity is of interest as it provides a measure of the ability of subsurface material to store groundwater and in certain cases can be related to permeability. Permeability is important because it affects the flow of groundwater directly and also determines the resident time that groundwater will spend in contact with specific lithologic units thereby affecting the potential for chemical reaction. The geophysical expressions of porosity are acoustic velocity, gamma ray absorption, and neutron absorption. No direct expression that can be measured by geophysical methods exists for permeability, but inferences can be made based on lithology, porosity, temperature, and fluid movement. The latter two properties can be measured in boreholes with geophysical logging techniques.

The potentiometric surface of an aquifer is important because it controls the flow direction and rate. Specifically, lateral variation in the potentiometric surface (hydraulic gradient) provides the driving force for groundwater movement. Knowledge of the potentiometric surface also provides an estimate of the potential for aquifer communication along boreholes, fault planes, or fracture zones. For the case of an unconfined aquifer, the geophysical expressions of the potentiometric surface (water table) are acoustic velocity and electrical resistivity. Within the borehole environment, indication of relative potentiometric surface can be obtained from fluid movement and thermal measurements.

The single most important factor in the study of the groundwater-pollutant problem is aquifer flow. The flow equation may be expressed as:

$$Q = kiA$$

where

- Q = rate of flow
- k = permeability
- i = hydraulic gradient
- A = total cross-sectional area across which flow occurs

The permeability and hydraulic gradient have been discussed previously in this section while the cross-sectional area may be determined from stratigraphic studies as discussed in Section 2.1. Determination of flow is therefore a process of integrating several characteristics which can be determined by geophysical means rather than a separate process. For example, suppose that groundwater flow through a buried drainage channel is of interest. Through the use of geophysical methods, the permeability of the infilled material, the potentiometric surface (and hence the hydraulic gradient), and the cross-sectional dimensions (and hence cross-sectional area) can be quantified. Using the previously defined equation, the flow can be calculated from these parameters. Also important under the category of flow is preferred direction which can be impacted by all the above factors, as well as those discussed in Section 2.2.

Temperature of groundwater is important because it may control the solubility of pollutants and may govern chemical reaction rates in the subsurface. Temperature is a geophysical expression which can be measured directly in boreholes.

Water chemistry is of interest to the extent that it affects possible groundwater-pollutant and groundwater-lithology reactions. The physical expressions of water chemistry that are detectable by geophysical methods are few and consist of gamma radiation (from uranium, potassium, and thorium) and electrical resistivity (as a function of ionic concentration).

The above discussions indicate that fluid movement and thermal logging techniques should be added to the list of potentially useful geophysical methods.

3.0 DESCRIPTION OF GEOPHYSICAL TECHNIQUES

The following sections describe various geophysical techniques which have been identified in Chapter 2.0 as being potentially valuable for attaining the project objectives. Within the category of geophysical surface techniques, the following are included:

- Seismic refraction
- Seismic reflection
- Resistivity
- Gravity
- Magnetics
- Radar

Within the category of geophysical borehole-logging techniques, the following are included:

- Spontaneous potential
- Resistance
- Natural gamma
- Gamma-gamma
- Neutron
- Caliper
- Fluid-movement
- Temperature
- Sonic

The description of techniques includes basic theory, field procedures, data format, equipment, data processing, prerequisites, calibration of equipment, personnel qualification, verification and review, and documentation and record requirements.

3.1 SEISMIC REFRACTION

The seismic refraction method consists of measuring the travel times of acoustic compressional waves between an impulsive source on or near the surface and a surface receiver for varying source-receiver spacings.
The raw data consist of travel times and distances which are processed to determine the subsurface acoustic wave velocity distribution.

In general, only the first wave arrival is of interest and can be attributed to one of the two following wave types:

- The direct wave
- The critically-refracted wave

The direct wave travels through the near-surface layer along the shortest path between the source and receiver, while the critically-refracted wave travels along layer boundaries where the lower layer has an appreciably higher wave velocity than the upper layer. The type of wave which arrives first is determined by the subsurface wave velocity distribution and the source-receiver spacing.

For subsurface materials that can be represented by a sequence of horizontal layers whose wave velocity increases appreciably with depth, the first arrival for small source-receiver spacings will be a direct wave through the uppermost layer. As the source-receiver spacing is increased, the first arrival finally will become a critically-refracted wave from the boundary of the first and second layer with an observed apparent wave velocity equal to the wave velocity of the second layer. This situation is depicted in Figure 1. For greater spacings, the first arrival will be a critically-refracted wave from deeper layer boundaries and the observed apparent velocity will be that of the lower, high-velocity layer.

The systematic change of travel time with source-receiver offset is characteristic of subsurface wave velocity distribution within the limitations of the seismic refraction technique.

3.1.1 Field Procedures

3.1.1.1 Reversed Profiling

The basic refraction field method involves shooting reversed refraction profiles using a long linear spread of many geophones shot from each end. The distance between the shot point and the geophones is great enough so that the dominant portion of the travel path is a critically-refracted wave from the layer boundary or refractor being mapped. To provide near-surface coverage, an additional shot is sometimes made at the center of the spread. Additional deep information can be determined by shooting off both ends at increasing distances. Profiles may be overlapped along a line to produce continuous coverage.

When a refraction survey is started in a new area, it is common practice to shoot a profile in segments with the geophones tightly grouped. The source-receiver spacing is systematically increased, yielding a highly detailed time-distance curve. This curve is used to determine the spread geometry necessary to map the refracting horizons of interest. Optimum source strength, amplifier gain, and filter settings can be determined concurrently.

3.1.1.2 Broadside Refraction and Fan Shooting

In broadside refraction shooting, the shotpoints and geophones are located along two parallel lines. The distance between the two lines is determined such that critically-refracted waves from the horizon of interest will arrive with a minimum of interference from other wave types. All data from this technique provide information about the refractor. Broadside refraction shooting should be combined with reversed profiling methods to check the identity of the event being mapped.

Fan shooting utilizes geophones arranged in a fan-shaped pattern with the shotpoint at the apex. Any appreciable low- or high-velocity masses located between the geophones and the shotpoint will cause abnormally long or short travel times, respectively.

3.1.1.3 Engineering Surveys

Shallow refraction surveys used in engineering applications, such as in determining depth to bedrock, do not require large energy sources or complex instrumentation. Actual field procedures are similar to reversed profiling; however, geophone spreads are much shorter in length.

3.1.2 Data Format

Information obtained during a seismic refraction survey should be presented according to a standard data format. The standard data sheet should be developed so that all data pertinent to the interpretation of the survey are clearly presented. The data should be recorded on field data sheets, as well as on subsequent processing records. A sample seismic refraction data sheet is presented as Figure 2.

3.1.2.1 General Heading Information

As a minimum, the heading for each data sheet should contain the following information:

- Project name, number, and location
- Survey company or organization
- Date
- Observor's name
- Recorder model and serial number
- Amplifier gain settings
- Filter settings
- Source type
- Geophone model and natural frequency
- Weather and temperature
- Profile number

3.1.2.2 Survey Data

Survey data should be presented in a systematic fashion with all information for each profile presented on a single data sheet, if possible. Survey data should include:

- Coordinates of all ground stations
- Shotpoint number and location
- Energy source specifics
- Receiver number and location
- Travel time to each receiver (milliseconds)

Permanent film or paper records should be attached to the data sheet. Magnetic tape records should be labeled with the project name, number, and location. A unique identification number should be assigned to each magnetic tape record, and these numbers should be indicated on the magnetic tape and the applicable field data sheet.

3.1.2.3 <u>Remarks</u>

Additional information describing survey conditions, equipment calibration, failure or changes, and changes in survey parameters or method should be recorded on the field data sheet.

3.1.3 <u>Seismic Refraction Equipment</u>

Seismic refraction is a technique that allows deduction of properties in the earth based on the time required for an acoustic pulse to travel between two points. The acoustic pulse is produced by an energy source and detected and converted to an electrical signal by a geophone. The electrical signal from the geophone is transmitted through a spread cable to a recorder where the signal is amplified and recorded. Suppliers of seismic refraction equipment are listed in Appendix A.

3.1.3.1 <u>Energy Source</u>

The most common source for refraction surveys is an explosive charge in a borehole. Associated equipment for this type of source includes an auger or drilling rig to drill the boreholes, a magazine to store the explosives, a vehicle to transport the explosives, and a blasting box to detonate the explosives. Other types of energy sources include sledge hammers, drop-weights, seismic shotguns, and contained explosive devices such as the Dinoseis.

The choice of energy source depends mainly on the depth of investigation and the proximity of cultural features. Explosive sources are generally employed for depths of investigation in excess of 100 to 300 feet where the surrounding area is unpopulated. Charge sizes used can vary from one pound of explosives for investigations to a depth of 100 feet to several thousand pounds for investigations to a depth of ten or twenty thousand feet. Mechanical and contained explosive sources are generally used when the depth of investigation is less than 100 to 300 feet or in populated areas.

3.1.3.2 Geophones

Geophones consist of a moveable magnet suspended inside a coil of wire. The magnet-coil assembly is mounted inside a plastic case with a spike on the bottom for coupling the geophone to the earth. Movement of the earth causes the magnet to move inside the coil, inducing a voltage proportional to the velocity of ground motion. Refraction geophones usually have a low natural-resonance frequency of about 8 Hz.

3.1.3.3 Spread Cable

The spread cable provides an electrical path for signals between the geophones and recorder. The cable may contain from 1 to 24 pairs of conductors for transmitting signals from several geophones. Take-outs or connectors are provided at equal intervals along the cable for connecting in the geophones. Additional connectors are provided at the ends for connecting the cable to a recorder.

3.1.3.4 Recorder

The recorder consists of 1 to 24 amplifiers and filters as well as an oscillograph or magnetic tape device. Amplifiers receive the electrical signals from the geophones and increase them to a level suitable for recording. The filters are electronic devices used to reduce undesirable noise in the signal on the basis of frequency. The oscillograph produces a paper record of the signals by a photographic process, whereas the magnetic tape device produces a magnetic tape record of the signals. The recorder also includes special circuitry to synchronize the source with the recorder.

Signal enhancement recorders are similar to conventional recorders, but include circuitry for algebraic summation of repeated signals. The summation process is used to enhance the signal when relatively high levels of background noise are present. The signal enhancement recorder is generally used for shallow surveys with a hammer or weight drop source.

3.1.3.5 Calibration of Seismic Refraction Equipment

For most applications the only piece of seismic refraction equipment which requires calibration is the recorder. Seismic refraction recorders are calibrated for time-break accuracy and internal timing. Time-break calibration is performed to ensure that the field recording commences at the same instant or after a precise interval following triggering of the source. This calibration can be accomplished by placing a geophone next to the source and connecting it to the recorder. The source is triggered and the resulting record is examined to ensure that the recorded energy arrives at or near zero time. More sophisticated calibration can be performed using pulse generators and oscilloscopes.

Internal timing is calibrated with a signal generator. The signal generator is used to input a sine wave of carefully controlled frequency into the recorder. The recorder is manually tripped and a normal length record is taken. Internal timing is checked by counting the number of cycles present on the record. For example, with a 100-Hz input signal a half-second record should show exactly 50 cycles. The signal generator can also be used to check functional operation of signal enhancement circuitry in recorders so equipped. With a constant input signal, the recorder is manually tripped several times and the signal build-up is observed.

3.1.4 Processing of Seismic Refraction Data

The most widely used of all field techniques for refraction work is profile shooting. For this reason, the following discussion will concentrate on processing these types of data. The processing of seismic refraction data may be grouped into the following two categories:

- Reduction
- Inversion

3.1.4.1 Reduction of Seismic Refraction Data

Seismic refraction data must be corrected for elevation differences and for changes in the thickness of any weathered layer. The elevation correction removes differences in travel times due only to variations in the surface elevation of the shotpoint and receiver locations. Without elevation corrections, surface irregularities will be superimposed on the interpreted positions of the subsurface wave velocity interfaces. The correction for weathered layer thickness is designed to remove the additional time for seismic signals to traverse the low-velocity layer that sometimes covers the earth's surface. Without weathered layer thickness corrections, irregularities similar to those caused by elevation differences will be superimposed on the subsurface wave velocity interfaces.

The most common method for determining elevation corrections is to put both the shotpoint and receiver on an imaginary datum by subtracting the times that would be required for the wave to travel from the imaginary datum to the respective shot or detector locations if they are higher than the datum or by adding the times if they are lower. Determination of these corrections requires that the wave velocity of the first two layers be known so that the geometry and length of the raypath can be determined. These velocities can usually be determined with acceptable accuracy from the field data.

Weathering corrections are usually determined by calculating the thickness of the weathered layer from a simple two-layer depth intercept-time formula. The correction is equal to the slant path thickness of the weathered layer divided by its wave velocity. For shallow refraction surveys where the objective may include mapping the weathered layer, no weathering correction is applied and the weathered layer is treated as another lithologic unit.

3.1.4.2 Inversion of Seismic Refraction Data

There are many inversion methods for seismic refraction data, but most of them are based on time-distance relations or delay times. Time-distance relations may be used when the refracting interface is a horizontal or inclined plane. Delay time methods are used when the refracting interface is irregular.

Time-distance methods utilize three parameters which can be measured from a plot of wave arrival time versus distance. For a horizontal two-layer case, the plot consists of two intersecting straight line segments with each segment representing arrivals from a single layer. This situation is shown in Figure 1. The required parameters for time-distance interpretation are the slope of both line segments and either the distance at which the segments intersect (X_c) or the time when the upper segment would intersect the time axis if it were extended (T_i). The wave velocities of the first and second layer (V_1 and V_2) are given by the inverse of the slope for each line segment and the depth (Z) to the refracting interface is given by:

$$Z = \frac{T_i}{2} \quad \frac{V_1 \; V_2}{V_2^2 - V_1^2}$$

or

$$Z = \frac{X_c}{2} \quad \frac{V_2 - V_1}{V_2 + V_1}$$

More complex but similar formulas have been developed to handle multi-layer cases with either horizontal or dipping refracting interfaces. It is important to note that refraction profiles must be shot from both ends to uniquely solve the case of dipping beds. An alternative method for determining subsurface velocities is by direct measurement in boreholes, as discussed in Section 4.7.4.

Delay time is defined as the additional time taken for a wave to follow a trajectory to and along a buried refracting interface over and above the time to follow the same interface if it were at the ground surface. The delay time is composed of the shot delay time (the time required for the wave to travel from the shotpoint to the refracting interface) and the receiver delay time (the time required for the wave to travel from the refracting interface to the receiver). Since delay times are not directly measurable, it is necessary to separate the delay times from time-distance information by indirect means. Some of the more common methods for doing this are:

- Barthelmes' Procedure
- Wyrobeck-Gardner Method
- Tarrant Method

Following separation of the delay times, the depth to the refracting interface can be determined by multiplying the delay time by an appropriate factor based on velocity values.

Perhaps the best use of both time-distance and delay-time methods is in preliminary field interpretation to provide direction and evaluation of surveys during the data acquisition stage. The best overall interpretive methods are carried out using computers which combine time-distance and delay-time methods with raypath-tracing and statistical routines. An example of such a program is FSIP (Fast Seismic Interpretation Program) developed by the U.S. Bureau of Mines. This program requires only that the user identify the recorded wave arrivals and assign them to specific layers. Options are available which allow the user to specify velocity and depth for the case where such information is available from alternative sources.

3.2 SEISMIC REFLECTION

The seismic reflection method consists of measuring the travel time required for acoustic compressional waves, generated in the earth by a near-surface explosion, mechanical impact, or vibration, to return to the surface after reflection from interfaces between subsurface materials or formations with differing acoustic properties. The reflections are detected by receivers located on the ground surface at distances which are generally small compared to the depth of the reflecting interface. Figure 3 provides an illustration of the seismic reflection method. Variations in the reflection time between receivers on the surface usually indicate structural features in the strata below. Depths to reflecting interfaces can be determined from the travel times using wave velocity information that can be obtained from the reflected signals or from borehole surveys.

The criterion which determines if an interface is reflecting is the acoustic impedance contrast between the two materials. The acoustic impedance for a material is equal to the product of wave velocity and density. The contrast or reflection coefficient across an interface is given by the difference between the acoustic impedances of the two materials divided by their sum.

Seismic reflection data are usually recorded in digital format on magnetic tape. The data are then processed by specialized computers designed specifically for this purpose.

3.2.1 Field Procedures

3.2.1.1 Conventional Surveys

The standard field technique for seismic reflection surveys is common depth point (CDP) profiling. This form of profiling consists of advancing shotpoints and equally spaced receivers along a line so that multiple coverage (redundancy) of the subsurface is obtained. Redundant coverage provides a statistically improved reflection signal plus additional information on subsurface wave velocities.

In areas where there is not adequate borehole coverage or previous geophysical surveys, it is recommended that the initial portion of the survey be designed to analyze local noise conditions and design techniques to improve the signal/noise ratio. The receivers should be placed in line at short intervals and shots fired from one end for several increasing distances. The resulting record is then analyzed for undesirable noise caused by direct waves, refracted waves, ground roll, and multiple reflections. Various techniques are then employed to reduce undesirable noise. These techniques include varying the depth and size of explosive charges, arranging multiple geophones for each recorder channel in patterns, drilling multiple shotholes in patterns, or arranging surface sources in patterns.

Commonly, seismic reflection surveys are conducted along lines forming a grid. The resulting intersection of lines can be used for verifying the validity of data along lines. Dimensions of the grid should be established based on the degree of detail desired.

3.2.1.2 High Resolution Surveys

Conventional seismic reflection surveys usually involve up to 96 channels of recording with geophone groups spaced 100 to 300 feet apart. Shallow engineering or high-resolution surveys use 12 to 48 channels of recording with geophones spaced 10 to 50 feet apart. High-resolution surveys normally use smaller energy sources and higher frequency geophones than conventional surveys. In addition, high-resolution surveys usually use single receivers in shallow boreholes.

3.2.1.3 Areal Surveys

Areal surveys are an extension of profiling to two dimensions. Receivers are arranged on a square grid instead of along a line. The resulting subsurface coverage is also in the form of a grid and profiles can be produced through any sequence of grid points. Areal surveys are preferable in areas of complex geologic structure or excessive cross dip.

3.2.2 Data Format

All information obtained during a seismic reflection survey should be presented according to a standard data format. Information required for the processing and interpretation of field tapes should be recorded on a standard data sheet. The data should be recorded on field data sheets as well as on subsequent processed versions. In addition, field notes should be recorded in accordance with a standard format. A sample seismic reflection data sheet is shown in Figure 4.

3.2.2.1 General Heading Information

As a minimum, the heading for each data sheet should contain the following information:

- Project name, number, and location
- Survey company or organization
- Date
- Observer's name
- Recorder model and serial number
- Number of recorded channels
- Sample rate
- Amplifier gain settings
- Filter settings
- Source type
- Source pattern
- Geophone model and natural frequency
- Geophone pattern
- Spread type and gap
- Geophone interval
- Shotpoint interval
- Line number
- Line progression direction

3.2.2.2 Survey Data

Reflection survey data should be presented in a systematic manner with all information for a particular record on one line. The information should include:

- Shotpoint number and location
- Tape file number
- Geophone number and location
- Roll-along switch position
- Recorder location
- Dead channels
- Recorder length and start delay (seconds)
- Vertical source sums
- Energy source specifics
- Shotpoint offset and direction

3.2.2.3 Remarks

Additional information describing survey conditions, equipment calibration, failure or changes, and changes in survey parameters should be recorded on the field data sheet.

3.2.2.4 Tape Format

Field tapes should be recorded in a format endorsed by the Society of Exploration Geophysicists (SEG). Tapes should be labeled with the following:

- Project name, number, and location
- Line number
- Tape file numbers

3.2.2.5 Land Survey Data

The results of land surveys conducted to establish the horizontal and vertical coordinates of seismic lines should be presented in a standard form. A sample land survey data form is included as Figure 5. The form should include:

- Project name, number, and location
- Land survey company or organization
- Land surveyor's name
- Line number
- Station number
- North coordinate
- East coordinate
- Elevation

3.2.3 Seismic Reflection Equipment

The seismic reflection technique is used to determine subsurface acoustic properties based on measurements of the time required for an acoustic pulse to be reflected off subsurface acoustic interfaces. The equipment required is similar to refraction equipment, but is more sophisticated because the shape of the acoustic pulse as well as the travel time is recorded.

3.2.3.1 Energy Source

Common energy sources for seismic reflection surveys include explosives in a borehole, contained explosive devices, and the Vibroseis. Associated equipment for explosive sources is similar to that required for seismic refraction surveys.

Contained explosive devices, such as the Dinoseis, generate acoustic pulses by the explosion of an oxygen-propane mixture inside a surface-coupled chamber. This type of source can be exploded rapidly to facilitate high production rates. The Dinoseis is synchronized to the recorder through a cable or by radio.

The Vibroseis is a radically different type of source because it imparts a long (3-7 second) continuous wavetrain into the earth rather than a distinct pulse. The Vibroseis consists of a truck-mounted hydraulic vibrator which can be coupled to the earth by jacking the truck up onto a base plate. The frequency of the vibrator is increased (upsweep) or decreased (downsweep) smoothly during generation of the wavetrain. The resulting seismic record is specially processed on a computer to compress the wavetrain into a discrete pulse. The Vibroseis is synchronized to the recorder by radio.

3.2.3.2 Detectors

Detectors for seismic reflection surveys include acceleration sensors (accelerometers), velocity sensors (geophones), and pressure sensors (hydrophones). The accelerometer and hydrophone are generally used for high-resolution, shallow penetration surveys where their superior high-frequency response is required. Physically, the accelerometer and hydrophone are similar in appearance to geophones.

Geophones are the most widely used detectors for reflection surveys. Reflection geophones are similar to refraction geophones, but are available with natural resonant frequencies from 4 to 100 Hz. Geophones are commonly wired together in groups of 8, 10, 12, or 16 to form geophone arrays. These arrays can be physically configured on the ground to discriminate between vertically-traveling signals and undesirable horizontal-traveling noise. The output from each array is recorded on a separate channel.

3.2.3.3 Spread Cable

The spread cables for reflection surveys are similar to those used for refraction surveys, but generally are constructed to carry more signal channels. Also, it is common practice for the cables to be constructed in short segments to facilitate handling and horizontal movement. A truck is usually provided to transport the spread cables and geophones.

3.2.3.4 Roll-Along Switch

The roll-along switch provides an electrical means of positioning the recorder channels along the spread cables. The roll-along switch may have inputs for up to 240 conductor pairs with outputs to 12, 24, 48, or 96 recording channels. The roll-along switch is located with the recorder.

3.2.3.5 Recorder

Seismic reflection recorders are extremely complex and sophisticated devices. They must be capable of recording signals over a wide range of amplitudes with frequencies ranging from 10 to 1,000 Hz depending on local conditions and survey design. Modern reflection recorders are digital devices which measure signal amplitude and polarity at discrete times rather than continuously as in analog systems. Rates at which the recorder must measure signal amplitudes are as high as 4,000 samples/second.

The seismic reflection recorder consists of 12 to 96 input channels which can be individually amplified and frequency filtered. Also included are special filters to reduce interference from powerlines and buried electrical cables. The amplified and filtered signals are routed to an analog/digital converter which measures the amplitude of the signal at selected times and records the result in digital format on magnetic tape. Also included are an oscillograph or thermal plotter to facilitate field inspection of the data. Processing of the data on tape is performed by field or office computer.

The more advanced recorders have instantaneous floating point (IFP) capability which is a method of automatically varying amplification of signals according to their strength. This feature allows accurate recording over the full range of seismic signal amplitudes. Also available on some recorders is a signal enhancement capability similar to that discussed for refraction recorders.

3.2.3.6 Calibration of Seismic Reflection Equipment

For most applications the only piece of seismic reflection equipment which requires calibration is the recorder. Seismic reflection recorders are calibrated for time-break accuracy, internal timing, amplitude coherency, and phase coherency. The time-break calibration is performed to ensure that the field recording commences at the same instant or after a precise interval following triggering of the source. This calibration can be accomplished by placing a geophone next to the source and connecting it to the recorder. The source is triggered and the resulting record is examined to ensure that the recorded energy arrives at or near zero time. More sophisticated calibration can be performed using pulse generators and oscilloscopes.

Internal timing, amplitude coherency, and phase coherency are all calibrated with a signal generator. The signal generator is used to input a sine wave of carefully controlled frequency and amplitude into the recorder. The recorder is manually tripped and a normal length record is taken. Internal timing is checked by counting the number of cycles present on the record. For example, with a 50-Hz input signal, a one second record should show exactly 50 cycles. Amplitude and phase coherency are checked by examining the traces for all channels to ensure that the recorded amplitudes are approximately equal and the test signal peaks and troughs are aligned. Most modern seismic reflection recorders contain built-in calibration oscillators running on independent time standards.

Geophones may be calibrated by placing them on a vibrating table whose frequency and amplitude of oscillation can be precisely controlled. This device is commonly called a shaker table. Such calibration is performed rarely and then only for special purposes or research surveys. For all surveys, however, geophones should be checked for short circuits, open circuits, and electrical leakage.

3.2.4 Processing of Seismic Reflection Data

Since the vast majority of seismic reflection data is acquired using the CDP technique discussed in Section 3.2.1.1, the following discussion concentrates on the processing of these types of data. The processing of seismic reflection data is almost universally performed using high-speed digital computers and is conveniently grouped into the following five categories:

- Reduction
- Velocity Analysis
- Signal Enhancement
- Migration
- Data Presentation

3.2.4.1 Reduction of Seismic Reflection Data

The initial step in processing seismic reflection data is to remove undesirable effects introduced by elevation differences and near-surface weathering. If reflected energy from a horizontal subsurface interface is received by geophones spread over a hill or valley, the reflection times would indicate a structure associated with the earth's surface rather than with those of the subsurface. Additionally, some of the earth's surface is covered by a weathered layer. Since the wave velocity of the weathered layer is less than that of deeper material, additional time will be required for a reflected signal to return through this layer.

Effects of elevation and weathering are removed in a single step called the datum correction. First, a reference elevation is selected which is always deeper than the base of the weathered layer. Next, the wave velocity and thickness of the weathered layer are determined from the arrival times of the first energy at the geophones using refraction techniques (the first arrivals are either direct or critically-refracted waves and provide the same information as a refraction survey). Alternatively, weathered layer velocity can be obtained by measuring the time required for energy to travel from the bottom of the shotholes to the surface. Finally, the datum correction for each geophone is determined by calculating the total travel time for a wave to travel from the reference elevation to the base of weathering and from the base of weathering to the geophone.

Other steps in the data reduction process are the sorting of data traces into CDP gathers (groups of traces reflected from the same subsurface points for varying shotpoint-receiver distances) and the editing of poorly defined traces.

3.2.4.2 Determination of Velocity

Subsurface wave velocities may be determined from seismic reflection data or from borehole information, as discussed in Section 4.7.4. Since reflected signals are obtained from equivalent points along subsurface interfaces for several different shotpoint-receiver distances, the average wave velocity to the interface may be determined by examining the differences in arrival times. Specifically, the increase in reflection time with increasing distance from the shotpoint is a hyperbolic function, the curvature of which is controlled by the average wave velocity. One method for determining wave velocity consists of summing amplitudes along several trial hyperbolas across a CDP gather. The correct wave velocity is that which provides the maximum amplitude sum. Other techniques use several trial wave velocities to remove the effect of increasing shotpoint-receiver seperation. The correct wave velocity is that which makes the reflections appear at the same time.

Velocity information may also be obtained from boreholes by continuous velocity measurements (sonic logging) or from a discrete number of measurements made by detonating explosives on the surface and measuring the travel time to borehole geophones.

3.2.4.3 Signal Enhancement

The quality of reflected signals may be enhanced by processes such as frequency filtering, velocity filtering, CDP stacking, and deconvolution. Frequency filtering consists of selectively altering the spectral content of the recorded signal. Since undesirable noise may have a different frequency content than desired signal, frequency filtering may significantly improve the signal/noise ratio. Optimum frequency filtering parameters are usually selected by trial-and-error procedures. Velocity filtering is a multitrace technique used to discriminate signal on the basis of direction. The velocity filter is particularly useful for attenuating horizontally-travelling noise such as ground roll while not affecting vertically-traveling reflected signals. CDP stacking consists of removing travel-time increases caused by increasing shotpoint-receiver separation using previously determined wave velocities and then summing the resultant traces. The removal of the travel-time increases is often termed as the normal moveout (NMO) correction. Deconvolution is a technique used to remove undesirable reverberations by compressing the recorded wavetrain.

3.2.4.4 Migration

With conventional seismic reflection coverage, there is no good method to determine from a single trace where a reflecting point is located in space. If the subsurface can be represented by a series of horizontal layers, then the reflecting point will be midway between the shotpoint and receiver. With the introduction of dip in the subsurface, the reflecting point will shift creating distortion. If the line of profile is perpendicular to the strike, the direction of shift will be along profile. Otherwise, the shift will be offline so that the resulting coverage is not along profile. These effects become significant for dips in excess of about 5 degrees. With multiple trace information it becomes possible to correct the resulting distortion by examining reflection time differences between adjacent traces. The transformation of apparent reflecting positions to true positions is referred to as migration. The most widely used migration methods are two-dimensional and are applicable in a strict sense only when the field profiles are perpendicular to strike. Two-dimensional wave equation migration may be used to resolve dip distortion for dips up to 45 degrees. For those cases where the seismic coverage is areal or along crooked lines, more sophisticated three-dimensional migration techniques can be used to resolve dip distortion in any direction.

3.2.4.5 Data Presentation

The standard format for seismic data presentation is the corrected record section which consists of a series of closely spaced traces along the line of profile. Each trace represents the reflected energy from the subsurface as a function of time for stations along profile. Alternatively, velocity information is sometimes used to convert the reflected energy to a function of depth. A sample seismic reflection section is presented as Figure 6. The dark coherent display of energy across the section is caused by an unconsolidated sediment-crystalline bedrock contact at a depth of about 700 feet.

3.3 RESISTIVITY

According to Ohm's Law, the electrical potential between any two points in an electrical circuit is equal to the applied current multiplied by the resistance offered by the path. Ohm's Law is expressed by the formula:

$$E = IR$$

where

E = electrical potential
I = applied current
R = resistance

The resistivity of a conductor is defined as the resistance multiplied by the cross sectional area divided by the length. In the form of an equation, the expression is:

$$\rho = RA/L$$

where

ρ = restivity
R = resistance
A = cross-sectional area
L = length

Resistivity is a property that depends only on the material nature of a conductor, and not on its dimension. The resistivity method consists of transmitting electrical current into the ground and measuring the associated response. The relationship between the transmitted current and the response is used to deduce the subsurface resistivity distribution.

The preferred method of measuring earth resistivity is the four-electrode method. A known current, I, is transmitted into the ground through two current electrodes, C1 and C2. A potentiometer is used to measure the associated potential across two potential electrodes, P1 and P2. Apparent resistivity is then calculated according to an expression involving the ratio of potential to current as well as a geometric factor based on electrode configuration.

If the earth is electrically homogeneous in a volume which is large compared to the electrode configuration, then the apparent resistivity will equal the true resistivity. Otherwise, the apparent resistivity must be viewed as a means to represent the distribution of electrically homogeneous materials.

3.3.1 Field Procedures

3.3.1.1 Electrode Configuration

The three most common electrode configurations for the four-electrode method are:

- Wenner
- Schlumberger
- Dipole-Dipole

In the Wenner configuration the electrodes are arranged in line as C1-P1-P2-C2 where C1 and C2 are current electrodes and P1 and P2 are potential electrodes. The electrodes are uniformly spaced. This type electrode configuration is depicted in Figure 7.

The Schlumberger configuration is similar to the Wenner except that the distance between current and potential electrodes is kept at least five times as large as the spacing between potential electrodes. This type electrode configuration is depicted in Figure 8.

In the Dipole-Dipole configuration, the electrodes are arranged in line as C1-C2-P1-P2. The separation between C1 and C2 is equal to that between P1 and P2, but the separation between C2 and P1 is equal or greater. This type electrode configuration is depicted in Figure 9.

The Wenner and Schlumberger configurations are most often used for vertical investigation whereas the Dipole-Dipole configuration is most often used for lateral investigation. The Schlumberger configuration is less sensitive to lateral inhomogeneity than the Wenner and involves less field effort because the potential electrodes are usually stationary.

3.3.1.2 Vertical Electrical Sounding

The vertical electrical sounding (VES) method consists of systematically and symmetrically expanding a Wenner or Schlumberger electrode configuration in line about a point. Measurements of potential and input current are made for each set of electrode spacings. The resultant plot of spacing versus apparent resistivity is interpreted to yield the subsurface resistivity distribution with depth beneath the point.

3.3.1.3 Horizontal Profiling

The horizontal profiling method has three variations. The first variation consists of making measurements with a fixed-spacing Wenner, Schlumberger, or Dipole-Dipole electrode configuration at several locations. The change in apparent resistivity as a function of location is then representative of lateral change. VES soundings are usually made to locate the subsurface objective and to determine the optimum fixed spacing for the electrodes.

The second variation is to make VES soundings at several locations and compare the resulting subsurface resistivity distributions to determine lateral change. This variation results in more complete information.

The third variation is to make Dipole-Dipole measurements with the current or potential dipole fixed and the other dipole located at increasing distances along a line. The fixed dipole is then advanced down the line and the process is repeated. The measurements from this variation can be interpreted to yield a resistivity "cross section" beneath the line.

3.3.2 Data Format

Information obtained during a resistivity survey should be presented according to a standard data format. The standard data sheet should be developed so that all data pertinent to the interpretation of the survey are clearly presented. The data should be recorded on original field data sheets and any subsequent revisions. A sample resistivity field data sheet is included as Figure 10.

3.3.2.1 General Heading Information

As a minimum, the heading for each data sheet should contain the following information:

- Project name, number, and location
- Survey company or organization
- Date
- Operator's name
- Instrument model and serial number
- Test location
- Electrode configuration
- Electrode type
- Line number if applicable
- Weather and temperature

3.3.2.2 Survey Data

Resistivity survey data should be presented in a systematic manner with all information for each sounding or profile on a single sheet if possible. Survey data should include:

- Electrode location as applicable
- Electrode spacing as applicable
- Input current
- Measured potential

3.3.2.3 Remarks

Additional information describing survey conditions, equipment calibration, failure or changes, and changes in survey parameters or method should be recorded on the field data sheet.

3.3.3 Resistivity Equipment

Resistivity surveys measure the electrical response of the earth to an applied current. The basic components of a field resistivity system are electrodes, cables, current source, and potentiometer. Suppliers of resistivity equipment are listed in Appendix A.

3.3.3.1 Electrodes

Two types of electrodes are used in resistivity surveys; current electrodes are used to pass current into the earth and potential electrodes are used for voltage measurements with the potentiometer. Current electrodes may be stainless-steel or copper rods, buried copper screens, drill steel in a borehole, or buried metal culverts. Potential electrodes may be stainless steel rods or porous containers filled with copper sulfate.

3.3.3.2 Cables

Resistivity cables carry the current from the source to the current electrodes and the signal from the potential electrodes to the potentiometer. The cables must be well insulated to prevent short circuits and electrical leakage. The cables to the current electrodes must be capable of carrying the full output from the current source. Cables from the potential electrodes are usually light duty because high currents do not flow through them.

3.3.3.3 Current Source

The current source consists of a power supply (generator or batteries) and shaping circuitry to produce a DC, commutated DC, or AC signal. Capacities may range from a few watts to several kilowatts depending on the objectives of the survey. Also included are devices to measure and regulate the current. Some current sources have switches to select different sets of electrodes.

3.3.3.4 Potentiometer

The potentiometer measures the voltage between the potential electrodes. Potentiometers may include special circuitry to reject undesirable noise. Sometimes small current sources are combined with a potentiometer into a single device commonly called a megger.

3.3.3.5 Calibration of Resistivity Equipment

The components of a resistivity system which require calibration are the current source and the potentiometer. Calibration of the current source consists of placing a reference ammeter in series with the cables leading to the electrodes. The reading on the reference ammeter is compared with the reading indicated on the current source ammeter and adjustments are made accordingly. Similarly, the potentiometer is calibrated by comparing the indicated potential with that measured by a reference voltmeter. Alternatively, a precision resistor of known value may be placed in series with the current loads and the potentiometer is connected across the resistor. The potential across the resistor should be equal to the product of known resistance and indicated current. The potentiometer is then adjusted to indicate this value. The advantage of this method is that only the potentiometer needs to be adjusted. Although this form of calibration is relative (the current is not adjusted against a reference), it is sufficient because only the ratio of current to voltage is important.

Megger type devices are calibrated by shorting each pair of potential and current leads and then connecting a precision resistor between the current leads. The megger reading is adjusted to conform with the known resistance.

3.3.4 Processing of Resistivity Data

The processing of resistivity data can be divided into two categories. The first category is reduction, which is the process of converting the field data into a form more suited to inversion. The second category is inversion, which is the process of determining the subsurface resistivity distribution from the reduced data.

3.3.4.1 Reduction of Resistivity Data

The reduction of resistivity data is usually simpler than that for other geophysical techniques since no corrections for elevation or position are made. The first step in resistivity data reduction is the conversion of measured input current and observed potential for each electrode spacing to apparent resistivity. This conversion is accomplished by forming the ratio of observed potential to input current and then multiplying the ratio by a geometric factor based on electrode configuration and spacing. For the Wenner configuration, the geometric factor is given by $2\pi A$ where A is the electrode spacing in meters. The second and final step in data reduction is to construct an apparent resistivity curve by plotting apparent resistivity versus electrode separation on log-log graph paper.

3.3.4.2 Inversion of Resistivity Data

The preferred method of resistivity data inversion is curve matching either by hand or with the aid of a computer. The initial step in resistivity inversion is selection of an appropriate model. The selection of the model is based on comparing the general characteristics of the observed apparent resistivity curve (slope, inflection points, maxima, and minima) with a catalog of theoretical curves for the appropriate electrode configuration. Due to computational complexity, the theoretical curves are available only for horizontally layered resistivity models. The selection of an appropriate model fixes the number of discrete resistivity layers as well as the sense of resistivity contrast (high-low or low-high) at each layer boundary. Determination of layer thicknesses and resistivities is accomplished by further comparison of the observed apparent resistivity curve with more specific theoretical curves (for the general model) which are calculated for a wide range of layer thickness and resistivity values. The correct values are those for which the variation between the observed and theoretical curve is minimized. Alternatively, the correct values may be determined by direct borehole measurement, as discussed in Section 4.7.4.

Currently, catalogs of theoretical curves are available for models containing up to three layers and all possible combinations of relative resistivity contrasts (i.e., high-low-high, low-high-low, etc.). Inversion of data for up to five layers can be accomplished by using special procedures.

The advent of modern high-speed digital computers has revolutionized both the reduction and inversion of resistivity data. One obvious limitation of the hand curve-matching method is that only a finite number of models can be contained in any one catalog of curves. With digital computers it is feasible to calculate the theoretical curve for any combination of layer thickness and resistivity values quickly and economically. Further, after selecting a general model, iterative routines can be employed which optimize the solution by trial and error until a specified degree of conformance between the observed and theoretical curve is obtained; such routines are both rapid and highly objective. An example of a computer program for resistivity inversion is CRIMPA (Complete Resistivity Interpretation and Modeling Package Automatic) developed by Dr. Charles Stoyer of the Colorado School of Mines. CRIMPA handles models with up to five layers and any combination of layer thicknesses and resistivities.

Although the final inversion of resistivity data is best performed with a digital computer, the hand curve-matching method is extremely useful for obtaining approximate results in the field. Such results can provide valuable information for directing the field activities.

3.4 GRAVITY

The gravity method consists of measuring variations in the vertical intensity of the earth's gravitational field at a number of stations located throughout an area of interest. Measurements are usually made along a profile or across a grid. The raw data consist of the gravitational attraction at each station, the time of the measurement, and the survey coordinates of the station. Because the intensity of a gravitational field is determined by the density of the mass creating the field, a knowledge of the gravitational attraction at many points on the surface serves as an indicator of changes in the subsurface density distribution.

The gravity method differs significantly from previously discussed methods in several ways:

- The gravity method involves passive measurement of an existing potential field.
- The variation in field strength being measured may be extremely small, approaching one part in 10^8 in some cases.
- Extensive data corrections to account for elevation, terrain, regional gradient, temporal drift, latitude, datum density, and earth tides are required.
- The accuracy with which gravity stations must be located is much higher requiring, for example, an accuracy of $\pm$ 0.1 foot in elevation.

3.4.1 Field Procedures

Field procedures for conventional gravity surveys consist of establishing a base station, locating gravity stations, surveying the stations to determine elevation and coordinates, and performing the actual gravity measurement at each station.

3.4.1.1 Base Station

In any area where a gravity survey is to be performed, a base station must be established to monitor temporal drift, independent of position, in the intensity of the gravitational field. A base station can be any stable point, such as a large rock or a block of concrete, where the gravity meter can be precisely and consistently positioned many times. During the course of a survey, the gravitational field at the base station is measured every few hours with the same instrument used for the gravity measurements. The information obtained from successive reoccupations of the base station is used to correct the raw data for temporal drift.

3.4.1.2 Locating Gravity Stations

Gravity measuring stations are usually located across a rectangular grid or at equal intervals along a profile. Important considerations in laying out a pattern of measuring stations are the depth and lateral extent of the target geological feature, topography, and access.

As an example of suitable grid spacing, consider that the target geological feature is a salt dome one mile in diameter and one mile deep at the top surface. The range of suitable grid spacings would then be from 1/4 to 1 mile.

Usually it is desirable to shift measuring stations from their position on a uniform grid to avoid topographic features that can distort gravity readings to such an extent that standard correction procedures for terrain cannot produce sufficiently precise results. Published charts are available that provide estimates of the magnitude of topographic effects; these charts are useful for making field decisions about shifting measuring points. Access is affected by topograpy, but also depends on the distribution of roads, trails, streams, or other pathways along which gravity instrumentation can be transported. Except in the case of microgravity and borehole gravity surveys, which are limited in geographic extent, survey progress will be greatly reduced if the measuring stations are not accessible to motor vehicles.

3.4.1.3 Surveying Gravity Stations

Surveying accuracy requirements for gravity surveys are much higher than for any other geophysical technique. Since the gravitational attraction of mass varies inversely as the square of the distance, changes in distance from the center of the earth (elevation changes) cause variations in the intensity of the gravitational field. For surveys where high precision is required, the elevation of each gravity station must be determined to an accuracy of ± 0.1 foot. Also, since the earth is not a perfect sphere, the intensity of the gravitational field varies as a function of position. The change in gravitational intensity as a function of position is less pronounced than as a function of elevation, however, and an accuracy of ±10 feet for the horizontal coordinates is sufficient for most surveys.

For regional surveys, where the target geological features are large, it is often acceptable to determine elevation barometrically rather than geodetically. Horizontal coordinates for these types of surveys can generally be spotted from a base map.

3.4.1.4 Gravity Measurements

Gravity measurements are relatively simple to perform. The measuring instrument (gravimeter) is levelled at each gravity station using a special dish and the local gravitational intensity is measured by adjusting a dial to null the gravimeter. The reading from the adjusting dial is recorded along with the time of the measurement and the station location and number. Gravity measurements are always performed as a gravity loop. A gravity loop begins and ends with a measurement taken at a base station. The "length" of the loop may be from two to six hours, depending on the desired accuracy of the survey. In general, the base station gravity value will vary between successive occupations due to temporal drift. This temporal drift is caused by rotation of the earth through the gravitational fields of the sun and moon, as well as by instrumental drift. Knowledge of the temporal drift is used to apply corrections to the raw data by distributing the error around each gravity loop.

3.4.1.5 Microgravity Surveys

Microgravity surveys differ from conventional surveys primarily in scale. Target geological features are smaller and shallower, grid spacing is tighter, surveying requirements are more stringent, instrumentation must be more accurate, and base station reoccupations are performed more regularly. Additionally, more consideration must be given to topographic effects. As an example, a microgravity survey might be used to locate a 30-foot-diameter cavity at a depth of 50 feet. Proper grid spacing might range from 25 to 100 feet; base station reoccupation might be performed every hour; surveying accuracy might be ±0.05 feet in elevation and ±1 foot in horizontal coordinates.

3.4.2 Data Format

Information obtained during a gravity survey should be presented according to a standard data format. The standard data sheet should be developed so that all data pertinent to the interpretation of the survey are clearly presented. The data sheet should be recorded on field data sheets as well as on subsequent processing records. A sample gravity field data sheet is provided as Figure 11.

3.4.2.1 General Heading Information

As a minimum, the heading for each data sheet should contain the following information:

- Project name, number, and location
- Survey company or organization
- Date
- Observor's name
- Gravimeter model and serial number
- Gravimeter constant
- Base station location and coordinates
- Weather and temperature
- Grid or profile number

3.4.2.2 Survey Data

Survey data should be presented in a systematic fashion with all information for each gravity loop presented on a single data sheet, if possible. Survey data should include:

- Initial base station gravimeter reading and time
- Gravimeter reading, time, and station number
- Elevation and coordinates of each station
- Final base station gravimeter reading and time
- Temporal correction for each station
- Topographic features at each station

3.4.2.3 Remarks

Additional information describing survey conditions, equipment calibration, failure or changes, and changes in survey parameters or method should be recorded on the field data sheet.

3.4.3 Gravity Equipment

Gravity surveying is a technique used to deduce the subsurface density distribution by measuring local variations in the earth's gravitational field. These variations can be detected by a single device called a gravimeter. Other equipment required for a gravity survey include a transit, distance measuring device, rod, and level; this equipment is not discussed here because it is not unique to gravity surveying. Suppliers of gravimeters are listed in Appendix A.

3.4.3.1 Gravimeter

The gravimeter is essentially an extremely sensitive mechanical balance with a mass supported at the end of a nearly horizontal beam by an inclined spring. Variations in the gravitational field cause the mass to move, which changes the angle between the beam and the spring which in turn changes the moment of the spring's pull on the beam. This inherent instability accentuates any gravity variation. Practically, the beam deflection and hence the gravity variation is determined by the amount of counter-tension applied with a knob necessary to return the beam to its stable position. While the principle of the gravimeter is simple, design complications arise due to mechanical creep, thermal, and barometric effects.

3.4.3.2 Calibration of Gravimeters

Gravimeters are calibrated using two methods. The first method consists of clamping the gravimeter to a table whose angle with the horizontal may be precisely controlled. Since the vetical component of gravity changes systematically with tilt angle, the response of the instrument can be determined for a range of tilt angles. The second and most common method of calibration is to occupy at least two stations with different gravity values, as determined from pendulum observations. If the gravity difference between the two stations represents a signficant portion of the gravimeter's range, then linear response can usually be assumed and the whole scale can be calibrated on the basis of the two readings. Greater precision can be obtained by using a larger number and range of reference stations.

3.4.4 Processing of Gravity Data

The processing of gravity data is conveniently divided into two categories. The first category is reduction which is the process by which undesirable effects (those effects not attributable to the target geologic feature) are removed from the data. The second category is inversion which is the process of mapping the target geological feature using the reduced data.

3.4.4.1 Reduction of Gravity Data

In order to be useful for detecting and mapping the target geological feature, field gravity data must be corrected for temporal drift, elevation, latitude, influence of topography, and influence of regional gradient.

The correction for temporal drift is calculated by dividing the difference in gravimeter readings between successive base station occupations by the elapsed time. The drift at each station is equal to this number multiplied by the elapsed time between the first base station occupation and the time of the station reading.

The corrections for elevation consist of the free-air correction and the Bouguer correction. The free-air correction is a consequence of gravitational intensity change as a function of the distance from the center of the earth. This correction is applied by establishing a reference datum and adding or subtracting 0.09406 mgal/ft for each foot that the station is above or below the datum, respectively. The Bouguer correction is applied to remove the effects of material located above the selected datum. The Bouguer correction in milligals is equal to $0.01277\ \rho h$ where ρ is the near-surface density and h is the height with respect to the datum. Knowledge of the near-surface density is required to calculate the Bouguer correction and may be obtained from borehole density measurements or by trial-and-error until the least topographic variation is noted. The Bouguer correction is subtracted from the observed reading and together with the appropriate free-air correction forms the elevation correction. The resulting elevation-corrected data are referred to as the Bouguer anomaly.

The latitude correction is made by establishing an arbitrary reference latitude in the vicinity of the survey area and correcting all readings to this latitude by assuming linearity in the local geodetic gradient. The local gradient is equal to $1.307 \sin 2\phi$ mgal/mile where ϕ is the reference latitude. The linear assumption is valid for a survey area within one degree of latitude about the reference.

The topographic or terrain correction arises from the upward attraction exerted by nearby hills and the downward attraction due to nearby valleys. The standard procedure for determining topographic corrections is to calculate the attraction of all the mass that would have to be added to the valleys below and all that would have to be removed from the hills above to give perfectly flat topography having the same elevation as the station. Either correction, from a hill or valley, is added to the observed gravity. The reconstructed terrain then corresponds to the slab removed by the Bouguer correction. Practically, the topographic correction is computed from special templates or by computer. As in the Bouguer correction, the topographic correction requires knowledge of near-surface density. This density may be determined as discussed above for the Bouguer correction.

The regional gradient correction is applied primarily to separate the anomaly due to the target geological feature from anomalies caused by larger-scale regional features. The two basic methods for removing the regional gradient are the graphical method and the analytic method. The graphical method consists of estimating the regional gradient from large-scale gravity maps in areas close to but not affected by the target feature. This method is extremely subjective, but has the advantage that available geologic information can be incorporated in estimating the regional correction. The difference between the regional value, as determined from the gradient, and the observed value is the corrected reading and is referred to as the residual. One analytic method consists of averaging the large-scale gravity readings equally spaced along the circumference of a ring about each station. The difference between the average and the station reading is the residual; this method is extremely sensitive to the choice of ring diameter. Another analytic method uses least-squares fitting of a surface to the observed regional values; the difference between the least-squares surface and the observed reading is taken as the residual.

3.4.4.2 Inversion of Gravity Data

The goal of gravity data inversion is to determine the subsurface density distribution from the reduced data; the subsurface density distribution is used to infer the shape and dimensions of the target geologic feature. There are two major inversion methods, direct and indirect. The direct method is an attempt to invert the reduced data directly to a unique density distribution. The indirect method consists of proposing various models and comparing the calculated theoretical anomaly with the observed anomaly.

In general, there is no unique density distribution for a given gravity anomaly. However, for an anomalous body that can be represented as a plane (practically speaking, a thin sheet) direct inversion by a process known as downward continuation is possible. The downward continuation process is essentially a high-pass filter which permits computation of the gravity anomaly which would be observed on a datum below the survey datum. As the continuation process is peformed at successively deeper depths above the target, the anomaly becomes sharper and sharper. At the true depth of the target, the downward continued data are related to the local density distribution by a simple constant. Below the target depth, the continuation process becomes unstable and oscillatory.

In actual practice, the indirect method is the only method of gravity inversion which can be applied to a wide variety of target geometries. For simple shapes such as a sphere, horizontal cylinder, or vertical sheet, closed-form analytical solutions exist for calculating the theoretical anomaly. More complex three-dimensional bodies of arbitrary shape can be handled by modern computers. The choice of model should be based on geological considerations and information in order to limit the inherent ambiguity of gravity data as much as possible. The importance of independent information such as discussed in Section 4.7.4 for selecting an appropriate model and range of parameters cannot be overemphasized.

3.5 MAGNETICS

All substances when subjected to a magnetizing force, such as that which exists in the earth's magnetic field, acquire a certain intensity of magnetization; such magnetism is said to be induced by the causative field. The physical parameter which relates the intensity of magnetization to the strength of the magnetic field is called the magnetic susceptibility. As a consequence of the induced intensity of magnetization, the original field is modified; that is, the total field becomes greater or less depending on the sign of the magnetic susceptibility. The magnetic method consists of measuring local variations in the intensity of the earth's magnetic field at a number of stations located throughout the area of interest. Because the local intensity of the earth's magnetic field depends in part on the magnetic susceptibility of subsurface material, a knowledge of the field intensity at many points on the earth's surface serves as an indicator of the subsurface magnetic susceptibility distribution.

Measurements of magnetic intensity are usually made at stations located along a profile or across a grid. The raw data consist of the magnetic field strength at each station, the time of the measurement, and the survey coordinates of the station.

The magnetic method is similar to the gravity method, but differs in the the following ways:

- Magnetic susceptibility changes are much larger and more irregular than density changes; consequently, magnetic anomalies are larger and more irregular than gravity anomalies.

- The instruments used for magnetic prospecting are less sensitive than those used for gravity prospecting (one part in 10^4 as opposed to one part in 10^8). Also, the same magnetic instrument can be used to measure total field strength as well as minor variations.

- The time variation of the magnetic field is much more rapid and complex than that of the gravity field.

- The data reduction for magnetics is much simpler than for gravity.

3.5.1 Field Procedures

Field procedures for ground magnetic surveys consist of establishing a base station, locating magnetic stations, surveying the stations to determine coordinates, and performing the actual magnetic measurement at each station. Because the procedures for ground magnetic and gravity surveys are so similar, the two methods are often used in conjunction for the sake of economy.

3.5.1.1 Base Station

In any area where a magnetic survey is to be performed, a base station must be established to monitor temporal drift of the magnetic field strength, independent of position. A base station can be any stable point where the magnetic instrument can be consistently positioned many times. During the course of a survey, the magnetic field strength at the base station is measured every few hours with the same instrument used for the magnetic measurements. An alternative method is to employ a dedicated magnetic instrument to continually monitor the base station while a second instrument is used for the actual measurements. The information obtained from successive reoccupations or continuous monitoring of the base station is used to correct the raw data for temporal drift.

3.5.1.2 Locating Magnetic Stations

Magnetic measuring stations are usually located across a rectangular grid or at equal intervals along a profile. Important considerations in laying out a pattern of measuring stations are the depth and lateral extent of the target geological feature, presence of iron objects and power lines, access, and to a lesser extent topography.

As a general rule, the distance between adjacent stations should be between one-fourth to one times the lateral extent of the target geological feature. Regardless of station spacing, there should be no railroad tracks within 500 feet and no automobiles or fences within 100 feet of a measuring station. Additionally, power lines, bridges, steel-cased wells, underground metal pipes, culverts, and houses should be avoided.

Access is affected by topography, but also depends on the distribution of roads, trails, streams, or other pathways along which magnetic instrumentation can be transported. Except in the case of micromagnetic or aeromagnetic surveys, progress will be greatly reduced if the measuring stations are not accessible to motor vehicles. The effect of topography on magnetic surveys is generally negligible due to the low vertical gradient of the earth's magnetic field. Topographic effects can be very significant in areas of high relief where the country rock contains magnetite. In such cases a form of terrain correction is required, although it cannot be applied merely as a function of topography. A terrain correction can be applied, if necessary, by reducing measurements taken along an irregular (ground) surface to a horizontal plane situated above it. This technique is called upward continuation and is similar to the process of downward continuation used in gravity surveying.

3.5.1.3 Surveying Magnetic Stations

Surveying accuracy requirements for magnetic surveys are less stringent than for gravity surveys. Horizontal and vertical gradients of the earth's magnetic field are so low that no corrections are generally necessary. The only real requirement for positioning accuracy is that required to properly locate the line of profile or grid with respect to the target geological feature. As a rule of thumb, horizontal accuracy of 5 percent of the station spacing is sufficient. Elevation control can be determined to required accuracy ($\pm$ 10 feet) from topographic maps. Economy can be realized by combining gravity and magnetic surveys since gravity stations can also be used for magnetic measurements.

3.5.1.4 Magnetic Measurements

Magnetic measurements are very simple to perform. The instrument operator should not be wearing or carrying any magnetic objects such as belt buckles, knives, compasses, or steel spectacle frames which can produce significant variations in magnetometer readings. The measuring instrument (magnetometer) is switched on at each station, the appropriate scale is selected, and the local magnetic intensity is measured by reading a meter or digital display. The reading from the meter or display is recorded along with the time of the measurement and the station location and number. Magnetic measurements can be made continuously without base station reoccupation if a separate base station magnetometer is employed. Otherwise, magnetic measurements are always performed as a magnetic loop. A magnetic loop begins and ends with a measurement at the base station. The "length" of the loop may be from one to three hours, depending on the desired accuracy of the survey. In general, the base station magnetic value will vary between successive occupations due to temporal drift. This temporal drift is caused by the solar wind and atmospheric disturbances as well as by instrumental drift. Knowledge of the temporal drift permits correction to the raw data by distributing the error around each magnetic loop.

3.5.1.5 Micromagnetic Surveys

Micromagnetic surveys differ from conventional surveys primarily in scale. Target geological features are smaller and shallower, grid spacing is tighter, instrumentation is more accurate, and base station reoccupations are performed more regularly. As an example, a micromagnetic survey might be used to locate a small, laterally restricted dike. Proper grid spacing might range from 10 to 50 feet; base station reoccupation might be performed every hour; surveying accuracy might be ± 5 feet in elevation and ± 0.5 feet horizontally.

3.5.1.6 Aeromagnetic Surveys

Aeromagnetic surveys are an extension of ground surveys wherein the magnetometer is carried in an aircraft. Aeromagnetic surveys are used when large areas must be surveyed rapidly and economically (for small areas aeromagnetic surveys are not economical due to large mobilization and daily operating costs). Moreover, air coverage is usually more complete than ground coverage and there is the advantage that data are obtained in the form of continuous profiles, rather than as isolated point readings; this permits anomalies to be studied in more detail.

The disadvantages of aeromagnetic methods are related to the high speed at which data is obtained. Small navigational errors can lead to serious position errors and anomalies of limited lateral extent may be missed if the magnetometer does not respond quickly.

3.5.2 Data Format

Information obtained during a magnetic survey should be presented according to a standard data format. The standard data sheet should be developed so that all data pertinent to the interpretation of the survey are clearly presented. The data should be recorded on original field data sheets and any subsequent revisions. A sample magnetic field data sheet is provided by Figure 12.

3.5.2.1 General Heading Information

As a minimum, the heading for each data sheet should contain the following information:

- Project name, number, and location
- Survey company or organization
- Date
- Observer's name
- Magnetometer model and serial number
- Magnetometer constant
- Magnetometer range
- Base station location and coordinates
- Weather and temperature
- Grid or profile number

Data sheets should be filled out for both the survey magnetometer and the base station magnetometer as appropriate.

3.5.2.2 Survey Data

Survey data should be presented in a systematic fashion with all information for each gravity loop presented on a single data sheet, if possible. Survey data should include:

- Initial base station magnetometer reading and time
- Magnetometer reading, time, and station number
- Elevation and coordinates of each station
- Final base station magnetometer reading and time
- Temporal correction for each station

3.5.2.3 Remarks

Additional information describing survey conditions, equipment calibration, failure or changes, and changes in survey parameters or method should be recorded on the field data sheet.

3.5.3 Magnetic Equipment

Magnetic surveying is a technique used to deduce the subsurface magnetic susceptibility distribution by measuring local variations in the earth's magnetic field. These variations can be detected by a single device called a magnetometer. Other equipment required for a magnetic survey include a transit, distance measuring device, rod, and level; this equipment is not discussed here because it is not unique to magnetic surveying. Magnetometer suppliers are listed in Appendix A.

3.5.3.1 Magnetometer

The three main types of field magnetometers in current use are:

- Flux-gate magnetometer
- Nuclear resonance or proton magnetometer
- Optical-pumping magnetometer

The flux-gate magnetometer is used to measure any desired vector component of the earth's magnetic field. This instrument makes use of a ferromagnetic element of such high susceptibility that the earth's field can induce a magnetization that is a substantial proportion of its saturation value. With a sufficiently large alternating current flowing through a coil around the element, the combined field will saturate the element. For decreasing strength of the earth's field, more current will be required to saturate the element and vice-versa. The place in the energizing cycle at which saturation is reached gives a measure of the earth's field. In actual practice, two parallel elements with oppositely wound coils connected in series are employed. The magnetic field component parallel to the elements will reinforce the field created by one coil and oppose the field of the other. Nominal sensitivity for this type magnetometer is 10 gammas.

The nuclear resonance or proton magnetometer consists of a coil wound around a bottle of proton-rich fluid such as water. Sufficient current is introduced through the coil to produce an external magnetic field about 100 times stronger than the earth's. As a result, the magnetic moment of the protons will align themselves with the new field. When the external field is removed, the magnetic moment of the protons returns by precession to its original orientation with the earth's field. The precessional oscillation will induce a voltage in a second coil wound around the bottle and the total field strength is determined by measuring the frequency of the induced voltage. Nominal sensitivity for this type magnetometer is 1 gamma.

The optical-pumping magnetometer is based on quantum theory. In the absence of a magnetic field, the valence electron of an alkali-metal atom (such as rubidium or cesium) has two states, A, the normal level, and B, the excited level. In the presence of a magnetic field, level A splits into two sub-levels, A1 and A2. The energy difference between these levels is in the radio frequency range and is proportional to the strength of the magnetic field. By irradiating a gaseous sample of the metal with light from which spectral line A2B has been removed, electrons in sub-level A1 can absorb energy and rise to level B, but electrons in sub-level A2 will not be excited. When the excited electrons fall back to ground state, they may return to either sub-level, but if they fall to sub-level A1, they can be removed by excitation to level B again. The result is an accumulation of electrons in sub-level A2 and the gaseous sample becomes transparent to the irradiating light beam. This technique of overpopulating one energy level is known as optical pumping. To determine the energy difference between A1 and A2 and hence the strength of the magnetic field, radio waves of continually varying frequency are passed through the sample until electrons start moving from A2 to A1 and the optical pumping process is re-initiated. The resumption of optical pumping is indicated by a sharp drop in sample transparency; the energy difference between A1 and A2 can then be determined by measuring the corresponding frequency of the radio waves. The optical-pumping magnetometer measures total magnetic field strength with a nominal sensitivity of 0.01 gamma.

3.5.3.2 Calibration of Magnetometers

All magnetometers can be calibrated by placing them in a suitably oriented variable magnetic field of known value. The preferred method employs a Helmholtz device large enough to surround the instrument. The Helmholtz device consists of a pair of identical coils coaxially spaced apart a distance equal to the radius of the coils. A magnetic field of precisely known strength can be created by passing current through the coils. Calibration of the magnetometer is performed for several different currents corresponding to different field strengths. The great advantage of the Helmholtz device is that the magnetic field between the coils is uniform.

3.5.4 Processing of Magnetic Data

The processing of magnetic data is conveniently divided into two categories. The first category is reduction which is the process by which undesirable effects (those effects not attributable to the target geological feature) are removed from the data. The second category is inversion which is the process of mapping the target geological feature using the reduced data.

3.5.4.1 Reduction of Magnetic Data

In order to be useful for detecting and mapping the target geological feature, field magnetic data must be corrected for temporal drift and influence of regional gradient.

The correction for temporal drift is calculated by dividing the difference in magnetometer readings between successive base station occupations by the elapsed time. The drift at each station is then equal to this number multiplied by the elapsed time between the earlier base station occupation and the time of the station reading. Alternatively, the correction may be determined directly if a base station magnetometer is employed. Since irregularities as great as 10 gammas can be missed during successive base station occupations, continuous monitoring of temporal drift at the base station is the preferred method of determining corrections for high-precision surveys.

The correction for influence of regional gradient is determined in a way similar to that for large scale regional anomalies in gravity work (in the United States, the regional magnetic field can be determined from maps and tables published by the National Oceanic and Atmospheric Administration). Regional corrections can also be determined with a computer using data from the observations which are being reduced provided that the area of the survey is large enough. A low order polynomial surface is fitted to the data and residuals are obtained by subtracting values calculated for this surface at each station from the observed magnetic field at that station.

Additionally, a base correction is sometimes applied to tie the magnetic survey with a preexisting net. The base correction is determined by occupying one or more stations of the preexisting net during the course of the survey.

3.5.4.2 Inversion of Magnetic Data

The end result of a magnetic survey is a set of profiles or a magnetic contour map. The objective of magnetic data inversion is to determine the subsurface magnetic susceptibility distribution from the profiles or contour map. This distribution is used to infer the shape and dimensions of the target geological feature.

The most common method of magnetic inversion is matching observed anomalies with calculated anomalies for simple geometrical shapes. This procedure can become more complicated than similar procedures for gravity inversion because a direction as well as intensity of magnetization must be assumed. If the body for which the anomaly is being calculated is surrounded by a magnetized medium, the intensity and direction of magnetization of the medium must also be assumed.

Upward continuation, downward continuation, and second derivative techniques are also used for inversion. Upward continuation may be used to remove topographic effects as discussed in Section 3.5.1.2, but may also be used to suppress complex shallow magnetic anomalies. Downward continuation consists of mathematically calculating the magnetic field on some surface beneath ground level; this technique is particularly useful for estimating sedimentary cover in basins as well as mapping intrabasement features. Second derivative analysis is useful for enhancing shallow magnetic anomalies.

As in gravity inversion, the choice of model for magnetic inversion should be based on geological considerations and auxiliary information in order to limit inherent ambiguities as much as possible. Independent information must be input to the process of selecting an appropriate model and range of parameters.

3.6 RADAR (RAdio Detection And Ranging)

The propagation of an electromagnetic wave through any medium is controlled by the property known as electromagnetic impedance. The electromagnetic impedance of a given material is defined by a very complicated relationship between the magnetic permeability, the dielectric constant[1], and the electrical conductivity of the material. As an electromagnetic wave propagates through a medium and encounters a change in electromagnetic impedance (an electromagnetic interface), part of the wave energy is reflected away from this boundary, while the rest of the energy is transmitted through the boundary. The amount of energy which is reflected at this boundary, or electromagnetic interface, is described by the reflection coefficient:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

where

R = reflection coefficient

Z_1, Z_2 = electromagnetic impedance of the first and second materials, respectively

Aside from the complexity of describing the electromagnetic impedance with measurable physical parameters, the relationship between the electromagnetic impedance and the propagation of electromagnetic waves is completely analagous to the relationship between the acoustic impedance and the propagation of seismic waves.

In principle, the radar technique is very similar to the seismic reflection technique in that both techniques rely on the measurement of the time required for a wave to travel to an interface and return to the surface after reflection. While the geometry of wave raypaths is the same for both seismic and radar methods, there are some important differences between these methods:

[1] The dielectric constant is a measure of the capacity of a material to store charge when an electric field is applied. It is the dimensionless ratio of the capacitivity of the material to that of free space.

- The definition of an acoustic interface is based on the seismic wave velocity and density of the materials on either side of the interface while an electromagnetic interface is defined by changes in magnetic permeability, electrical conductivity, and dielectric constant.

- Seismic waves travel at the speed of sound while electromagnetic waves travel at the speed of light. Consequently, the travel times of electromagnetic waves must be measured very precisely (nanoseconds) as compared to the travel times of seismic waves (milliseconds).

- Electromagnetic radar waves are of a much higher frequency (15 to 500 MHz) than seismic waves (10 to 300 Hz). Consequently, radar has much higher resolution (0.25 inch) than seismic reflection, but has a very limited penetration (30 to 100 ft) when compared to seismic reflection.

- Because of the high frequencies employed by radar, extremely specialized and sophisticated equipment is required to transmit, receive, and record the radar pulse.

- Seismic reflection data is typically gathered using the common depth point technique. While it is possible to use this acquisition technique with radar, radar data is usually gathered with no redundancy.

- The seismic reflection technique requires a great deal of computer processing to interpret profiled data. Typically, the analog records generated by a radar profile are interpreted directly. These records can be digitized and processed with the same methods used in seismic processing if a more sophisticated approach is desired. However, due to the quantity of data and the difficulty of digitizing radar signals, this is seldom done.

- The acquisition of profile radar data is performed very quickly. Profiles can be run at rates ranging from two to three miles per hour for detailed surveys and up to ten miles per hour for reconnaissance surveys. The acquisition rate of high-resolution seismic reflection profile data is typically one-half mile per day.

A schematic representation of the radar method is provided in Figure 13.

3.6.1 Field Procedures

Field procedures for surface radar surveys consist of locating profile lines and performing the radar measurement. At several points in the region of interest, it may be desirable to drill to observed radar reflectors so that the wave propagation velocity in the subsurface materials can be determined.

3.6.1.1 Locating Radar Profile Lines

In a given area, radar profile lines should be placed in a grid to provide the most efficient subsurface coverage. Profile line spacing is largely a factor of the size of the subsurface feature to be located. Since the transducer must pass directly over an anomalous feature to detect it, profile lines should be spaced such that the transducer will pass over a part of the smallest feature to be detected.

In general, profile lines can be located any place where the transducer can be towed or pushed. The transducer is roughly the size of a large lawnmower, and can be pushed or towed manually over flat ground. Profile lines running up steep slopes should be avoided in order to reduce access problems and to avoid potential data reduction problems caused by rapid elevation changes along a profile line. Zones of very wet soil and swampy areas should also be avoided both from the standpoint of access and from the reduced penetration of the radar signal in water-saturated regions. In areas of rough topography it is preferable to run the profiles along contour lines.

Typically, a ground radar transducer is mounted on small wheels with only a few inches of clearance above the ground. This is done to improve the coupling between the source of the radar pulse and the ground through which it will travel. As a consequence of this design, radar profile lines should be cleared of vegetation and, if possible, the ground surface should be smoothed.

Land surveying requirements for radar profile lines are relatively lenient. Horizontal control is dependent entirely on the accuracy requirements of locating subsurface targets. In areas of .elatively little change in slope along a profile line, very little vertical control is required, except at the endpoints of the profile. If a profile runs across an area of undulating terrain, the peaks and troughs of the undulations should be surveyed in order to place observed subsurface features at their true elevations. As with horizontal control, the vertical control is dependent on the accuracy requirements of target location. Vertical control does not need to be better than 0.1 foot, however, as this is the inherent inaccuracy of the radar technique when all sources of error are considered.

3.6.1.2 Radar Measurement

While the equipment necessary to perform a radar survey is sophisticated and complex, the actual data acquisition procedure is simple. Recording instruments are located in a truck with a signal and power cable connected to the transducer. The transducer can either be towed behind the recording truck or, in areas of difficult access, it can be pushed or pulled manually. The distance from one end of the profile line as well as the radar reflections are automatically recorded by the equipment.

3.6.2 Data Format

Much of the data obtained in a radar survey are automatically recorded by the instrumentation. Additional information necessary to interpret each profile should be recorded on a standard data sheet. The information contained on this sheet should accompany any data, either magnetic tape or strip chart, that are recorded by the radar instrumentation. A sample field radar data sheet is included as Figure 14.

3.6.2.1 General Heading Information

As a minimum, the heading for each profile data sheet should contain the following:

- Project name, number, and location
- Survey company or organization
- Date
- Operator's name
- Profile line designation

- Transducer serial number
- Recording equipment serial number(s)
- Direction of transducer movement
- Weather and temperature
- End point coordinates of profile line

A data sheet for each profile line should be completed prior to beginning the profiling operations.

3.6.2.2 Other Survey Data

Aside from the heading information, the equipment records most of the data. Hence a profile data sheet is simply a log of any unusual event that occurs during the course of profile data acquisition.

3.6.3 Radar Equipment

Subsurface profiling by electromagnetic radar is a technique that utilizes the travel times of reflected electromagnetic waves to identify regions of anomalous magnetic susceptibility (such as pipes or metallic objects) and anomalous conductivity and dielectric constant (such as water-filled fractures and voids and the water table) in the subsurface.

The equipment required to perform this task consists of a transducer, a controller, and a data recorder. Some sort of power supply is required to power these various components. The functions of these individual components are discussed in the following sections.

3.6.3.1 Transducer and Transmitter

A radar transducer is a device which either emits a radar pulse, receives the pulse, or does both. Basically, a radar transducer is a form of radio antenna, specially modified to obtain a very high signal to noise ratio.

The transmitter is a device which, when triggered, sends a very short-duration voltage pulse to the transducer. The duration of this pulse ranges from 1 to 6 nanoseconds and the pulse repetition rate is typically 50 KHz. The peak power pulsed to the transducer is approximately 35 watts with an average power of about 5 milliwatts. Physically, the transmitter is contained in the same housing as the transducer.

3.6.3.2 Control Unit

The control unit consists of a transmit-receive selector, a radar signal receiver, and ancillary signal processing units.

The transmit-receive selector switches the antenna from the transmit mode to the receive mode and disables the pulse transmitter a few nanoseconds after the transmitter is triggered. This selector also prevents damage to the receiver while the transmitter is emitting a pulse by disconnecting it from the antenna.

The receiver system amplifies the reflected signal received by the antenna and then transforms the signal from radio frequencies to audio frequencies so that the signal can be recorded by conventional recording equipment. This transformation is accomplished by a time domain sampling technique that uses progressive amplitude samples from each successively received waveform and constructs a similar waveform with a much longer time base (audio frequency range). Approximately 3,125 radar waveforms are required to reconstruct the audio replica. At a repetition rate of 50 KHz, this reconstruction takes approximately 60 milliseconds to perform.

Since the antenna is moving during profiling, the time period required to construct the audio waveform can be related to lateral resolution. At a profiling speed of 2 mph (typical high-resolution scan speed) the antenna moves 2.2 inches in the time required to construct one audio trace. The seismic reflection equivalent to this would be to have a geophone spacing of 2.2 inches. At a reconnaissance speed of 10 mph, the antenna moves 11 inches between audio waveforms.

The ancillary signal conditioning units perform a variety of functions; one of these units has the ability to preselect repetition rates and apply various filters to the signal. Another unit allows for either real time or off-line signal enhancement and can be used to superimpose different position markers on the data.

3.6.3.3 Recorders

Two types of data recorders are used with a radar system: a tape recorder and a graphic recorder. The graphic recorder is the same type used in marine bottom and sub-bottom profiling. The data are presented in an intensity modulated format. That is, the reflected signal is sinusoidal in shape, which, when intensity modulated, is transformed to a series of dark and light bands. The more positive signal (higher amplitude) is represented by a darker band. Those portions of the signal which have zero amplitude or negative polarity are left blank. The recording pen is synchronized to the audio signal transmit pulse (the equivalent of the transmitter trigger before its transformation to audio frequencies) and the recording paper is synchronized to the wheels of the transducer. As the transducer moves, so does the paper, and when a complete audio waveform is generated, the pen sweeps across the paper displaying the wave form in the intensity modulated format. The result is a profile or section with time in nanoseconds as one axis and distance as the other. Time can be converted to depth with a knowledge of the wave propagation velocity through the subsurface.

The tape recorder stores the audio signal and all of the synchronization signals on magnetic tape so that the profile may be reproduced later at a scale more suited to interpretation. If digital signal processing is deemed necessary, the tape may be played back through an analog to digital (A/D) converter.

3.6.3.4 Calibration of Radar Equipment

There are two critical areas involving the calibration of radar equipment: system timing and the accurate conversion of the radio frequency signal to an audio frequency signal. The calibration of both is accomplished in a straightforward manner.

System timing is checked by means of an accurate timer-counter. By triggering the timer-counter with the transmitter pulse, the repetition rate can be calibrated. The pulse width is checked with a high-frequency oscilloscope.

The oscilloscope can also be used to calibrate the timing and waveform conversion portions of the receiver unit. First, the transducer should be placed on a wooden table several feet above the ground surface. A good electromagnetic reflector can then be constructed by simply placing a piece of ferrous sheet metal on the ground surface directly beneath the transducer. With the radar unit in operation, a constant reflected waveform will be received by the antenna. If the oscilloscope is connected to this signal (after amplification) the received waveform can be observed directly. If the lower frequency waveform output by the receiver has the same shape as the waveform received by the antenna, then the waveform conversion circuitry is functioning properly. Timing can be checked by measuring the indicated time to the first reflection (the sheet metal) on the audio frequency record. This time should be equal to twice the distance from the transducer to the sheet metal divided by the velocity of light.

3.6.4 Processing of Radar Data

With typical radar profiles, the data processing involves the conversion of travel times to depths. The conversion of travel times to depths is accomplished by drilling to a known reflector, measuring its depth and applying the following relationship:

$$V_m = \frac{2D}{t}$$

where

V_m = velocity of light in the region between the surface and the reflector

D = measured depth to reflecting interface

t = elapsed time between transmitted pulse and pulse from reflector

Once V_m is known at several points in the area of interest, the above relationship can be used to derive the depths to various reflecting interfaces.

Most radar units in use today do not employ the common depth point (CDP) technique of profiling (see Section 3.2.1.1). Some CDP radar profiling has been performed experimentally, but only to a limited extent. The data were processed in exactly the same manner as high-resolution CDP seismic reflection data. This technique is discussed in Section 3.2.4.

The CDP method is not used for conventional radar surveys because of data density. As stated in Section 3.6.3.2, a high-resolution radar profile generates the equivalent of one trace every 2.2 inches. Compared to a high-resolution seismic reflection profile (one trace every 20 feet), this represents an increase in data density by a factor of 100. The resulting increase in computer time required to process data of this density is prohibitively expensive.

3.7 BOREHOLE LOGGING

Borehole logging consists of measuring various subsurface parameters in a well or boring using a borehole sensor or sonde designed specifically for the parameter to be measured. The parameters most often measured are:

- Spontaneous potential
- Resistance
- Natural gamma radiation
- Gamma absorption
- Neutron absorption
- Borehole diameter
- Fluid movement
- Temperature
- Sonic velocity

3.7.1 Field Procedure

The field procedures for borehole logging are virtually identical regardless of the parameter to be measured. A sensor or sonde is lowered slowly into a borehole using a wireline and winch. Appropriate measuring scales and instrument settings are selected while the sonde is descending. After the sonde reaches the bottom of the borehole, the winch is reversed and a continuous record of the measured parameter as a function of depth is made from the bottom of the hole to the ground surface.

3.7.2 Spontaneous Potential Logging

Spontaneous potentials are naturally occurring electrical potentials arising chemically and physically at the contacts between the drill hole fluid and the subsurface materials as well as at the contacts between the various lithologic units and their contained fluid. The spontaneous potential or SP log measures and records these potentials.

Qualitative uses for the SP log include lithologic correlation between drill holes and location of permeable beds. Quantitative uses include determination of bed thickness and formation water resistivity.

The sonde for SP logging consists of an oxidized lead or iron electrode. The SP measurement is the potential between the downhole sonde and a reference electrode at the surface. Also, a differential SP measurement can be made between two separate electrodes on the sonde. The basic elements of a borehole SP measurement system are shown in Figure 15.

3.7.3 Resistance Logging

Resistance logging consists of measuring the resistance, in ohms, of the in situ materials between an in-hole electrode and a surface electrode, or between two in-hole electrodes. A constant current is maintained between the two electrodes and the potential difference is measured. Resistance logging is also called single-point, point-resistance, or single-electrode logging.

Qualitative uses for resistance logging include lithologic correlation between drill holes and location of fractured zones. Quantitative uses include determination of bed thickness. The resistance log is sensitive to changes in drill hole diameter (caving, washouts, and fractures) and in areas of hole enlargement will primarily measure electrical properties of the drilling fluid. Thin lithologic units with resistivities higher than that of the drill hole fluid may be indistinguishable.

The sonde for resistance logging is similar to the SP sonde and often both measurements are made simultaneously with a single sonde. One variation of the resistance log is the differential-resistance log which measures the resistance between two in-hole electrodes. The basic elements of a borehole resistance measurement system are illustrated in Figure 16.

3.7.4 Natural Gamma Logging

The natural gamma log is a passive-type log. Measurements are made of naturally occurring gamma radiation and an active radiation source is not required.

The natural gamma log is used qualitatively for stratigraphic correlation and quantitatively for estimates of porosity and permeability based on clay content. Logging speed must be adjusted in relation to the instrumental time constant to avoid loss of sensitivity.

The natural gamma sonde consists of a scintillation-type receiver and associated counting circuitry. The basic elements of a borehole natural gamma radiation measurement system are depicted in Figure 17.

3.7.5 Gamma-Gamma Logging

The gamma-gamma log uses an active gamma source to measure bulk density. Gamma radiation is emitted from a radioactive source, usually Cobalt 60 or Cesium 137, and directed into the formation surrounding the drill hole. At a fixed distance from the source, a receiver detects changes in the gamma radiation absorption caused by changes in formation bulk density. The gamma absorption is converted to bulk density by a computer.

The gamma-gamma log is most often used for determination of bulk density, but may be used to calculate porosity when the fluid and grain densities are known. Response of the log is affected by drill hole diameter, drilling fluid density, mud cake, and washed-out zones; instrument correction charts are used to adjust results for these effects. A caliper log (Section 3.7.7) must be run to determine drill hole diameter.

The dual-spacing sidewall density log compensates for many of these effects automatically. Logging speed must be selected in relation to the instrumental time constant to maintain sensitivity.

The gamma-gamma sonde consists of a radioactive gamma source, one or two receivers, and associated counting circuitry. In addition, the sidewall log has mechanical arms to hold the sonde against the wall. The basic elements of a borehole gamma-gamma density measurement system are illustrated in Figure 18.

3.7.6 Neutron Logging

The neutron log uses an active neutron source to measure porosity. A downhole chemical neutron source emits a continuous flux of energetic neutrons which reduce in energy as they migrate spherically away from the source, across the drill hole and through the formation. A radiation detector senses either the low energy neutrons or the gamma radiation resulting from slow neutron absorption.

The three major types of neutron logs are the neutron-gamma, neutron-thermal neutron, and neutron-epithermal neutron logs. The first type responds to gamma rays produced by slow neutron absorption, but is influenced by other sources of gamma-radiation. The second and third types differ in the energy range of slow neutrons over which their receivers are sensitive. Of the three, the neutron-epithermal neutron type is the most accurate and least sensitive to external effects.

The neutron log can be used to infer porosity although the direct response is to hydrogen content. Porosity determination from neutron logs assumes that all hydrogen within a formation is in the form of pore fluid (water) and that the formation is saturated. Log response is affected by hole diameter, mud salinity, mud density, mud-cake thickness, and the presence of casing. These effects can be minimized using special correction charts if the source of perturbation can be quantified. The use of a sidewall neutron log reduces many of these effects.

A caliper log (Section 3.7.7) must be performed to obtain drill hole diameter. As with other types of nuclear logs, the correct selection of logging speed relative to the instrumental time constant is important.

The neutron sonde consists of a radioactive neutron source, one or two receivers, and associated counting circuitry. The sidewall log also contains mechanical arms to hold the sonde against the wall. The basic elements of a borehole neutron porosity measurement system are shown in Figure 19.

3.7.7 Caliper Logging

The caliper log is a continuous record of the average diameter of a drill hole. Most caliper sondes consist of one to four feelers or bow springs which follow the wall of the hole. The feelers or springs are mechanically connected to potentiometers. As the feelers or springs move, the resistance of the potentiometer changes. Resistance changes are converted to diameter by surface circuitry. The basic elements of a borehole caliper measurement system are depicted in Figure 20.

The primary application of caliper logs is to measure hole diameter so that diameter effects on other logs can be corrected. Other applications are based on inferences from hole diameter and include lithologic identification, stratigraphic correlation, location of fractured and caved zones, and computation of material quantities for grouting.

3.7.8 Fluid Movement Logging

Fluid movement logging is used to measure vertical movement of fluid within a drill hole. Measurements can be made as a function of depth or as a function of time at a fixed depth. The two main types of fluid movement devices are the impeller flowmeter and the tracer injector. Both types should be centralized in the hole to avoid velocity distortion.

The impeller flowmeter consists of an impeller mounted in an annular housing with the axis of rotation parallel to the drill hole axis. The number of revolutions per unit time are counted, averaged, and electronically converted to velocity. In the moving mode, the hole is logged in both directions at the same speed. The fluid velocity is equal to one-half the difference in velocity as recorded in each direction. The logging direction in which the lowest velocity is measured is the same direction as the fluid movement. In the stationary mode, the flowmeter is held in one position and velocity is recorded as a function of time.

The tracer injector consists of a device used to inject a thermal, conductive, or radioactive tracer which is detected at some fixed distance by a thermistor, fluid conductivity device, or radiation detector. The tracer injector is used only for stationary measurements. The flow velocity is determined by measuring the time interval between injection and detection. The basic elements of a borehole fluid movement measurement system are shown in Figure 21.

Common applications of fluid movement logging include the determination of fluid movement in drill holes open to multiaquifer artesian systems and the determination of relative permeability under imposed hydraulic pressure.

3.7.9 Temperature Logging

Temperature logs are continuous records of the temperature of the drill hole environment. The temperature recorded is for the fluid surrounding the sensor, which may or may not be representative of the temperature in the surrounding mterial. The temperature log is generally performed as a function of depth, but may also be run at a constant depth as a function of time. Temperature logs are usually performed in uncased fluid-filled holes.

Qualitative applications for temperature logs include identification of aquifers, location of permeable zones, and mapping of groundwater flow. Quantitative applications include location of grout beyond a casing after cementing and determination of geothermal gradient. The geothermal gradient can be determined only when the drill hole fluid has reached thermal equilibrium with in situ materials and there is no vertical fluid movement. Logging speed should be slow enough to allow the sonde to respond to temperature changes. Mixing of the drill hole fluid by movement of the sonde must be considered.

Temperature logging sondes contain a thermistor which changes resistance as a function of temperature. The resistance is monitored on the surface and electronically converted to temperature. The differential-type sonde contains two separate thermistors and the difference in temperature between the thermistors is measured. Another type of differential sonde uses a single sensor with an electronic memory to store readings which are compared with previous readings to determine temperature differential. The basic elements of a borehole temperature measurement system are illustrated in Figure 22.

3.7.10 Sonic Logging

Sonic logging is a measurement of the time required for an acoustic pulse to travel from an electromechanical source to a receiver. The velocity is determined by multiplying the reciprocal of travel time by the transmitter to receiver spacing. The basic elements of a borehole sonic velocity measurement system are shown in Figure 23.

The primary use of sonic logging is the determination of porosity. The average velocity of sound in the subsurface is a function of matrix velocity and fluid velocity. Matrix velocity depends on lithology and is usually determined from core samples in a laboratory.

Another important application of sonic logging is to provide data for seismic reflection surveys. Knowledge of subsurface velocity distribution can be used in converting travel-time sections to depth sections. Artificial or synthetic seismic sections can be constructed from velocity and density logs.

3.7.11 Standard Log Format

All logs obtained during a geophysical borehole logging program should be presented according to a standard log format. The standard log format should be developed so that all data pertinent to the interpretation of the logs are clearly presented. The data should be recorded on field versions of the log as well as on subsequent reproductions. The log formats developed by the American Petroleum Institute are recommended. A sample borehole logging data sheet is shown in Figure 24.

3.7.11.1 General Heading Information

As a minimum, the heading for each log should contain the following information:

- Project and site location
- Logging organization and company
- Log type
- Borehole number
- Date
- Run number
- Depth determined by logger
- Depth determined by driller
- Top and bottom of logged intervals
- Size, type, and depth of casing
- Bit size
- Fluid type
- Equipment identification numbers
- Logger's name
- Scale settings and changes made during logging

3.7.11.2 Remarks

Additional information describing borehole conditions, equipment performance, and unusual conditions encountered should be recorded in the remarks column of the log. This information can include:

- Specific instrument settings
- Drilling fluid density (including measuring technique)
- Drilling fluid pH and loss
- Source of drilling fluid sample

- Drilling fluid, drilling fluid filtrate, and mud-cake resistivity for surface and maximum borehole temperature
- Source of resistivity data
- Calibration procedure
- Time since last circulation
- Begin time of logging run and direction
- Maximum borehole temperature
- Equipment failures
- Changes in hole diameter

3.7.11.3 Log Presentation

The log should be presented on a paper or film strip beneath the heading with log measuring units indicated across one axis and depth of hole along the other axis. In general, a linear scale should be used for presentation of data; however, this should not preclude using the most appropriate scale. Standard log measuring units, as detailed in the following subsection should be used. Whenever possible, calibration data including electrical and mechanical zeros should be shown on the log. More than one type of data curve may be displayed on a log as long as identification of the curve and appropriate scale is clearly indicated.

3.7.11.4 Standard Log Measuring Units

The following standard log units should be used depending on the specific log type:

- The standard unit for spontaneous potential logging is the millivolt. Positive voltages are normally to the right of zero. This convention may be reversed if justified and clearly indicated.
- The standard unit for resistance logging is the ohm. Increasing resistance is normally to the right.
- The standard unit for natural gamma logging is the API gamma ray unit. Radiation count normally increases to the right.

- The standard unit for gamma-gamma logging is the gram per cubic centimeter. Density normally increases to the right. An alternate unit for gamma-gamma logging is percent porosity with increasing values to the left.

- The standard unit for neutron logging is the API neutron unit. Radiation count normally increases to the right. An alternate unit for neutron logging is percent porosity with increasing values to the left.

- The standard unit for caliper logging is the inch. Diameter normally increases to the right.

- The standard unit for fluid-movement logging is feet per minute. Velocity normally increses to the right.

- The standard unit for temperature logging is the degree Fahrenheit. Increasing temperature is normally to the right.

- The standard unit for sonic logging is microseconds per foot which is the inverse of velocity. Increasing time is normally to the left. An alternate unit for sonic logging is percent porosity with increasing values to the left.

3.7.12 Borehole Logging Equipment

The necessary tools and equipment to conduct geophysical borehole logging can include:

- Downhole probe or sonde
- Electrical cable to which the sonde is attached
- Powered winch to hoist the sonde
- Measuring sheave to determine depth
- Weight indicator
- Power supply
- Surface control circuits
- Recording system.

3.7.12.1 Downhole Probe

The probe or sonde contains the instrumentation necessary to conduct the physical measurement of interest and to prepare the signal for telemetering through the cable to the surface. Specific detail on sondes is contained in Sections 3.7.2 to 3.7.10.

3.7.12.2 Electrical Cable

Logging cables are steel-armoured and contain one to seven conductors. Diameters range from 3/16 to 9/16 inch. The cable is used to carry electrical signals and supply voltages between the surface circuitry and the sonde, as well as to physically hold the sonde.

3.7.12.3 Powered Winch

The cable is spooled on a powered winch to raise and lower the sonde. The winch also includes collectors or slip rings to preserve electrical continuity between the sonde and the surface circuitry.

3.7.12.4 Measuring Sheave

The measuring sheave is a pulley with a calibrated diameter used to determine the length of cable in the hole.

3.7.12.5 Weight Indicator

The weight indicator measures cable tension so that cable stretch corrections can be made. These corrections are usually negligible for borehole depths less than 1,000 feet.

3.7.12.6 Power Supply

The power supply is usually a generator mounted in the logging vehicle. The power supply furnishes all power required by the sonde, surface circuitry, winch, and recorder.

3.7.12.7 Surface Control Circuits

Surface circuitry provides efficient control of the logging to be performed. Control panels permit the selection of circuitry needed for a given operation or group of simultaneous operations. Appropriate safety features are incorporated to protect equipment and operating personnel.

3.7.12.8 Recording System

The logging signals are generally recorded by a photographic camera driven in synchronous motion with the probe in the hole. In certain logging units, the log is automatically traced in ink on paper. For computer processing, logging data can also be recorded simultaneously on magnetic tape.

3.7.12.9 Calibration of Borehole Logging Equipment

The components of a borehole logging system which require calibration are the recorder, surface control circuits, and borehole sensor. These various components are usually calibrated as a unit with field reference standards. The sensor is exposed or connected to the standard and the associated recorder response is checked and adjusted accordingly. Listed below are descriptions of the field reference standard for each type log:

- Spontaneous Potential - The field standard consists of a precision adjustable voltage source which is connected across the borehole SP electrode and ground. Calibration is checked for several different voltages.

- Resistance - The field standard consists of a precision adjustable resistor which is connected across the borehole resistance electrode and ground. Calibration is checked for several different resistances.

- Natural Gamma - The field standard consists of a gamma source for which the API radiation is defined at a fixed distance from the source. Calibration is checked by placing the source at the specified distance from the borehole gamma sensor and the noting response.

- Gamma-Gamma - The field standard consists of a set of blocks constructed of different materials (e.g., plastic, aluminum, magnesium) with known densities. Calibration is checked by placing one of the blocks over the borehole sensor and noting the response. The procedure is repeated for the remaining blocks.

- Neutron - The field standard consists of a set of blocks constructed of different materials (e.g., paraffin, plastic) with known hydrogen content. Calibration is checked in the same fashion as for gamma-gamma.

- Caliper - The field standard consists of a metal paddle with holes drilled at known separations. Calibration is checked by slipping the paddle over the borehole tool, placing the caliper arm in one of the holes, and noting the associated response. This procedure is repeated for several different radii.

- Fluid Movement - The field standard consists of a precision adjustable voltage source. The impeller assembly is bypassed and a known voltage is input directly to the surface circuitry. This procedure is repeated for several different voltages corresponding to different fluid velocities. Tracer injector devices require calibration of the recorder time base with a time interval counter.

- Temperature - The field standard consists of a precision adjustable resistor. The sensing element (thermistor) is bypassed and a known resistance is connected across the surface circuitry. This procedure is repeated for several different temperatures. For precision thermal logging, ice-bath calibration of the thermistor is also performed.

- Sonic - The field standard consists of a precision pulse generator. The surface sonic circuitry is triggered by an initial pulse and stopped by a subsequent pulse occurring after a known interval. This procedure is repeated for several different time intervals corresponding to different velocities.

3.7.13 Processing of Borehole Logging Data

The processing of borehole logging data consists primarily of correcting the field data for hole size, casing, and fluid type, and then converting the results to a desired property.

3.7.13.1 Borehole Corrections

Within the borehole environment there are several effects which must be corrected if the logging data are to be used for quantitative purposes. Even when the data are used for qualitative purposes, an awareness of borehole effects will aid in preventing the situation where log response caused by external factors is interpreted as being due to lithologic changes. The borehole parameters which impact logging interpretation are:

- Hole size
- Casing composition, size, and thickness
- Mud type, density, and resistivity

These effects can usually be corrected if the parameters can be quantified. Hole size is particularly important when conducting any of the nuclear logs (gamma, gamma-gamma, neutron), and can be measured directly with a caliper. The appropriate correction is determined directly from charts pertaining to the particular borehole sonde being used. Casing composition, size, and thickness can be determined from drilling logs or completion records; again, appropriate corrections are determined from charts for the particular sonde (note that only the nuclear logs are run in cased holes). Mud type, density, and resistivity can affect spontaneous potential, resistance, and nuclear logs. While spontaneous potential and resistance logs are used primarily for qualitative applications, a knowledge of mud resistivity allows the interpreter to anticipate log response as a function of lithology; for example, when the mud resistivity is relatively low, the resistance log will become insensitive to high resistivity formations. Mud resistivity can be determined in the field with standard test cells. Similarly, mud type and density affect the nuclear logs, but can be corrected if these parameters are known. Test kits are available so that these parameters can be determined in the field.

Borehole corrections are becoming less important for certain types of tools. Modern sidewall sondes, particularly nuclear, overcome the need for many corrections either by the fact that the sensor is held against the borehole wall or that corrections are applied in real time by the surface control circuitry. Sidewall nuclear logs often contain built-in calipers which provide hole size information to the surface control circuitry so that appropriate corrections can be computed and applied to the data.

3.7.13.2 Data Conversion

The conversion of borehole logging data to a desired property can be accomplished in several ways. Many modern logging devices contain built-in circuitry or minicomputers which perform the conversion in real time. Gamma-gamma devices, for example, actually measure the absorption of gamma rays primarily by Compton scattering. The related density is usually calculated from the absorption data by on-board circuitry or computers.

A second means of conversion can be accomplished by referring to standard charts. Sonic velocity, for example, can be converted to porosity by comparison with published charts for specific lithologies and fluid velocities.

A third means of conversion can be accomplished by cross-plotting techniques. These techniques are similar to matrix solution of simultaneous equations as they require more than one measurement to accomplish the conversion. Cross-plotting charts are available from most of the major logging companies to facilitate the process. Basically, these charts are constructed with one type of borehole measurement on the ordinate and a different type of borehole measurement on the abscissa. For example, cross-plot charts are available for sonic velocity and neutron porosity measurements. The values for each type measurement are plotted on the respective axis. The point on the plane of the chart with those coordinates indicates the grain density of the subsurface independent of porosity.

A final means of conversion consists of utilizing digital computers to implement conversion from charts or by solution of systems of simultaneous equations. The major advantage of computer conversion is the speed with which large amounts of data can be processed. It is perfectly feasible, for example, to cross-plot two types of borehole measurements at one foot increments for the entire logged interval. The resultant display can be used to spot trends such as the major lithologies in the subsurface. With sufficient quantity and type of logging measurements, multicomponent lithologies can be studied by solving simultaneous equations. Such a process is extremely useful for sulfur exploration where the sulfur is associated with limestone and silt. With sonic, density, and neutron logs it is possible to solve for the bulk volume fraction of each component and to display the result as a function of depth. Such information is useful for planning subsurface operations.

3.8 PREREQUISITES

Prerequisites for a geophysical survey program are assessment of site conditions, determination of survey type and extent, site preparation, equipment selection and preparation, and mobilization.

3.8.1 Assessment of Site Conditions

Site conditions pertinent to geophysical surveys should be assessed by review of existing site data and physical inspection. Important characteristics are:

- Physical access
- Climate
- Topography
- Geology

3.8.2 Determination of Survey Type and Extent

Survey technique and extent of coverage by each technique should be determined on the basis of:

- Site conditions
- Type of information required
- Limit of information required
- Results from previous geophysical surveys
- Availability of equipment and personnel

3.8.3 Site Preparation

Site preparation activities should be performed on the basis of site conditions and the type of survey to be conducted. Preparation, as appropriate, can include:

- Obtaining permits for access, explosives, nuclear material, and radio equipment
- Clearing, surveying, and staking survey lines and locations to specified accuracies
- Drilling shotholes or exploratory boreholes
- Establishing field offices
- Providing explosives storage

3.8.4 Equipment Selection and Preparation

Geophysical survey equipment should be selected on the basis of suitability, range, accuracy, precision, and reliability. All equipment should be assembled, tested, and calibrated as required. Calibration should include equipment and field reference standards.

3.8.5 Mobilization

All operating personnel should be aware of specific details pertaining to the particular survey program. Prerequisites should be reviewed for compliance prior to mobilizing equipment and personnel.

3.9 CALIBRATION OF EQUIPMENT

Geophysical equipment used to obtain quality-related field measurements should be controlled by a calibration program. This program should assure that equipment is of the proper type, range, precision, and accuracy to provide results which are compatible with the required scope of work.

Field equipment should be calibrated and maintained in accordance with documented procedures at prescribed intervals and/or prior to use. Calibration should be done with standards which have known relationships to nationally recognized standards or physical constants. Calibration can be performed by an organization using in-house standards that are only used for calibration, or by manufacturers and external agencies. The calibration of new equipment by manufacturers or calibrations by external agencies should be acceptable if certificates of calibration which are traceable to nationally recognized standards are provided. External calibration is particularly applicable to new equipment and the recalibration of in-house standards.

3.9.1 Calibration Procedures

Documented procedures should be developed to control equipment calibration. Calibration procedures should be based on the type of equipment, the effect of error on the quantities measured, stability characteristics of the equipment, required accuracy, or other conditions affecting measurement control. Procedure content should include, as appropriate:

- Identification of equipment to be calibrated
- Documented or referenced method of calibration
- Acceptance limits
- Frequency of calibration
- Tagging of equipment to indicate calibration status
- Identification and traceability of calibration standards
- Segregation and identification of equipment failing calibration to prevent inadvertent usage
- Required documentation

Calibration procedures should be reviewed for completeness by both technical and quality assurance personnel within the preparing organization. Evidence of review should be by signing and dating the copy that is reviewed. Approval of the calibration procedures should be provided by the organization and quality assurance personnel.

All changes to calibration procedures should be subject to the same level of control as in the preparation of the original document.

3.9.2 Identification of Equipment

Equipment calibrated by an organization, equipment manufacturers or external agencies should be uniquely identified by using either the manufacturer's serial number or an assigned identification number. Whenever possible, an assigned number should be indicated by a label or tag attached to the equipment.

To identify calibration status, a label or tag should be attached to the equipment which indicates the calibration due date. If this is not possible, records traceable to the equipment should be readily retrievable for reference with the due date for recalibration clearly indicated.

Identification and tagging practices shall be applied to both measuring and test equipment and in-house calibration standards.

3.9.3 Calibration Frequency

Equipment should be calibrated at prescribed intervals and/or prior to use. The frequency of calibration can be based on the type of equipment, the manufacturer's recommendations, equipment sensitivity, the effect of error on the quantities measured, and values given in national standards. For some specially designed equipment, the frequency can be determined using calibration and field performance information obtained during the site studies.

For geophysical survey activities, the following calibration frequencies are recommended:

- Biannual calibration of geophysical survey equipment and in-house standards against nationally recognized standards.
- Daily calibration of geophysical survey equipment against in-house standards.

3.9.4 Traceability

Equipment should be calibrated, whenever possible, using calibration standards having known relationships to nationally recognized standards

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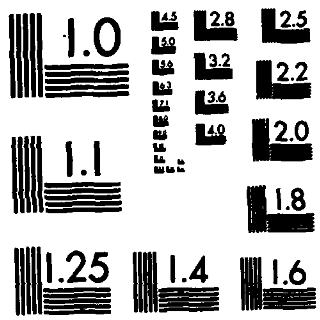
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(i.e., the National Bureau of Standards) or physical constants. If national standards do not exist, the basis for calibration should be documented in the records.

Calibration standards should be used only for calibration purposes and be traceable to the National Bureau of Standards whenever possible. Calibration standards should be stored separately from measuring and test equipment to prevent inadvertent use and exposure to hostile environments.

3.9.5 Calibration Failure

Equipment that fails calibration or becomes inoperable during use should be isolated and clearly identified as nonconforming. Such equipment should be repaired and satisfactorily recalibrated prior to reuse. If repair within the specified acceptance limits is not possible, the equipment should be permanently removed from service. The means for documentation of failure and subsequent repair should be included in calibration procedures and maintained as calibration records.

Results of completed field activities using equipment that has failed recalibration should be evaluated to determine the effects, if any, caused by use of the nonconforming instrument. The results of the evaluation should be documented.

3.9.6 Calibration Records

Records should be prepared and maintained for each piece of equipment subject to calibration to indicate that established schedules and procedures have been followed. The records should contain a history of calibration, acceptance/failure, and repair. Each file should include, as appropriate:

- Name and identification number of the equipment
- Calibration frequency
- Names of individuals performing the calibrations
- Dates of calibration

- Acceptance limits
- Calibration data and results of equipment evaluation
- Identification of calibration standards used
- Certificates or statements of calibration provided by manufacturers and external agencies
- Records of calibration failure and repair

3.10 PERSONNEL QUALIFICATION

Geophysical surveying activities should be performed by personnel qualified on the basis of education, experience, and training. Whenever possible, surveying should be performed by a professional geophysicist or geologist having practical experience in conducting geophysical surveys. As a substitute, other degreed technicians can be used providing they have extensive experience in geophysical surveying procedures.

It is recommended that field personnel attend orientation programs prior to beginning surveying activities. The programs should provide instruction in the technical objectives of the characterization study; procedures, specifications, and regulations used to control field work; and the quality assurance and/or quality control requirements.

Personnel qualification should be documented. For professional staff members (e.g., geophysicists and geologists), and as a minimum for other personnel, resumes should be prepared. Resumes should include academic credentials, employment history, Civil Service classification (if applicable), registrations, and certifications. Explicit descriptions of previous relevant work experience should be included.

3.11 VERIFICATION AND REVIEW

Geophysical survey data and data processing which affects the results of a site characterization study should be subject to a review and/or verification process. The process should include:

- Peer review of field data
- Verification of data processing
- Verification of computer programs.

3.11.1 Peer Review of Field Data

To provide technical review of geophysical surveying, peer reviews should be established by the organization responsible for the surveying. Peer reviews should be performed by personnel not involved with this aspect of the site characterization study but who have technical expertise equal to those performing the surveys or processing the data. Review should begin during the planning phase of the survey and extend through the field work and to the evaluation of the final data. The review should address the following, as appropriate:

- Are the procedures and specifications, as developed, sufficient to control the field activities?

- Is the work being performed in accordance with the requirements of approved procedures and specifications?

- Do the procedures and specifications being used result in obtaining reasonable data compatible with the purpose of the site exploration?

- Are any interpretations, judgments, or decisions based on the geophysical survey data supported by the data?

It is also suggested that the review be coordinated with quality assurance personnel so that the recommendations of the reviewers and subsequent responses by program personnel can be verified.

All peer reviews should be documented. A review report can include the following:

- Identification of participants

- Date(s) of review

- Activity and/or data reviewed; including any interpretations, judgments, or decisions based on recorded data.

- Recommendations for revisions to field practices.
- Statement of agreement or disagreement with any interpretations, judgments, or decisions.
- Means for making revisions or resolving disagreements.

Reports should be transmitted to technical and quality assurance management and to field supervisors.

3.11.2 Verification of Data Processing

The extent of verification required for geophysical survey data processing should be a function of the importance of the processing and results to the site characterization study. Data processing which affects results should be verified by individuals other than those who performed the original processing. These individuals should have technical expertise in the subject area equivalent to the originator.

Data processing can be verified using limited or detailed documented evaluations as discussed in the following subsections. All changes to the processing of field data subsequent to verification should be subject to the same level of evaluation.

3.11.2.1 Limited Evaluation

If the method or means for processing geophysical survey data has been previously verified and the processing will not directly affect the results of an overall site characterization program, the evaluation of the processing can be limited. In this case, the evaluation should consider only the numerical verification of the calculations (i.e., complete or spot checking). If the processing is performed with a verified computer program, only the input to the code should be verified.

Reviewing personnel should be assigned or approved by appropriate management of the organization processing the data. The results of the verification should be clearly documented with the identification of the reviewer and the data of review.

3.11.2.2 Detailed Evaluation

The processing of geophysical survey data which will provide design input to, or affect the results of a site characterization study should be completely verified. Detailed evaluations can be performed by the complete independent review of the processing, or the preparation of alternate calculations. The results of detailed evaluations should be documented and include the identification of reviewing personnel and the date of review.

An independent review should consist of a thorough evaluation of the assumptions made and the processing method, numerical verification of the calculations, formal checking of all computer input, review of results, and the checking of drawings, graphs, and tables prepared from the results. Independent reviews can involve only a single reviewer or, in the case of certain critical geophysical survey activities, can be interorganizational. The review should address the following, as appropriate:

- Has the processing been identified as to project, site, subject, originator, and date performed?
- Have assumptions been adequately described?
- Has an appropriate methodology been used?
- Are all calculations correct and have they been completely documented?
- Are the results reasonable considering the input?

Reviewing personnel should be assigned or approved by appropriate management or the organization(s) performing the review.

An example of an acceptable data processing review procedure, which provides documentation of the review, follows:

- The originator provides the reviewer with a machine copy of the processing. The originator should keep the originals until they are ready for reviewer signature.

- The reviewer indicates all differences with the work; whether in assumptions, theory, model, or numerical calculations; on the machine copy. The reviewer signs and dates the review copy.

- The originator reviews all recommended corrections and questions of the reviewer.

- If the originator does not agree with the reviewer, the differences must be resolved between them.

- After agreement, the originator corrects the originals so they present the final consensus.

- The reviewer compares the originals and check copy to assure there is one-to-one correspondence between them. The reviewer then signs and dates the original work.

- Both the original work and check copy are maintained as records. The check copy documents that the review has been performed.

Analogous procedures can be developed to review computer input, drawings, graphs, and tables.

Verification of data processing may also be accomplished by comparison with alternate methods of calculation, if an alternate means exists. Alternate calculations may employ a simplified approach, but they must provide results consistent with the original processing for proper verification. Alternate calculations should be prepared by an individual other than the originator of the processing to be verified.

3.11.3 Verification of Computer Programs

Computer programs used for data processing requiring evaluation should be documented and verified. Documentation of programs should, as appropriate, include:

- Program identification
- Operating instructions for the program
- Detailed theoretical basis
- Program listing
- Sample problem
- Verification status and documentation.

Program verification should be accomplished by applying one of the following methods:

- If the program has been accepted as an "industry standard," the program may be considered as verified. However, if the program is to be used on a system other than the one on which it was developed, it should be checked against available example problems to assure compatibility. Programs that are accepted as "industry standards" will be those which are widely used throughout the profession and which have a proven performance.

- Program results can be compared to the results of an "independently developed" computer program which performs the same calculation. Independent development could mean a program developed external to the user or by a different group within the user's organization. If possible, a program should not be compared with a program developed by the same persons unless the methodology is totally different. The input to both the program being verified and the second program should be independently checked.

- Hand calculations can be prepared to validate computer programs. The calculations should be checked to assure assumptions and results are identical to those of the program.

- Program output can be compared to analyses published in textbooks and journals. A complete reference for such material should be provided with program documentation. This type of verification includes comparison against closed-form solutions.

3.12 PERFORMANCE DOCUMENTATION AND RECORD REQUIREMENTS

The results of geophysical surveying activities must be completely documented to provide evidence of satisfactory completion and provide the basis for interpretations, judgments, and decisions made using the survey data. Documentation required for geophysical surveys should, as appropriate, include:

- Specific procedures and specifications and review copies

- Procurement documents for equipment and services

- Resumes and certifications of personnel
- Operating and explosive permits
- Field data forms
- Land survey data, including plats
- Calibration records and certificates
- Documentation of data processing and verification
- Equipment manuals
- Peer review reports and responses
- Surveillance, inspection, and/or audit reports
- Photographs
- Interpretations of data or results
- Reference material

The above information should become part of the records collected and maintained for the site characterization study.

4.0 EVALUATION OF GEOPHYSICAL TECHNIQUES

The following sections provide an evaluation of the geophysical techniques which have been identified in Chapter 2.0 as potentially valuable for attaining the project objectives and have been described in Chapter 3.0. Within the category of geophysical surface techniques the following are included:

- Seismic refraction
- Seismic reflection
- Resistivity
- Gravity
- Magnetics
- Radar

Within the category of geophysical borehole-logging techniques the following are included:

- Spontaneous potential
- Resistance
- Natural gamma
- Gamma-gamma
- Neutron
- Caliper
- Fluid movement
- Temperature
- Sonic

The evaluation of techniques includes a discussion of the effectiveness of each technique for defining the stratigraphic, structural, and aquifer characteristics discussed in Chapter 2.0. Also included is a cost-of-application estimate for each technique in 1980 dollars.

4.1 SEISMIC REFRACTION

Seismic refraction surveys are most often used to map the top of high velocity surfaces such as basement surfaces, soil-rock contacts, and water tables. Any geologic feature which has high-velocity expression can, in principle, be detected by the refraction method provided that the velocity increase is appreciable (greater than 20 percent) and that the dimensions are sufficient. These conditions are most often satisfied in sedimentary environments or along the contact between sedimentary units and igneous or metamorphic basement. The refraction technique has very little application in igneous or metamorphic environments.

The primary limitation of the seismic refraction method is that only interfaces across which the wave velocity appreciably increases with depth can be mapped. Also, if intervening layers exist between the target and the surface for which the velocity increase is lower or slightly higher, then the results of the survey can be adversely affected. Another limitation is if a layer occurs which is so thin that it cannot be detected but causes changes in travel times. Usually it is not possible to correct the data for this situation because the occurrence of the layer may not be known unless it has been detected by other types of surveys or in boreholes. Further limitations are:

- The distance between shotpoint and receiver must be large compared to the depth of the refracting horizon. As a role of thumb, the ratio is about three or four. This requirement may introduce complications when trying to avoid cultural features and excessively rugged terrain, as well as rendering the method sensitive to lateral variations in geology.

- The refraction technique is sensitive to velocity inhomogeneities, excessive dip of strata, and highly irregular subsurface relief.

- The refraction technique cannot be used in areas of high cultural noise and may be adversely affected by rain, wind, and electrical disturbances in the atmosphere.

4.1.1 Stratigraphy

The seismic refraction method can be used to define lithology only to the extent that wave velocity is controlled by lithology. In areas where the stratigraphic column is well defined and consists of rocks with distinctly differing velocities, the seismic refraction method can be used to identify lithology. The more typical case is that in which the subsurface consists of rocks with overlapping velocity ranges. Table 1 contains a list of lithologies and their representative seismic velocities. The utility of the seismic refraction method for lithological identification is also controlled by the requirement that the velocity must increase with depth.

Within the restriction that velocity must increase with depth, the seismic refraction method is useful for lithologic correlation since it provides profile information. Correlation by seismic refraction is useful in both consolidated and unconsolidated sedimentary sequences.

The refraction method is one of the most reliable and often used methods for mapping surficial material over bedrock and buried topography where the thickness is less than approximately 100 feet. The accuracy with which the thickness of cover can be determined averages 20 percent and is often as good as 5 to 10 percent under favorable conditions. Difficulties may arise when the cover consists of glacial till as this type of material is notoriously inhomogeneous and exhibits abrupt and unpredictable changes in velocity. Nevertheless, results with an accuracy of 20 percent are usually attainable when working under these conditions.

4.1.2 Geologic Structure

The seismic refraction method is applicable to a wide class of structural problems although the reflection method generally yields better results. The requirement that velocity must increase with depth limits the range of conditions for which subsurface geometry can be determined, in an absolute sense, with the refraction method. On the other hand, if a relative determination is sufficient and at least one high-speed marker bed exists in the area, then the refraction method is most useful. A good example of this type condition would be an evaporite bed bounded by sands and shales.

The refraction method is useful for mapping dipping strata and folding, provided that the amplitude of folding exceeds that due to velocity inhomogeneities and the dip of strata does not exceed the complement of the critical angle. The last requirement is particularly important because refracted waves will not return to the surface unless this condition is met. The critical angle can be calculated according to the formula:

$$\theta = SIN^{(-1)} (V_1/V_2)$$

where

θ = critical angle
V_1 = velocity above interface
V_2 = velocity below interface

For a V_1/V_2 ratio of 0.5 (saturated soil over bedrock) the critical angle is 30 degrees.

Detection of faulting is another capability of the seismic refraction method. If a high-speed bed situated under low-speed overburden is vertically faulted, then a refraction profile across the fault can be used to locate the faulting and measure its throw. When the shotpoint is located on the upthrown side of the fault, the segment of the time-distance curve representing arrivals from the high-speed layer will be displaced vertically upward in the vicinity of the fault. Conversely, when the shotpoint is located on the downthrown side of the fault, the segment of the time-distance curve representing arrivals from the high-speed layer will be displaced vertically downward in the vicinity of the fault. The horizontal position at which the vertical discontinuity in the travel time curve occurs and the amount of displacement in a time sense are diagnostic of the location of the fault and the amount of throw. The minimum detectable throw depends almost entirely on local conditions, but a reasonable estimate for a two to one velocity increase at a depth of 100 feet is about 5 to 10 feet.

The refraction technique is not generally useful for detecting fracturing due to a lack of velocity expression where fracturing is wide-spread. However, some approximate indication of location and extent of fracturing may be given by anomalous increases in travel time. The success of this procedure is dependent on the amount of subsurface control that is available to eliminate other possible causes for travel-time increases. Similarly, travel-time increases might be used to detect dissolution features. Unfortunately the feature itself would not have expression as a refracting interface because the velocity contrast at the boundary would be of opposite sense.

A widely used and often successful application of the refraction method is the detection and mapping of buried channels. Conceivably the refraction method can be employed in two ways for this purpose. The first way is to shoot parallel refraction profiles across the area of interest in conventional profiling fashion. The channel would be revealed on any intersecting profile by the associated bedrock relief and successive intersections can be linked to provide an areal view of the course. The second way uses fan shooting procedures and requires that the location of the channel be known in at least one place. A shotpoint is situated at the known location and geophones are deployed in an arc at some distance away. The direction in which the most anomalous increase in travel time is observed indicates the likely direction of the channel. A second shotpoint is then placed in the newly determined position and the process is repeated. In this fashion, the course of the channel can be constructed segment by segment.

Another use of the seismic refraction technique is mapping buried topography. Successful utilization of the seismic refraction technique for this purpose depends on the existence of sufficient velocity increase across the interface between surficial materials and the buried topographic surface.

Incidental applications for the refraction method include mapping of high velocity bodies by fan shooting. For this application, anomalous travel-time decreases rather than increases are taken to indicate the direction of the body. Real life examples of high-velocity bodies include salt domes and igneous intrusives in sediments.

4.1.3 Aquifer Properties

The aquifer property that can be measured by the refraction technique is the location of the potentiometric surface of an unconfined aquifer (water table). This is possible because the wav. velocity increases in saturated material. The wave velocity increase due to saturation is variable, but in saturated surficial material it often increases as much as a factor of two. The ability of the refraction method to detect the water table is dependent not only on the velocity increase due to saturation, but also on the proximity of the water table to other refractors. As a rule of thumb, the refraction method is useful for mapping water tables to a depth of 100 feet when there is at least 10 vertical feet of separation between the water table and the next lower refractor. Otherwise, only a short portion of the time-distance curve will represent arrivals from the water table refractor and loss of definition will result. This situation sometimes occurs when the water table is located in alluvium or soil above bedrock. The vertical separation becomes less critical as the difference beween wave velocities in the saturated soil and bedrock diminishes.

The refraction method can provide partial information for assessing aquifer flow since the vertical and lateral extent of water-bearing units can be determined. Additionally, location of the water table permits calculation of hydraulic gradients.

4.1.4 Cost

The cost estimate for conducting seismic refraction surveys is based on 1980 dollars and the following assumptions:

- The field crew consists of one geophysicist and two technicians working ten hours per day. Effective hourly rates are $44 per hour for the geophysicist and $25 per hour for each technician.
- The daily production rate is 1,000 to 2,000 feet (20 to 40 shotpoints) per day.
- Daily subsistence (per diem and lodging) for the crew is $165 per day.

- Vehicle and instrument rental is $350 per day.
- Processing and interpretation costs are $20 per shotpoint.
- The recorder has 12 channels.
- The target depth is less than 100 feet.
- The total cost per day for the source (dynamite or oxy-propane exploder) is $400.
- No land surveying, shothole drilling, brushing, or mobilization is included.

Based on these assumptions, the cost per foot of coverage ranges from $1.45 to $2.51 depending on production. A sample round-trip mobilization for a distance of 1,000 miles would be $3,000. If the target depth was less than 30 to 40 feet, then a hammer source could be used and the crew could be reduced to one geophysicist and one technician. The cost per foot of coverage would then range from $1.76 to $2.44 with a sample 1,000 mile mobilization of $2,100. Savings could be realized if this mobilization is combined with mobilization for other geophysical techniques.

4.2 SEISMIC REFLECTION

Seismic reflection surveys are used for mapping geologic features on the basis of acoustic contrast. Any geologic feature which has expression as an acoustic impedance contrast can be detected by the seismic reflection method provided that the contrast is large enough (i.e., about five percent or more). Examples of geologic features with acoustic impedance contrast are salt domes, basement topography, soil-rock contacts, water tables, and lithologic contacts.

The primary limitation of the seismic reflection method is that a geologic feature must have contrasting acoustic properties to be detected. This limitation implies that the reflection technique should be used only to map sedimentary rocks or features or sedimentary-basement contacts. The reflection technique is only rarely useful for mapping igneous, metamorphic, or volcanic rocks. Further limitations are:

- The maximum resolution falls off rapidly with depth. Even at shallow depths (less than 300 feet), the seismic reflection technique cannot individually distinguish two acoustic interfaces separated by less than about ten feet. This means that the top and bottom of thin units will appear to be merged.

- The reflection technique can be adversely affected by velocity and density in homogeneities or excessive (greater than 45 degrees) dip of strata.

- The reflection technique maps the subsurface in terms of time. Converting time information to depth information requires that the velocity distribution be well established if distortion of the subsurface is to be avoided.

- The reflection technique cannot be used in areas of high cultural noise and may be adversely affected by rain, wind, and electrical disturbances in the atmosphere.

- The reflection technique is costly at depths less than 100 to 300 feet depending on local conditions.

4.2.1 Stratigraphy

The seismic reflection method has limited utility for determining lithology. When the relationship of velocity and depth for different rock types in an area is known, it is sometimes possible to identify lithology from seismic velocity data alone. Table 1 provides a list of lithologies and their representative seismic velocities. More advanced and recently developed methods attempt to define lithology on the basis of seismic wave attenuation. Presently, however, direct determination of lithology from seismic reflection data is difficult and requires borehole information. A more suitable use for the reflection method is lithologic correlation. While borings generally provide excellent vertical resolution, seismic reflection surveys generally provide better horizontal or profile information. With seismic reflection coverage, stratigraphic features such as facies changes, pinch-outs, unconformities, channel sands, and clay lenses can often be mapped.

The ability of the reflection method to depict subsurface geometry is also valuable for reconstructing depositional history. Reflection patterns often make it possible to understand how deposition took place in areas under investigation. A knowledge of depositional history often makes it possible to determine lithology and to predict the type of geologic features to be expected. Some examples of reflection patterns and the associated depositional environment are listed below:

- Divergent - Unconformity
- Parallel - Quiescent
- Prograding - Deltaic

The reflection method is also very useful for mapping surficial materials over bedrock and buried topography where the thickness exceeds approximately 100 feet. For lesser thicknesses, the refraction method is preferable. In areas where the cover consists of coarse dry gravels, high seismic energy attenuation may occur. Such attenuation can reduce reflected energy to levels below the detection threshold. In such applications, gravity or magnetic methods may yield superior results.

4.2.2 Geologic Structure

The seismic reflection method can often be used to detect and map folding providing that the data are of good quality, the amplitude of the folding exceeds that due to velocity inhomogeneities, and the associated dip of strata does not exceed 45 degrees. In areas of complex folding, migration techniques are particularly helpful for improving definition. The detection of faulting is another good application of the reflection technique. Indications of faulting on a seismic section can range from obvious to subtle depending on the geology, type of faulting, and amount of displacement. The most common indicators of faulting on reflection sections are the following:

- Warping or disappearance of reflections below fault planes
- Misclosures in tying reflections around loops on a seismic grid
- Dip divergence not attributable to stratigraphy
- Diffraction patterns, particularly when the vertices line up in a manner consistent with local faulting
- Linear reflection discontinuities.

Current high-resolution seismic techniques have the capability of detecting faults with throw as small as 3 feet in saturated and unconsolidated sedimentary sequences. Under less favorable conditions, the detection threshold increases to 10 to 20 feet of throw.

The reflection technique is not generally useful for detecting fracturing due to insufficient acoustic expression. In special cases, however, where the fracturing is extensive and bounded by undisturbed rock, the reflection method may give some indication of areal fracturing extent based on disruption of reflecting horizons and shadow zones beneath the fractured material.

The detection of dissolution features is another potential use for seismic reflection methods although efforts in this direction are still largely experimental. Based on experiments conducted over abandoned coal mines, it appears that subsurface voids can be detected provided that the dimensions of the feature are at least approximately 10 percent of the depth of occurrence. One disadvantage of the reflection method compared to the gravity method for this application is that the line of profile on the surface must pass over the void; the gravity method is far less sensitive in this regard. Another limitation arises from resolution considerations. If the void is small and situated near the top of a lithologic unit, then the reflection from the void and the top of the unit may merge into one signature making detection difficult if not impossible.

A powerful use of the reflection method is the detection and mapping of buried drainage channels. Currently, developmental work is under way to refine channel-detection capabilities in response to needs of the coal-mining industry. Sand channels often occur in coal seams and pose both safety and economic problems when they are encountered during mining. With good quality data obtained on a grid of intersecting lines, it is often possible to determine the width and course of a channel across the area of interest. Recent studies have been successful in mapping entire tributary systems. Similarly, the reflection method is useful for mapping buried topography at depths greater than 100 feet. The preferred field procedure for this application is acquisition of seismic data along an intersecting grid of profiles.

Igneous features in sedimentary sequences can be detected with seismic reflection methods provided that sufficient acoustic contrast exists due either to the innate properties of the intrusive or the associated disturbance (fracturing) caused during emplacement.

4.2.3 Aquifer Properties

The aquifer property that can be directly determined by the seismic reflection method is the potentiometric surface of an unconfined aquifer (water table). Since there is an increase in both velocity and density for saturated material, the water table forms an acoustic interface. The degree of acoustic contrast will be greatest for granular, uncompacted material. Velocity increases associated with saturation of this type material can approach a factor of two, resulting in a high reflected energy ratio. The reflection method is best applied to water-table mapping at depths greater than 100 feet because the refraction method is generally less expensive and provides better results at depths less than 100 feet. As with the refraction method, the water table should be at least 10 vertical feet from other acoustic interfaces or signal merging and loss of definition may occur.

The reflection method can provide partial information for assessing aquifer flow since the vertical and lateral extent of water-bearing units can be determined. Additionally, location of the water table permits calculation of hydraulic gradients.

The other identified aquifer properties (porosity, permeability, temperature, and water chemistry) cannot be directly determined by seismic reflection techniques due to insufficient acoustic expression. Current research efforts toward porosity determination from seismic reflection data are underway, largely in response to the needs of the petroleum industry. These efforts are still highly experimental, and it will be several years before reliable methods are developed.

4.2.4 Cost

The cost estimate for conducting seismic reflection surveys is based on 1980 dollars and the following assumptions:

- The field crew consists of one geophysicist and three technicians working ten hours per day. Effective hourly rates are $44 per hour for the geophysicist and $25 per hour for each technician.
- The daily production rate is 25 to 50 shotpoints per day.
- Daily crew subsistence (per diem and lodging) is $220 per day.
- Vehicle and instrument rental is $600 per day.
- Processing and interpretation costs are $41 per shotpoint.
- The desired multiplicity of coverage is six fold.
- The recorder has 24 channels.
- The target depth is less than 300 feet.
- The total cost per day for the source (dynamite or oxy-propane exploder) is $400.
- No land surveying, shothole drilling, brushing, or mobilization is included.

Based on these assumptions, the cost per shotpoint ranges from $89.20 to $137.40 depending on production. The cost per lineal foot for profile coverage are listed below for two different station spacings typical of shallow surveys (25-foot spacing is for targets approximately 300 feet deep and 10-foot spacing is for targets approximately 100 feet deep):

STATION SPACING	COST PER FOOT
25 feet	$1.78-$2.75
10	$4.46-$6.87

A sample round-trip mobilization for a distance of 1,000 miles would be $3,200. Savings could be realized if this mobilization is combined with mobilization for other geophysical techniques.

4.3 RESISTIVITY

Resistivity surveys are used for mapping geologic features on the basis of resistivity contrast. Any feature which has expression as a resistivity contrast can be detected by the resistivity method provided that the contrast is large enough (i.e., at least 20 percent but preferably 50 percent). Examples of geologic features with resistivity expression are soil-rock contacts, clay-sand contacts, igneous intrusives, and water tables.

The primary limitation of the resistivity method is that there is no unique inversion for a given data set. While a given subsurface resistivity distribution gives rise to a unique data set, the converse is not true. In theory, any given data set will fit an indefinite number of models. Knowledge of the local geology and subsurface control from borings, electrical well logs, or other geophysical techniques must be used to constrain the range of acceptable models. The validity of any model must be tested not only by comparing the observed apparent resistivity curve with the theoretical or calculated curve, but also by consistency with other available information. Further limitations are:

- The maximum resolution falls off rapidly with depth. Even at shallow depths the resistivity method cannot reliably locate boundaries with accuracy better than approximately 20 percent.
- The resistivity method can be adversely affected by dipping strata and lateral resistivity variation.
- The surface dimensions for electrode layouts are large compared to the depth of investigation. For Wenner electrode configurations, the ratio is about 3:1. This characteristic may introduce complications when trying to avoid cultural features, rugged terrain and lateral variations in geology.
- The resistivity method cannot be used to map the subsurface beneath extremely high resistivity (insulating) or extremely low resistivity (conducting) horizons. An example of an insulator is a coal seam and an example of a conductor is saline groundwater.

Since resistivity contrasts exist in sedimentary, igneous, and metamorphic environments, the applicability of the resistivity method is not generally restricted by geology.

4.3.1 Stratigraphy

The resistivity method can be used to define lithology only to the extent that resistivity is controlled by lithology. In areas where the stratigraphic column is well defined and consists of rocks with distinctly different resistivities, the resistivity method can be used to identify lithology. Table 2 contains a list of lithologies and their representative range of resistivities. Typically, however, the subsurface consists of materials with overlapping resistivity ranges. A good estimate of the variation of resistivity with lithology in a given area may be made from borehole electrical logs. One notable exception to the typical case of overlapping resistivity ranges is the high resistivity contrast usually present at clay-sand interfaces. The utility of the resistivity method for determining lithology can be severely restricted where insulating or conducting layers are present.

The resistivity method is inherently useful for correlating lithology due to its ability to provide profile-type information. Correlation by resistivity methods is most useful in unconsolidated sedimentary environments; a common application for this case is mapping sands, clays, and gravels in water-resource and construction investigations.

Mapping surficial material over bedrock and buried topography is another common application of the resistivity method. While the inherent accuracy of the resistivity method is less than that of the refraction method, offsetting consideration may result from the lower cost of conducting resistivity surveys. Furthermore, the resistivity method may yield better results if resistivity inhomogeneities are less than velocity inhomogeneities. Savings in resistivity survey costs can sometimes be realized when mapping soil and alluvial cover if the subsurface can be reasonably represented by a two-layer model. In this case, only two measurements, one with tight electrode spacing to measure the resistivity of the surficial materials and one with broader electrode spacing to measure the effect of the bedrock, are necessary to determine the thickness of cover.

4.3.2 Geologic Structure

The resistivity method is a good, low cost means for defining geologic structure. While generally less accurate than seismic methods, the resistivity method has some unique advantages, particularly when dealing with unconsolidated sediments. In this type environment, velocity and density expression may be practically nonexistent, but resistivity contrasts may be high. A folded and unconsolidated stratigraphic section may be successfully mapped with resistivity techniques when seismic methods are totally ineffective. Similarly, faulting of shallow unconsolidated sediments can often be detected by the resistivity method. The preceding discussion is not meant to imply that the resistivity method is ineffectual in consolidated sedimentary environments, rather the implication is that the method is usually more successful in unconsolidated sedimentary environments. The success of the resistivity method for mapping folding and faulting depends not only on the existence of appreciable resistivity contrast, but also on sufficient vertical expression. As a rule of thumb, for the application of the resistivity method it is desirable that the amplitude of folding or the throw of faulting be about 20 percent of the depth of occurrence.

Additionally, the resistivity method is extremely useful for mapping folding and faulting in metamorphic rocks which retain some semblence of layered structure. Folding and faulting of igneous rocks is more difficult to define with resistivity methods due to the lack of marker horizons. Nevertheless, fault and shear zones in igneous rock are often marked by low resistivity due to infilling by mineralized groundwater. The resistivity method is extremely useful for mapping folding and faulting in basement complexes due to the high resistivity contrast which usually exists along the top surface.

A significant amount of effort has been spent in developing and applying resistivity methods for mapping fracturing and dissolution features, largely in response to the needs of geotechnical engineering. Fracturing can most often be detected when the resultant void spaces are filled with groundwater. The more saline or mineralized the groundwater is, the better the chance of detection of the resultant low resistivity zone. With sufficient resistivity profile coverage, the areal extent and thickness of fracturing may be determined. Faulting with throw too little to detect directly may often be indicated by the low resistivity zone which accompanies associated shearing or fracturing.

A good example of the use of resistivity methods for locating dissolution features is given by surveys conducted in Kansas to locate filled sinks. These sinks occur in carbonate rocks, are roughly hemispherical, filled with low resistivity material, and are concealed beneath thin alluvial cover. These sinks are economically important due to associated mineral deposits. Many of these sinks have been located using fixed-spacing Wenner array measurements along profiles. The sinks are indicated by a sharp rise in resistivity followed by an even sharper drop. For this application, the electrode spacing is set at 1.0 to 1.5 times the depth of occurrence and profiles are spaced no wider than the anticipated diameter of the sinks. A water-filled void in limestone should yield approximately the same expression while a dry void should yield the opposite expression (that is, a sharp drop in resistivity followed by an even sharper rise).

Mapping buried topography is another application for resistivity methods provided that sufficient resistivity contrast exists across the buried interface. The comments concerning the two-measurement procedure discussed in Section 4.3.1 for mapping surficial material are especially pertinent here since this procedure can be used for a rapid and inexpensive estimate of buried topographic contours.

Resistivity methods are also useful for detecting and mapping igneous features in sedimentary sequences. As indicated in Table 2, the resistivity contrast between igneous and metamorphic rocks can be as high as 200:1. Even when the contrast between the country rock and the intrusive is small, the disturbance (fracturing, contact metamorphism, etc.) may have some resistivity expression.

4.3.3 Aquifer Properties

Resistivity methods are potentially useful for directly or indirectly defining four of the five identified aquifer properties. The only property for which the resistivity method has no application is determination of temperature.

Mapping of the potentiometric surface for the case of an unconfined aquifer (water table) is one of the most common applications of resistivity methods. The addition of water to dry media often reduces the resistivity by several orders of magnitude. The high resistivity contrast which is usually present at the upper surface of the water table presents an exceptionally good target. In fact, the resistivity contrast at the water table is sometimes so high that penetration below it is difficult or impossible. This is particularly true for saline or mineralized water.

As may be inferred from the previous paragraph, the resistivity of groundwater is low and becomes even lower with the introduction of salts or minerals. This property is often used to map the extent of saline intrusion into groundwater resources in coastal areas. Resistivity surveys conducted in coastal areas of Italy, West Germany, and Israel have been very successful in mapping the extent of such intrusions. Similarly, the extent of intrusion by mineralized water can be determined by resistivity methods. As mentioned previously, the salinity or mineral content (chemistry) of groundwater is important because it may control the solubility of pollutants or may directly indicate the presence of pollutants.

Porous and permeable zones may be indicated by low resistivity when such zones are filled with groundwater. For such application, auxiliary information is required to identify external effects which could also produce low resistivity zones. If porosity and permeability of a specific horizon is of interest, then a fixed-spacing survey can be used for rapid areal coverage. Relative permeability can also be assessed by the resistivity method, since it often provides good information concerning the distribution of clays and shales which could act as permeability barriers.

The resistivity method can provide partial information for assessing aquifer flow since the vertical and lateral extent of water-bearing units can be determined. Also, hydraulic gradients can be calculated from the location of the water table.

4.3.4 Cost

The cost estimate for conducting electrical resistivity surveys is based on 1980 dollars and the following assumptions:

- The field crew consists of one geophysicist and two technicians working ten hours per day. Effective hourly rates are $44 per hour for the geophysicist and $25 per hour for each technician.

- The daily production rate for vertical electrical soundings is 6 to 12 points per day at depths up to 100 feet and 4 to 8 points per day at depths up to 300 feet.
- The daily production rate for horizontal profiling is 600 to 1,200 feet at depths up to 100 feet and 1,200 to 2,400 feet at depths up to 300 feet.
- The daily production rate for fixed-electrode spacing surveys is 20 points per day independent of depth. Depending on electrode spacing, fixed-electrode measurements could be used to generate 2,000 to 6,000 feet of profile per day.
- Daily crew subsistence (per diem and lodging) is $165 per day.
- Vehicle and instrument rental is $250 per day.
- Processing and interpretation costs are $80 per point for vertical electrical soundings.
- Processing and interpretation costs are $240 to $400 per day for horizontal profiling.
- Processing and interpretation costs are $20 per point for fixed-electrode spacing measurements.
- No land surveying, brushing, or mobilization is included.

Based on these assumptions, the cost for each vertical electrical sounding to a depth of 100 feet ranges from $193 to $306 depending on production. For vertical electrical soundings to a depth of 300 feet, the cost per point ranges from $249 to $419 depending on production. The cost for fixed-electrode spacing surveys is $88 per point. The table below lists the costs per foot of profile for two different field methods:

METHOD	DEPTH OF INVESTIGATION	COST PER FOOT
Horizontal Profiling	100 feet	$1.46 - $2.66
Horizontal Profiling	300 feet	$0.73 - $1.33
Fixed Electrode	100 - 300 feet	$0.29 - $0.88

A sample round-trip mobilization for a distance of 1,000 miles would be $2,100. Savings could be realized if this mobilization is combined with mobilization for other geophysical techniques. An important point to remember when evaluating the cost of electrical resistivity surveys is that very little land surveying or other preparation is required. Typically, survey stakes are set with only one percent lateral accuracy at each end of an electrode spread (50- to 300-feet spacing). Adequate elevation information can usually be obtained from topographic maps.

4.4 GRAVITY

The gravity method is sensitive to changes in subsurface density distribution. Therefore, any geologic feature or parameter which has sufficient density expression can, in principle, be detected by the gravity method. In addition, when sufficient control is available, it is possible to map the feature or parameter in three dimensions. Of fundamental importance to the successful application of the gravity method is the understanding that no absolute measurements of the gravitational field are made; the method responds only to variations in the gravitational field. In areas where there is no lateral variation of subsurface density distribution, the gravity method will yield no information other than the fact that the subsurface is probably laterally homogeneous in terms of density.

Also important is an understanding of the inherent ambiguity of gravity data inversion. While a given subsurface configuration will produce a unique data set, the converse is not true. In theory, any given data set will fit an indefinite number of models. Knowledge of the local geology and subsurface control from borings or other geophysical techniques must be input to the interpretation process if reasonable results are to be obtained. The validity of any model must be tested not only by comparing the observed anomaly with the theoretical or calculated anomaly, but also by consistency with other available information.

4.4.1 Stratigraphy

The gravity method is not useful for determining or correlating lithology due to its limited resolution and the large number of unknowns that must be considered. In areas where the strata are laterally homogeneous and planar, the gravity technique will not provide any information, because gravity variations attributable to stratigraphy will not be observed.

The gravity method is useful for mapping surficial material. Common applications in this area include mapping the bedrock profile of buried valleys and determining the thickness of soil over bedrock. The resolving power of the gravity method for these applications is generally less than that of the refraction or resistivity methods, but this limitation is often offset by lower costs. In some cases, however, density inhomogeneities may be less than velocity or resistivity inhomogeneities, and the gravity method may result in more accurate results. Successful utilization of the gravity method for these applications requires knowledge of the subsurface material densities involved and may require the drilling of borings for control.

4.4.2 Geologic Structure

The gravity method is generally not useful for locating and mapping fractures due to insufficient density expression, but it can be very useful for mapping folding, faulting, dissolution features, and buried drainage channels. To apply the gravity method to mapping folding and faulting, the stratigraphic section must contain at least one unit with appreciably different density than the surrounding units. Table 3 contains a list of lithologies and their representative bulk densities. The need for control is again important; for example, faulting in a crystalline basement unconformably overlain by sediments could yield the same gravity expression as faulting extending from the basement through overlying sediments.

An extremely powerful use of the gravity method is locating and mapping dissolution features and buried drainage. A dissolution feature such as a cavity in limestone presents a density contrast because it is characterized by the absence of material. The degree of density contrast decreases, however, if the feature is filled with water or clay and gravel. Assuming spherical geometry, the minimum cavity size that can be detected from the surface can be calculated as a function of depth if the host rock density and instrumental sensitivity are known. The list below gives the results of such calculations for a host rock density of 2.5 g/cc (limestone) and an instrumental sensitivity of 0.02 milligal (note that depth is measured from the surface to the center of the cavity):

DEPTH (ft)	DETECTABLE RADIUS (ft) (air-filled cavity)	DETECTABLE RADIUS (ft) (water-filled cavity)
20	7	9
40	12	14
60	15	18
80	18	22
100	21	25

An illustration of the model used to determine these results is shown in Figure 25.

Similar calculations can be performed to determine the minimum detectable size buried channel as a function of depth. For these calculations, horizontal semi-cylindrical geometry as shown in Figure 26 is assumed. This model simulates a stream channel incised into bedrock and subsequently buried by alluvial material. Instrumental sensitivity is again assumed to be 0.02 milligal and the densities for alluvial material and bedrock are set at 1.8 and 2.5 g/cc, respectively. Depth is defined as the distance from the surface to the top of the semi-cylindrical channel. The results of the calculations are listed below:

DEPTH (ft)	DETECTABLE CHANNEL WIDTH (ft)
20	9
40	13
60	16
80	19
100	21

Often, the gravity method is used for rapid and economical mapping of buried topography for those cases where 20 percent accuracy is sufficient. The gravity method also provides a means for locating igneous features in sedimentary sequences. Further, the gravity method can be used to distinguish between mafic and sialic rocks in igneous and metamorphic terrains.

4.4.3 Aquifer Properties

The gravity method is not useful for determining any of the identified aquifer properties. While the borehole gravity technique is sometimes used in the petroleum industry to determine large-scale porosity, it is not considered to be applicable to site investigations due to the high cost and the large amount of auxiliary information required.

4.4.4 Additional Comments

The gravity method may be used over a wide range of geologic and hydrologic conditions to detect and map geologic features or parameters with sufficient density and hence gravitational expression. The resolving power of the method falls off rapidly with depth.

Results of gravity surveys can be adversely affected by several factors discussed below:

- Geologic noise - local density inhomogeneities, regional gradients, and bedrock relief may act singly or together to obscure anomalies caused by the target geologic feature. Bedrock relief, for example, may produce an anomaly identical to that produced by a sinkhole.

- Topographic noise - in areas of high topographic relief, lack of detailed knowledge of subsurface density distribution may result in incomplete topographic corrections Incomplete topographic corrections can reduce instrumental sensitivity or completely obscure the target feature.

- Position error - errors in gravity station elevation and latitude can result in erroneous corrections which adversely affect the gravity survey.

The gravity method should be used as a reconnaissance tool in conjunction with other techniques. Results based solely on gravity exploration should be viewed as approximate.

4.4.5 Cost

The cost estimate for conducting gravity surveys is based on 1980 dollars and the following assumptions:

- The field crew consists of one geophysicist working 10 hours per day at an effective rate of $44 per hour.
- Daily crew subsistence (per diem and lodging) is $55 per day.
- Vehicle and instrument rental is $250 per day.
- Processing and interpretation costs are $7.50 per station.
- No land surveying, brushing, or mobilization is included.

Based on these assumptions, the cost per gravity station ranges from $16.81 to $26.13 depending on production. The cost per lineal foot for profiles and per acre for areal coverage are listed below for three different station spacings typical of shallow surveys:

PROFILES

Station Spacing	Cost per Foot
100 Feet	$0.17 - $0.26
50	$0.34 - $0.52
25	$0.67 - $1.05

AREAL COVERAGE

Grid Spacing	Cost per Acre
100 Feet	$76 - $118
50	$298 - $463
25	$1183 - $1838

A sample round-trip mobilization for a distance of 1000 miles would be $1350. Savings could be realized if this mobilization is combined with mobilization for other geophysical techniques.

4.5 MAGNETICS

The magnetic method is sensitive to changes in the subsurface magnetic susceptibility distribution. Any geologic feature or parameter which has sufficient susceptibility expression can, in principle, be detected by the magnetic method. Additionally, when sufficient control is available, it is possible to map the feature or parameter in three dimensions. Of fundamental importance to the successful application of the magnetic method is the understanding that magnetic susceptibilities of rocks are known to range over four orders of magnitude; thus, for example, a relatively small amount of magnetite with high susceptibility may yield the same magnetic expression as relatively large amounts of granite with low to moderate susceptibility.

Further consideration must be given to the direction of the magnetic field. In the United States, the earth's magnetic field forms an angle with the earth's surface of about 60 degrees. Usually the local magnetic field will be in approximately the same direction, but this is not always true and allowance for any deviation must be made. The direction of the local magnetic field is rarely determined with any accuracy because most survey magnetometers measure either total field strength or the strength of the vertical component.

Additional complications arise from remanent magnetization which may obscure or complicate induced magnetic anomalies. On the other hand, remanent magnetization can produce anomalies of significance; for example, varved clay layers sometimes exhibit remanent magnetization which can be detected with magnetic surveys. Any offset of such layers would produce an anomaly.

Also important is an understanding of the inherent ambiguity of magnetic data inversion. While a given subsurface susceptibility distribution will produce a unique data set, the converse is not true. In theory, any given data set will fit an indefinite number of models. Knowledge of the local geology and subsurface control from borings or other geophysical techniques must be input to the interpretation process if reasonable results are to be obtained. The validity of any model must be tested not only by comparing the observed anomaly with the theoretical or calculated anomaly, but also by consistency with other available information.

4.5.1 Stratigraphy

The magnetic method is generally not useful for determining or correlating lithology due to limited resolution and lack of magnetic expression. In special cases such as varved clay layers or magnetite sands, the magnetic method may provide information concerning lateral extent and thickness.

The magnetic method can be used to map bedrock profiles and to determine the thickness of surficial materials over bedrock when the bedrock is igneous or metamorphic. The resolving power of the magnetic method for these applications is generally less than that of refraction or resistivity methods, but this limitation may be offset by lower cost.

4.5.2 Geologic Structure

The magnetic method is not useful for locating and mapping fractures due to lack of magnetic expression, but can be useful for mapping folding, faulting, and buried drainage channels under the right conditions. One major qualification to application of the magnetic method for mapping folding and faulting is that the stratigraphic section must contain at least one unit with appreciably different magnetic susceptibility than the surrounding units. A list of lithologies with representative magnetic susceptibilities is provided in Table 4. This qualification is most often fulfilled in the case of thin sediments overlying igneous or metamorphic rock. The need for outside control is again important; for example, faulting in a crystalline basement could yield the same magnetic expression as lateral change in basement composition.

As an example use of the magnetic method to locate faulting beneath alluvial cover, consider the case where shallow, sub-horizontal granitic bedrock has been vertically faulted and a magnetic traverse intersects the strike at a right angle. Assuming horizontal slab geometry and known values of the magnetic susceptibility of granite and the instrumental sensitivity, the minimum throw that can be detected from the surface can be calculated as a function of depth. The list below gives the results of such calculations for granite susceptibility of 2.7×10^{-3} CGS units and an instrumental sensitivity of 10 gammas (note that depth is measured from the surface to the top of the upthrown block):

DEPTH (ft)	DETECTABLE THROW (ft)
20	3
40	5
60	8
80	11
100	13
200	26
300	39

An illustration of the model used to determine these results is shown in Figure 27.

Another potential use of the magnetic method is mapping buried drainage and topography when the surficial material possesses remanent or induced magnetization. For example, calculations can be performed to determine the minimum detectable buried channel as a function of depth. For these calculations, horizontal semi-cylindrical geometry, as shown in Figure 28, is assumed. This model simulates a stream channel incised into bedrock and subsequently buried by alluvial material with remanent or induced magnetization. Instrumental sensitivity is assumed to be 10 gammas and the susceptibility of the infilled material is set at 0.01 CGS units, corresponding to 2 percent magnetite content. Depth is defined as the distance from the surface to the top of the semi-cylindrical channel. The results of the calculations are listed below:

DEPTH (ft)	DETECTABLE CHANNEL WIDTH (ft)
20	2
40	5
60	7
80	9
100	11
200	23
300	34

The magnetic method is also useful for mapping igneous features in sedimentary sequences. Additionally, the magnetic method can be used to distinguish between igneous features with differing times of emplacement. This application is based on the fact that the orientation of the earth's magnetic field varies with time. As a recently emplaced igneous feature cools to below the Curie point, it will acquire the existing magnetic orientation.

4.5.3 Aquifer Properties

The magnetic method is not useful for determining any of the identified aquifer properties.

4.5.4 Additional Comments

The magnetic method is applicable over a restricted range of geologic and hydrologic conditions. Magnetic techniques are most applicable in areas with igneous or metamorphic geology or in areas where sediments contain appreciable quantities of magnetic material such as magnetite and ilmenite. The resolving power of the method falls off rapidly with depth.

Magnetic techniques have incidental application to locating buried cultural features. Pipelines, buried structures, and well casing composed of steel or iron can often be located by magnetic surveys.

Results of magnetic surveys can be adversely affected by several factors discussed below:

- Geologic noise - local susceptibility inhomogeneities, regional gradients, bedrock relief, and permanent magnetization may act singly or in conjunction to obscure anomalies caused by the target geological feature.
- Topographic noise - in areas of high topographic relief with magnetic rocks, corrections are extremely difficult to calculate with any confidence due to complex magnetization of irregular shapes. Erroneous topographic corrections can limit instrumental sensitivity or completely obscure the target feature.
- Cultural noise - railroad tracks, power lines, steel-cased wells, metal pipes, and metal structures all have non-geologic magnetic expression. Additionally, metal objects carried by the magnetometer operator can cause erroneous readings.

The magnetic method should be used as a reconnaisance tool in conjunction with other techniques and available information. Results based solely on magnetic exploration are approximate.

4.5.5 Cost

The cost estimate for conducting magnetic surveys is based on 1980 dollars and the following assumptions:

- The field crew consists of one geophysicist working 10 hours per day at an effective rate of $44 per hour.
- The daily production rate is 40 to 80 stations per day.
- Daily crew subsistence (per diem and lodging) is $55 per day.
- Vehicle and instrument rental is $250 per day.
- Processing and interpretation costs are $7.50 per station.
- No land surveying, brushing, or mobilization is included.

Based on these assumptions, the cost per magnetic station ranges from \$16.81 to \$26.13 depending on production. The cost per lineal foot for profiles and per acre for areal coverage are listed below for three different station spacings typical of shallow surveys:

PROFILES

Station Spacing	Cost per Foot
100 feet	\$ 0.17-\$0.26
50	\$ 0.34-\$0.52
25	\$ 0.67-\$1.05

AREAL COVERAGE

Grid Spacing	Cost per Acre
100 feet	\$ 73-\$ 114
50	\$ 293-\$ 455
25	\$1171-\$1821

A sample round-trip mobilization for a distance of 1,000 miles would be \$1,350. Savings can be realized if the mobilization is combined with mobilizations for other geophysical techniques. Additional savings can be realized if magnetic surveys are combined with gravity surveys.

4.6 RADAR

As detailed in Section 3.6, the parameters which must change in order to create an electromagnetic interface, are magnetic permeability, dielectric constant, and electrical conductivity. For most nonferrous materials the magnetic permeability may be considered to be constant ($\mu=1$). The magnetic permeability of magnetite and other ferromagnetic materials is much higher than nonmagnetic substances ($\mu=1.5$), making any magnetic material a very good radar reflector.

Assuming a nonmagnetic subsurface section, the radar technique can be used to map changes in electrical conductivity or dielectric constant, or both. Table 5 shows the conductivities and dielectric constants of some common near-surface materials. Notice that granite and limestone have anomalously low conductivities, water of any kind has a very high dielectric constant, and salt water has a very high conductivity.

From the above, it follows that the radar technique can be used to identify the following:

- Presence of water
- Presence of metallic or magnetic substances
- Contacts between overburden (alluvium) and hard dry rocks such as granite or limestone.

Caution must be used, however, when evaluating the usefulness of this technique in identifying subsurface geologic conditions as they relate to the above parameters. A considerable change in the magnetic permeability, conductivity, or dielectric constant is required to create a radar reflector and if such a reflector exists, additional changes in any of these parameters may not be detectable (such as a lateral change in groundwater salinity). The following sections outline various subsurface conditions and their relationship to these parameters, hence the effectiveness of the radar technique in identifying them.

4.6.1 Stratigraphy

The potential of the radar technique for determining lithology is limited. If the magnetic permeability, conductivity, and dielectric constants of all rock types in an area were known, then the method could be employed with a high degree of success. Unfortunately, it is not economical to make the measurements necessary to define these parameters for all rock types. A better approach to the problem of defining lithology is to combine borehole data with profiled radar data. It is very likely that certain rock units within the stratigraphic section will exhibit a sufficient electromagnetic impedance contrast to be detected by the radar method. These rock units could then be used as marker horizons to provide "spot checks" at various points within the subsurface section.

Because radar is a profiling technique, it can be used for lateral correlation. Features such as facies changes, pinch outs, channel sands, and clay lenses can often be mapped, provided they are within the range of penetration of the signal (approximately 50 feet depending on site conditions). Of special importance is the effect of clay on radar signal penetration. Clay is highly conductive and will limit penetration of the radar signal (20 to 40 feet depending on the conductivity). The presence of water in clay will increase the conductivity, further limiting radar penetration.

The radar method can also be used to map the surficial material over bedrock. In areas where the cover is less than 100 feet and consists of dry gravels or sands, the bedrock is commonly a very good reflector. The excellent resolution of this method makes it a superior tool for mapping the bedrock surface under these conditions.

4.6.2 Geologic Structure

The radar method can be used to map folding if the associated strata exhibit sufficient electromagnetic impedance contrast. Due to the lack of the use of sophisticated processing techniques, excessive dip (greater than 5 degrees) on the limbs of folds can cause errors both in the positions of the folds and in the apparent dip as detected by radar reflections. The apices of the folds, however, will retain their true position on the radar profile, because these points provide a direct reflection back to the transducer which is not affected by the geometry of the limbs. In areas of very complex folding, folds beneath the uppermost set may be difficult to detect, due to the complicated raypath of the reflected wave back to the transducer.

A fault can be detected by this technique if it has sufficient throw or if the shear zone is filled with water. The most common indicator of a fault on a radar profile section is a displacement of the reflections accompanied by a series of diffractions, the apices of which line up in a manner consistent with the displacement pattern. Although this technique has high resolution, a fault must have a throw of at least one foot to be definitely identified. Faults with throws less than this will probably be interpreted as a simple fracture.

Fractures can be detected by radar if they are filled with water. Similar problems exist for the detection of fractures as for the detection of the limbs of folds. That is, if the fractures dip excessively, they will be displaced on the profile and if there are a sufficient number, only the uppermost fractures will be detected due to the complexity of the reflected raypath.

The radar method is an excellent tool for the location of dissolution features, whether water or air filled. Typically the feature must have a diameter of at least one foot to be detected but under ideal conditions it may be possible to detect a feature with a diameter of a few inches. A disadvantage of this technique is that the radar transducer must pass directly over the void in order to detect it.

The radar method should be very useful for mapping shallow buried drainage and topography. A shallow channel should have the necessary conductivity contrast and, if water filled, would certainly have the necessary dielectric contrast to be an excellent reflector.

The radar method should also be useful for mapping igneous intrusives for those cases where the upper surface of the intrusive is above the water table.

4.6.3 Aquifer Properties

The only aquifer property that can be determined by radar is the potentiometric surface for an unconfined aquifer. Water affects the propagation of radar signals in two ways. Firstly, water has a high dielectric constant which will produce radar reflections. Secondly, groundwater will increase the gross conductivity of subsurface materials, thereby reducing radar penetration. Consequently, strong radar reflections will be received from the potentiometric surface and only limited radar signal penetration will be realized below the surface.

The radar method can provide partial information for assessing aquifer flow since the vertical and lateral extent of water-bearing units can be determined. Additionally, location of the water table permits calculation of hydraulic gradients.

The other identified aquifer properties (porosity, permeability, temperature, and water chemistry) cannot be determined by the radar technique, as they have little, if any, electromagnetic expression. It is possible that lateral changes in water chemistry may change the amplitude of the reflected signal due to changes in water conductivity, but any qualitative or quantitative inference of water chemistry based on reflection amplitude is impractical.

4.6.4 Cost

The cost estimate for conducting a radar profiling survey is based on the following assumptions (1980 dollars):

- The field crew consists of one geophysicist and one technician working ten hours per day. Effective hourly rates are $44 per hour for the geophysicist and $25 per hour for the technician.
- Daily subsistence for the crew (per diem and lodging) is $110 per day.
- The daily production rate is two to five miles of profile per day. This rate is based on the assumption that the transducer may be towed behind a four wheel drive vehicle, with the recording equipment mounted inside.
- Processing and interpretation costs are $500 per mile of profile.
- The target depth is less than 100 feet.
- No land surveying, brushing and smoothing of profile lines, or mobilization is included.
- Vehicle costs are $50 per day.
- Equipment rental is $400 per day.

Using these assumptions, the cost will vary from $1,125 per line mile (at two miles/day production) to $250 (at five miles/day production).

The above calculations assume that the necessary radar equipment is owned by the geophysical contractor. For those situations where the necessary equipment must be rented, additional costs will be incurred due to restrictive rental terms imposed by the limited number of suppliers. Presently these terms are:

- The minimum rental period for equipment is three months at a rate of 15 percent of the total cost per month.
- Any operator who will use this equipment must attend a one week seminar on the operation of the equipment. The cost of this seminar is $1,000, not including lodging and expenses.
- A rental agreement must be made 60 days in advance of the time that the equipment is required.

The additional costs imposed by the rental terms will vary as a function of survey progress and extent. The table below lists these additional costs for two different production rates and three different extents:

SURVEY EXTENT (miles)	ADDITIONAL COSTS (2 mile/day production)	ADDITIONAL COSTS (5 mile/day production)
10	$17,000	$18,200
20	$15,000	$17,400
50	$ 9,000	$15,000

Typical round-trip mobilization for a distance of 1,000 miles is about $2,400. This number could be reduced if the mobilization is combined with mobilizations for other geophysical surveys.

4.7 BOREHOLE LOGGING

Borehole logging is conducted to measure electrical, nuclear, mechanical, thermal, and acoustic properties of subsurface materials in proximity to boreholes. Borehole logs can be interpreted to determine resistance, lithology, structure, bulk density, porosity and permeability and also to define the source, movement, and chemical and physical characteristics of groundwater. Quantitative interpretation of well logs can be used to provide numerical values for some of the parameters used in modeling groundwater.

Borehole logging can provide continuous objective records with values that are consistent from well to well and from time to time. In contrast, the widely used geologist's or driller's log of subsurface samples is subjective, highly dependent upon personal skills and terminology, and is limited to the characteristics being sought. The latter point is particularly important in areas of repetitive sequences, or of thick, monotonous sections which provide little visual evidence upon which correlations can be made between borings. As a means of minimizing these effects, and of providing a complementary set of data to evaluate and interpret subsurface situations, borehole logging should be incorporated as part of any detailed subsurface investigation. Because absolute physical properties determine the log response, an unbiased sampling of the subsurface is obtained, and this allows comparison of several sets of data. The consistency of log signatures of specific formations or intervals enables accurate mapping of specific horizons or thicknesses through comparison of logs from various borings across the area of interest and also allows determination of relevant physical properties.

The primary limitation of borehole logging is one of lateral sampling ability. While borehole logging is considered to be an efficient technique for measuring physical properties in the immediate vicinity of the borehole wall, it must be noted that most conventional borehole logs are representative of only a small volume of the subsurface adjacent to the borehole.

Confidence regarding global property representation may be improved if log signatures can be traced from one borehole to another or if subsurface conditions are known to be relatively continuous. Correlation of several specific horizons or intervals can be made between two adjacent boreholes only if the same distinctive repetition of signature is seen in both boreholes. Correlation of a single horizon, where the dip and strike are unknown, is possible only with data from four different boreholes. It follows that stratigraphic correlations between specific horizons are generally difficult when only two or three boreholes are available. It is appropriate, therefore, to examine the logs from adjacent boreholes for general similarities. If adjacent boreholes exhibit the same general characteristics, it is likely that the logs are representative of the subsurface.

Further limitations to the application of borehole logging are:

- Interpretation of borehole logs is considered an art. The numerous factors influencing log response are difficult to analyze quantitatively. Even when theoretically derived equations are available, empirical data are required to determine unknowns in equations; therefore, direct empirical methods may be more reliable. This generally applies to the determination of properties such as permeability and water chemistry rather than to correlation.

- The spontaneous potential, resistance, caliper fluid movement, temperature and sonic logs can generally be run only in open uncased boreholes. Additionally, the borehole must be fluid filled for all the above logs except the caliper. The open borehole requirement can lead to scheduling difficulties and higher costs, especially in areas where the subsurface is unstable.

- The minimum diameter opening through which most logging tools will pass is about two inches, and three inches is preferable. Due to differences in tool design, any boring program should include an investigation of available tool diameters.

- Caliper logging in soft or unconsolidated formations may cause caving or hole enlargement. Errors in hole size corrections can result from this behavior.

A summary of required borehole conditions for each type log is presented in Table 6.

4.7.1 Stratigraphy

The geophysical borehole logging method is extremely useful for defining stratigraphy. For the purpose of determining and correlating lithology, borehole logging is superior to any other geophysical technique. The borehole logs most useful for defining and correlating lithology are the spontaneous potential, resistance, and natural gamma log. Additionally, nuclear, sonic, and caliper logs have some utility for lithologic identification.

In a sand-shale sequence containing formation water that is more saline than the drilling mud, the greatest positive spontaneous potential (SP) readings can be expected in shales, and the greatest negative readings can be expected in sands. A shale line which passes through as many of the largest positive SP readings as possible, and a sand line which passes through as many of the largest negative SP readings as possible can be constructed. Assuming that the ionic concentration of the borehole fluid and the aquifer water are constant throughout the depth of the borehole, then the shale-sand ratio can be determined by the position of the associated SP reading with regard to the shale and sand lines. This method is most applicable to aquifers with water of high salinity, but is not applicable when the borehole fluid is more saline than the aquifer. Additionally, the SP log is very useful for correlation purposes, because the log is sensitive to lithology and highly repeatable.

The resistance log is useful in that any increase in formation resistance produces a corresponding increase in resistance on the log. Typically, the measured resistance increases in lignites, sands, and sandstones and decreases in clays, shales, and siltstones. The resistance log is widely used for lithologic correlation because of its unique response to changes in lithology and the good vertical detail obtained in formations of low to moderate resistance. Disadvantages of the resistance log are lack of detail in intervals of borehole enlargement or when the formation resistance is radically different from that of the drilling mud.

The natural gamma radiation (NGR) log is useful for determining and correlating lithology, although not to the degree that spontaneous potential and resistance logs are. The physical parameter measured by the NGR log is the natural gamma radiation emitted by all rocks and soils. Clays, however, are a decomposition product of feldspars and micas and have a relatively high concentration of radioactive potassium (K^{40}). Moreover, clays concentrate additional radioactive elements through the processes of ion-exchange and adsorption. Normally, low levels of activity would be expected in formations such as salt, sandstone, limestone, and dolomite. Higher levels of activity are found with increasing clay/shale content and the maximum activity is found in potash beds and organic marine clays and shales. There are, however, sequences in which the natural gamma radiation levels for sands and shales overlap making distinction of the two difficult. The relative gamma radiation levels for individual formations in a restricted geologic setting tend to be fairly constant, however.

The remaining nuclear logs (gamma-gamma and neutron) are useful for lithologic identification and correlation in situati ns where bulk density and porosity are controlled by lithology. In situations where large density and porosity contrasts exist along lithologic contacts, such as for soil-rock or alluvium-bedrock contacts, the gamma-gamma and neutron logs can be diagnostic. However, bulk density is affected to a large degree by porosity, so that bulk density changes can be caused by variations in porosity as well as in lithology. With both gamma-gamma and neutron logs from the same borehole, grain density can be determined independently from porosity using cross-plotting techniques. The grain density, however, does not indicate lithology uniquely, since a given grain density may represent a single lithology or a combination of lithologies. Independent information and experience in the area of interest can provide important guidelines in this situation.

The caliper log is useful for lithologic identification in situations where borehole size is related to lithology. Evaporites, for instance, are characterized by borehole enlargement due to solutioning and bentonite clays are characterized by borehole restriction due to swelling.

The sonic log is useful for lithologic identification and correlation in situations where acoustic velocity is controlled by lithology. Table 1 contains a list of lithologies and representative acoustic velocities.

All of the previously discussed logs are potentially useful for mapping the thickness of soil and alluvial cover to the extent that boreholes provide a representative sample of the subsurface.

Because of their unique response to lithology, the spontaneous potential, resistance, and natural gamma radiation logs are the best and most widely used borehole logs for defining stratigraphy.

4.7.2 Geologic Structure

Geophysical borehole logs can be used to define geologic structure to the extent that structure may be inferred from borehole conditions. Folding and faulting can often be inferred by drawing profiles based on interpretations of borehole logs. Alternatively, folding or faulting may be inferred when characteristic behavior such as repetition of sequences is noted. However, for a relative offset of strata observed between two boreholes, a variety of explanations may exist. The offset could be due to faulting, folding, or dip of strata. Only when the dip required to explain the offset becomes unrealistic in light of known local geologic conditions can the presence of faulting be assumed. A better use of borehole logs is to provide control for surface geophysical techniques. With sufficient integration of surface geophysical and borehole geophysical methods, it is possible to map structural features such as folding and faulting with considerable accuracy.

A variety of borehole logs can be used to detect fracturing, including resistance, gamma-gamma, neutron, caliper, and sonic. Fracturing will be indicated by a sharp change in resistance, a decrease in gamma absorption, an increase in neutron absorption, a decrease in sonic velocity, and may be indicated directly by the caliper. Of the above, the resistance log is the most sensitive and accurate indicator of fracturing. Borehole televiewers, television, and dipmeters also have some utility for detecting fracturing, and are discussed in Chapter 5.0.

Dissolution features may be detected by borehole logs given favorable conditions. Large dissolution features are indicated directly by the caliper log, although this situation is rarely encountered. More likely is the case where such features are distributed throughout the subsurface (e.g. vugularity) and are indicated by rapid fluctuations of resistance and caliper, decrease in density, increase in porosity, and decrease in sonic velocity.

Borehole logs may be used for locating buried drainage channels depending on the number of borings drilled. The location of a buried channel may be inferred by drawing profiles based on interpretations of well logs, if a line of borings intersects the channel. Otherwise, borehole logs must be viewed as stratigraphic tools capable of indicating channel environments on the basis of lithology and interval thickness. Here again the resistance, spontaneous potential, and natural gamma logs are the most appropriate methods.

4.7.3 Aquifer Properties

All of the identified aquifer properties can be defined to some degree with borehole logs. These properties are:

- Porosity and permeability
- Potentiometric surface
- Flow direction and rate
- Temperature
- Water chemistry

4.7.3.1 Porosity and Permeability

Porosity within the immediate environment of the borehole may be determined with gamma-gamma, neutron, and sonic logs. When using borehole logs to measure porosity, it is advisable to run at least two of the above three logs to limit possible ambiguities and to ensure that the required information is obtained. The use of gamma-gamma logs for measuring porosity is based on the following equation which relates bulk density to porosity, fluid density, and matrix density:

$$P_b = \phi P_f + (1-\phi)P_m$$

where

P_b = bulk density
ϕ = porosity
P_f = fluid density
P_m = matrix density

Given the bulk density (measured directly by the gamma-gamma log), the fluid density (1.0 g/cc for fresh water and 1.1 g/cc for saline water), and the matrix density (determined in the laboratory from core samples or gamma-gamma/neutron cross plots), the porosity can be calculated.

The determination of porosity with neutron logs is based on the assumption that all of the hydrogen in a formation occurs as water in the pore spaces and that the absorption of neutrons is largely controlled by hydrogen content. This assumption is usually true, but does not hold for minerals such as gypsum and trona which contain bound water. Further, porosity is calculated based on an assumed matrix composition, the two most common being calcite and quartz. Charts are available, however, for converting neutron porosity values from one matrix composition to another.

The determination of porosity with sonic logs is based on the Wyllie time-average equation which relates formation sonic velocity to porosity, fluid velocity, and matrix velocity. This equation is given below:

$$\frac{1}{V_s} = \frac{\phi}{V_f} + \frac{(1-\phi)}{V_m}$$

where

V_s = formation sonic velocity

ϕ = porosity

V_f = fluid sonic velocity

V_m = matrix sonic velocity

Given the formation sonic velocity (measured directly by the sonic log), the fluid sonic velocity (5,000 ft/s for fresh water, 5,680 ft/s for saline water), and the matrix sonic velocity (determined from charts which list representative matrix velocities for different lithologies), the porosity can be calculated.

There are no geophysical logs which measure permeability directly. Several logs are useful, however, for determining relative permeability based on porosity, lithology, temperature, fluid movement, or fracturing. The determination of relative permeability based on porosity assumes that more porous rocks are also more permeable. Given this assumption, all of the previously discussed porosity logs are potentially useful for determining relative permeability. Note that clays and shales are not covered by this assumption as they may have high porosity but low permeability. The relationship between log response and permeability, however, is generally dependent on the determination of porosity and permeability of a number of samples as an intermediate step.

Relative permeability may also be inferred based on lithology as defined by borehole logs. A good example of such an inference is that clays generally exhibit much lower permeability than sands. Using spontaneous potential and natural gamma logs, a reasonable estimate of clay content and hence relative permeability can be made. Similarly, borehole logs can be used to identify evaporites which have extremely low permeabilities. All of the previously discussed lithology logs are, therefore, potentially useful for inferring relative permeability.

Permeable zones in the subsurface may also be characterized by inflow or outflow of water within the borehole. Such movement of water is often indicated by abrupt thermal discontinuitites in the drilling mud which can readily be detected with temperature logging equipment. Direct detection of water movement is also possible using fluid movement logging. This type of log will indicate the direction and speed of the moving fluid along the length of the borehole. Inflow and outflow are indicated by divergence and convergence of movement, respectively. Fluid movement logging can also be used to measure fluid flow in monitoring wells during pump tests. The resultant log can be used to determine the relative permeability of specific horizons based on fluid velocity. Alternatively, fluid movement logging can be performed in a well during injection or recharge. Relative permeability can be determined in this case by constructing an injectivity profile which shows the water lost within each depth interval of the hole where fluid movement measurements are made.

A variety of combined borehole logging-radioactive tracer techniques can be used to locate permeable zones within a borehole. The single-well pulse technique utilizes a radioisotope dissolved in the stream of water injected into a well. Water injection continues until the tracer moves out into the aquifer. The well is then pumped and the time of recovery for 50 percent of the injected tracer indicates the permeability of the aquifer under injection conditions. A natural gamma probe is used to measure concentration and to determine the zone that is taking the water and tracer. The single-well pulse technique is most successful in a single, homogeneous aquifer. Another type of borehole tracer technique utilizes fine particulates or insoluble radioisotopes, such as Gold-198 or Cobalt-60. The isotope is introduced into the well under injection conditions and is filtered out on the face of aquifers in proportion to the relative permeability of the units. Gamma logs are then run to determine the relative permeability profile. Additionally, gamma logs can be used to monitor the flow of radioactive tracers between an injection well and a monitoring well. The tracer is injected, flows through the aquifer, and is detected by gamma measurements in the monitoring well. The required transit time indicates the permeability.

Relative permeability estimates can also be made based upon the frequency of occurrence of fracturing (fracture permeability is often present in crystalline rocks). All of the logs which are sensitive to fracturing (discussed in Section 4.7.2) are potentially useful for this application.

4.7.3.2 Potentiometric Surface

Borehole logging methods can be used to determine the potentiometric surface of aquifers. The conventional method of monitoring piezometers depends in part on borehole methods, since measurement of the water level is usually accomplished with a simple borehole device (M-Scope). Estimates of the potentiometric surface can be made with fluid movement or temperature devices which can detect water inflow. For inflow to occur, the hydraulic head of the aquifer must exceed that of the drilling mud column. Such estimates are inexact because the measurement is made under non-equilibrium conditions. Relative potentiometric difference between two aquifers can also be determined by fluid movement logging, since flow will occur toward the aquifer with the lowest potentiometric surface.

4.7.3.3 Flow Direction and Rate

The primary subsurface parameters which are related to the flow of groundwater are the permeability, hydraulic gradient, and cross-sectional area through which the groundwater flows. Borehole logging is an extremely useful tool in the analysis of flow, because it provides some quantification of these parameters. The utility of borehole logging for measuring permeability and the potentiometric surface have been previously discussed in Sections 4.7.3.1 and 4.7.3.2, respectively. Implementation of a well-designed borehole logging program will provide information concerning lateral variation of these parameters. This information can be used to map lateral permeability changes and to calculate hydraulic gradient (lateral variation of potentiometric surface). Conventional techniques such as pump tests and installation of piezometers usually provide more reliable data, but borehole logs are useful for designing pump test and piezometer programs. For example, the location of packers can be targeted using lithologic and porosity logs and grout quantities can be calculated using caliper log data. The most important use of borehole logging within the realm of flow is in determining the thickness and lateral extent of water-bearing formations. Borehole logs also provide additional stratigraphic and structural information which relates to the direction and the rate of flow.

4.7.3.4 Temperature

As discussed in Section 4.7.3.1, temperature logs are useful for locating zones of water inflow. The temperature log has additional utility in that it also indicates aquifer temperatures when inflow is present. Such data are useful because the solubility of pollutants can be controlled in part by aquifer temperature.

4.7.3.5 Water Chemistry

Borehole logging methods can be used to address two aspects of water chemistry. Gamma ray spectroscopy logs (specialized natural gamma logs) can be used to determine relative concentractions of uranium, thorium, and potassium in aquifer water when all of the naturally occurring gamma radiation is attributable to formation water (clay-free formations) and the porosity is known. Resistivity logs (more sophisticated resistance logs) can be used to determine the ionic concentration of formation waters when the following conditions are met: (1) the aquifer is clastic, (2) the clay content and porosity of the aquifer are relatively constant both laterally and vertically, and (3) the aquifer is relatively uniform both vertically and laterally and at least 20 feet thick.

4.7.4 Additional Uses

Borehole logs have a variety of additional uses pertaining to the calibration of surface geophysical surveys. These uses are discussed below on an individual log basis:

- Gamma-gamma - The gamma-gamma log can be used to construct a vertical density profile to provide control for gravity surveys.

- Sonic - The sonic log can be used to construct a vertical velocity profile to provide control for seismic reflection and refraction surveys. When combined with density information, sonic data can be used to construct a vertical acoustic impedance profile for seismic reflection modeling studies.

- Resistance - The resistance log can be used to construct a vertical resistivity profile to provide control for electrical resistivity surveys.

4.7.5 Cost

Geophysical borehole logging tools are typically constructed with multiple sensors so that more than one parameter can be measured during a single run. For this reason, it is practical to determine the cost for suites of logs rather than on a single log basis. Also, a large increase in equipment sophistication is required to run gamma-gamma, neutron, and sonic logs. Listed below are cost estimates and relevant assumptions for four different logging suites:

Suite 1

- The logging suite consists of natural gamma, spontaneous potential, and resistance logs. Caliper and temperature logs are available as an option.

- The field crew consists of one technician working ten hours per day.

- The field equipment consists of a lightweight, portable logging unit and one vehicle.

- The daily production rate is 3 to 5 holes in the 50- to 300-foot depth range.

- No land surveying, borehole drilling, brushing, or mobilization is included.

- No restriction exists on the duration of field activities.

Based on these assumptions, the cost for running Suite 1 is $560 per day plus $0.20 per foot. The incremental cost for caliper and temperature logs is $0.10 per foot for each type log. A sample round-trip mobilization for a distance of 1,000 miles would be $2,000.

Suite 2

- The logging suite consists of caliper, resistance, natural gamma, and gamma-gamma. Sonic and fluid movement logs are available as an option.
- The field crew consists of one technician working ten hours per day.
- Sophisticated, truck-mounted equipment is used.
- The daily production rate is 4 to 7 holes in the 50- to 300-foot depth range.
- No land surveying, borehole drilling, brushing, or mobilization is included.
- Field activities are restricted to less than one week duration.

Based on these assumptions, the cost for running Suite 2 is $590 per day plus $0.30 per foot. The incremental cost for sonic and fluid-movement logs is $0.15 per foot for each type log. a sample round-trip mobilization for a distance of 1,000 miles would be $3,620.

Suite 3

- The logging suite consists of natural gamma, spontaneous potential, resistance, and neutron logs.
- The field crew consists of one technician working ten hours per day.
- Sophisticated, truck-mounted equipment is used.
- The daily production rate is 4 to 7 holes in the 50- to 300-foot depth range.
- No land surveying, borehole drilling, brushing, or mobilization is included.
- Field activities are restricted to less than one week duration.

Based on these assumptions, the cost for running Suite 3 is $590 per day plus $0.30 per foot. A sample round-trip mobilization for a distance of 1,000 miles would be $3,220.

Suite 4

- The logging suite consists of caliper, resistance, natural gamma, gamma-gamma, spontaneous potential, and neutron (Suites 2 and 3 combined).
- Other assumptions are the same as in Suites 2 and 3.

Based on these assumptions, the cost for running Suite 4 is $590 per day plus $0.60 per foot. A sample round-trip mobilization for a distance of 1,000 miles would be $3,920.

Potential savings could be realized for Suite 1 if borehole logging activities were combined with other geophysical surveys. The logging equipment could be mobilized simultaneously with other equipment for an incremental mobilization cost of $300.

For extended logging programs (more than one week duration), savings could be realized for Suites 2, 3, and 4. The list below summarizes the daily charge and footage charge for the basic logging suite and the 1,000-mile round-trip mobilization charge for extended duration surveys:

SUITE	DAILY CHARGE	FOOTAGE CHARGE	MOBILIZATION CHARGE
2	$450	$0.15	$2,400
3	$450	$0.15	$2,400
4	$450	$0.30	$3,250

5.0 ADDITIONAL GEOPHYSICAL TECHNIQUES

The following subsections provide a limited discussion and evaluation of additional geophysical techniques, which have been included for completeness. These techniques have not been identified as being potentially valuable for attaining the project objectives due to limited application, high cost relative to information gained, or need for further development.

5.1 SURFACE TECHNIQUES

Within the category of surface techniques, the following additional geophysical methods are discussed:

- Audio Magneto-Telluric Resistivity
- Electromagnetics
- Induced Polarization
- Self Potential
- Acoustical Holography

5.1.1 Audio Magneto-Telluric (AMT) Resistivity

The magneto-telluric resistivity method uses electrical currents induced in the subsurface by fluctuations in the earth's magnetic field to measure resistivity. Assuming that time variations in the magnetic field can be treated as the magnetic component of a plane electromagnetic wave, a simple relationship exists between the amplitude of the magnetic field changes, the voltage gradients induced in the earth, and the earth resistivity. Also, since the penetration depth of an electromagnetic wave in a conductor is both frequency and resistivity dependent, resistivity of the earth can be measured as a function of depth within the earth if the amplitudes of the magnetic and electrical field can be measured at several frequencies. Conventional magneto-telluric resistivity methods measure magnetic and electrical field amplitudes for frequencies in the range of 10^{-5} to 10^{1} Hz; consequently, penetration on the order of several tens of kilometers is achieved. The audio magneto-telluric (AMT) resistivity method measures magnetic and electrical field amplitudes for frequencies in the audio range (10-10,000 Hz); resulting penetration is a few hundred feet.

Magneto-telluric resistivity field procedures consist of measuring the electrical field gradient and magnetic field intensity at a fixed location. The most common technique for measuring electrical field gradient uses three electrodes, in the form of an L, with the lengths of the arms varying according to anticipated subsurface resistivity. If measurements are being made over highly resistive rock, such as igneous or metamorphic rocks, the electrical field strength will be large and short electrode separations will be adequate. If measurements are being made over very conductive rock, larger electrode separations may be required to obtain sufficient voltage for accurate measurements. With the L-spread, the corner electrode is used as common ground for two recording channels. The signal for each channel is developed by measuring the potential between the ground electrode and the end of one of the arms with a high-impedance recorder. The recorder consists of an amplifier, filters to cancel undesirable frequencies and static self-potential voltages, and a tape deck or strip chart device.

The measurement of magnetic field micropulsations is considerably more difficult than the measurement of electrical field oscillations, and only in the last ten years or so has sufficiently sensitive measuring equipment become available. Magnetometers used for magnetic field measurements comprise (1) flux gate magnetometers, (2) optical pumping magnetometers, and (3) induction coil magnetometers. The first two types have been discussed previously in Section 3.5.3.1. The induction coil magnetometer consist of a large multi-turn coil which is laid on the ground and connected to a high-impedance voltmeter. The magnetic field fluctuations induce a voltage in the coil proportional to the oscillation frequency.

The processing of magneto-telluric resistivity data proceeds in two steps. In the first step, the magnetic and electrical measurements are analyzed by power spectra techniques to determine amplitude as a function of frequency. After values have been obtained for magnetic and electrical amplitudes, apparent resistivity values are computed for each frequency according to the equation:

$$\rho_a = \frac{0.2}{F} \left(\frac{E}{H}\right)^2$$

where

ρ_a = apparent resistivity
F = frequency
E = electrical field amplitude
H = magnetic field amplitude

The second step in interpretation is to construct a log-log graph of apparent resistivity versus frequency. This graph is then compared to theoretically calculated curves to determine subsurface resistivity configuration.

The primary advantage of magneto-telluric resistivity methods compared to conventional resistivity methods is that measurements are made with currents induced in the earth; consequently no problem is encountered in determining the resistivity beneath a highly resistive bed. The primary disadvantages are the instrumental difficulty associated with measuring small (milligamma), rapid magnetic field fluctuations and the disturbing effects of magnetic storms, metal bodies, and power lines. Another disadvantage is that techniques for the interpretation of magnetotelluric data are not well developed. Inasmuch as the AMT method measures resistivity as a function of depth, the applications are similar to those for conventional resistivity methods.

5.1.2 Electromagnetics

Electromagnetics refers to a large class of methods in which a controlled time-varying magnetic field is used as a source. When a time-varying magnetic wave propagates through the ground, it induces electric currents in any conductor in its path. These induced currents flow in closed loops in paths normal to the direction of the magnetic field and will, in turn, generate their own magnetic fields so that at any point in space the total magnetic field may be thought of as consisting of two parts: the primary or source field and a secondary or disturbing field due to the currents induced in conductors. The strength of the induced currents depends on the resistivity and magnetic susceptibility of the conductor concerned and the frequency with which the primary field is alternating. Ordinarily, the range of effects which can be attributed to variations in magnetic susceptibility is small compared to the range of effects caused by variations in resistivity. However, distortion of the magnetic field caused by anomalously large values of magnetic susceptibility in the earth is sometimes observed over highly magnetic rocks.

Electromagnetic field procedures consist of generating a time-varying magnetic field and measuring the disturbance associated with subsurface conductors. A time-varying magnetic field can be generated by driving an alternating current through a loop of wire, or through a wire grounded at both ends. The most common source for shallow surveys is a small hand-held transmitter loop powered by a battery-powered oscillator. The power used is in the range of 0.5 to 50 watts. The disturbance associated with subsurface conductors is measured by determining the phase, amplitude, or direction of the secondary field with a hand-held receiver loop. For shallow surveys, the source-receiver distance is no more than a few hundred feet. Data are usually gathered along profiles with the source and receiver separated by a constant distance or with the source fixed and the receiver occupying a number of points.

The processing of electromagnetic data may consist only of plotting the receiver measurement as a function of position and using the spatial pattern to infer the location of conductors. Alternatively, the receiver measurements can be compared with theoretical results for a more qualitative determination of the subsurface resistivity (or magnetic susceptibility) distribution.

The primary advantage of electromagnetic methods compared to conventional resistivity methods is that highly conductive or resistive beds impact penetration to a lesser degree, because the source frequency can be varied to provide partial compensation. Secondly, in the case of loop-type sources, no contact with the ground surface is required so that measurements can be made rapidly on the ground or from an aircraft. The primary disadvantage is that the interpretation of electromagnetic data is not well understood; thus results can be affected by a large number of unknowns. Another disadvantage of the electromagnetic method is that it is sensitive to magnetic activity, power lines, and metal objects. Since electromagnetic methods can be used to determine the subsurface resistivity distribution, the applications are similar to those for conventional resistivity methods, although electromagnetic methods are generally less reliable. The best application of electromagnetic methods is rapid areal reconnaisance to detect localized conductive features such as ore-bodies and mineralized dikes.

5.1.3 Induced Polarization

Electric currents in the ground are normally related to the driving potential by the electrical resistance of the formations involved. When the formations contain metallic minerals, the currents give rise to an exchange of ions at the surface of contact between the minerals and the electrolytes dissolved in the fluid in the intergranular pore spaces. This exchange of ions creates a voltage that tends to oppose the flow of electric current across the contact surface. When the driving potential is removed a residual voltage continues to exist, due to bound ionic charge, but it decreases continuously as the ions slowly diffuse back into the pore electrolytes. This phenomenon is known as the induced polarization (IP) effect and is usually taken to indicate the presence of metallic minerals. Measurement of the decay characteristics of the IP voltage provides a means for determining relative concentrations of metallic minerals along the path of the current. Alternatively, the ratio of apparent resistivity for two different source frequencies can be used, because the presence of metallic minerals causes apparent resistivity to decrease with increasing frequencies.

Induced polarization field procedures are nearly identical to those for conventional dipole-dipole horizontal-profiling resistivity techniques. A commutated DC source current is input to the ground through a pair of electrodes and the associated potential is measured through a second pair of electrodes. The time-domain IP method consists of measuring the transient potential at closely spaced intervals following termination of the source current. The frequency-domain IP method consists of measuring conventional resistivity for two different source frequencies. The time-domain and frequency-domain methods can mathematically be shown to provide equivalent indication of metallic minerals.

The processing of IP data is generally restricted to the construction of profiles of the level of activity along traverses, or contour maps of similar data. For time-domain IP measurements, the level of activity is called chargeability and is calculated by integrating the transient potential decay curve. For frequency-domain IP measurements, the level of activity is called frequency effect and is calculated according to the equation.

$$P = \frac{\rho_2-\rho_1}{\rho_2 \ \rho_1} \times 100$$

where

P = frequency effect
ρ_1 = apparent resistivity (high frequency)
ρ_2 = apparent resistivity (low frequency)

Factors which may unfavorably impact IP measurements are similiar to those for conventional resistivity surveys. The primary application of IP methods is the detection of disseminated sulphide bodies. Recent efforts, however, have shown that polarization effects are associated with water tables in clay-sand mixtures so that water-table mapping with IP techniques may be possible under special circumstances.

5.1.4 Self Potential

The self-potential method involves measurement at the ground surface of electric potentials developed in the earth by electrochemical action between minerals and the solutions with which they are in contact. If two electrodes are driven into the ground and connected to the terminals of a sensitive voltmeter, an electric potential will be found to exist between them. Such voltages normally range from a few millivolts to a few tens of millivolts. Above some sulphide bodies, however, such as those containing pyrite, chalcopyrite, and pyrrhotite, and above graphite these potentials may attain values as high as several hundred millivolts. The sign of these anomalous potentials is always negative. Several theories have been proposed to explain the origin of self potential (SP) anomalies, but the most widely accepted theory to date is that the ore body, being a good conductor, carries current from oxidizing electrolytes above the water table to reducing ones below it without being oxidized itself.

The basic field procedure for SP surveys involves measuring the potential developed between two porous, non-polarizing electrodes with a sensitive voltmeter. This measurement may be conducted in two ways. In the first, one electrode is kept fixed at a base station while the other electrode, together with a reel of cable and the voltmeter, is carried to different points and the electric potential of each point with respect to the base is read on the voltmeter. The second and less frequently used SP procedure consists of advancing two electrodes, with a constant separation of 20 to 100 feet, along lines of profile in steps equal to the mutual separation.

The processing of SP data is generally restricted to the construction of profiles or contour maps depicting the level of SP activity. This level of activity is then utilized to infer the location of ore bodies. The measure of the level of SP activity may be defined as the potential (as measured with the base station-moving electrode procedure) or the gradient (as measured with the fixed-separation electrode procedure). Potentials are plotted at the location of the moving electrodes, while gradients are plotted at the midpoint of the two measuring electrodes.

The primary disadvantage of the SP method for locating ore bodies is that the body must straddle the water table for SP anomalies to be developed. As the measurement of self-potentials requires direct electrical contact with the ground, the method cannot be employed in areas where the surface layer is a poor electric conductor (dry crystalline rock, frozen ground, etc.). Disturbing factors in SP measurements are buried metal pipes, electrical grounding systems, chemical fertilizers, mine slags, topography and groundwater drainage. Although the SP method is primarily an ore-prospecting tool, it may have application to locating oxidation-reduction boundaries in the subsurface which can control groundwater chemistry.

5.1.5 Acoustical Holography

The acoustical holography technique consists of interpreting the interference pattern which results from comparing the subsurface response tc acoustic energy with the source signal.

The field procedure for acoustical holography surveys consists of introducing acoustic energy into the ground with a constant frequency magnetostrictive, piezoelectric, or hydraulic source and detecting the associated subsurface signal with conventional seismic receivers. The subsurface signal as well as the source signal are recorded simultaneously in digital form on magnetic tape.

The processing of acoustical holography data consists of generating interference patterns between the subsurface signal and the source signal. These interference patterns can then be transferred to a photographic format which can be viewed with light to "see" the structure which produced the subsurface signal. Alternatively, the resulting interference pattern can be inverted by computer to generate raster displays or contour maps.

While acoustical holography offers several exciting capabilities, there is need for much improvement in the areas of data acquisition, data processing, and interpretation before it will become a reliable technique.

5.2 BOREHOLE LOGGING TECHNIQUES

Within the category of borehole logging techniques, the following additional geophysical methods are discussed:

- Gravity
- Magnetic
- Dipmeter
- Television and Televiewer

5.2.1 <u>Gravity Logging</u>

Gravity logging consists of lowering a borehole gravimeter into an exploratory borehole and measuring the vertical component of gravity at discrete, evenly-spaced points. This method differs from conventional surveys in that the investigation is performed vertically rather than horizontally. Borehole gravity instrumentation is more complex than conventional instrumentation, primarily due the hostile environment in which it is operated. Borehole gravity data corrections are similar to those for conventional gravity surveys, but differ in some aspects due to geometry (i.e., measurements are made beneath the earth's surface).

The primary use for gravity logging is the determination of wide-radius porosity in petroleum exploration. Other potential uses include detection of subsurface voids and calibration for downward-continuation interpretive techniques used in conventional gravity methods. The primary disadvantage of borehole gravity methods is high cost. Borehole gravity logs can be run in cased holes (5.0-inch minimum diameter) or in uncased holes (6.0-inch minimum diameter) with or without fluid.

5.2.2 <u>Magnetic Logging</u>

Magnetic logging includes magnetic field logging, magnetic susceptibility logging, and nuclear magnetic resonance logging. Magnetic logs should only be run in fluid-filled or dry boreholes which are uncased or cased with nonmagnetic material.

5.2.2.1 <u>Magnetic Field Logging</u>

The magnetic field log measures either total magnetic field intensity or a vector component thereof. The equipment used for magnetic field logging represents an adaptation of the magnetometers discussed in Section 3.5.3.1 to the borehole environment. For total magnetic field intensity measurements, borehole versions of the nuclear precession or proton magnetometer are used. For vector component measurements, borehole versions of the fluxgate magnetometer are used.

Magnetic field logging has limited application and is used primarily in mineral exploration to measure vertical magnetic gradients and to fix the depth of magnetic anomalies. Magnetic field logs also provide control for downward continuation interpretation procedures. Magnetic field logs require a 2.5- to 3.0-inch diameter uncased or non-metallic cased borehole.

5.2.2.2 Magnetic Susceptibility Logging

Magnetic susceptibility logs are used to measure the ratio of the intensity of subsurface magnetization to the strength of the magnetic field causing the magnetization. Additionally, the magnetic susceptibility log provides a measure of formation conductivity (inverse of electrical resistivity).

Magnetic susceptibility is measured with a coil wound on a low-reluctance core. The coil assembly is balanced with an inductance bridge in a magnetically barren environment. In the presence of formations with anomalous susceptibility or conductivity, the bridge becomes unbalanced because the susceptibility effect changes the coil reactance and produces an out-of-phase voltage across the coil while the conduc-in-phase voltages are separated by phase detectors and recorded to measure susceptibility and conductivity. The penetration depth of the susceptibility log is approximately equal to the coil length.

Susceptibility logging has some application for lithologic correlation when magnetic units are present, although it is not generally useful for lithologic identification. Susceptibility logs can also be used to provide numerical values for interpreting surface and airborne magnetic surveys. The conductivity log measured simultaneously with the susceptibility log has little character in low resistivity mud, but compares favorably with conventional resistivity logs for higher mud resistivities. Magnetic susceptibility logs require a 2.5- to 3.0-inch diameter uncased or non-metallic cased borehole.

5.2.2.3 Nuclear Magnetic Resonance Logging

Nuclear magnetic resonance (NMR) logs operate in the same fashion as nuclear precession magnetometers except that the formation fluid replaces the bottle of proton-rich liquid, as discussed in Section 3.5.3.1. NMR logs are usually used to determine the amount of free fluid in a formation as well as to distinguish between hydrocarbons and water. Further development of NMR logs could provide several new and unique capabilities. Every substance has a unique NMR response or "fingerprint," so that NMR techniques could potentially provide qualitative determination of water chemistry. Current efforts are aimed at both instrumentation and interpretive techniques. NMR logs require a 4.0-inch diameter uncased or non-metallic cased borehole.

5.2.3 Dipmeter

Dipmeter logs are used to determine the orientation of planar features in a borehole such as bedding planes or fractures. The dipmeter consists of three or four microresistivity devices spaced equally about the sonde. Planar features will produce a sharp, characteristic resistivity signature. Correlation of the indiviudal response on each microresistivity device is used to determine the best fit plane; this correlation is performed by electronic circuitry. For example, an east dipping plane will be indicated on the east microresistivity device first, followed by the north and south devices, and finally by the west device.

Dipmeter logs are widely used in the petroleum industry for stratigraphic analysis, but also have application for determining fracture orientation. Dipmeters must be run in fluid-filled uncased holes with a minimum diameter of 4.0 inches. Dipmeters perform best in holes containing fresh water-based muds. Good results can also be obtained in holes containing salt muds if special precautions are taken. If dipmeter measurements are required in holes with oil-base mud, it is customary to spot some water-base mud over the section to be surveyed.

5.2.4 Television and Televiewer

Borehole television and televiewer logs are used to provide an image of the borehole wall. Borehole television probes are based on the same principles as conventional television cameras and are similar in construction except that additional measures provide hostile environment protection. Borehole televiewers are different in principle because the recorded image is acoustic rather than visual; a piezoelectric transducer with a predominant frequency of about 1 MHz serves as both the transmitter and receiver. Pulses of acoustic energy are directed at the borehole wall at a rate of about 1,500 pulses per second. A portion of the energy is reflected from the wall toward the transducer where the associated circuits process the information for transmission to the surface; at the surface, the processed information is combined with depth and azimuth information to form the complete log. Borehole television logs are usually recorded on videocassettes for later playback while televiewer logs are recorded on paper.

Borehole television and televiewer logs are commonly used for formation evaluation, fracture orientation, and inspection of both open and cased holes. Borehole television provides higher resolution than the 0.01 foot capability of televiewers, but the televiewer has the advantage that it does not require transparent borehole fluid. This limitation of borehole television can often be overcome with the use of flocculating agents or by packing off selected zones and flushing with clear water. Borehole televiewers contain built-in fluxgate devices to determine orientation with respect to magnetic north while borehole television cameras do not usually provide a means of orientation. Both types of logs require a minimum hole diameter of 2.5 to 3.0 inches.

6.0 SUMMARY

An important consideration in the transmission of pollutants in the shallow geologic environment is groundwater. The features and conditions which affect and control groundwater movement can be classified on the basis of stratigraphy, geologic structure, and aquifer properties. The following is a list of these features and conditions by category:

Stratigraphy

- Lithology
- Correlation
- Surficial materials

Geologic Structure

- Folding
- Faulting
- Fracturing
- Dissolution features
- Buried drainage and topography
- Igneous features (dikes and sills)

Aquifer Properties

- Porosity and permeability
- Potentiometric surface
- Flow direction and rate
- Temperature
- Water chemistry

The geophysical expressions of these features and conditions are presented in Table 7.

The geophysical techniques which are useful for detecting and quantifying these physical expressions fall into the categories of surface techniques and borehole logging techniques. The identified surface techniques are:

- Seismic refraction
- Seismic reflection
- Resistivity
- Gravity
- Magnetics
- Radar

The identified borehole logging techniques are:

- Spontaneous potential
- Resistance
- Natural gamma radiation
- Gamma-gamma
- Neutron
- Caliper
- Fluid movement
- Temperature
- Sonic

For a condensed evaluation of both surface and borehole logging techniques refer to Figure 29. Listed down the left side of the figure are the various geophysical techniques and listed across the top of the figure are the features and conditions which control groundwater movement. For each square whose vertical position is indicated by a technique and whose horizontal position is indicated by a feature or condition, there is a symbol indicating the relative effectiveness of the technique for detecting or quantifying the feature or condition. The key to the symbols is listed on the lower left side of the figure under "Geological-Hydrological Information." Following is a definition of each symbol:

- Best Information - The relevant technique represents the best or one of the best means for detecting or quantifying the relevant feature or condition.

- Good Information - The relevant technique represents a workable method for detecting or quantifying the relevant feature or condition, but better or more workable means exist.

- Partial Information - The relevant technique represents a workable method for determining some but not all of the parameters which define the feature or condition.

- Inferred Information - The relevant technique can be used to provide information from which the existence or extent of the relevant feature or condition can be inferred.

- No Information - The relevant technique does not provide any information concerning the relevant feature or condition.

On the far top right of the figure under the heading "External Factors" are listed application notes and cost for each technique. The key to the symbols for application notes is located at the lower center of the figure.

At the lower right of the figure is the key to the symbols for relative cost of conducting geophysical surveys. A more detailed cost schedule for surface geophysical surveys is contained in Table 8. A corresponding cost schedule for borehole logging is contained in Table 9. A thorough discussion of costs for each technique is contained in Chapter 4.0.

In addition to the geophysical techniques presented above, there are additional geophysical techniques which may be of potential value in special circumstances or pending further development. These techniques are:

- Audio magneto-telluric resistivity
- Electromagnetics
- Induced polarization
- Self potential
- Acoustical holography
- Magnetic field logging
- Magnetic susceptibility logging
- Nuclear magnetic resonance logging
- Dipmeter logging
- Borehole television and televiewer

TABLES

TABLE 1
SEISMIC VELOCITIES OF ROCK MATERIALS

MATERIAL	AVERAGE VELOCITY (ft/s)	VELOCITY RANGE (ft/s)
Alluvium, Clay, etc.	2,760	400-7,900
Glacial Till	6,820	1,980-9,230
Sandstones, Shales	9,000	2,020-13,800
Limestones, Dolomites	11,000	6,060-20,200
Granites, Metamorphics	16,900	10,100-23,300
Weathered Granites and Metamorphics	13,800	10,100-15,600
Basalts	18,640	17,800-21,000
Salt, Anhydrites	18,900	13,800-25,000
Fresh Water	4,910[1]	4,710-5,110
Salt Water - 100,000 ppm	5,200[1]	5,000-5,400
Salt Water - 200,000 ppm	5,590[1]	5,390-5,790
Air	1,140[1]	1,090-1,190

[1] Measured at 25 degrees Centigrade.

TABLE 2

ELECTRICAL RESISTIVITIES OF ROCK MATERIALS[1]

MATERIAL	RESISTIVITY (ohm/m)
Surface Soils, Loam, etc.	1-50
Clay	2-100
Sand and Gravel	50-1,000
Surface Limestone	100-10,000
Limestones	5-4,000
Shales	5-100
Sandstone	20-2,000
Granites, Basalts, etc.	1,000
Decomposed Gneisses	50-500
Slates	10-100
Fresh Water	5,000[2]
Salt Water - 100,000 ppm	0.075[2]
Salt Water - 200,000 ppm	0.045[2]
Air	10^6-10^8[2]
Copper	1.7×10^{-8}

(1) Taken from Evershed and Vignoles Bulletin 245.

(2) Measured at 25 degrees Centigrade.

TABLE 3
BULK DENSITIES OF ROCK MATERIALS

MATERIAL	AVERAGE DENSITY (g/cc)	DENSITY RANGE (g/cc)
Sand, Clay, Gravel	1.58	1.20-1.93
Shale, Claystone, Slate	2.38	2.06-2.66
Limestone, Dolomite	2.57	2.23-2.80
Sandstone	2.41	2.17-2.70
Granite	2.67	2.52-2.81
Gabbro	2.98	2.85-3.12
Diorite	2.84	2.72-2.96
Fresh Water	1.00(1)	0.99-1.00
Salt Water - 100,000 ppm	1.07(1)	1.06-1.07
Salt Water - 200,000 ppm	1.14(1)	1.13-1.14

(1) Measured at 25 degrees Centigrade.

TABLE 4

MAGNETIC SUSCEPTIBILITIES OF ROCK MATERIALS(1)

MATERIAL	MAGNETIC SUSCEPTIBILITY ($K \times 10^6$, CGS units)
Magnetite	300,000-800,000
Pyrrhotite	125,000
Ilmenite	135,000
Franklinite	36,000
Dolomite	14
Sandstone	17
Serpentine	14,000
Granite	28-2,700
Diorite	47
Gabbro	68-2,370
Porphyry	47
Diabase	78-1,050
Basalt	680
Olivine-Diabase	2,000
Peridotite	12,500

(1) Adapted from C. A. Helland, "Geophysical Exploration."

TABLE 5

APPROXIMATE VHF ELECTROMAGNETIC PARAMETERS OF TYPICAL EARTH MATERIALS[1]

MATERIAL	APPROXIMATE CONDUCTIVITY σ(mho/m)	APPROXIMATE DIELECTRIC CONSTANT
Air	0	1
Fresh Water	10^{-4} - 3×10^{-2}	81
Sea Water	4	81
Sand "Dry"	10^{-7} - 10^{-3}	4 - 6
Sand, Saturated (Fresh Water)	10^{-4} - 10^{-2}	30
Silt, Saturated (Fresh Water)	10^{-3} - 10^{-2}	10
Clay, Saturated (Fresh Water)	10^{-1} - 1	8 - 12
Dry, Sandy, Flat Coastal Land	2×10^{-3}	10
Marshy, Forested Flat Land	8×10^{-3}	12
Rich Agricultural Land Low Hills	10^{-2}	15
Pastoral Land, Medium Hills, and Forestation	5×10^{-3}	13
Fresh Water Ice	10^{-4} - 10^{-2}	4
Permafrost	10^{-5} - 10^{-2}	4 - 8
Granite (Dry)	10^{-8}	5
Limestone (Dry)	10^{-9}	7

(1) Taken from GSSI promotional brochure, "Continuous Profiling by Impulse Radar."

TABLE 6

BOREHOLE LOGGING INFORMATION

LOG TYPE	HOLE DIAMETER (inches minimum)	BOREHOLE FLUID	CASING	CORRECTIONS
Spontaneous Potential	2.25	Required(1)	Uncased	Mud resistivity for quantitative uses.
Resistance	2.25	Required(1)	Uncased	Same as spontaneous potential.
Natural Gamma	2.25	Not Required But Allowable	Any Type or Uncased	None for qualitative uses. Hole diameter, casing thickness, casing composition, casing size, and mud density for quantitative uses.
Gamma-Gamma	2.25	Not Required But Allowable	Any Type or Uncased	Same as natural gamma with addition of formation fluid and matrix density corrections.
Neutron	2.25	Not Required But Allowable	Any Type or Uncased	Same as natural gamma with addition of temperature, fluid salinity, and matrix composition corrections.
Caliper	2.00	Not Required But Allowable	Uncased	None.
Fluid-Movement	2.25	Required(2)	Uncased	None.
Temperature	2.00	Required(2)	Uncased	None.
Sonic	2.25	Required(2)	Uncased	Hole diameter, formation fluid and matrix velocity corrections for quantitative uses.

(1) Any type but performance deteriorates in highly conductive or resistive fluids.

(2) Any type.

TABLE 7

SUMMARY OF GEOPHYSICAL EXPRESSIONS OF GEOLOGIC FEATURES AND CONDITIONS

GEOLOGIC FEATURE/CONDITION	GEOPHYSICAL EXPRESSIONS
<u>Stratigraphy</u>	
Lithology	Acoustic velocity, electrical resistivity, spontaneous potential, density, gamma ray emission, gamma ray absorption, neutron absorption
Lithologic Correlation	See Lithology
Surficial Materials	See Lithology
<u>Geologic Structure</u>	
Folding	Acoustic velocity, electrical resistivity, density, magnetic susceptibility
Faulting	See Folding
Fracturing	Acoustic velocity, electrical resistivity, gamma ray absorption, neutron absorption, dielectric constant
Dissolution Features	Acoustic velocity, density, electrical resistivity, gamma ray absorption, neutron absorption, dielectric constant
Buried Drainage and Topography	Acoustic velocity, density, electrical resistivity, magnetic susceptibility
Igneous Features	See Buried Drainage and Topography
<u>Aquifer Properties</u>	
Porosity and Permeability	Acoustic velocity, gamma ray absorption, neutron absorption
Potentiometric Surface	Acoustic velocity, electrical resistivity, fluid movement, temperature
Flow Direction and Rate	See Porosity and Permeability and Potentiometric Surface
Temperature	Temperature
Water Chemistry	Electrical resistivity, gamma ray emission

TABLE 8

SUMMARY OF COSTS FOR CONDUCTING SURFACE GEOPHYSICAL SURVEYS[1]

SURVEY TYPE	DEPTH OF INVESTIGATION	UNIT COST[2]
Seismic Refraction	40 ft	\$1.76 - \$2.44/ft
Seismic Refraction	100 ft	\$1.45 - \$2.51/ft
Seismic Reflection	100 ft	\$4.46 - \$6.87/ft
Seismic Reflection	300 ft	\$1.78 - \$2.75/ft
VES Resistivity[3]	100 ft	\$193 - \$306/point[7]
VES Resistivity	300 ft	\$249 - \$419/point[8]
HP Resistivity[4]	100 ft	\$1.46 - \$2.66/ft
HP Resistivity	300 ft	\$0.73 - \$1.33/ft
FE Resistivity[5]	100-300 ft	\$0.29 - \$0.88/ft
Gravity	N/A	\$16.81 - \$26.13/point[9]
Magnetics	N/A	\$16.81 - \$26.13/point[9]
Radar[6]	50 ft	\$0.05 - \$0.21/ft

[1] Does not include land surveying, shothole drilling, brushing, or mobilization.

[2] 1980 Dollars.

[3] Vertical Electrical Sounding.

[4] Horizontal Profiling.

[5] Fixed Electrode.

[6] See Section 4.6.4 for additional costs.

[7] Points spaced at 150-600 feet.

[8] Points spaced at 450-1800 feet.

[9] Points spaced at 25-100 feet.

TABLE 9

SUMMARY OF COSTS FOR CONDUCTING BOREHOLE GEOPHYSICAL SURVEYS[1]

LOGGING SUITE	DAILY CHARGE[2]	UNIT CHARGE[2]
Suite 1 Natural Gamma, Spontaneous Potential, Resistance	\$100-\$560	\$0.20/ft
Caliper	No Additional Charge	\$0.10/ft
Temperature	No Additional Charge	\$0.10/ft
Suite 2 Natural Gamma, Caliper, Resistance, Gamma-Gamma	\$590	\$0.30/ft
Sonic	No Additional Charge	\$0.15/ft
Fluid Movement	No Additional Charge	\$0.15/ft
Suite 3 Natural Gamma, Spontaneous Potential, Resistance, Neutron	\$590	\$0.30/ft
Suite 4 Natural Gamma, Caliper, Resistance, Gamma-Gamma, Neutron, Spontaneous Potential	\$590	\$0.60/ft

(1) Does not include drilling or mobilization.

(2) 1980 Dollars

FIGURES

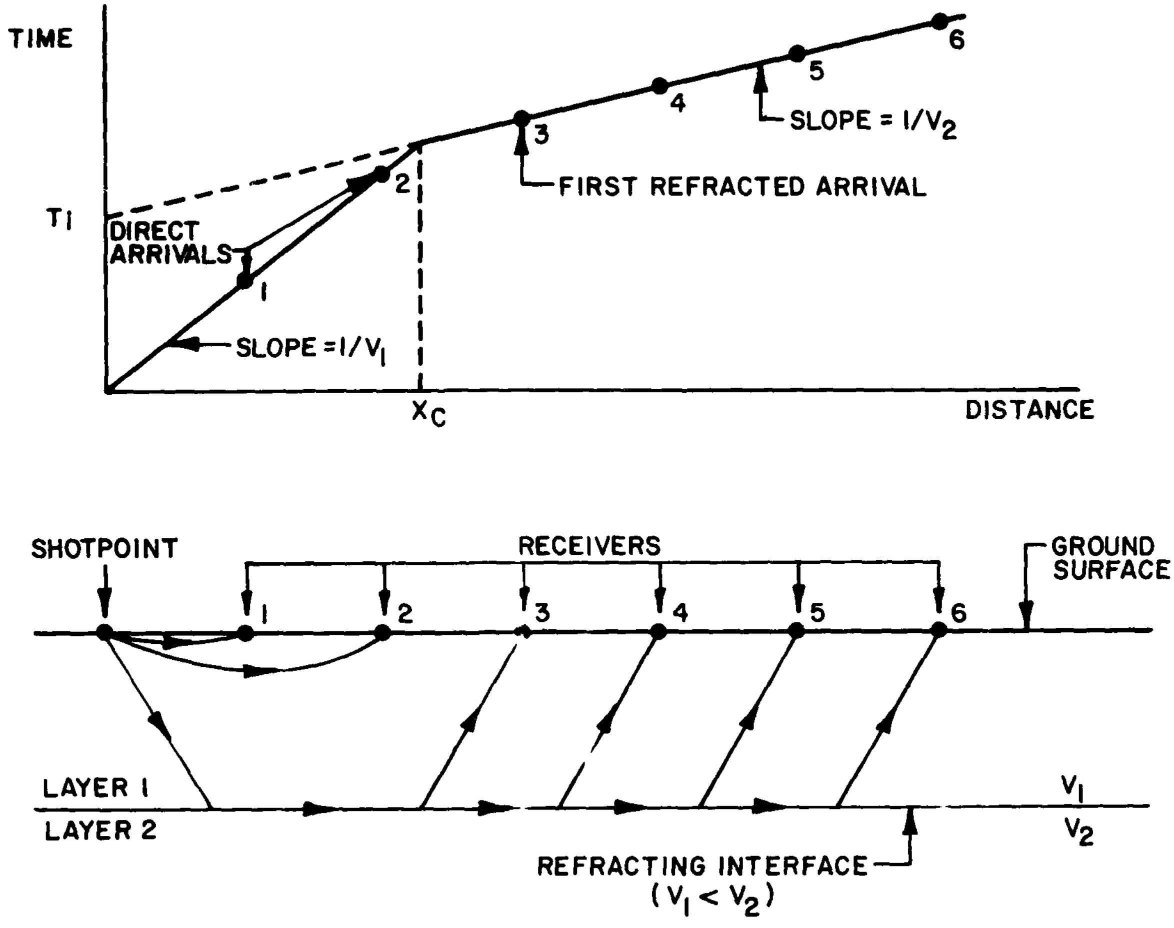


FIGURE 1

SCHEMATIC REPRESENTATION OF SEISMIC REFRACTION METHOD (TWO-LAYER CASE)

PREPARED FOR

U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

DRAWN BY	MEL 6-24-80	CHECKED BY RLC 7-22-80	DRAWING NUMBER 79-658-A23
		APPROVED BY A.J.C. 12 Nov 80	

DRAWN BY	MBM 6-26-80	CHECKED BY RLC 7-22-80	APPROVED BY ATE 13 Nov 80	DRAWING NUMBER 79-658-A16

SEISMIC REFRACTION SURVEY
FIELD DATA SHEET

PROJECT NAME ACME PROJECT NO. SAMPLE PAGE 1 OF 5

BY RLC DATE 10 FEB 80 LOCATION CLAY COUNTY, VA

RECORDER NIMBUS ES-1210F RECORDER S/N 1806

GAIN

1	2	3	4	5	6	7	8	9	10	11	12

FILTERS OUT

SOURCE 0.6 LB 80% NITRO @ 5.0'

GEOPHONES MARK L-8 8 HZ PROFILE NO. SRS-1

GEOPHONE NO.	SHOT NO.___	SHOT NO.___	SHOT NO.___	SHOT NO.___	SHOT NO.___
	TIME (MS)	TIME (MS)	TIME (MS)	TIME (MS)	TIME (MS)
1	4.0	21.4	34.4	—	—
2	8.0	18.0	32.4		
3	12.0	14.0	30.4		
4	16.0	1[illegible].0	28.4		
5	20.0	6 0	26.4		
6	22.4	2 0	24.4		
7	24.4	2 0	22.4		
8	26.4	4 0	20.0		
9	28.4	10.0	16.0		
10	30.4	14.0	12.0		
11	32.4	18.0	8.0		
12	34.4	21.4	4.0		

SKETCH

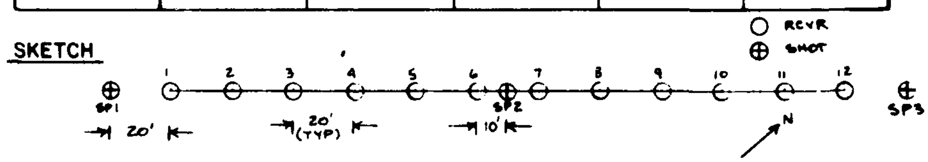


FIGURE 2

SAMPLE SEISMIC REFRACTION SURVEY FIELD DATA SHEET

PREPARED FOR

U S ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

10 1253 HERCULENE ABB SMITH CO PGH PA LT1930-1079

DRAWN BY clb/ 6-24-80 | CHECKED BY | APPROVED BY AJE | DRAWING NUMBER 79-658-A5

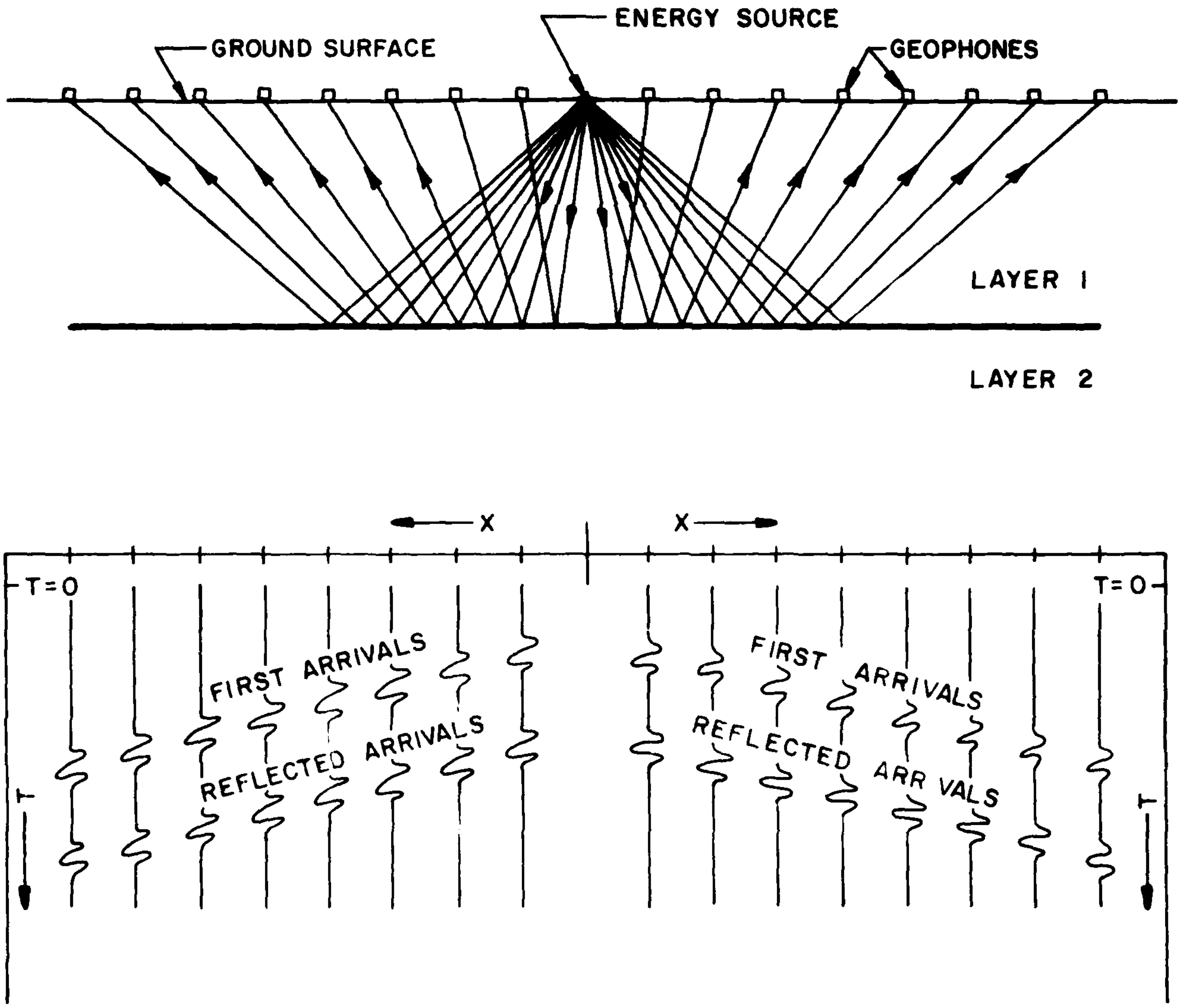


FIGURE 3

SEISMIC REFLECTION PRINCIPLE AND
SCHEMATIC OF REFLECTION DATA RECORD

PREPARED FOR

U. S. ARMY TOXIC AND
HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

PAGE 1 OF 2

SEISMIC REFLECTION FIELD REPORT

PROJECT NO. SAMPLE
CLIENT ACME
LOCATION CLAY COUNTY, VA
DATE 14 OCT 78
LINE NO. 99-4
RECORDER DHR-1632
RECORDER S/N 667
NO. CHANNELS 24
SAMPLE RATE (MS) 1

RECORD LENGTH (SEC) 1
GAIN MODE FIXED
PREAMP GAIN (dB) N/A
FINAL GAIN (dB)
(FIXED MODE ONLY)

1	2	3	4	5	6	7	8	9	10	11	12
78											
13	14	15	16	17	18	19	20	21	22	23	24
78											

25	26	27	28	29	30	31	32	33	34	35	36
37	38	39	40	41	42	43	44	45	46	47	48

SOURCE DINOSEIS
NO. ELEMENTS 16
PATTERN 1-2-3-4-3-2-1
SPACING (FT) 13.3
TOTAL LENGTH (FT) 80

GEOPHONES L-25E 40 HZ
NO. ELEMENTS 12
PATTERN NESTED
SPACING (FT) N/A
TOTAL LENGTH (FT) N/A

SPREAD TYPE OFF END GAP N/A
GEO. INT. (FT) 40
S.P. INT (FT) 80

SHOTPOINT NUMBER	FILE NUMBER	GEOPHONE STATION FOR THE FOLLOWING RECORDER CHANNELS CH/STA	CH/STA	CH/STA	CH/STA	CDP SWITCH POSITION	RECORDER BETWEEN STA/STA	DEAD CHANNELS	FILTERS LOW (HZ)	HIGH (HZ)	NOTCH (HZ)	REC START DELAY (MS)	VERTICAL SUMS	CHARGE DEPTH (FT)	WEIGHT (LB)	PERP SHOTPOINT OFFSET (FT) & DIRECTION	COMMENTS Timing, Phase, Amplitude or Indicative Time Break on all files. RLC, PDC, DAW, DEF on site
2	10	1/14	24/37	—	—	1	37/38	—	30	—	—	—	16	—	—	—	Redo and Plot
4	11	1/16	24/39			3											
6	12	1/18	24/41			5											
8	13	1/20	24/43			7											
10	14	1/22	24/45			9											Redo and Plot
12	15	1/24	24/47			11											
14	16	1/26	24/49			13											
16	17	1/28	22/49			15		23-24									Redo and Plot Rolling off line
18	18	1/30	20/49			17		21-24									
20	19	1/32	18/49			19		19-24									
22	20	1/34	16/49			21		17-24									
24	21	1/36	14/49			23		15-24									Redo and Plot

WEATHER OVERCAST
WIND 5 MPH
TEMP 65° F

GROUND CONDITIONS DRY
TIME START 0730 TIME FINISH 1300
LINE TRAVERSED (FT) 1920

LINE PROGRESSION
W TO E

LOGGED BY RLC
REVIEWED BY PDC
DATE 14 OCT 78

NOTE SOURCE AN[illegible] PATTERNS ARE REFERENCED TO THE STATION AT THE CENTER OF THE PATTERN

FIGURE 4

SAMPLE SEISMIC REFLECTION DATA SHEET

PREPARED FOR

U. S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

DRAWN BY	c/b/ 6-24-80	CHECKED BY	RLC 7-22-80	APPROVED BY	ATE 8 Jul 80	DRAWING NUMBER	79-658-A1

19 1293 HERCULENE A&B SMITH CO PGH PA LT1530-1079

DRAWN BY MBM 6-26-80
CHECKED BY RLC 7-22-80
APPROVED BY ATE
DRAWING NUMBER 79-658-A27

D'APPOLONIA

SEISMIC LINE COORDINATES

PROJECT NO. SAMPLE
CLIENT ACME
LOCATION CLAY COUNTY, VA
LINE NO. 95-2
LOGGED BY RLC DATE 18 OCT 79
REVIEWED BY JCC DATE 18 OCT 79

STATION NUMBER	N. COORDINATE (FT)	E COORDINATE (FT)	ELEVATION (FT)	STATION NUMBER	N COORDINATE (FT)	E. COORDINATE (FT)	ELEVATION (FT)	STATION NUMBER	N COORDINATE (FT)	E COORDINATE (FT)	ELEVATION (FT)
1	0.0	1200.0	137.1	19	720.0	1200.0	140.7	37	1440.0	1200.0	141.8
2	40.0	1200.0	138.0	20	760.0	1200.0	140.3	38	1480.0	1200.0	142.1
3	80.0	1200.0	137.2	21	800.0	1200.0	139.2	39	1520.0	1200.0	143.9
4	120.0	1200.0	137.5	22	840.0	1200.0	138.3	40	1560.0	1200.0	144.0
5	160.0	1200.0	138.1	23	880.0	1200.0	137.9	41	1600.0	1200.0	146.1
6	200.0	1200.0	140.0	24	920.0	1200.0	136.9	42	1640.0	1200.0	147.6
7	240.0	1200.0	139.2	25	960.0	1200.0	136.8	43	1680.0	1200.0	148.6
8	280.0	1200.0	137.5	26	1000.0	1200.0	135.3	44	1720.0	1200.0	151.5
9	320.0	1200.0	136.7	27	1040.0	1200.0	134.1	45	1760.0	1200.0	149.7
10	360.0	1200.0	135.9	28	1080.0	1200.0	136.2	46	1800.0	1200.0	147.6
11	400.0	1200.0	133.8	29	1120.0	1200.0	137.3	47	1840.0	1200.0	139.2
12	440.0	1200.0	137.2	30	1160.0	1200.0	138.1	48	1880.0	1200.0	139.9
13	480.0	1200.0	137.3	31	1200.0	1200.0	138.9	49	1920.0	1200.0	139.7
14	520.0	1200.0	140.1	32	1240.0	1200.0	139.9	50	1960.0	1200.0	138.0
15	560.0	1200.0	140.6	33	1280.0	1200.0	136.2	—	—	—	—
16	600.0	1200.0	140.7	34	1320.0	1200.0	141.1				
17	640.0	1200.0	140.8	35	1360.0	1200.0	141.1				
18	680.0	1200.0	141.7	36	1400.0	1200.0	141.2				

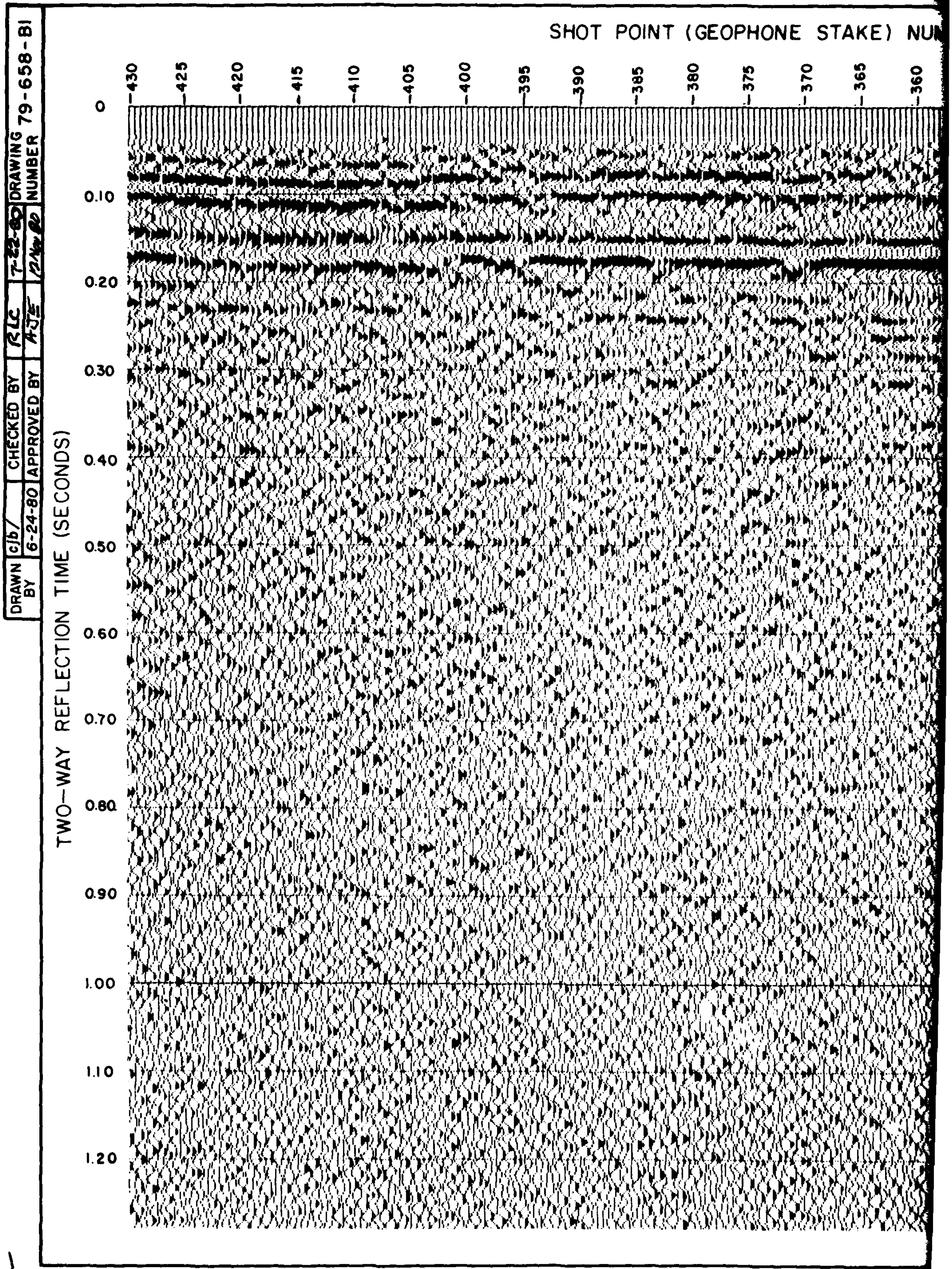
FIGURE 5

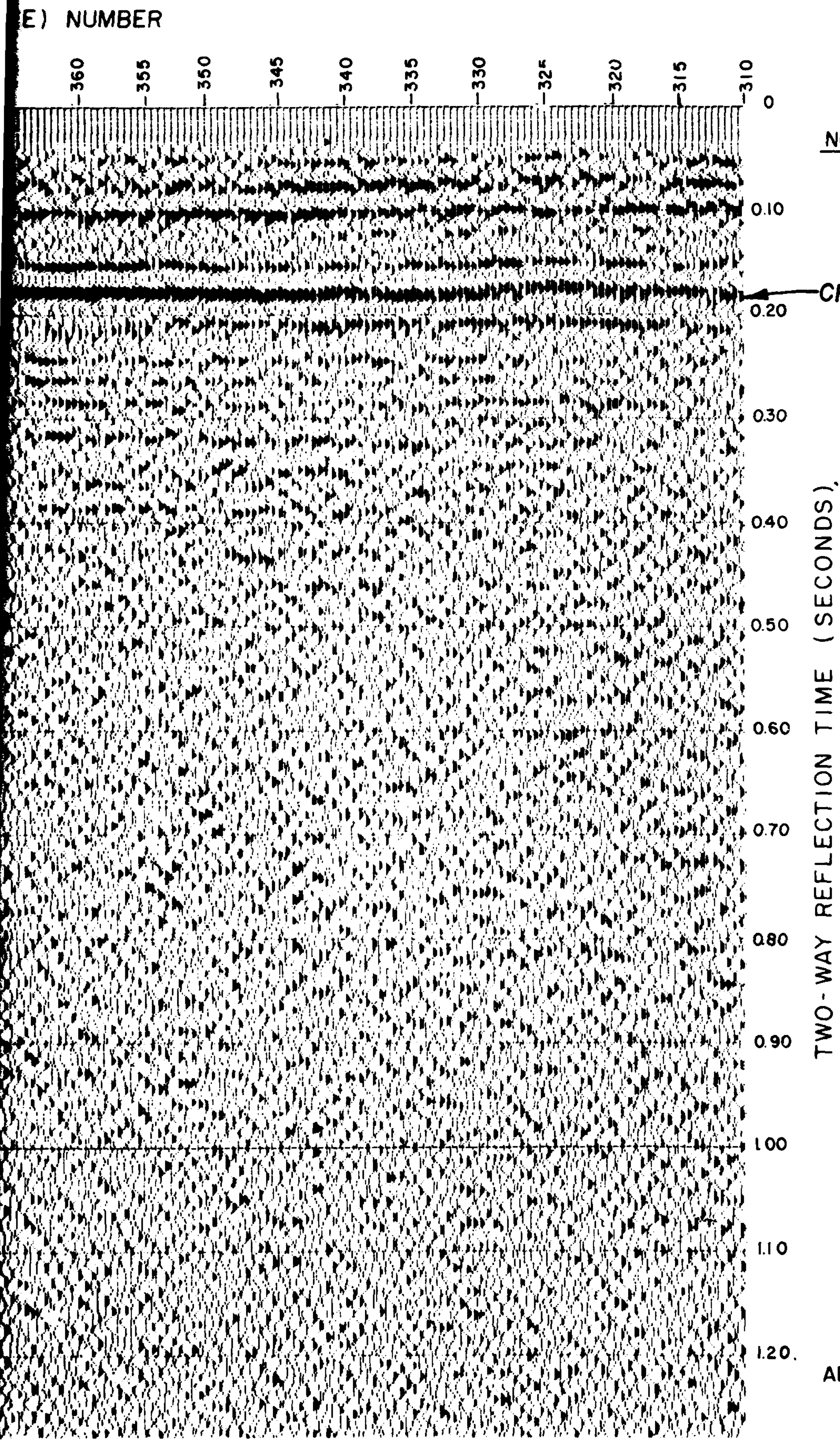
SAMPLE SEISMIC LINE COORDINATE DATA SHEET

PREPARED FOR

U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA


SHOT POINT (GEOPHONE STAKE) NUM
430
425
420
415
410
405
400
395
390
385
380
375
370
365
360
TWO-WAY REFLECTION TIME (SECONDS)
0
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
DRAWN BY
clb/
6-24-80
CHECKED BY
RLC
7-22-80
APPROVED BY
DRAWING NUMBER
79-658-B1



NOTES:

1. SPACING OF GEOPHONE STAKES IS 12.0 METERS.
2. DATA ARE 6-FOLD CDP STACKED.

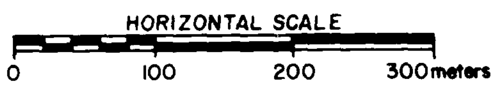


FIGURE 6

TYPICAL COMPUTER PROCESSED HIGH RESOLUTION REFLECTION SURVEY

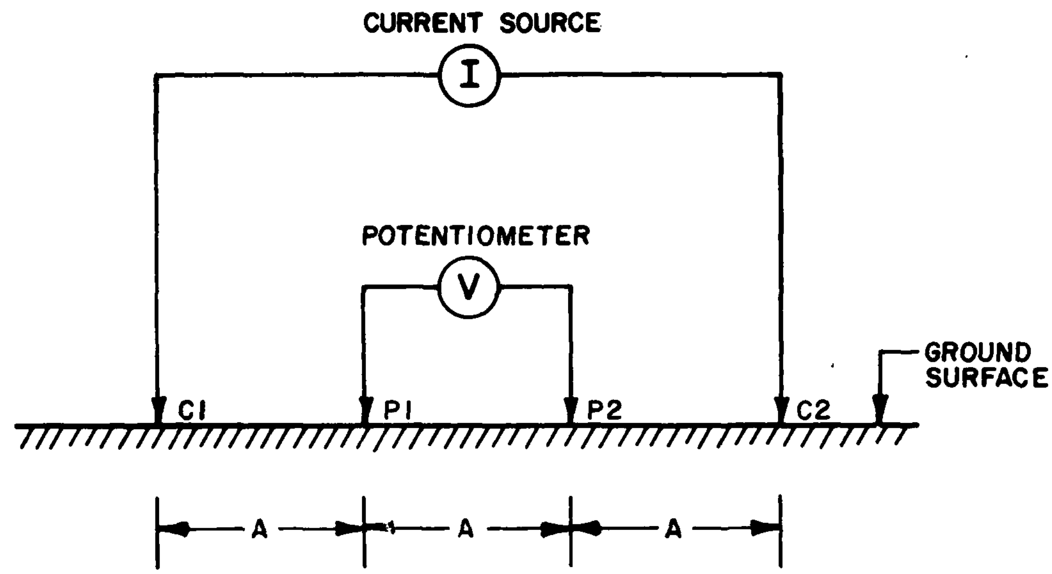
PREPARED FOR

U. S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

2

DRAWN BY MEL 6-24-80 | CHECKED BY RLC 7-22-80 | APPROVED BY AJW 12 Nov 80 | DRAWING NUMBER 79-658-A24



C1, C2 = CURRENT ELECTRODES

P1, P2 = POTENTIAL ELECTRODES

ρ_A = APPARENT RESISTIVITY = $2\pi A \frac{V}{I}$

FIGURE 7

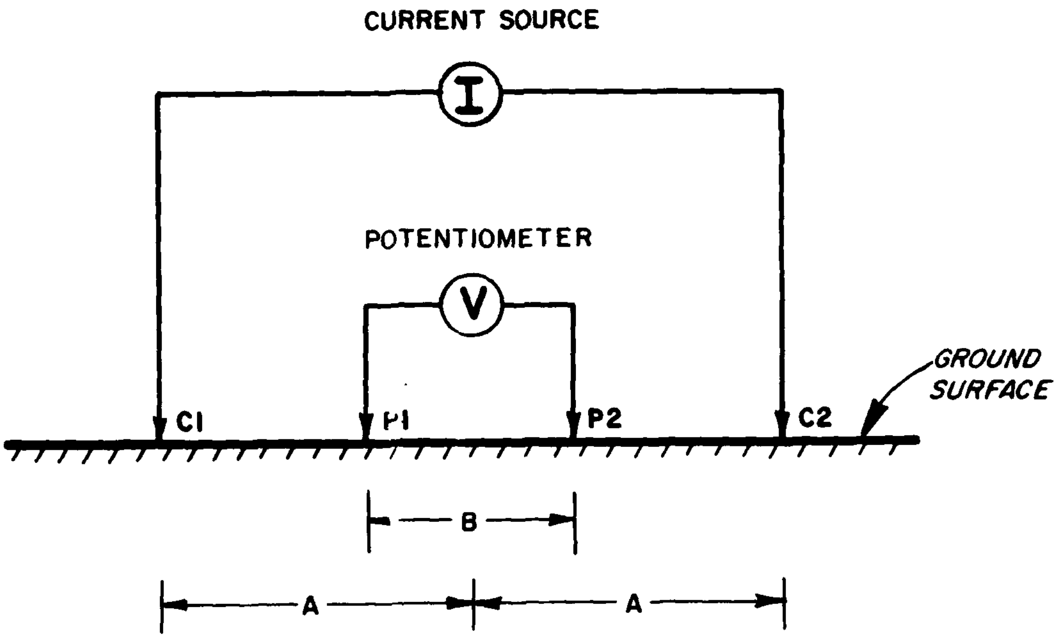
SCHEMATIC REPRESENTATION OF ELECTRICAL RESISTIVITY METHOD (WENNER CONFIGURATION)

PREPARED FOR

U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

DRAWN BY	TRS 10-30-80	CHECKED BY RLC 10NOV80	APPROVED BY	DRAWING NUMBER 79-658-A30



C1, C2 = CURRENT ELECTRODES

P1, P2 = POTENTIAL ELECTRODES

ρ_A = APPARENT RESISTIVITY = $\frac{\pi A^2}{B}\frac{V}{I}$ $(B<0.4A)$

FIGURE 8

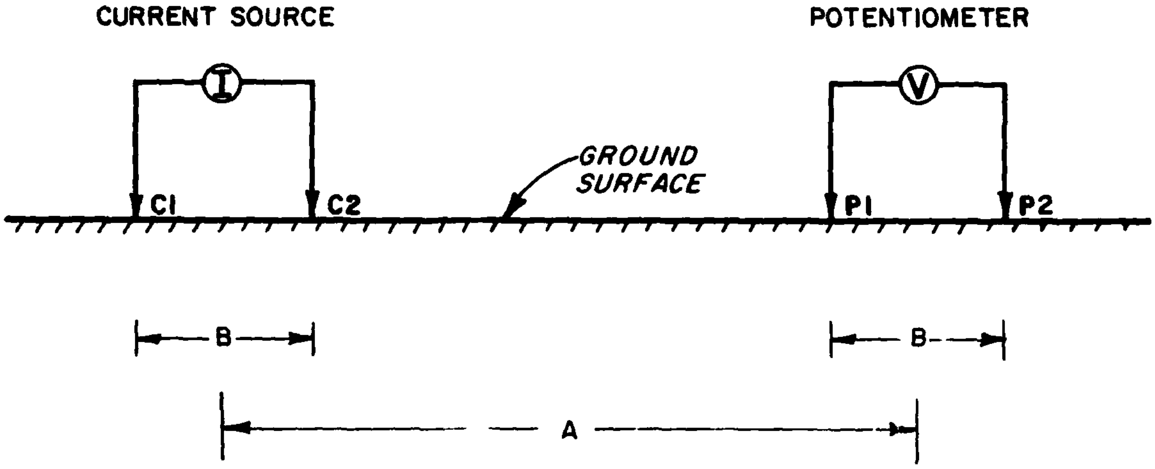
SCHEMATIC REPRESENTATION OF ELECTRICAL RESISTIVITY METHOD (SCHLUMBERGER CONFIGURATION)

PREPARED FOR

U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

DRAWN BY | TRS 10-30-80 | CHECKED BY RLC 10/30/80 | APPROVED BY | DRAWING NUMBER 79-658-A29



C1, C2 = CURRENT ELECTRODES

P1, P2 = POTENTIAL ELECTRODES

ρ_A = APPARENT RESISTIVITY $= \pi\left(\frac{A^3}{B^2} - A\right)\frac{V}{I}$

FIGURE 9

SCHEMATIC REPRESENTATION OF ELECTRICAL RESISTIVITY METHOD (DIPOLE-DIPOLE CONFIGURATION)

PREPARED FOR

U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

DRAWN BY C|D/ 6-24-80 | CHECKED BY RLC 7-22-80 | APPROVED BY [illegible] 12 Aug 80 | DRAWING NUMBER 79-658-A2

RESISTIVITY SURVEY
FIELD DATA SHEET
WENNER CONFIGURATION

PROJECT NAME ACME PROJECT NO. SAMPLE PAGE 1 OF 1

BY RLC/JCC DATE 6 JUL 79

LOCATION CLAY COUNTY, VA

COMMENTS USING PHOENIX RT-1, S/N 101 STAINLESS ELECTRODES SUNNY, DRY, 85°F

TEST NO.	LOCATION	"A" SPACING	I	ΔV	FREQUENCY
1	R-17	2 FT	0.01 A	0.17 V	DC
		4	0.01	0.028	
		6	0.1	0.15	
		8	0.1	0.11	
		10	0.1	0.092	
		12	0.1	0.081	
		16	0.1	0.071	
		20	0.1	0.068	
		30	0.1	0.053	
		40	0.1	0.051	
		50	0.1	0.046	
		60	0.1	0.041	

SPREAD CONFIGURATION

LINE ORIENTATION = N 65° W

C1 —"A"— P1 —"A"— P2 —"A"— C2

$$\rho_A = 2\pi \text{"A"} \frac{\Delta V}{I}$$

FIGURE 10

SAMPLE ELECTRICAL RESISTIVITY DATA SHEET

PREPARED FOR

U. S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

10 1253 HERCULENE. A&B SMITH CO. PGH PA LT1530-1079

DRAWN BY MBM 6-26-80 CHECKED BY RLC 7-2-80 APPROVED BY [illegible] DRAWING NUMBER 79-658-A15

GRAVITY SURVEY

FIELD DATA SHEET

PROJECT NAME ACME PROJECT NO. SAMPLE PAGE 1 OF 1

BY RLC DATE 12JAN80 LOCATION CLAY COUNTY, VA

INSTRUMENT LACOSTE-ROMBERG INSTRUMENT S/N 6906

INSTRUMENT FACTOR 0.876 MGAL/DIV

BASE STATION LOCATION NEWBURRY CHURCH 37° 38.2' N 78° 41.3' W

PROFILE NUMBER GS-1

STATION NO.	READING (DIV)	TIME	ELEVATION (FT)	N. COORD. (FT)	E. COORD. (FT)	DRIFT CORR.
BASE	405.22	0703	697.25	0.00	0.00	
1	404.64	0722	703.12	105.12	2407.13	-0.01
2	404.33	0731	706.27	155.17	2407.13	-0.02
3	403.92	0742	710.33	205.12	2407.13	-0.02
4	404.12	0750	708.79	255.14	2407.13	-0.03
5	402.73	0801	721.88	305.21	2407.13	-0.03
6	404.48	0813	706.11	355.16	2407.13	-0.04
7	404.76	0823	703.68	405.29	2407.13	-0.05
8	404.08	0832	709.95	455.18	2407.13	-0.05
9	403.95	0844	711.24	505.13	2407.13	-0.06
10	404.08	0853	710.02	555.21	2407.13	-0.06
11	404.07	0906	710.29	605.07	2407.13	-0.07
12	403.95	[illegible]	711.63	655.25	2407.13	-0.08
BASE	406.31	0937	697.25	0.00	0.00	-0.09

COMMENTS BASE STATION IS BRASS MARKER ON SW SIDE OF CHURCH

FIGURE 11

SAMPLE GRAVITY SURVEY
FIELD DATA SHEET

PREPARED FOR

U S ARMY TOXIC AND
HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

MAGNETIC SURVEY
FIELD DATA SHEET

PROJECT NAME ACME PROJECT NO. SAMPLE PAGE 1 OF 1

BY RLC DATE 17 JUN 79 LOCATION CLAY COUNTY, VA

INSTRUMENT GEOMETRICS G-819 INSTRUMENT S/N 8651

BASE STATION LOCATION DAWSON FARM 37° 12.6' N 78° 03.1' W

PROFILE NUMBER MS-1

STATION NO.	READING (GAMMAS)	SCALE (GAMMAS)	TIME	N. COORD. (FT.)	E. COORD. (FT.)	DRIFT CORR.
BASE	484	50,000	0626	0.0	0.0	—
1	529		0636	207.3	1416.2	-1
2	531		0641	227.3	1416.2	-2
3	533		0645	247.3	1416.2	-2
4	537		0650	267.3	1416.2	-2
5	544		0654	287.3	1416.2	-3
6	551		0702	307.3	1416.2	-4
7	561		0709	327.3	1416.2	-4
8	546		0714	347.3	1416.2	-5
9	541		0721	367.3	1416.2	-6
10	537		0728	387.3	1416.2	-6
11	536		0735	407.3	1416.2	-7
12	536		0744	427.3	1416.2	-8
BASE	493		0754	0.0	0.0	-9

COMMENTS BASE STATION IS CEMENT POST ON WEST SIDE OF BARN

FIGURE 12

SAMPLE MAGNETIC SURVEY
FIELD DATA SHEET

PREPARED FOR

U.S. ARMY TOXIC AND
HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

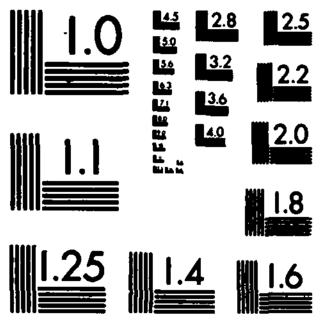
D'APPOLONIA

DRAWN BY	MBM 6-26-80	CHECKED BY / APPROVED BY	RLC 7-22-80 / 12 Nov 80	DRAWING NUMBER 79-658-A28

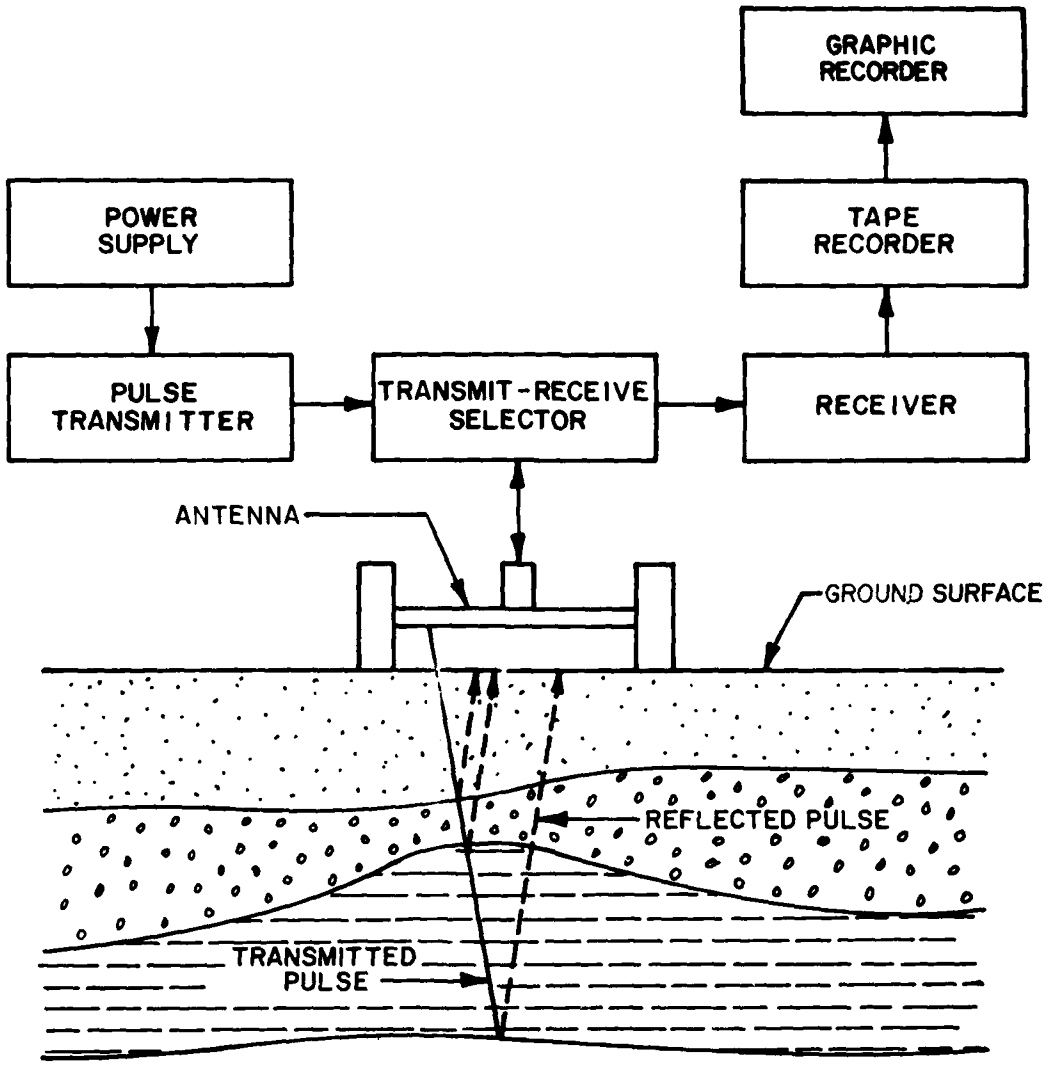
AD-A123 939 IDENTIFICATION AND DESCRIPTION OF GEOPHYSICAL TECHNIQUES(U) D'APPOLONIA CONSULTING ENGINEERS INC PITTSBURGH PA R L COSTELLO NOV 80 79-658-A1 3/3

UNCLASSIFIED DRXTH-TE-CR-80084 DAAK11-80-C-0029 F/G 8/7 NL

END
DATE FILMED
83
DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



ADAPTED FROM GSSI
PROMOTIONAL BROCHURE

FIGURE 13

SCHEMATIC REPRESENTATION OF
GROUND RADAR METHOD

PREPARED FOR

U.S. ARMY TOXIC AND
HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

DRAWN BY	MEL 6-24-80	CHECKED BY	RLC 7-22-80	DRAWING NUMBER	79-658-A25
		APPROVED BY			

DRAWN BY	MBM	6-26-80	CHECKED BY	RLC	7-22-80	APPROVED BY		12-...	DRAWING NUMBER	79-658-A17

GROUND RADAR SURVEY DATA SHEET

PROJECT NAME ACME PROJECT NO. SAMPLE PAGE 1 OF 1

BY RLC DATE 10-...-79 LOCATION CLAY COUNTY, MA

TRANSDUCER GSSI 3065 TRANSDUCER S/N 804

RECORDER GSSI SIR-7 RECORDER S/N 186

PROFILE NO. RP-1 LINE PROGRESSION SW→NE

END POINT COORDINATES — START 0.0 FT N 0.0 FT E

FINISH 4236.2 FT N 3076.1 FT E

REMARKS ANOMALY BETWEEN STATIONS 29 AND 30 CAUSED BY CATTLE GUARD. BREAK IN COVERAGE AT STATION 87 TO CHANGE BATTERIES. WEATHER - SUNNY, 85°F

START TIME - 0756 FINISH TIME - 0933

FIGURE 14

SAMPLE GROUND RADAR SURVEY
DATA SHEET

PREPARED FOR

U.S. ARMY TOXIC AND
HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

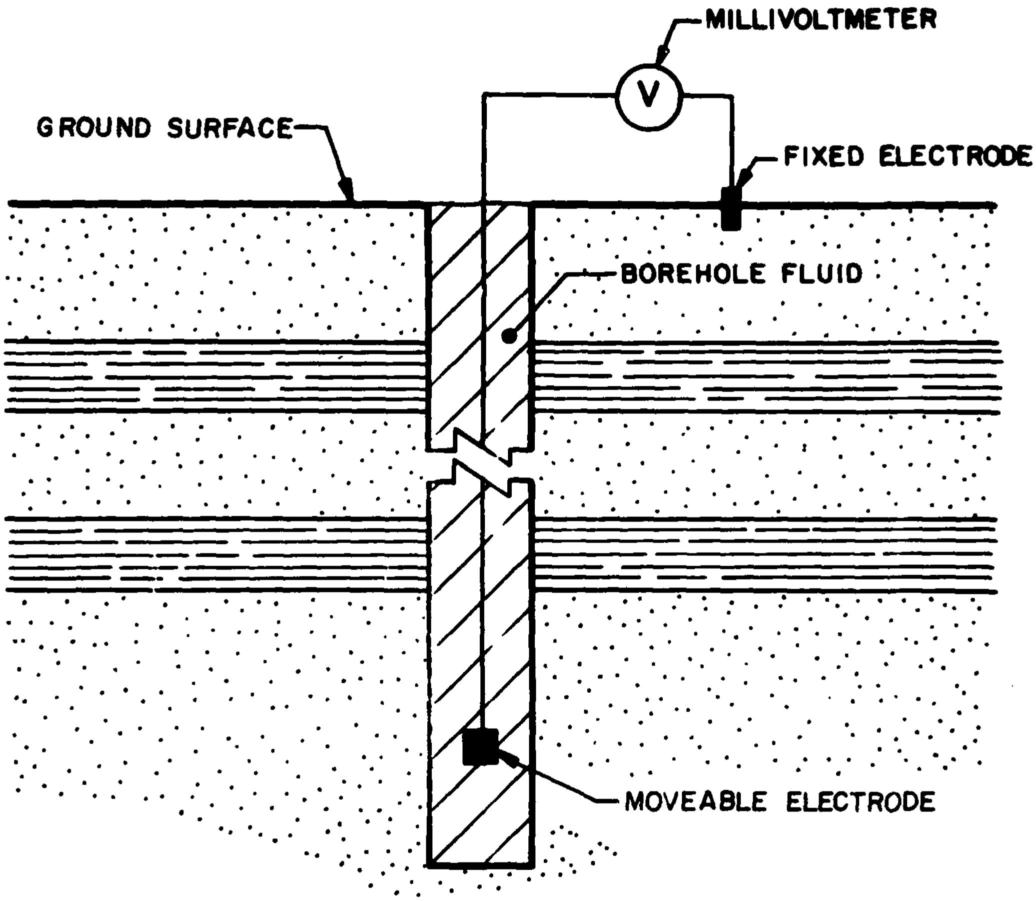


FIGURE 15

BASIC ELEMENTS OF BOREHOLE SPONTANEOUS POTENTIAL (SP) MEASUREMENT SYSTEM

PREPARED FOR

U. S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

DRAWN BY cjb/ 6-24-80 | CHECKED BY RJC | APPROVED BY NJE | DRAWING NUMBER 79-658-A6

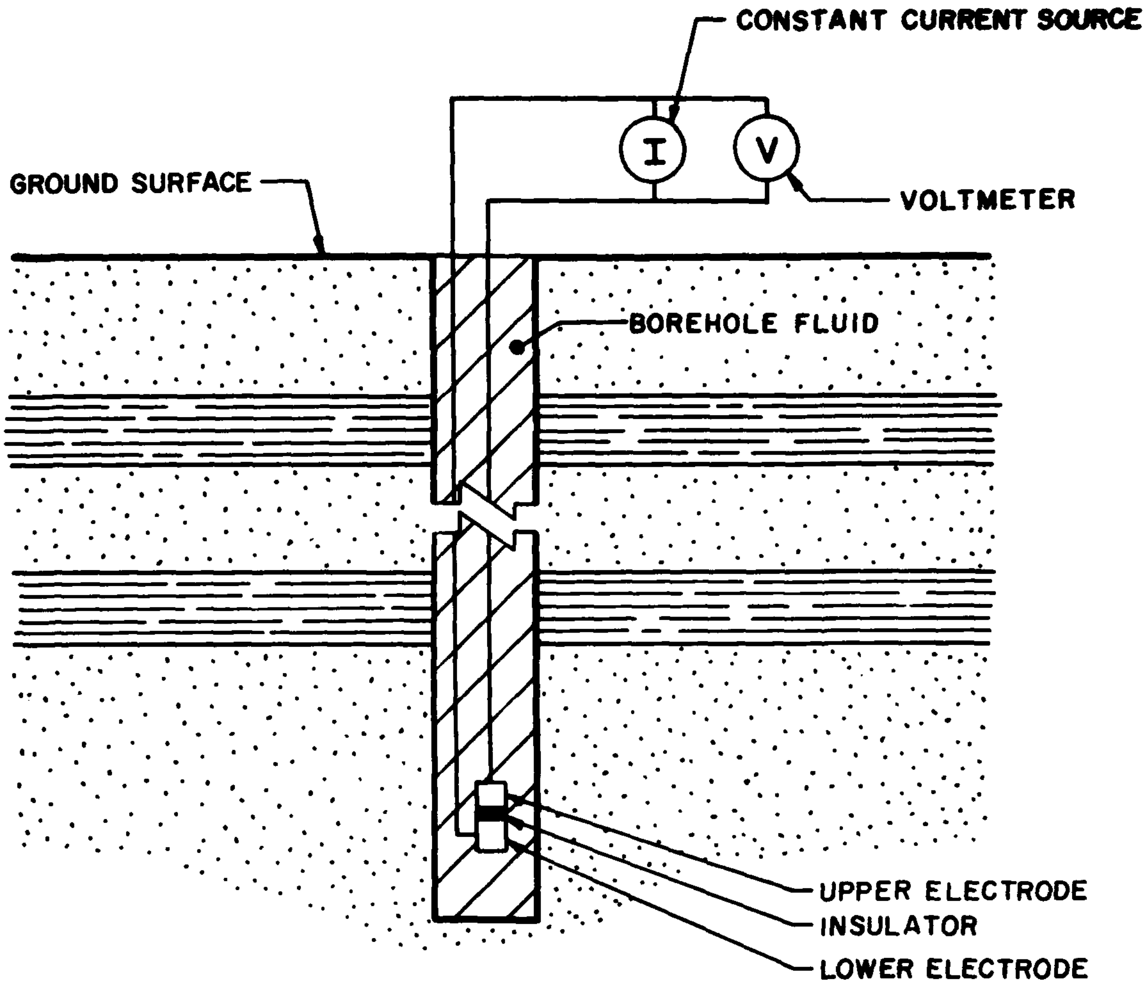


FIGURE 16

BASIC ELEMENTS OF BOREHOLE RESISTANCE (R) MEASUREMENT SYSTEM

PREPARED FOR

U. S. ARMY TOXIC AND
HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

DRAWN BY	cjb/ 6-24-80	CHECKED BY	RLC 7-22-80	APPROVED BY		DRAWING NUMBER	79-658-A3

DRAWN BY gib 6-24-80 | CHECKED BY | APPROVED BY | DRAWING NUMBER 79-658-A4

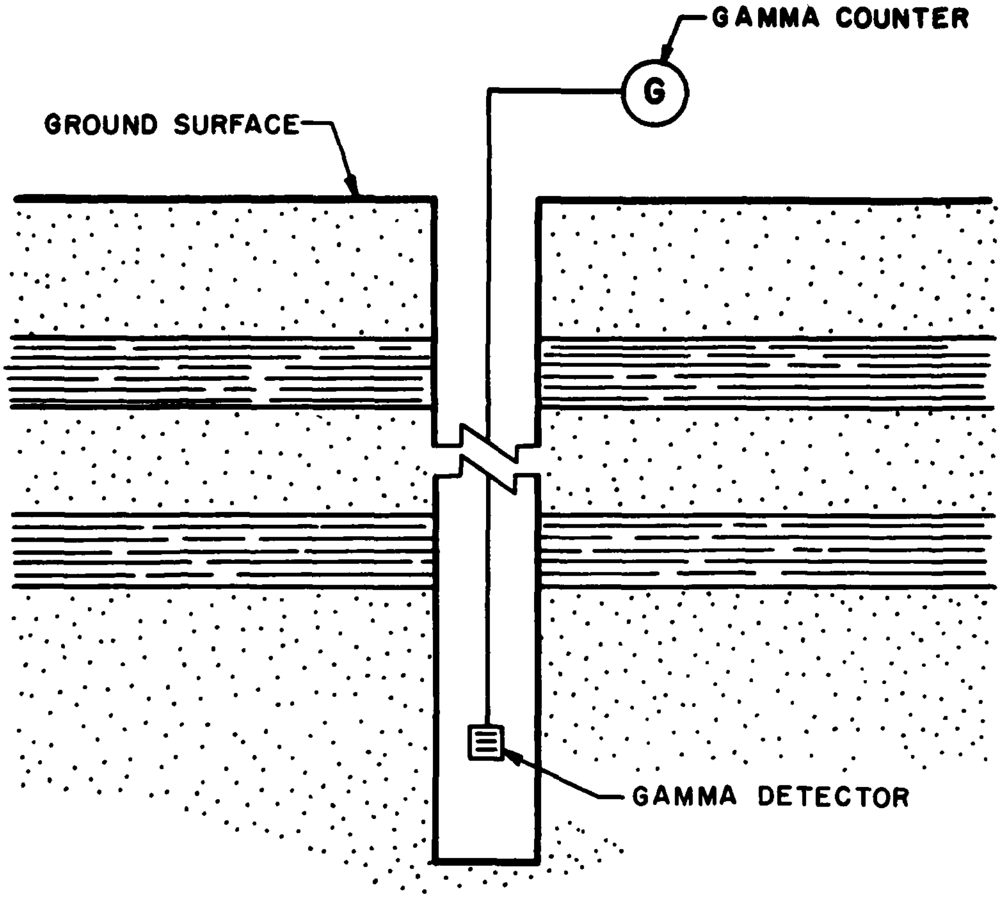


FIGURE 17

BASIC ELEMENTS OF BOREHOLE NATURAL GAMMA RADIATION (NGR) MEASUREMENT SYSTEM

PREPARED FOR

U. S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

DRAWN BY ACS 6-25-80 | CHECKED BY | APPROVED BY | DRAWING NUMBER 79-658-A12

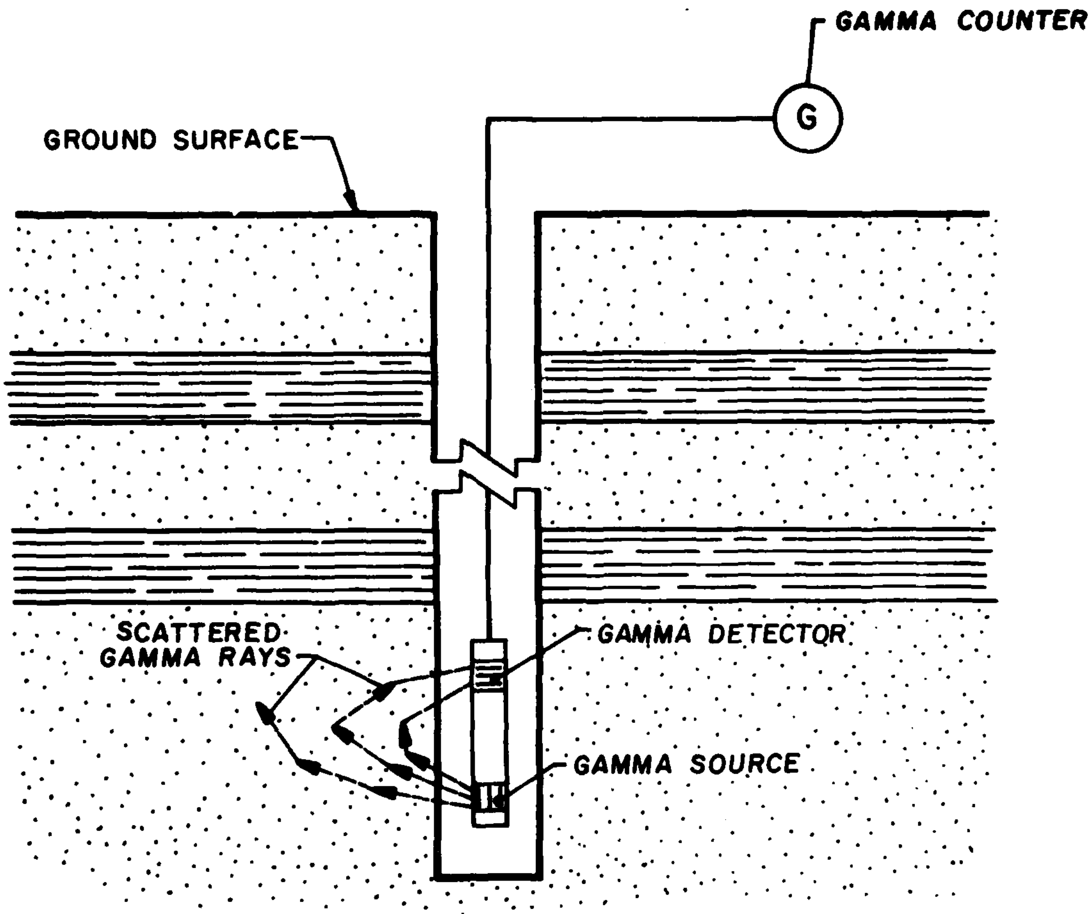


FIGURE 18

BASIC ELEMENTS OF BOREHOLE GAMMA-GAMMA(γ-γ) MEASUREMENT SYSTEM

PREPARED FOR

U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

DRAWN BY ACS 6-25-80 | CHECKED BY | APPROVED BY | DRAWING NUMBER 79-658-A8

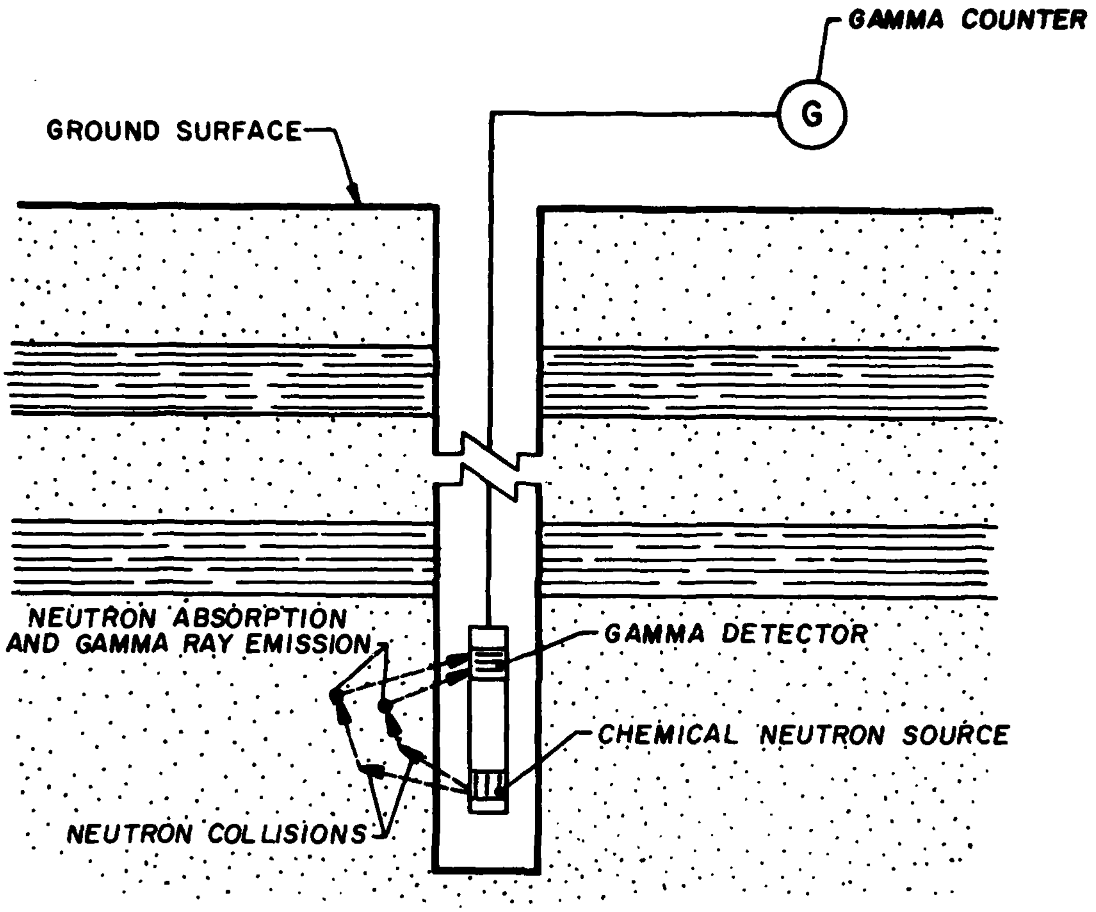


FIGURE 19

BASIC ELEMENTS OF BOREHOLE NEUTRON (N) MEASUREMENT SYSTEM

PREPARED FOR

U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

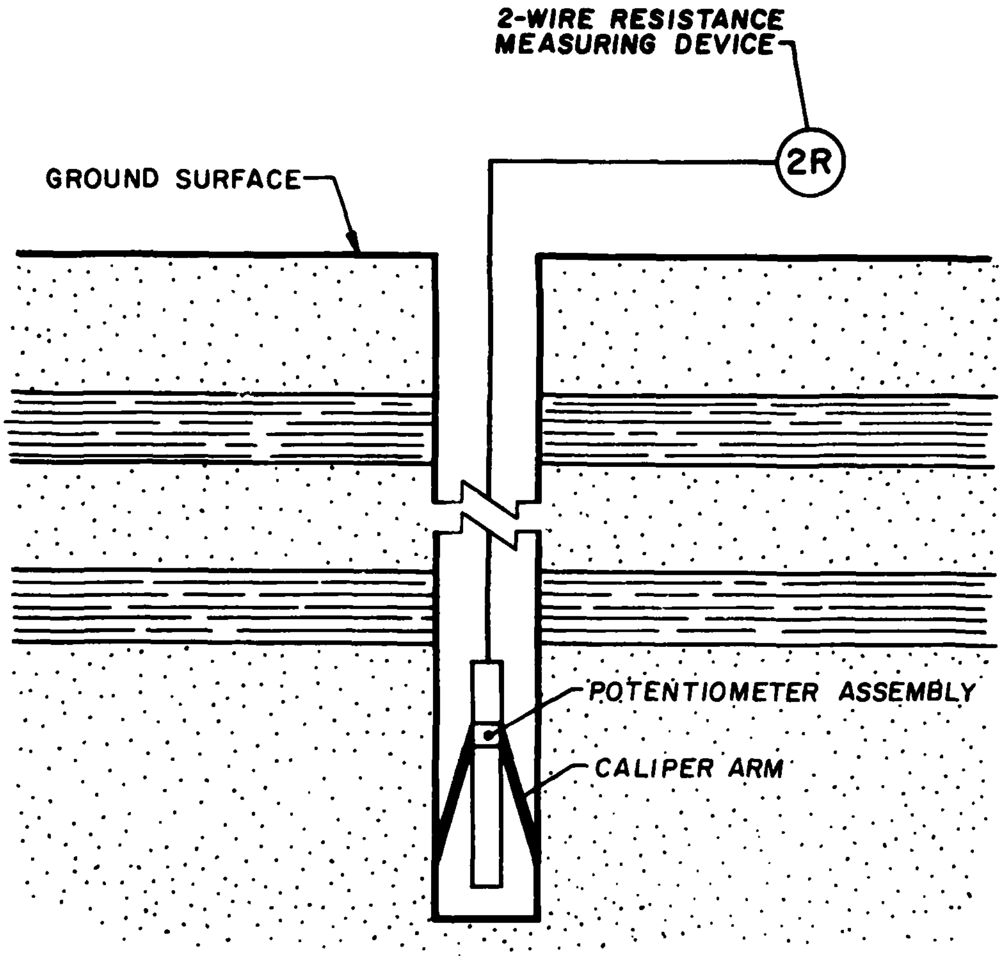


FIGURE 20

BASIC ELEMENTS OF BOREHOLE
CALIPER MEASUREMENT SYSTEM

PREPARED FOR

U.S. ARMY TOXIC AND
HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

DRAWN BY	ACS 6-25-80	CHECKED BY	RLC	APPROVED BY	AJS	DRAWING NUMBER	79-658-A7

19 1253 HERCULENE ABB SMITH CO PGH PA LT1530-1079

DRAWN BY ACS 6-25-80 | CHECKED BY | APPROVED BY | DRAWING NUMBER 79-658-A9

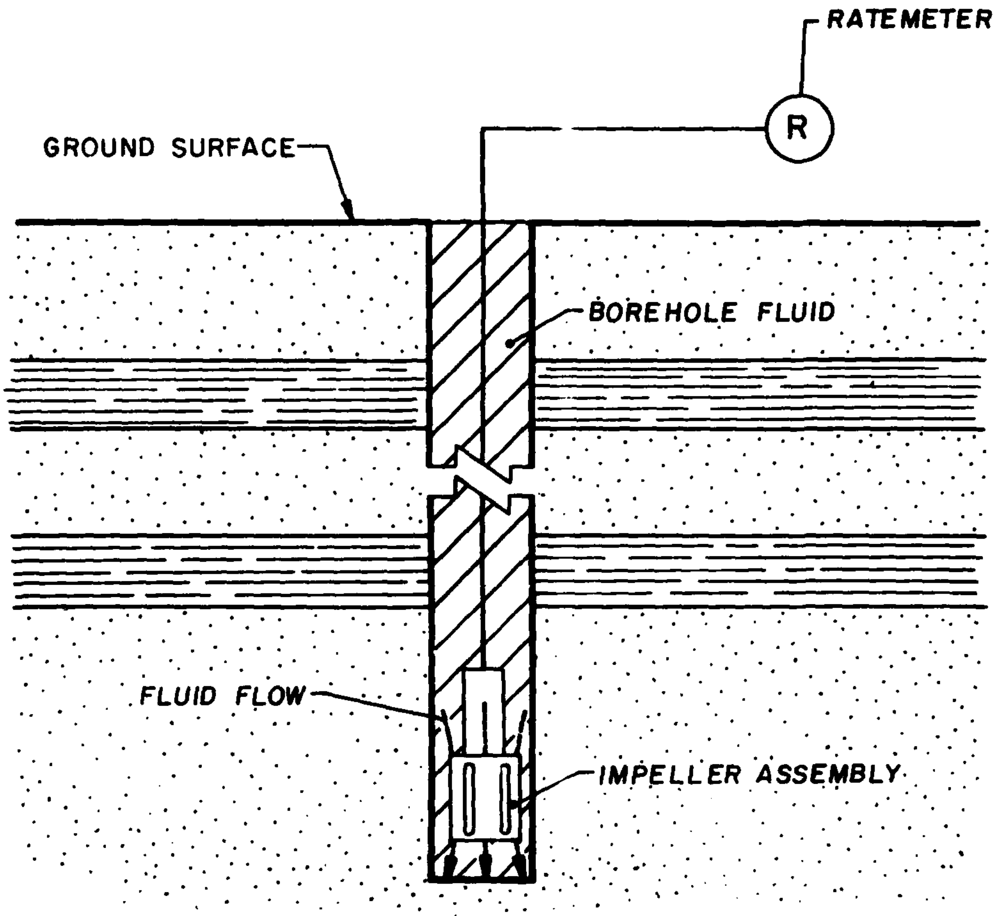


FIGURE 21

BASIC ELEMENTS OF BOREHOLE FLUID MOVEMENT MEASUREMENT SYSTEM

PREPARED FOR

U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

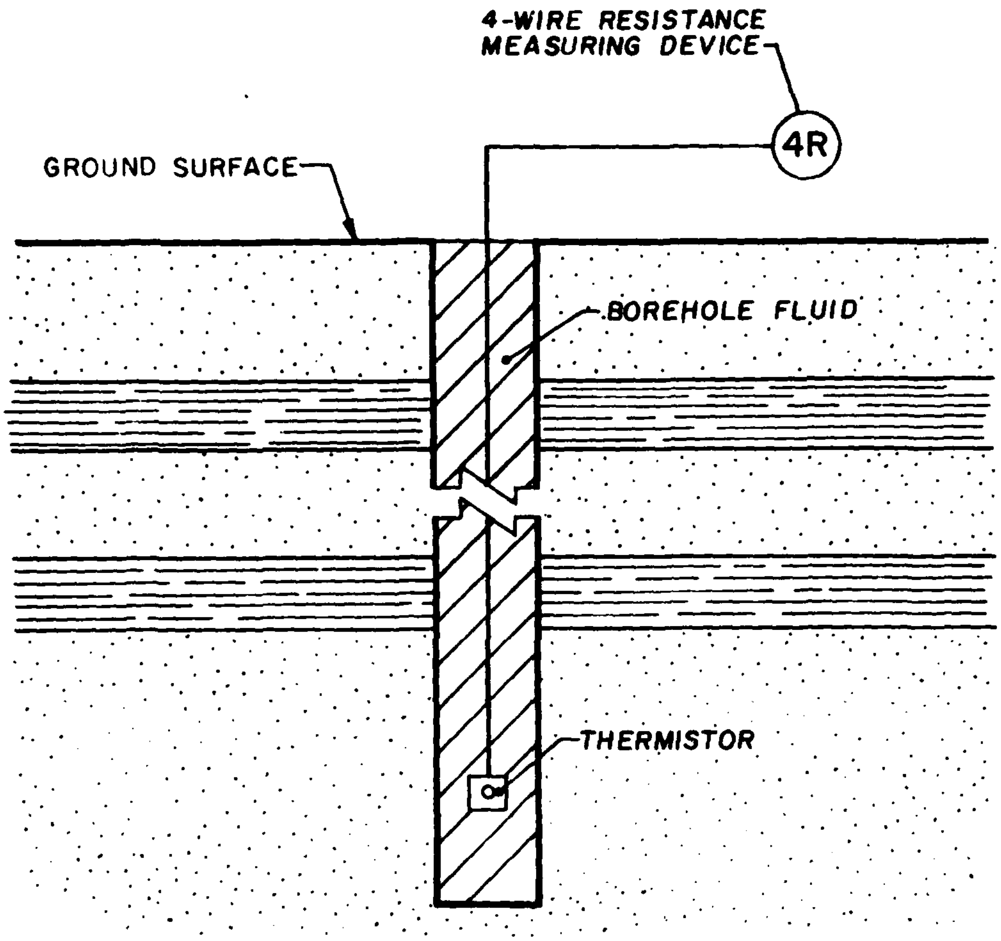


FIGURE 22

BASIC ELEMENTS OF BOREHOLE
TEMPERATURE MEASUREMENT SYSTEM

PREPARED FOR

U.S. ARMY TOXIC AND
HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

DRAWN BY	ACS 6-25-80	CHECKED BY	RLC 7-22-80
		APPROVED BY	12/16/80

DRAWING NUMBER 79-658-A10

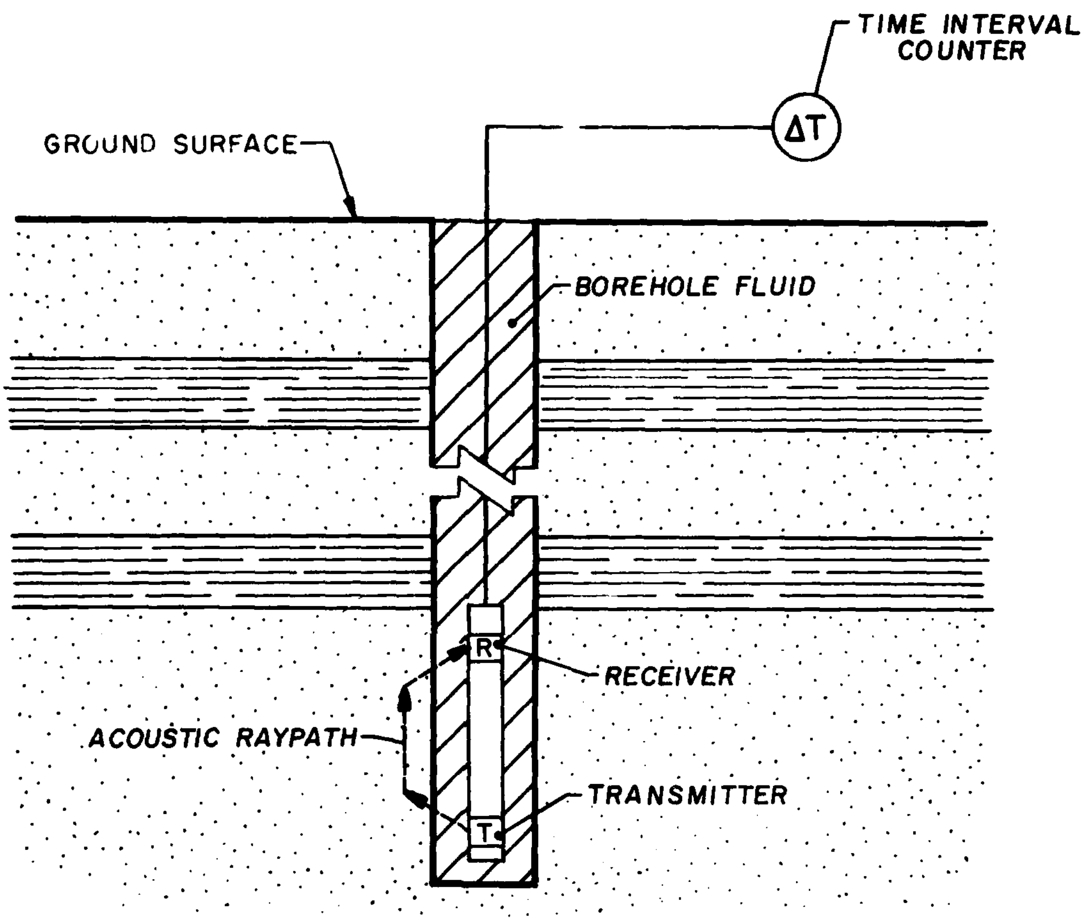


FIGURE 23

BASIC ELEMENTS OF BOREHOLE SONIC VELOCITY(ΔT) MEASUREMENT SYSTEM

PREPARED FOR

U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

DRAWN BY	ACS	6-25-80	CHECKED BY	RLC	7-22-80	DRAWING NUMBER
			APPROVED BY	ATG	12 Nov 80	79-558-A11

DRAWN BY	MBM 6-26-80	CHECKED BY / APPROVED BY	RLC 7-?-80 / [illegible] 12 Nov 80	DRAWING NUMBER	79-658-A18

BORE HOLE LOG HEADING

PROJECT NO. SAMPLE PROJECT NAME ACME BY RLC

BORING NO. BH-371 DEPTH FROM 35' TO 297' DATE 20 FEB 80

HOLE DIA. 3.0" CASING NONE MUD BENTONITE

LOGGING DATA DEPTH LOGGER 297' DEPTH DRILLER 297'

VERTICAL SCALE 1" = 20' EQUIPMENT WRI 10406 S/N 22071

[X] GAMMA LOG				[X] SP LOG				[X] RESISTIVITY LOG			
RUN NO.	1			RUN NO.	1			RUN NO.	1		
RATE (CPS)	100			FS (MV)	100			FS (OHM)	100		
TC (SEC)	2			DEPTH CORR.	5.0'			DEPTH CORR.	5.0'		
LOG SPEED (FT/MIN)	5			LOG SPEED (FT/MIN)	15			LOG SPEED (FT/MIN)	15		

REMARKS:

FIGURE 24

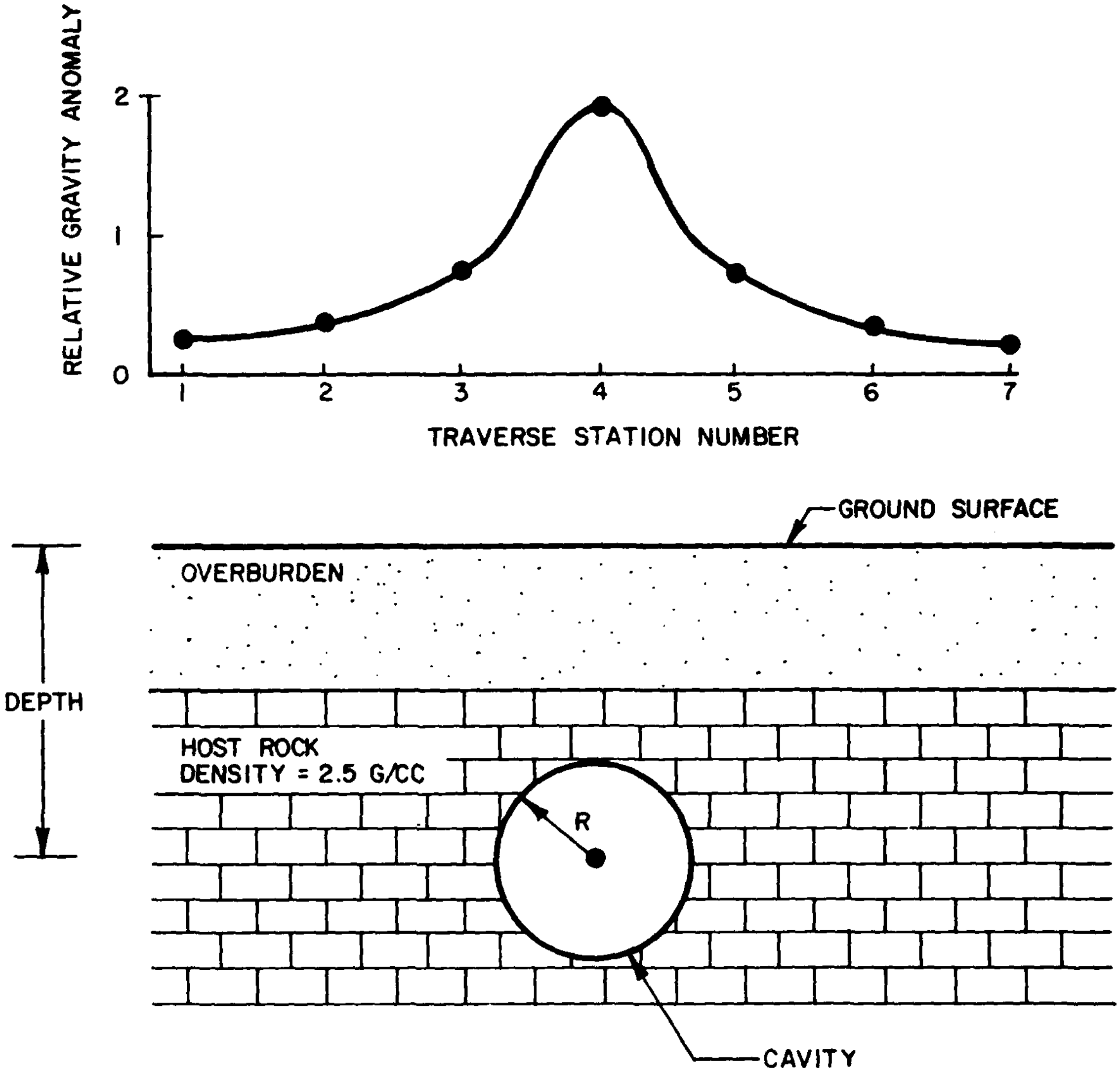
SAMPLE BORE HOLE LOG HEADING

PREPARED FOR

U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

DRAWN BY MBM 6/24/80 | CHECKED BY RLC 7-22-80 | APPROVED BY | DRAWING NUMBER 79-658-A14



NOTES:

1. OVERBURDEN DENSITY IS ARBITRARY BUT UNIFORM
2. CAVITY MAY BE DRY OR WATER FILLED
3. VERTICAL PLANE THROUGH LINE OF TRANSVERSE INTERSECTS CENTER OF CAVITY.
4. SENSE OF ANOMALY IS NEGATIVE.

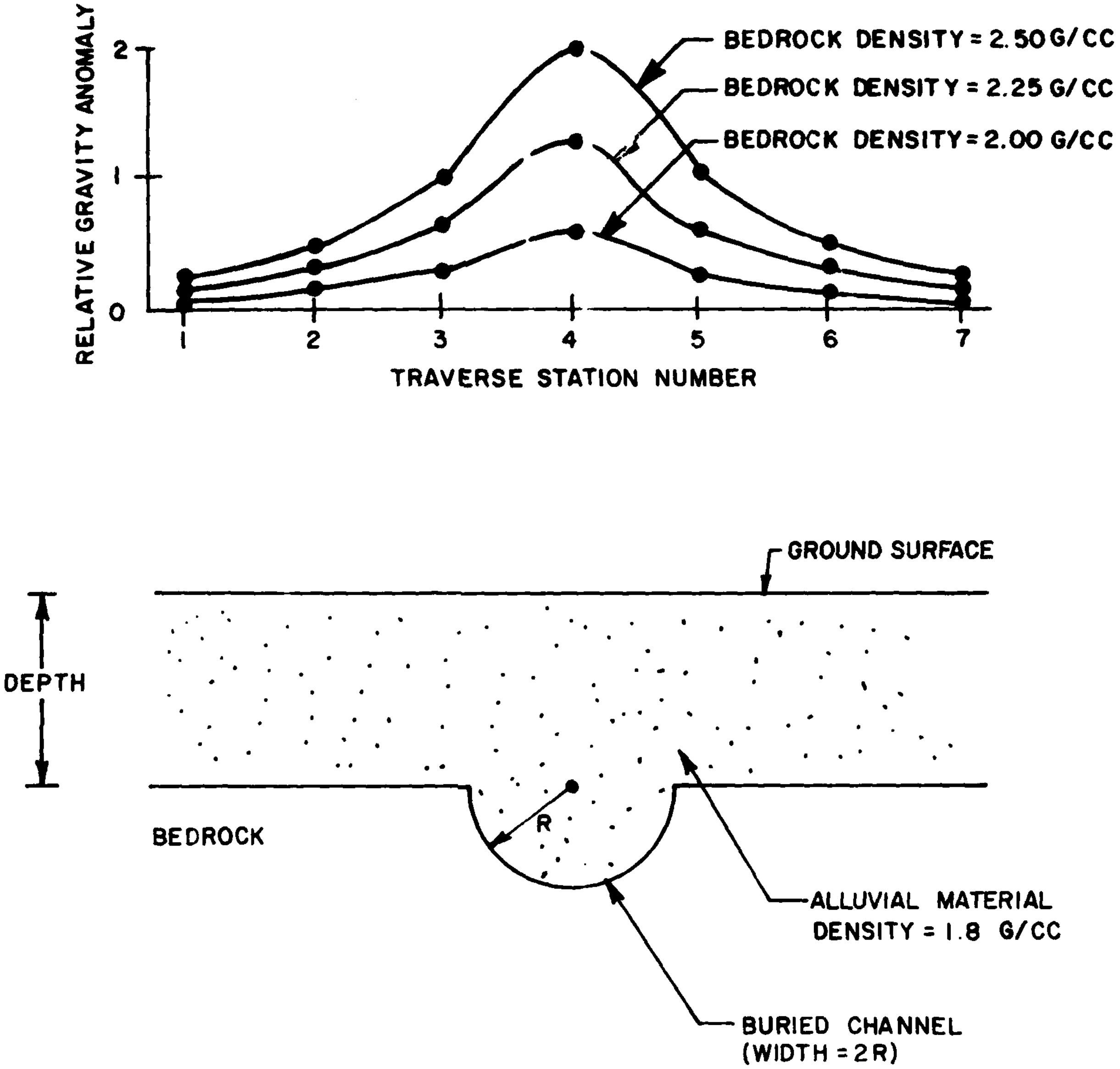
FIGURE 25

SCHEMATIC REPRESENTATION OF GRAVITY METHOD TRAVERSE OVER SUBSURFACE CAVITY

PREPARED FOR

U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA



NOTES:
1. TRAVERSE PERPENDICULAR TO CHANNEL AXIS
2. SENSE OF ANOMALY IS NEGATIVE.

FIGURE 26

SCHEMATIC REPRESENTATION OF GRAVITY METHOD TRAVERSE OVER BURIED CHANNEL

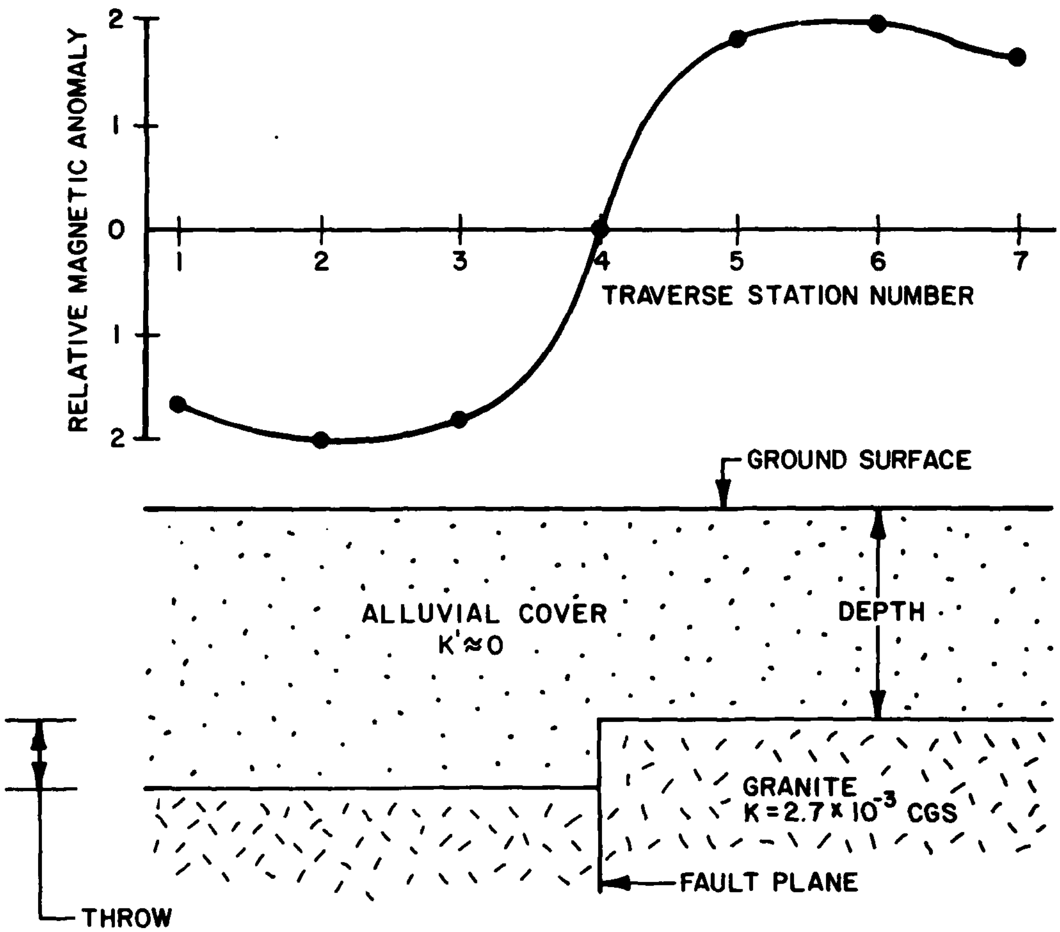
PREPARED FOR

U S ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

DRAWN BY	sh	6-25-80	CHECKED BY		7-2-80	DRAWING NUMBER	79-658-A19
			APPROVED BY				

DRAWN BY	MEL 6-25-80	CHECKED BY	7-22-80	DRAWING NUMBER 79-658-A13
		APPROVED BY	AJE 12/4/80	



NOTES:

1. FAULT STRIKES NORTH-SOUTH
2. TRAVERSE ORIENTED EAST-WEST

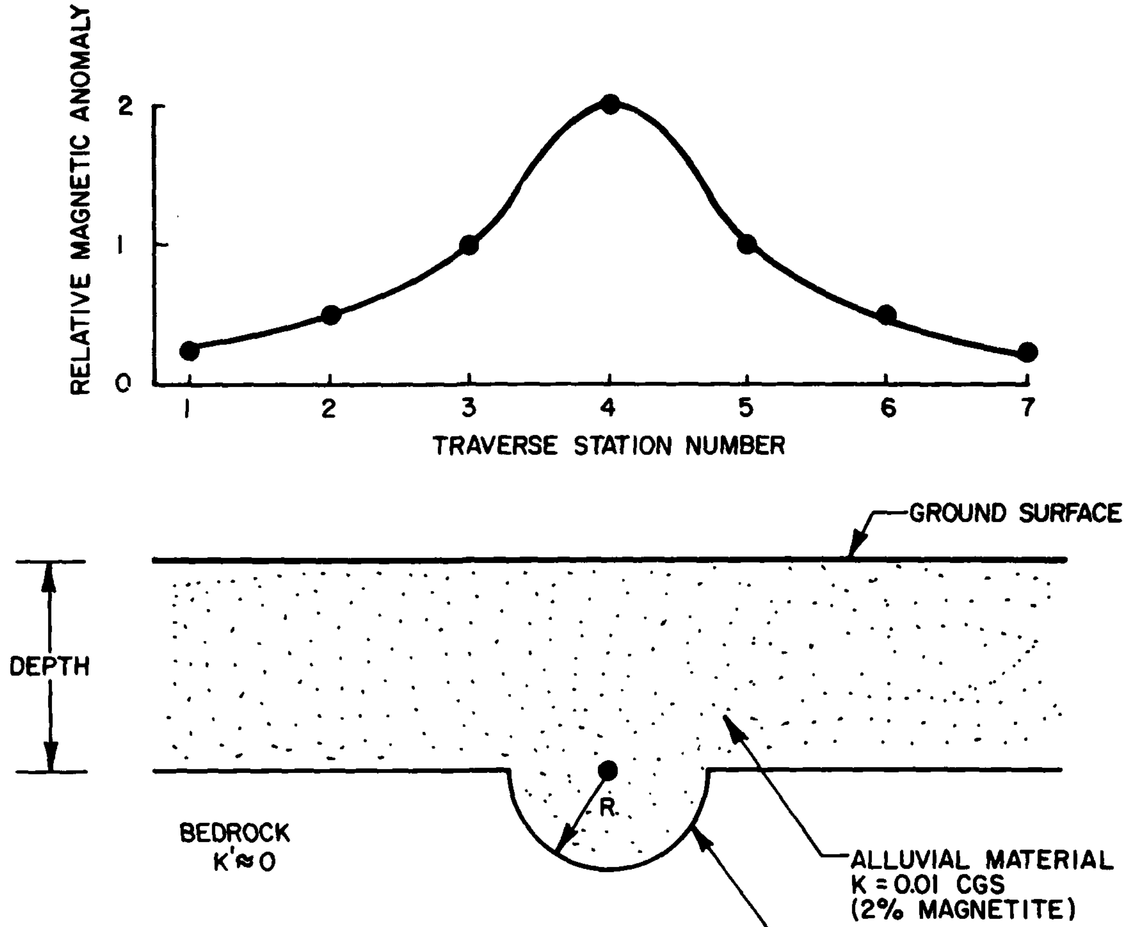
FIGURE 27

SCHEMATIC REPRESENTATION OF
MAGNETIC METHOD
TRAVERSE OVER BURIED FAULT

PREPARED FOR

U.S. ARMY TOXIC AND
HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA



NOTES:

1. AXIS OF BURIED CHANNEL IS PARALLEL TO MAGNETIC MERIDIAN
2. TRAVERSE PERPENDICULAR TO CHANNEL AXIS

FIGURE 28

SCHEMATIC REPRESENTATION OF MAGNETIC METHOD TRAVERSE OVER BURIED CHANNEL

PREPARED FOR

U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

DRAWN BY	MBM 6/24/80	CHECKED BY	RLC	7-22-80	DRAWING NUMBER	79-658-A20
		APPROVED BY	[illegible]	[illegible]		

DRAWN BY	MBM	6-26-80
CHECKED BY	[illegible]	[illegible]
APPROVED BY	[illegible]	[illegible]
DRAWING NUMBER	79-658-A26	

1. GEOLOGICAL-HYDROLOGICAL INFORMATION

GEOPHYSICAL METHODS		Stratigraphy			Geologic Structure						Aquifer Properties					External Factors	
		LITHOLOGY	LITHOLOGIC CORRELATION	SURFICIAL MATERIALS	FOLDING	FAULTING	FRACTURING	DISSOLUTION FEATURES	BURIED DRAINAGE AND TOPOGRAPHY	IGNEOUS FEATURES	POROSITY AND PERMEABILITY	POTENTIOMETRIC SURFACE	FLOW DIRECTION AND RATE	TEMPERATURE	WATER CHEMISTRY	2. APPLICATION NOTES	3. COST
SURFACE	SEISMIC REFRACTION	•	⊕	⊕	○	○	•	○	⊕	○		⊕	⊗			⊕	○
SURFACE	SEISMIC REFLECTION	•	⊕	⊕	⊕	⊕	•	○	⊕	○		⊕	⊗			○	⊕
SURFACE	RESISTIVITY	•	○	○	○	○	•	○	○	○	•	○	⊗		⊗		○
SURFACE	GRAVITY			○	○	○		⊕	○	○							○
SURFACE	MAGNETICS			○	○	○			○	⊕							○
SURFACE	RADAR	•	⊕	⊕	○	○	⊕	⊕	⊕	○		⊕				⊗	•
BOREHOLE LOGGING	SPONTANEOUS POTENTIAL	⊕	⊕	⊕	•	•			•				⊗			•	•
BOREHOLE LOGGING	RESISTANCE	⊕	⊕	⊕	•	•	⊕		•		•		⊗		⊗	•	•
BOREHOLE LOGGING	NATURAL GAMMA RADIATION	⊕	⊕	⊕	•	•			•		○		⊗		⊗		•
BOREHOLE LOGGING	GAMMA-GAMMA	○	○	⊕	•	•	○	○	•		⊕		⊗			•	•
BOREHOLE LOGGING	NEUTRON	○	○	⊕	•	•	○	○	•		⊕		⊗			•	•
BOREHOLE LOGGING	CALIPER	•					○	○									•
BOREHOLE LOGGING	FLUID MOVEMENT										•	•	⊗			•	•
BOREHOLE LOGGING	TEMPERATURE										•	•	⊗	⊕		•	•
BOREHOLE LOGGING	SONIC	○	○	○			○				⊕		⊗			•	•

1. GEOPHYSICAL METHOD EVALUATION

- ⊕ BEST INFORMATION
- ○ GOOD INFORMATION
- ⊗ PARTIAL INFORMATION
- • INFERRED INFORMATION
- (blank) NO INFORMATION

2. APPLICATION NOTES

- ⊕ TARGET DEPTH <100 FT
- ○ TARGET DEPTH 100-300 FT
- ⊗ PENETRATION <50 FT
- • REQUIRES OPEN FLUID-FILLED BOREHOLE
- ○ REQUIRES OPEN BOREHOLE
- • REQUIRES CALIPER LOG
- (blank) GENERALLY APPLICABLE

3. COST

- ⊕ HIGH
- ○ INTERMEDIATE
- • LOW

FIGURE 29

EVALUATION OF GEOPHYSICAL METHODS

PREPARED FOR

U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MARYLAND

D'APPOLONIA

APPENDIX A
GEOPHYSICAL EQUIPMENT SUPPLIERS

APPENDIX A
GEOPHYSICAL EQUIPMENT SUPPLIERS

Seismic Recorders

Bison Instruments, Inc.
5708 W. 36th Street
Minneapolis, MN 55416
612-926-1846

EG&G Geometrics
395 Java Drive
P.O. Box 497
Sunnyvale, CA 94086
408-734-4616

Electronic Systems Division/Geosource
P.O. Box 36827
Houston, TX 77036
713-777-1381

Input/Output, Inc.
8009 Harwin Drive
Houston, TX 77036
713-785-8660

Litton Resources Systems
3930 Westholme Drive
Houston, TX 77063
713-781-8871

Sercel, Inc.
4800 W. 34th Street
Suite D-10
Houston, TX 77092
713-688-9437

Texas Instruments, Inc.
P.O. Box 1443
M/S 6705
Houston, TX 77001
713-776-6521

APPENDIX A
(Continued)

Seismic Cables and Geophones

Electronic Systems Division/Geosource
P.O. Box 36827
Houston, TX 77036
713-777-1381

Applied Magnetics/Geo Space
5803 Glenmont
P.O. Box 36374
Houston, TX 77036
713-666-1611

Litton Resources Systems
3930 Westholme Drive
Houston, TX 77063
713-781-8371

Mark Products, Inc.
10507 Kinghurst Drive
Houston, TX 77099
713-498-0600

Vector Cable Company
555 Industrial Drive
Sugar Land, TX 77478
713-491-9196

Electrical Resistivity Instruments

James G. Biddle Company
Plymouth Meeting, PA 19462
215-646-9200

Bison Instruments, Inc.
5708 W. 36th Street
Minneapolis, MN 55416
612-926-1846

McPhar Geophysics
55 Tempo Avenue
Willowdale, Ontario
Canada M2H 2R9
416-497-1700

Phoenix Geophysics Limited
200 Yorkland Boulevard
Willowdale, Ontario
Canada M2J 1R6
416-493-6350

APPENDIX A
(Continued)

Scintrex
222 Snidercroft Road
Concord, Ontario
Canada L4K 1B5
416-669-2280

Gravimeters

LaCoste and Romberg, Inc.
6606 North Lamar
Austin, TX 78752
512-458-4205

Texas Instruments, Inc.
P.O. Box 1443
M/S 6705
Houston, TX 77001
713-776-6521

Magnetometers

EG&G Geometrics
395 Java Drive
P.O. Box 497
Sunnyvale, CA 94036
408-734-4616

Scintrex
222 Snidercroft Road
Concord, Ontario
Canada L4K 1B5
416-669-2280

Varian Canada
45 River Drive
Georgetown, Ontario
Canada L7G 2J4
416-457-4130

Subsurface Radar Systems

Geophysical Survey Systems, Inc.
15 Flagstone Drive
Hudson, NH 03051
603-889-4841

APPENDIX A
(Continued)

Borehole Logging Instruments

Comprobe, Inc.
9632 Crowley Road
Crowley, TX 76036
817-293-7333

Gearhart-Owen
P.O. Box 1936
Fort Worth, TX 76101
817-293-1300

McPhar Geophysics
55 Tempo Avenue
Willowdale, Ontario
Canada M2H 2R9
416-497-1700

Mount Sopris Instrument Company
P.O. Box 449
Delta, CO 81416
303-874-4852

APPENDIX B
BIBLIOGRAPHY

APPENDIX B

BIBLIOGRAPHY

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