COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

# STANDARD REFERENCES FOR MONITORING WELLS

## SECTION 8.1 INTRODUCTION

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# INTRODUCTION

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# 8.1 INTRODUCTION

A geophysical survey is an indirect method of determining the state of the subsurface in the survey area. By indirect, it is meant that the geophysical survey measures some physical property of the subsurface and uses the results to infer the material that caused it. Like a blind person trying to identify an object without the benefit of sight, the geophysicist cannot directly observe the subsurface but must instead rely on other, less direct methods of data collection to make his/her determination as to its state. Variations in the electrical field (applied and ambient), gravity and magnetic potentials, and seismic wave velocities, amplitudes and frequencies are systematically measured to infer the structure and composition of the subsurface soil, rocks and groundwater. Many geophysical methods produce results, which by themselves, cannot provide a definitive characterization of subsurface conditions; however, by using a combination of geophysical techniques (each of which measures a different physical property of the earth), the geophysicist can often eliminate incorrect possibilities to arrive at a correct interpretation.

The usefulness of geophysical techniques for site characterization and the evaluation of contaminated sites have been well established during the past two decades. Determination of depths to both bedrock and the water table are routinely performed. Geophysical techniques are also used with great success to locate buried metal objects (barrels, tanks, pipes, trucks), certain migrating contaminant plumes, debris-filled trenches, determine the integrity of "cut off" slurry trenches, and trace the migration of contaminants through fractured bedrock.

Geophysical investigations in environmental studies are best used to:

- Characterize geologic conditions
- Determine the source and extent of contamination problems
- Optimize test pit and boring locations

In many cases, the proper application of a geophysical investigation adds significant information and reduces the costs necessary to acquire the information required to determine effective site remediation and cleanup. The correlation of geophysical data methods, with borehole geologic and sampling data will usually provide the most meaningful results.

The physical characteristics of a site which geophysics can help determine include: characterization of the types of overburden materials and thickness, as well as soil classification and permeability characterization of the types of bedrock and depth to bedrock; characterization of water table elevations, hydraulic gradients, groundwater flow direction; and identification and characterization of all other physical site characteristics such as buried utility lines, sewers, and water mains.

In certain instances, geophysics can also be used to help identify the source and extent of release of contaminants by helping to establish: the source(s) of releases of oil or hazardous material; the horizontal and vertical extent and (relative) concentrations of certain oil or hazardous materials in some media; the estimated volume of contaminated soil and (ground) water; some of the existing and potential soil and groundwater pathways; and the existence of certain plume(s) of oil or hazardous materials (ie,

containing dissolved ionic contaminants) in the groundwater and the potential migration of the plume.

It should be noted that results of geophysical site investigations alone, rarely provide complete answers to the data requirements of an environmental investigation. An intrusive (e.g., soil boring) program is usually necessary to supplement a geophysical program. Results of the geophysical program, however, can minimize the number of borings necessary by optimizing their placement. In return, the borings provide important data that can be used to refine geophysical interpretations and results. Geophysical methods can provide accurate and inexpensive (in comparison with conventional intrusive techniques) measurements of average subsurface conditions over large areas, while borings provide detailed information for a limited area. A combined geophysical survey/boring program is therefore often the most cost-effective system for the complete analysis of site conditions.

## 8.1-1 Document Structure

This document has been divided into 3 sections and are as follows:

- o 8.I Introduction
- o 8.2 Synopsis of Geophysical Investigation Methods
- o 8.3 Borehole Geophysical Methods

Section 8.2 is a synopsis of the geophysical techniques (excluding marine geophysical methods), which are covered in greater detail in the MADEP publication: Standard References for Geophysical Investigations.

The entire Chapter 10 of the Standard References for Geophysical Investigations (WSC 94-311) has been included as Section 8.3 of this document. Chapter 10 was included in its entirety to increase the utility of this document as a reference document, since this chapter covers the suite of geophysical techniques that are commonly used in the investigation of subsurface conditions using soil borings and monitoring wells as measurement media.

## 8.1-2 Background Reference Materials

The reader is referred to the 1994 MADEP Publication: Standard References for Geophysical Investigations, WSC 94-311, for a more complete explanation of the methods briefly described in the following section. A comprehensive discussion of geophysical methods and their application to groundwater problems is included in the 1985 Electric Power Research Institute's Groundwater Manual for the Electric Utility Industry, Volume 3, Groundwater Investigation and Mitigation Techniques, Section 3.

Another useful document providing a broad non-technical overview is a compilation entitled "Geophysical Techniques for Sensing Buried Waste and Waste Migration," by Benson et al. (1987). Additional sources of information for specific methods are referenced in the discussions of each geophysical method. Texts that generally discuss the applicable geophysical techniques include Dobrin (1976), Telford et al. (1976, Mooney (1977), U.S. Army Corps of Engineers (1979), Grant and West (1965), and Griffiths and King (1981).

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# STANDARD REFERENCES FOR MONITORING WELLS

## SECTION 8.2 SYNOPSIS OF GEOPHYSICAL INVESTIGATION METHODS

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# 8.2 SYNOPSIS OF GEOPHYSICAL INVESTIGATION METHODS

The following are synopses of the geophysical methods described in the MADEP publication entitled: Standard References for Geophysical Investigations, WSC 94-311. This section and the accompanying Table 8.2-1 offer a brief overview of the various methods. The reader is encouraged to consult the aforementioned publication for a more detailed discussion of the methodologies.

## 8.2-1 SEISMIC METHODS

### 8.2-1.1 Operating Principle

The seismic methods of geophysical exploration are active (manmade energy sources are used) techniques used to characterize subsurface geology. These methods are an indirect means of determining the type and thicknesses of the various materials underlying a site. The general principle of seismic surveying is that dissimilar subsurface materials can be determined by the differences in their respective physical properties. Each material has a unique set of physical properties, which affect the amplitude and velocity of seismic waves traveling through them. Seismic surveys are conducted by inducing seismic energy into the subsurface and measuring the resultant velocity and amplitude of the seismic waves by detectors located on the ground surface. The resultant data can be used to infer the types of material present in the subsurface.

There are two basic methods of seismic surveying: reflection and refraction. The basic methodology for these seismic techniques consists of actively generating waves in the ground and detecting them at ground surface after they have either reflected or refracted off of subsurface layers. The energy (seismic waves) is generated by various means such as weight drops, explosives, mechanical sources, sledge hammers, etc.

Electromechanical transducers (which turn ground motion into electricity), called geophones, are used to detect the arrival time and amplitude of the induced ground motion. Arrays of geophones, called seismic spreads, are connected by electrically conductive cables to the seismograph, which processes and records the collected data. Recordings are made with either analog or digital seismographs. Preliminary data evaluation can usually be performed in the field with analog recordings. Playbacks of digital recordings are performed in the office for final data processing and report preparations.

Seismic refraction is by far the most prevalent method used in the shallow subsurface studies (less than 300 feet) employed during environmental investigations in Massachusetts and New England.

### 8.2-1.2 Applications

Seismic refraction surveys can be employed to: delineate the types and thicknesses of geologic materials; determine depth to groundwater; correlate stratigraphy across a study area (in conjunction with test pit and/or boring log data); detect sinkholes and cavities; detect bedrock fracture zones; determine extent of landfills; and determine extent of filled areas such as reclaimed quarries.

When a seismic refraction survey is performed prior to an intrusive field investigation, the data can be used to help determine the number, distribution, and depth of test pits, borings, and monitoring wells.

When a seismic refraction survey is performed after intrusive field investigation, the use of physical data to calibrate refraction data allows the interpolation of subsurface conditions across large areas with a great degree of confidence. Intrusive field data can also be used to refine the interpretations of seismic data, which had been collected prior to the start of the intrusive field program.

For larger investigations, especially those that require the delineation of bedrock competence and topography (DNAPL investigations), the combined use of seismic refraction with conventional investigative techniques can often result in a higher level of data volume and quality, while providing a considerable savings of time and money for the project.

### 8.2-1.3 Limitations

Seismic refraction does have limitations. The first is cost. Seismic refraction surveys cost between $2,000 and $4,000 per day. For smaller investigations, which might only require the installation of a few soil borings and water table monitoring wells, it probably would not prove cost effective to employ seismic refraction. Seismic refraction surveys by nature are sensitive to ground vibrations. Unfortunately, many human activities, including vehicle traffic, construction, and manufacturing, can create noise (unwanted ground vibrations) which can make collection of wanted data in a particular area difficult if not impossible. Seismic refraction surveying is seasonal. Frozen ground conditions make data collection difficult if not impossible. Interpretation of seismic refraction data is often non-unique. Some measured velocity values readily correlate with specific geologic materials such as massive, intact bedrock. Other velocity values, however, do not correspond to a unique interpretation of the nature of the materials surveyed and require correlation with soil borings or test pits for exact determination of the conditions and types of geologic layering.

## 8.2-2 RESISTIVITY METHOD

### 8.2-2-1 Operating Principle

Electrical resistivity surveying is an active geophysical technique that involves applying an electrical current to the earth and measuring the subsequent electrical response at the ground surface in order to determine physical properties of subsurface materials. The general principle of resistivity testing is that dissimilar subsurface materials can be identified by the differences in their respective electrical potentials. Differences in electrical potentials of materials are determined by the application of a known amount of electric current to these materials and the measurement of the induced voltage potentials. Ohm's law states that the voltage (V) of an electric circuit is equal to the electric current (I) times the resistivity (R) of the medium (V-IR). Resistivity surveys are conducted by: 1) applying a known amount of electric current (I) to the earth; 2) measuring the induced voltage (V) ; and, using these two measurements, 3) determining the resistivity (R) of the volume of earth being surveyed.

Resistivity methods usually require that both current inducing and measurement electrodes to be pushed or driven into the ground. With connecting wires from the instruments to the electrodes, electrical current is introduced into the ground using the current electrodes and resistivity measurements are performed using different measurement electrode configurations and spacings. There are a number of standardized testing procedures, some of which are described in detail in this section.

Resistivity surveys identify geoelectric layers rather than geologic ones. A geoelectric layer is a layer that exhibits a similar electric resistivity response. A geoelectric layer can, but does not always, correspond to a geologic one. For example, an isotropic homogeneous sand, which is saturated with a fluid exhibiting a single conductivity response, will appear to be a single geoelectric layer. The same sand, if filled with fluid layers containing different conductivities, (i.e., salinities) will appear to be more than one geoelectric layer. The interpretation of resistivity data is therefore best made in conjunction with other geophysical techniques (i.e., seismic refraction) or conventional subsurface investigations (i.e., soil borings).

### 8.2-2.2 Applications

Historically, resistivity surveys have been used for a number of geologic mapping objectives, including groundwater detection, sand and gravel mapping, bedrock depth determination, and other classic geologic exploration exercises. At present, these methods are commonly used to evaluate subsurface conditions as they relate to hazardous waste issues.

Resistivity measurements are commonly used to delineate either changes in resistivity with depth or lateral variations in resistivity. These applications are known respectively as:

- Vertical electrical soundings (VES)
- Horizontal profiling

VES surveys, which determine vertical resistivity changes, employ variable electrode spacings. VES surveys are used to identify geoelectrical layering in soil and rock. These data are often used to identify: the groundwater table; clay layers; the bedrock surface; and to select optimum electrode spacings for horizontal profiling surveys.

For horizontal profiling, which determines lateral resistivity changes at a fixed depth of investigation, the current measurement electrode spacings are kept constant. Horizontal profiling is used to identify lateral resistivity variations in a survey area. Horizontal profiling can be used to detect conductive groundwater plumes (ie landfill leachate), landfill limits, geologic contacts, and sink holes (often present in limestone lithology).

Electromagnetic induction (EM) survey methods have generally supplanted resistivity surveys as the method of choice for shallow horizontal resistivity profiling because of EM's ease of use and increased data collection speed. Resistivity methods, however, provide better vertical resolution and are therefore superior to most EM methods for vertical resistivity profiling and for deeper horizontal resistivity profiling. Resistivity may

also be applicable at sites where interferences from surface metal objects (e.g., fences) and/or power lines make the use of EM surveys impractical.

### 8-2-2.3 Limitations

Resistivity surveying methods can be carried out only in media that are neither extraordinarily conductive nor resistive. Cultural interference (from powerlines, pipelines, and metal fences) is another serious limitation of resistivity surveying. Thin layers, or targets of limited lateral extent, may be undetectable because the measured potentials integrate the effects of a large volume of material. Because this technique measures geoelectric layers rather than geologic ones, the solution is non-unique. Therefore, in the absence of correlating data (e.g. boring logs) incorrect stratigraphic conclusions can be drawn. Differentiation between highly conductive materials (i.e., clay or salt water versus contamination plumes) may not be possible. A resistivity horizontal profiling survey is more labor intensive and time consuming than an EM survey.

## 8.2-3 SELF-POTENTIAL METHOD

### 8-2-3. 1 Operating Principle

The self-potential (SP) survey method is a passive geophysical technique that measures extremely small, naturally occurring voltage variations in the earth. The technique is based on the observation that when certain materials are in contact with either a different material (e.g., buried iron next to buried copper) or a localized change in the condition of the same material (e.g., interface of saturated and unsaturated condition), an electrical current is created. This current is readily detectable with inexpensive, portable voltage measuring instrumentation.

The technique is simple to operate, consisting of a series of measurements of electric potential (voltage) across two electrodes that are in contact with the ground and spaced at varying distances.

### 8.2-3.2 Applications

The most relevant application of this method to environmental investigations is the tracing of shallow leachate seepage zones when such zones are known to exist.

### 8.2-3.3 Limitations

Given the small size of the naturally occurring voltage differentials (measured in thousandths of volts), the SP method is extremely sensitive to man-made electrical interferences.

Although the technique is receiving increased attention for groundwater contamination assessment, the reliability and applicability of this methodology are inconclusive at this time.

## 8.2-4 ELECTROMAGNETIC INDUCTION METHOD

### 8.2-4.1 Overview

Electromagnetic Induction (EM) methods are non-destructive geophysical techniques for measuring the apparent conductivity of subsurface materials. As with resistivity surveys, the general principal of EM surveys is that dissimilar subsurface materials can be identified by the differences in their respective electrical responses to the introduction of an electrical stimulus. There are two basic types of EM surveys, terrain conductivity and Very Long Frequency (VLF). Each survey method is explained below. Terrain conductivity, given its broader applicability and usage in environmental studies, is explained in greater detail.

#### 8-2-4.1.1 Terrain Conductivity - Operating Principle

Terrain conductivity surveys employ the same operating principals as conventional resistivity surveys (Section 4), but differ from a resistivity survey in the manner with which an electrical stimulus is introduced to the earth. The terrain conductivity method of EM surveying is an active geophysical technique that involves "inducing" an electric current in the subsurface and measuring the subsequent electrical response at the ground surface to characterize the physical properties of subsurface materials. In contrast, resistivity surveys directly apply an electrical current to the ground using current electrodes and measure the resultant voltage potential using measurement electrodes. The resistivity method requires that electrodes are driven into the ground and connected with wires at each survey point. Terrain conductivity surveys employ a transmitting coil, which is not directly coupled to the earth, to remotely induce a voltage potential in the ground and a remote receiving coil to measure a secondary current created by the effect of the induced voltage in a conductive medium.

The name "terrain conductivity" stems from the different manner (with respect to resistivity surveys) with which terrain conductivity measures the electrical properties of the materials investigated. The resistivity method directly applies a current (I) to the ground, measures the resultant voltage (V), and calculates the resistivity (R) of the material measured (given that V=IR). Terrain conductivity surveys use a known current (I), passed through a transmitting coil to create an electromagnetic field which induces a voltage (V) in the ground. If the ground material is conductive, then a secondary (induced) electromagnetic field will be created. The terrain conductivity receiving coil measures the currents (I) created by the primary (transmitted) electromagnetic field and the secondary (induced) electromagnetic field. The ratio of these two currents is proportional to the conductivity (which is the inverse of resistivity, R) of the material being surveyed. (A more complete explanation of the inductive measurement theory is presented below in the Introduction.)

Terrain conductivity surveys identify geoelectric layers rather than geologic ones. A geoelectric layer is a layer that exhibits a similar electric resistivity response. A geoelectric layer can, but does not always, correspond to a geologic one. For example, an isotropic homogeneous sand, which is saturated with a fluid exhibiting a single conductivity response, will appear to be a single geoelectric layer. The same sand, if filled with fluid layers containing different conductivities, (i.e. salinities) will appear to be more than one geoelectric layer. The interpretation of terrain conductivity data is therefore best made in conjunction with other geophysical techniques (i.e., seismic refraction) or conventional subsurface investigations (i.e., soil borings).

### 8-2-4.1.2 <u>Terrain Conductivity Applications</u>

Common applications for terrain conductivity surveys include: conductive contaminant plume mapping; locating buried metallic objects and identifying landfill boundaries.

EM measurements are commonly used to delineate either changes in conductivity with depth or lateral variations in resistivity. These applications are known respectively as:

- o Vertical electrical soundings (VES)
- o Horizontal profiling

VES surveys, which determine vertical conductivity changes, are best conducted with instruments that allow variable coil spacings (e.g., Geonics EM 34). A limited (by depth of investigation) VES survey can also be conducted using a fixed coil spacing instrument (e.g., Geonics EM-31) by altering the orientation (turning on its side) of the measuring equipment. VES surveys are used to identify geoelectrical layering in soil and rock. These data are often used to identify the groundwater table, clay layers, and the bedrock surface.

For horizontal profiling, which determines lateral resistivity changes at a fixed depth of investigation, the current measurement coil spacings are kept constant. A fixed coil spacing instrument can be operated by one person and is well suited for horizontal profiling. Horizontal profiling is used to identify lateral resistivity variations in a survey area. Horizontal profiling can be used to detect conductive groundwater plumes, landfill limits, geologic contacts, and sink holes (often present in limestone lithology).

As with other geophysical techniques, the effectiveness of terrain conductivity interpretation is increased by correlation with other geophysical techniques. For example, the combination of terrain conductivity and magnetometry surveys (Section 8) is ideal for a combination of location of buried drums, while the combined use of terrain conductivity and seismic surveys (Section 3) will effectively differentiate between conductive contaminant plumes and landfill boundaries.

The terrain conductivity survey method is non intrusive and can be conducted at a more rapid pace (and less expensively) than conventional resistivity surveys. The portable instrument requires only a one or two person field party. Measured conductivity values can be observed during data acquisition, and yield immediate preliminary information for an experienced operator. For this reason, terrain conductivity survey methods have generally supplemented resistivity surveys as the method of choice for shallow horizontal profiling of the subsurface.

8-2-4.1.3 Terrain Conductivity Limitations

Limitations of the terrain conductivity method include the following. The instrument is effective for only a limited dynamic range (1 to 1,0-00 millimho/meter) of soil and conductivities. Terrain conductivity is sensitive to the presence of other EM fields, such as those associated with power lines and/or the presence of highly conductive objects, such as metal fences. Terrain conductivity has less vertical resolution than conventional resistivity surveys. The limited strength of the terrain conductivity transmitter signal, due to battery and coil size constraints (a compromise to portability), limits the instrument penetration to shallower depths that conventional resistivity surveys. Even simple stratigraphic layering cannot be distinguished without complex application and interpretation.

8.2-4.1.4 VLF - Operating Principle

The VLF survey method is an EM prospecting technique based on the principle of radio wave transmission and reception. The VLF method does not employ an operator induced electromagnetic field, but instead utilizes low frequency transmissions from a submarine communications network established and maintained by the U.S. Navy as a power source.

VLF signals are transmitted by vertical radio antennae several hundred feet high with signal outputs ranging from 300 to 1,000 kWatts. The effective range of these transmitters as a VLF survey power source is on the order of thousands of miles. (It should be noted that a site must be a minimum of 50 miles from a transmitter for this technique to be effective.) A worldwide network of VLF stations has been established in such varied locations as Bordeaux. France (15.1 kHz), Moscow, USSR (17.1 kHz), and Cutler, Maine (24.0 kHz).

The field emitted by VLF antennae is horizontal, and its magnetic lines comprise concentric rings that "ripple" out from the transmitter. When this magnetic field encounters an electrically conductive structure on the surface or underground, weak secondary currents are generated around the structure. These currents create a secondary magnetic field.

VLF can detect long conductors such as electric cables, pipelines, and certain bedrock fractures. In order for the VLF method to be effective in detecting underground geologic structures, the structure must have: 1) the direction of its long axis within 30 degrees relative to a line tangent to the concentric rings that "ripple" from the transmitter (to initiate induction); 2) minimum dimensions of approximately 50 meters in length, 10 meters in depth, and about one meter in thickness; 3) a dip angle not less than 30 degrees from horizontal; and 4) higher electrical conductivity than the surrounding material.

Unlike terrain conductivity, the depth of VLF penetration is not a function of coil spacing, but rather the resistivity of the materials surveyed. Depth of penetration of VLF signals is directly proportional to (varies by approximately four times the square root of) the material's resistivity. For example, VLF signals propagating through granite (a highly resistive material) can penetrate to depths greater than 300 meters. However, a material such as salt water may limit depth of penetration to one to five meters.

8.2-4.1.5 VLF - Applications

The VLF receiver measures the current density due to the primary (transmitted) and secondary (induced) magnetic fields. From these measurements, structures such as water-saturated fracture zones, metallic ore bodies, mineralized zones, and long conductors such as electric cables or pipelines may be detected. The ability to detect water-filled bedrock fracture zones makes this type of survey method useful for bedrock water supply development and for site investigations that involve bedrock contamination.

8.2-4.1.6 VLF – Disadvantages

The VLF survey operator has no control over power source - VLF transmitters are sometimes turned off for maintenance. Even when the transmitters are operating, the orientation (both strike and dip) of the object surveyed to the power source (which the operator also has no control over) will affect the success of the survey.

VLF data interpretation is difficult - VLF data does not provide data that can be directly related to subsurface conductivity.  Interpretation is more subjective and therefore relies heavily on operator experience.

VLF survey limitations are:  susceptibility to surface anthropogenic interferences (e.g., fences, automobiles, power lines).   The effective depth of VLF investigation is extremely reduced in areas that contain shallow material of high conductivity.

## 8.2-5 GROUND PENETRATING RADAR (GPR)

### 8.2-5.1 Operating Principle

Ground penetrating radar  (GPR) is an active geophysical system that transmits high frequency (80-1,000 MHz) electromagnetic waves (radar energy) into the ground and records the energy reflected back to the surface.  It is a reflection technique similar to the single-trace seismic reflection method commonly used in marine subbottom profiling. The two techniques differ in that the seismic method uses audio frequency sound waves, while the radar method uses electromagnetic waves.

GPR is a continuous profiling method that transmits radar energy into the ground and records the radar energy reflected back by subsurface objects or layers.  GPR is useful when a rapid survey with detailed vertical and horizontal control is desired.  A GPR survey produces a graphic cross-sectional view of earth stratigraphy and targets (i.e., drums, pipelines, utilities, boulders, etc.) below the ground surface.   Under optimum conditions, this method can be effective to depths of 70 feet (using commercially available equipment), although depth penetration is core often limited to the range of ten feet or less below ground surface.

### 8.2-5.2 Applications

GPR has been used to locate: underground storage tanks; underground pipes; buried drums; buried foundations; voids in rock and concrete; buried archaeological artifacts, excavations, filled pits and lagoons, and numerous other site specific applications and lithologic contacts.  GPR can also be used to determine: stratigraphy; depth to the water table; and depth to bedrock.  GPR has also been successfully used to delineate the lateral extent of contaminant plumes.

### 8.2-5.3 GPR Limitations

The limitations of GPR include the following.  GPR survey lines must be cleared to ground level (e.g., may require cutting of brush and/or removal of obstructions).  The depth of GPR signal penetration is highly dependent on the materials present beneath the survey area (signal penetration in a saturated clay layer may be only a few inches). GPR interpretations are subjective, often requiring data corroboration using other geophysical methods and/or verification with borings or test pits.

To maximize resolution and minimize scattering losses, survey lines must be as smooth as possible to prevent bouncing and jarring the radar antenna. Survey lines cleared of debris also allow the antenna to be pulled at an even, continuous pace, permitting the easy determination of horizontal scale.

The depth of GPR investigation at a site is limited by soil type and/or the presence of high "loss" materials. Penetration of up to 75 feet has been reported for water-saturated, clean sands in a Massachusetts glacial delta using a commercial antenna. Signal penetration in saturated clays, on the other hand, is on the order of magnitude of only a few inches. In New England, the presence of glacial tills, and lacustrine and marine clays limit the depth of penetration. Delineation of materials beneath a conductive layer may also not be possible.

## 8.2-6 MAGNETIC METHODS

### 8.2-6.1 Overview

Magnetic surveying is a passive geophysical technique that measures the strength of the total magnetic field at any given point on the earth. The purpose of the magnetic survey in environmental investigations is to detect magnetic anomalies (variations in the expected field), which can be attributed to the presence of buried iron or steel objects. Magnetic surveys can also be used to locate bedrock fracture zones due to the fact that the hematite in fracture zones weathers to limonite, causing a change in magnetic signature.

Magnetism can be "induced" into materials that have a high magnetic susceptibility. Magnetic susceptibility is defined as the ability of a material to acquire a magnetization in the presence of a magnetic field (in this case the Earth's). The magnetic field induced is dependent upon the geometry, orientation, and magnetic properties of body, and the direction and intensity of the Earth's field. In order to recognize a magnetic anomaly, it must be several times larger than the background noise level along that profile.

Iron and steel (ferrous) objects have a high susceptibility and are therefore compatible with detection by magnetic survey methods. Buried ferrous metal objects such as steel drums or tanks cause local variations or anomalies in the earth's magnetic field that can be detected by a magnetometer. The size (amplitude) of this perturbation caused by the object is related to a number of factors such as the size of, distance to, and intensity of magnetization of the buried object.

Other non-ferrous metals, such as brass, copper, and aluminum, have low magnetic susceptibility and, therefore, will not be detected by a magnetic survey.

An instrument called a magnetometer is used in the performance of magnetic surveys. The magnetometer is used to determine the direction, gradient, and intensity of the total magnetic field. Various forms of magnetometers are used in land, airborne and marine type operations. The land instruments are lightweight and portable, and measurements are readily accomplished by a one- or two-person field party.

#### 8-2-6.2 Applications

Magnetic surveys, performed as part of environmental investigations, are nearly always used to detect induced magnetism in iron and steel objects such as buried drums, pipelines, and underground storage tanks (USTs). The results of magnetic surveying can be used to direct excavation activities of buried drums and USTs.

The results can also be used to direct the placement of both upgradient and downgradient monitoring wells (in conjunction with data regarding the known or inferred direction of groundwater flow) to facilitate the assessment of potential releases of contaminants from these objects on water quality.

Magnetic surveys utilizing portable field magnetometers are relatively easy to perform and are usually the easiest to interpret with regard to siting drilling locations. Magnetic surveys, however, are susceptible to interferences from manmade structures such as utilities, buildings, and fences.

#### 8-2-6.3 Limitations

Limitations of the magnetic survey method include the following. A magnetometer is susceptible to the interferences associated with the presence of other magnetic fields, such as those associated with power lines. Also, since the strength of the induced magnetic field is a function of the susceptibility of the material surveyed, the presence of highly susceptible objects, such as metal fences, also creates unwanted interferences. An anomaly of interest must be several times larger than the background noise (e.g., metal fences, remnant magnetism) to be detected. Interpretation is non-unique given the inherent complexity of dipole behavior and the fact that a number of different types and configurations of sources can cause the same anomaly.

## 8.2-7 GRAVITY METHOD

### 8.2-7.1 Overview

The gravity survey method is a passive geophysical technique that measures extremely small variations in the earth's gravitational field using a highly sensitive instrument. In gravity exploration the variation in density of the surveyed area is the only significant factor. Lateral variations in the distribution of mass in the earth's crust produce distortions or differences in the gravitational field. Tectonics, faulting, erosion, deposition, and other geologic movement involving rock often result in lateral density variations in the subsurface rocks. Measured gravitational differences are interpreted in terms of probable subsurface mass distributions, which are inferred from surface and near surface geologic conditions.

8.2-7.2 Applications

The "microgravity" survey method produces data that allows more detailed or higher resolution interpretation than ordinary gravimetric measurements taken on a regional scale.

Microgravity measurements can be used to detect the following conditions: joint and fracture zones; dissolutions; collapses: cavities; buried river channels; and fault scarps. The detailed resolution of the microgravity survey is more suited to the limited areal surveys associated with environmental investigations and may be useful to characterize sites prior to drilling test wells.

The advantages of a gravity survey are that field work can be carried out by one to three persons in any accessible area, including highly developed urban and industrialized sites, over pavements, fills, landfills, on lake ice, and inside buildings. Instrumentation is portable; the work can be silent and produce no visible disturbance to an environment other than stakes or other station markings. The method lends itself well to areal coverage; contour maps of bedrock or other features have obvious advantages over information at points or along profiles.

8.2-7.3 Limitations

The sensitivity of the "Microgravity" instrumentation creates logistical problems including: a greater need for more detailed elevation data; a "quiet" site with regard to background vibrations that might affect the microgravimeter; as well as some inherent stability problems for the instrument itself.

The other limitations of a gravity survey are that: applications are limited to mapping of density-dependent interfaces; accurate station locations and elevations are necessary; calibration with geological "knowns" such as outcrops, borings, or seismic profiles is necessary for quantitative work; and excessive topography, access problems, and certain bedrock complexities may seriously limit the accuracy of data interpretation.

# SECTION 8.2
# SYNOPSIS OF GEOPHYSICAL INVESTIGATION METHODS

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COMPARISON OF GEOPHYSICAL METHODS FOR HAZARDOUS WASTE APPLICATION

| Geophysical Method | General Applications | Advantages | Limitations | Relative Cost | Depth of Investigation |
|---|---|---|---|---|---|
| Seismic Refraction | Determine the depths to bedrock, water table, glacial tills. Identify zones of fractured weathered bedrock. Accuracy ±10% of depth to interface. | Accurately identifies soil and rock layering as reflected by contrasts in seismic compressional wave velocity values. | Does not detect contaminants in ground water. Sensitive to vibration, construction activities and electrical noise. Frozen ground precludes use of geophones and shot points. | Moderate to high | Shallow (0-10m) and deep (10-100+m) |
| Electrical Resistivity | Determine depth to water table, clays, bedrock, etc. Accuracy ±25% of total depth. Identify highly conductive or resistive contamination plumes. | Equipment is inexpensive, easy to operate. Rapid method for determining ground resistivity layering. | Interpretation is not unique. sensitive to fences, power lines, pipes, and other metal objects. Dipping strata complicates interpretation. | Moderate | Shallow (0-10m) and deep (10-100+m) |
| Self-Potential | Identify ground water flow and area of contamination. | Equipment is inexpensive and easy to operate. | Highly qualitative interpretation. Susceptible to interference due to lithological and vegetation changes. | Inexpensive | Shallow (0-20m) |
| Electromagnetic Induction | Plume detection and tracing. Depths to water table, bedrock, clays, etc. Accuracy approximately ±25%. | Walk-over method of determining ground conductivity | Lacks the vertical resolution and depth penetration of resistivity. | Moderate | Shallow (0-5m) and deep (5-60m) |
| Ground Penetrating Radar | Buried metal detection and general identification (drum, tank, debris, etc.). Accuracy ±20%. Filled trench identification. | Tow-along method, equipment is commercially available, easy to operate, high resolution. | Depth of penetration limited by conductivity of material. Sensitive to shallow lithologic changes. Highly qualitative interpertation. | Moderate | Shallow (0-10m) |
| Magnetics | Buried (ferrous) detection. | Walk-over method, equipment easy to operate, commercially available. Rapid method for metal (ferrous) detection. | Sensitive to metal fences, power lines, pipes, and cultural metal ferrous objects. | Inexpensive | Shallow (0-10m) and deep (10-100+m) |
| Gravity | Detection of fault scarps, buried river channels, cavities, and collapse or fill areas. | Field work conducted by one person, data can be acquired in highly developed urban areas, equipment is portable. | Interpretations not unique. Geologic data necessary for interpretation, highly trained experienced field personnel, instrument and survey support expensive. | High | Deep (10-100+m) |
| Borehole | Determine stratigraphy, fracture zones, porosity, permeability. | Known depth of measurement. Little data reduction needed. Rapid, most equipment easy to operate. Very good vertical resolution. | Limited lateral extent. Radioactive tools need special licensing. Borehole construction may limit techniques. | Low to Moderate | Not Applicable |

*All methods can be operated in a non-intrusive manner.

**Table 8.2-1**

**Comparison of Geophysical Methods for Hazardous Waste Applications**

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

# STANDARD REFERENCES FOR MONITORING WELLS

## SECTION 8.3 BOREHOLE GEOPHYSICAL METHODS

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# 8.3 BOREHOLE GEOPHYSICAL METHODS

## 8.3-1. OVERVIEW

Borehole geophysical surveys are designed to provide a continuous vertical profile of the soil, rock and water conditions immediately adjacent to the borehole. Logging is accomplished by lowering probes into the borehole to measure the electrical, acoustical, or radioactive properties of the materials surrounding a borehole. The surveys are non-destructive and can often be run in existing boreholes, monitoring wells, and water wells with no modifications.

Borehole geophysical methods are used primarily to characterize rocks, correlate overburden or rock units, and determine physical and hydrologic properties. Table 8.3-1 provides a listing of the applications for the methods described in this section. Specific applications include determining porosity, locating clay layers, determining water quality, estimating permeability, and finding fracture zones and zones of water loss or gain. More detailed discussion of the theory and interpretation of the use of borehole geophysical methods in groundwater investigations is presented by Keys and MacCary (1971), Kwader (1982), and Collier and Alger (1988).

The primary advantage of borehole methods is that they provide an unbiased, high density of measurements of soil, rock and water properties at precise depths. Borehole methods are fast and generally unaffected by surface features such as power lines, buildings and railroad tracks. Little data reduction is necessary before most logs can be interpreted; often, preliminary interpretations can be made as they are being run. Borehole logging is non-destructive and can often be run with no modifications in existing cased or uncased boreholes and in the screened and unscreened intervals of monitoring wells.

Some borehole methods, such as the temperature log (a log is the printed display of the parameter being measured vs. the depth where the measurement is taken), the caliper log, and the flowmeter log are relatively simple to operate and the data recordings are easy to interpret.

Other methods, such as logging with an active nuclear source and resistivity logging are much more complex for operation and/or for data interpretation. Borehole geophysical logging using such methods is a technical specialty that requires complex electronic equipment to be operated according to exact design specifications. Since no two boreholes exhibit the same geophysical response, and as responses can not be quantitatively validated during logging, the quality of a log depends strongly on the operator's experience and judgment.

The radius of investigation for most probes is commonly less than one foot. Depending on the permeability of the formation and the drilling techniques applied, the condition of materials investigated may be altered by the drilling method. The borehole surveys may therefore provide only limited representation of true formation properties.

Borehole geophysical methods may not be cost-effective for typical environmental investigations in Massachusetts, where shallow overburden wells dominate. Borehole geophysical methods are best suited for deep bedrock wells, where the information gathered will be most useful. When natural in-situ conditions are present, and several deep boreholes are logged and correlated, often very large areas can be geologically characterized with a minimum of time and cost.

## 8.3-2 INTRODUCTION

Borehole geophysical techniques (also called logging) are a group of active and passive geophysical methods used to provide detailed physical properties of soil, rock, and water. The term "active" implies subjecting the area around and in the borehole to a stress (either electric, thermal, acoustic, etc.) in which a response can be measured (formation-penetrating methods), while "passive" involves measuring only naturally occurring conditions (non-penetrating methods).

Table 8.3-1 shows the array of available borehole techniques keyed to types of subsurface information desired and limitations posed by borehole conditions. Many of the techniques are based on counterpart surface geophysical methods, adapted to the borehole environment. Typically, these adaptations include the reduction of equipment size (the probes for most techniques will fit inside a 2-inch diameter hole), reduction and standardization of the fixed source to receiver spacing (and sometimes a corresponding reduction in the depth of investigation), protection of probes from pressure and temperature effects, and interpretation of data with respect to vertical rather than horizontal changes.

Borehole geophysical logging methods to be discussed are:

- Downhole television camera
- Caliper
- Temperature
- Electrical methods (Single-point-resistance, Normal resistivity, SP, Fluid resistivity, Electromagnetic/Induction)
- Flowmeter
- Acoustic methods (Velocity. Waveform, Acoustic televiewer)
- Nuclear methods (Natural gamma. Neutron, Gamma-gamma)
- Vertical seismic profiling

Use of more than one logging technique is generally necessary to determine soil and water properties adjacent to the borehole. Because each probe has a different response, these logs are interpreted by cross-comparisons to determine specific characteristics of interest. For example, caliper, single-point resistance, acoustic and thermal logs may be run as a suite to identify fracture zones in rock.

### 8.3-2.1 Equipment

Figure 8.3-1 shows a typical geophysical logging set up. The surface and downhole equipment used in borehole geophysical surveys is connected by the logging cable. The cable provides transmission of electrical power to the downhole probe and a return path for signals generated in the probe. Cables are usually one- or four-conductor, insulated, wire-wrapped (shielded), and chemically stable.

Equipment on the ground surface at the hole includes:

- Power supply (AC or DC)
- Instrument and probe controls (on/off, open/close caliper, scale setting)
- Winch and depth counter
- Signal receiving and conditioning circuits
- Recorder and/or portable computer
- Well head cable tripod or sheave

Downhole equipment includes the measuring probe, which is connected to the cable by a threaded water-tight coupling. Two or more logging methods can occasionally be performed with the same probe (e.g., SP and normal resistivity). Probes can be changed quickly so that a number of logs can be performed at one borehole with minimal down-time.

Some logging systems are equipped with digital data acquisition systems connected to portable personal computers. Data are sampled at regular intervals (usually six inches or one foot) and stored on magnetic tape or disk. This setup is highly desirable because digital data can be manipulated easily for calculations or presentation. Although tedious, analog data can be digitized at the office using available digitizing hardware and software.

### 8.3-2.2 Field Procedures

Field procedures for logging generally consist of six steps, as outlined below:

- Equipment setup and assembly
- Verification (or calibration) of probe functions at surface
- Downhole run and total depth determination

- o Main run (uphole as appropriate)
- o Repeat run (if verification of anomalies warrants)
- o After-run calibration

Calibration measures the probe's response to a known standard. Checking the probe response against a known standard before and after a borehole survey ensures that the probe is operating and measuring correctly. After the probe response is calibrated, it is placed at the top of the borehole and the reference point of the probe is positioned at a reference elevation (usually ground surface or top of casing). The depth counter is then set to either zero or ground zero and the probe is lowered to the bottom of the bole. This process is known as depth calibration.

It is customary practice to make a record of log response when lowering most probes to the bottom, although a formal depth-registered log is normally not necessary or practical. However, it is important that the downhole run document the extremes in order to choose the optimal instrument settings for the uphole run, during which a formal depth-registered log is made. (Uphole and downhole recorded logs will not be identical for most geophysical probes because of probe design and delayed response in the direction of probe movement.)

The temperature and fluid resistivity probes are run from top to bottom so that the water in the borehole is not mixed or displaced appreciably by moving the probe. All other geophysical surveys are recorded during probe ascent in the borehole so that constant logging speed and cable tension can be maintained.

Once the probe reaches the bottom of the hole, the optimal instrument settings are activated, and the uphole log is made. The footage dial reading on the winch is recorded on the field chart (analog recorder paper) at the exact point of pen stoppage at the top of the hole to verify depth calibration. Agreement between pen and dial should be within 0.5 foot.

Analog recordings are usually made at a vertical (depth) scale of one inch equals 10 feet; however, a different scale may be used to show more detail, or less detail, if a digital recording is made simultaneously. If the data are not digitally recorded, it is very important to select instrument settings that will result in nearly full chart-width pen fluctuation without reaching the margins of the chart paper. Generally, one set of instrument settings can be selected to achieve this result for the entire depth logged. All setting changes must be accurately documented on the chart (beside the change or in the header), if the log appears uncharacteristic or suspect, the probe calibration is checked. A second complete or partial log should be made if any doubts persist concerning instrument/probe response.

When contaminants are (or may be) present, the cable must be decontaminated as it is removed from the well. When multiple logs are to be run in shallow wells, it is desirable and usually possible to set up the logger at a distance adequate to prevent the wet cable from wrapping on the spool between runs. In this case, cable decontamination is needed only after the last probe is extracted. A preliminary rinse should be performed while the cable is over the borehole. One method for decontamination is to set up stations along the cable for washing and rinsing (for a more thorough discussion of decontamination procedures, see Sections 3.3 and 6.5) as shown in Figure 8.3-1. Another method is to construct a jig to hold sponges and fluids for washing, or properly-attired field personnel can perform decontamination using spray bottles and sponges.

Downhole probes that will be in direct contact with potentially contaminated soil and water must be decontaminated between logging runs. Probes should also be thoroughly decontaminated, taking care to remove all contaminants from moving parts (e.g.. hinges on caliper arms). Without decontamination, contaminants can be transferred onto the spool, contaminating the remainder of the cable or other boreholes.

Borehole methods that employ the use of radioactive sources should only be used in boreholes that are either cased or completed in competent bedrock. Operators of probes with radioactive sources must be certified and licensed by the United States Nuclear Regulatory Commission.

## 8.3-3 PASSIVE BOREHOLE METHODS (NON-PENETRATING)

### 8.3-3.1 Borehole Television Camera Surveys

Although the borehole television camera is not technically a geophysical logging method, it is discussed in this section because of its usefulness in the investigation of open hole bedrock wells and the evaluation of casing integrity.

#### 8.3-3.1.1 Principles of Operation

A borehole television camera survey can be made of any well or boring of appropriate diameter that is filled with clear water or air. The camera, similar to a home video camera, is enclosed in a watertight, pressure-safe housing that contains a light source. A coaxial cable is attached to the camera and the light source. The cable allows the transmission of power to the downhole instruments and the transmission of video signal from the camera. Video signals sent up the coaxial cable are viewed on a television monitor at the surface. The survey is also recorded on videotape to permit future analysis.

#### 8.3-3.1.2 Applications

Borehole camera surveys are generally used for inspection of cased borehole sections. Camera surveys can reveal mechanical defects in casing such as:

- Cracks, holes and splits
- Oxidation (rust) of steel casing
- Scaling by contaminants
- Plugging of slots or screen

In an open hole, the borehole camera can assist in determining rock type, layering, the pretence of fracturing, and hole integrity.

### 8.3-3.1.3 Equipment

A number of borehole camera systems are commercially available. These systems are generally composed of a downhole camera with light source, hand or light duty electric winch with coaxial cable, television monitor, camera control panel, and video tape recorder. Manufacturers' specifications and options, which may vary considerably among systems include:

- Probe size (11/2-inch to 6-inch diameters are available)
- Black-and-white or color recording capabilities
- Size and quality of television monitor
- Camera lens quality (amount of distortion)
- Uphole remote controls (amount of light, focus, and aperture setting)
- Text and depth printed on log (recording)

Borehole cameras need a special coaxial cable for transmission of video data.

### 8.3-3.1.4 Field Procedures

Camera systems that do not have remote controls for adjustment of focus, amount of light or aperture must be lowered into the bole, checked for picture quality then removed and adjusted if necessary. The camera system should be raised and lowered slowly in the borehole to avoid stirring up sediment that may have settled in slots, the screen, or on the bottom.

### 8.3-3.1.5 Interpretation

The visual inspection of a borehole or casing requires no special interpretation techniques.

### 8.3-3.1.6 Advantages and Disadvantages

The borehole camera can provide a very accurate picture of the mechanical condition of the boring and casing. Small features such as open fractures and clogged slots and screens can be observed with this technique.

Resolution of the camera varies considerably between manufacturers. The camera's resolution may not be high enough to show hairline fracturing.

Water clarity is usually a limiting factor in the use of borehole camera surveys. The possible effect of contaminants on the optical lens of the waterproof case should be considered before running a survey. Also, the borehole camera cannot be attached to a standard one- or four-conductor logging cable like those used for electrical, nuclear or caliper logging.

### 8.3-3.2 Caliper Logging

#### 8.3-3.2.1 Principles of Operation

The caliper tool measures the diameter of the borehole. Spring-loaded arms, hinged to the probe body at their upper end, press against the borehole wall. The hinged end of the arm is connected to a variable resistor. As the arm moves out (in an enlarged section of the borehole), the resistance is lowered and a larger voltage is sent to the recorder and displayed is a change in borehole diameter. Figure 8.3-2 illustrates a three-arm and a four-arm caliper.

#### 8.3-3.2.2 Applications

The caliper log is generally used to assess the variation in hole diameter for use in conjunction with other geophysical logging techniques that are sensitive to borehole size and smoothness e.g., gamma-gamma, neutron, acoustic velocity), when appropriate, caliper log data may be need to determine corrections to other logs. Caliper logs can also be used to find fractures, solution channels, and vugs in hard rock, or to identify depths at which soft formations may be squeezing into the bole and substantially restricting other downhole testing.

#### 8.3-3.2.3 Equipment

The most common and accurate of the caliper probes has three or four arms. Probes with four arms provide two diameters (maximum and minimum). The surface electronics contain opening and closing controls for the probe arms, as well as controls for calibration setting. Both the three and four arm models are calibrated using two different size rings of known diameter.

#### 8.3-3.2.4 Field Procedures

No information can be obtained on the downhole run because the arms will not function properly in this direction. The caliper arms are opened at the bottom and a log is made pulling the probe uphole at a relatively slow rate of 8 to 15 feet per minute, in partially cased boles, the probe should be run in the casing to verify diameter calibration and chock for major casing breaks, if this information is desired.

### 8.3-3.2.5 Interpretation

The interpretation of the caliper log is straightforward because the hole diameter is recorded directly in inches. Three-arm calipers tend to show the maximum hole size, while four-arm calipers will also show minimum hole size. Fractures, if they are non-vertical, show as sudden increases in borehole size. Fractures less than about 1/4 inch in aperture or those that intersect the borehole at a steep angle may not affect the position of the probe's arms, and go unrecognized.

### 8.3-3.2.6 Advantages and Disadvantages

The caliper tool gives a good indication of the rugosity (degree of roughness) of the borehole. Data are relatively staple to interpret and should always be run if logging an uncased borehole. The probe requires inspection and possibly cleaning of arm hinges before using to prevent a loss of sensitivity to diameter changes.

## 8.3-3-3 Temperature Logging

### 8.3-3.3.1 Principles of Operation

Temperature logging provides a vertical profile of temperature (or differential temperature) in a water-filled borehole. The probe is quite simple and features a thermistor (temperature-dependent resistor) mounted at its bottom end. The voltage across the thermistor is sent to the uphole circuits, voltage readings are converted to counts per second (cps) and cps fluctuation versus depth are recorded directly on the log. Each probe and surface electronics system has a laboratory-derived relationship between cps and temperature in degrees Celsius.

A more sensitive version of the temperature log, called the differential temperature log, is a calculation of the change in temperature between two points in the borehole. Differential temperature probes may contain two thermistors a fixed distance apart, or may contain one thermistor and calculate temperature changes electronically by comparing the present reading to stored data from previous readings.

### 8.3-3.3.2 Applications

The temperature log is used to help identify the source and movement of water in the borehole. The specific applications include:

- Location of zones of water flow
- Location of leaks in easing
- Identification of discrete aquifers
- Indication of permeability

Temperature logging can also be used to identify the location of cement outside the casing in a grouted hole if the probe is run within 24 hours of cementing.

#### 8.3-3.3.3 Equipment

The equipment needed to run a temperature log includes a thermistor mounted on the end of the probe and protected by a thin metal cage, and a voltage-controlled recorder. The equipment is relatively simple to operate. The typical temperature probe can resolve differences in temperature of 0.02°c, and high-resolution equipment can attain a precision of about 0.001°C.

#### 8.3-3.3.4 Field Procedures

The temperature probe should be the first log run in a borehole if it is to be included in the investigative suite. It should be run from top to bottom to avoid mixing of the water. It is especially important to run the differential temperature probe at a very slow and consistent speed (6 to 8 ft/minute is recommended) so that physical mixing of thermally stratified water will not occur.

Generally, the temperature probe is not field-calibrated. However, its calibration can be crudely checked in air or water if another temperature measuring device is available. The responsiveness of the probe and recorder electronics can be verified by breathing on the thermistor.

#### 8.3-3.3.5 Interpretation

Normally, interpretation of the temperature log is based on the assumption that water in the well is at thermal equilibrium with the surrounding material. Water entering a well bore from different aquifers penetrated by the hole usually will have a different temperature and will cause a flattening or steepening of the log profile. Figure 8.3-3 demonstrates the standard interpretation of various configurations of temperature profiles. An abrupt anomaly on the log is caused by either warmer or cooler water entering or leaving the borehole at the depth of the anomaly. Permeable zones, especially major fractures and casing leaks, can thus be detected as anomalous points on the temperature logs if any groundwater movement is occurring.

#### 8.3-3.3.6 Advantages and Limitations

A temperature log must be made in a fluid-filled hole. The preferred situation for most investigations requires that a borehole has reached thermal equilibrium with the surrounding material and that this equilibrium has not been disturbed by sampling or other downhole activities. Depending on subsurface permeabilities and the degree of thermal disturbance, the equilibration time can vary from a day to perhaps several weeks. In order for this log to reflect natural subsurface conditions, it is also necessary that surficial water does not enter the hole, and that the well construction grout (which gives off heat) has cured for at least three days.

A temperature log is often very informative for holes several hundred or more feet deep, especially where deeper aquifers or fractures exist that are hydraulically not directly connected to a shallow aquifer. The equipment is easy to operate and is relatively inexpensive.

The thermistors may be quite fragile, and downhole breakage can occur if the borehole has edges that may catch the probe.

### 8.3-3.4 Self Potential (SP)

#### 8.3-3.4.1 Principles of Operation

Electrochemical potentials are generated by interactions between ions in the borehole water and pore water in the borehole wall. The Self Potential (SP) method is a passive technique that measures these naturally occurring voltage potentials in the borehole.

More importantly, in geologic environments in which groundwater enters the borehole through thin permeable zones, voltage potentials can also be generated electrokinetically (creating streaming potentials) when an electrolyte (groundwater) flows through a porous medium (rock or soil).

Zones of water gain or loss are often identified by a streaming potential on the log. Streaming potentials are generally negative and have a spikey, irregular character.

#### 8.3-3.4.2 Applications

SP measurements are used for the following:

- Identification of zones of water loss or gain (streaming potential)
- Qualitative indication of clay content/determination of clay layers
- Qualitative indication of water salinity
- Rock type correlation/layer thickness

The SP log may be used in conjunction with the resistivity log to identify clay zones. Other logs, such as the neutron, gamma ray or temperature, can be interpreted with the SP to determine lithology and relative permeability. More than any other technique discussed herein, the SP method is not a stand-alone technique; it requires correlation with other logs.

#### 8.3-3.4.3 Equipment

The downhole equipment for SP and resistivity logging includes a probe with lead or copper electrodes connected to the logging cable. The uphole equipment includes the winch, electric control circuits, power supply, and recorder. Correct measurement of SP in a borehole requires that a grounding (reference) electrode or stake, which is electrically connected to the SP measurement system, be driven into the ground at least 25 feet from the borehole.

8.3-3.4.4 Field Procedures

Field procedures for electrical logging follow the same rules as most other logging methods. The probe is lowered to the bottom of the hole and measurements are made as the probe is pulled up the borehole. When making SP and single-point resistance measurements, it is important to have an effective ground electrode. In very hard or dry material it may be necessary to saturate the ground with water or electrolyte so that a good electrical connection exists between the electrode and the surface material.

8-3-3.4.5 Interpretation

The SP log can be interpreted to give qualitative information on clay content and permeability. To accomplish this, a line is drawn on the log at the maximum deflection of the SP as shown in Figure 8.3-4. A second line is drawn along the baseline. Deflections from the baseline indicate permeable zones. The magnitude of the deflection is proportional to the salinity of the water in a clay-free zone and proportional to the clay content in a clayey zone. If the borehole water has a lower ionic concentration than the formation water, the deflection will be negative; however, if the formation water has a lower concentration, the deflection may be positive.

Zones of water loss or gain can be detected as negative excursions from the baseline with a noisy or spikey, irregular character.

8.3-3.4.6 Advantages and Disadvantages

The SP curve commonly has reduced character in holes drilled with natural (formation) water because there is little geochemical activity between the borehole and formation waters. Deflections on the SP log can be very subtle in holes drilled with natural or moderately resistive water so that scales used in presentation must be changed to show greater detail. SP deflections can be reversed in areas where formation water has lower ion concentration than borehole water.

8.3-3.5 Fluid Resistivity

8.3-3.5.1 Principles of Operation

The resistivity of the formation fluid, which is the inverse of the conductance of that fluid, varies as the amount of major dissolved ions of salt compounds vary (i.e., fluids with high NaCl concentrations have high conductance and low electrical resistance). The measurement of fluid resistivity is accomplished by measuring the AC-voltage drop between two closely spaced electrodes on a probe. This technique is the same as that discussed in Section 8.3-4.1 for formation resistivity in which a substantially greater spacing between electrodes causes the electrical field to easily penetrate the borehole environment and focus within the formation. Fluid resistivity is generally recorded in measurement units known as ohm-meters (times a constant that depends upon the manufacturer's design of the logging system).

## 8.3-3.5.2 Applications

Fluid resistivity logs are used to determine the general water quality with regard to total inorganic compound (namely salts) concentration. This geophysical method is commonly used to detect groundwater-conducting fractures in saturated rock environments. A procedure based on fluid resistivity (conductivity) logging has been demonstrated to quantify inflow rates from fractures into a borehole (Tsang, 1987). Because the SP and other resistivity-type logs are somewhat affected by borehole water quality, the fluid resistivity log can provide information to correctly interpret or quantitatively adjust other logs.

## 8.3-3.5.3 Equipment

Probes for fluid resistivity logging have two ring electrodes (four if multi-conductor winch-cable systems are used) spaced along a water intake tube that the borehole water flows through as the probe is lowered down the hole. Most groundwater investigative probes will fit into a 2-inch diameter hole, and are designed only for logging downhole. Electrical signals are transmitted to the standard surface electronics module, which converts these to counts per second as is done for most other log types. Some probes will measure both water temperature and fluid resistivity simultaneously. This arrangement is preferred as the water column in the borehole will not have been disturbed for either log type.

## 8.3-3.5.4 Field Procedures

The operation is very similar to that for temperature logging (i.e., slow downhole log recording). The tip of the probe housing the water intake tube must be kept open and clean. The log is begun with the probe end just under the water level in the well. The most sensitive span setting that will not cause full-scale deflection of the pen should be used, but commonly a conservative setting must be selected in the absence of knowledge of water chemistry variability in a particular logging environment. Dual recording systems (analog and digital) eliminate most problems with log insensitivity.

## 8.3-3.5.5 Interpretation

The fluid resistivity log is one of the more difficult logs to interpret in the absence of any groundwater quality analysis of borehole water and formation water (if different). The objective of fluid resistivity logging must be reconciled with the known (or unknown) condition of the borehole to derive reliable interpretation of general inorganic water quality. Most important is the status of chemical conditioning of the borehole prior to logging, which usually relates to what fluids were used during the drilling process and what percent of the chemical substances were removed by development of the hole. Conditioning (intentional or unintentional) may greatly influence the degree of difference between in-situ groundwater chemistry and borehole fluid chemistry when the hole was logged.

If logging is to determine natural groundwater quality, the drilling fluid within the borehole and its invaded circumference must be removed or allowed to dilute to the natural concentrations with time prior to logging. In some cases, a return to natural borehole conditions can be knowingly achieved, and in other cases uncertainty will remain.

Interpretation is less complicated when the objective is to correct other resistivity logs, or to identify depths where the formation is actively yielding water to the borehole. In the first instance, the actual resistivity readings with depth are used without environmental interpretation. In the second case, recognition of groundwater inflow (or outflow) from the fluid resistivity log requires identification of trace excursions or offsets that are not the result of extraneous stresses occurring at the borehole. The reliability of fluid resistivity interpretations largely depends on what is known of borehole conditions and on the interpreter's experience.

#### 8.3-3.5.6 Advantages and Limitations

Fluid resistivity logging provides a quick, relatively inexpensive means (as compared to extensive multi-depth water sampling) to qualitatively compare general inorganic water quality in various depth intervals of a borehole. It also may indicate depths where groundwater is moving into an open borehole and serve as collaborative evidence for such movement as suggested by a temperature or flowmeter log.

This technique requires that the hole be uncased, screened, or perforated over the depth interval of interest, and be filled with water to this level. The log must be made going downhole at a slow rate of speed. The most ideal situation for interpretation is that the drilling fluids be thoroughly flushed during development, and that enough subsequent time be allowed for chemical equilibrium to occur.

### 8.3-3.6 Inhole Flow Measurement (Flowmeters)

#### 8.3-3.6.1 Principles of Operation

Several means of measuring the flow of water within a borehole using wireline geophysical equipment have been developed (Keys and MacCary, 1971, and Patten and Bennett, 1962). Three techniques have been well documented: impeller flowmeter, tracer injection and monitoring and thermal flowmeter. The thermal flowmeter, which measures vertical notion with high sensitivity is a newly tested instrument and, as of this writing (1988), is not widely available. Although it shows much promise for accurately measuring very slow flow rates (Hess, 1982 and 1985), it is not discussed in this section.

Impeller flowmeters measure the revolutions of an impeller or vanes, mounted with its shaft parallel to the probe. This instrument is only capable of measuring flow velocities greater than about one to three feet per minute. Pulses are generated by the interaction between a very sensitive magnetic switch and a magnet placed on a shaft that rotates as a result of current flow. These pulses are sent up-cable to a standard rate-meter module, which registers each pulse on stationary time-drive or continuous depth-integrated logs. The speed of probe movement is critical to the log quality for the latter log type.

The tracer injection technique involves dispersing a "slug" of a tracer, such as salts, trivium, or fluorescein dyes (Driscoll, 1986), at a strategic depth in the borehole, and then monitoring its movement up or down the hole with respect to the exact recording of elapsed time intervals. The tracer hot-spot is assumed to move at exactly the same rate as the borehole water. Detectors located above and below the injection port on the probe are essentially fluid conductivity sensors. These data are used to calculate borehole fluid velocities.

### 8.3-3.6.2 Applications

Inhole flow logs can be used to determine the rate of water movement between two permeable zones (or fractures) intersected by the open borehole, or opposite well screens or perforations. Rates of movement can be used to calculate a volume flow per unit time, and if the thickness and percent of total flow contribution of the permeable zone(s) are known, hydraulic conductivities can be determined (Schimachal, 1981). As complementary data, caliper logs for open-borehole applications are strongly recommended so as to derive the appropriate representative diameter of the segment through which flow was measured.

Flowmeter logging under conditions of surface discharge of borehole water (pumping or artesian flow) can provide data to interpret percentages of the total flow attributable to each permeable zone. This technique could be applied in competent rock holes to locate a dominant fracture that contaminants might follow and, thus, provide detailed information for discrete chemical sampling.

### 8.3-3,6,3 Equipment

An impeller flowmeter consists of a vane-type spinner mounted in a vertical axis position inside a strong cage on the bottom end of a probe. The diameter of the probe is smaller than the spinner, which is usually between three and four inches in diameter. The up-hole end of the probe connects to common cable heads. Single-conductor cable flowmeter probes are available. Surface electronics of most standard logging units can receive and process the pulses.

Tracer injector probes are relatively complex, as the tracer solution must be loaded and remotely ejected through small ports on the side of the probe. Because the direction of fluid movement in the borehole is commonly not known beforehand, probes having conductivity (resistivity) detectors both above and below the ejection (ports) should be used because they allow measurement collection while holding the probe motionless in the hole (a very desirable condition). In large diameter boles, the probe should be centralized. To obtain a visual field log, the analog recorder must have a built-in time-drive mechanism, or a computerized digital playback of conductivity readings versus time.

### 8.3-3.6.4 Field Procedures

Two primary options exist for operating the impeller flowmeter: depth-stationary recording and constant probe-speed recording. The depth-stationary method assumes that borehole water velocity is faster than the stall speed of the meter, either through 1) natural artesian flow out the top of the well, 2) induced flow through pumping of the well, or 3) natural flow between two or more separated permeable zones (a phenomenon known as "thieving"). To collect flow data, the flowmeter is positioned at selected depths, and a time-drive log is made at each for several minutes duration. The log on the right in Figure 8.3-5 shows a typical measurement.

The constant-speed technique is used when the flow in the hole is presumed to be near the impeller sensitivity speed and/or a large depth interval must be logged. Proper procedure requires downhole and upbole log recordings, both made at the identical probe speed. The left logs in Figure 8.3-5 show an example with a probe speed of 40 feet per minute. With speeds of this magnitude, rugosity of open boreholes may cause artificial anomalies if the probe bounces off or momentarily bangs on a protrusion (the operator must carefully watch the cable's action).

The procedure for obtaining tracer injection logs is less rigid; it depends upon the logging system being used, the rate of fluid travel, and if the direction of travel is known beforehand. The user is referred to Keys and MacCary (1971) for consideration of the various options.

### 8.3-3.6.5 Interpretation

Flow velocity is easily computed from stationary time-drive flowmeter logs by counting the number of pulses per unit time, and applying the calibrated flow rating for each individual probe. Feet per minute of travel is then used to compute the volumetric rate of flow, using the most accurate determination of average borehole (or easing) diameter.

Using the constant probe-speed technique, zones of increased impeller rotation on a log made in one direction and decreased impeller rotation in the opposite log direction are identified as having vertical flow. This phenomenon, as illustrated on the logs shown on the left side of Figure 8.10-5, can be seen to occur between the depth interval of 260 and 270 feet. Again, through calibration of the meter and by knowing the logging speed, the velocity of flow can be computed.

Interpretation of trace injector logs is straightforward, assuming that the tracer plume passes a fluid conductivity detector during the monitoring period. The fluid velocity is computed as the distance traveled between the ejector and the detector (if the probe is held stationary as is normally the case) divided by the time span between ejection and the arrival of the peak conductivity recorded on the time-drive log. If the tracer substance has a specific weight much different than the borehole fluid, density corrections should be made. Radioactive tracers have been very successfully used in combination with gamma detectors installed in an ejector probe because they are detectable at very low concentrations. However, government regulation of radioactive tracers now is very stringent, discouraging their use.

### 8.3-3.6.6 Advantages and Limitations

Flowmeter logging can provide the best means to quantify natural movement of groundwater between two permeable zones in a borehole. It is the only direct method to determine the percent contribution of various permeable zones when a long section of an uncased bedrock hole, or long screened or perforated casing section, is pumped. Provided that the borehole fluid velocity is greater than 3 to 5 feet per minute, the impeller meter will detect the presence of fractures that are conducting water into or out of the borehole.

Use of flowmeters and other flow detection technologies to investigate groundwater movement is dependent on the existence of natural flow or the use of well pumps to create velocities greater than the detection limits of the technique. Impeller flowmeters must be calibrated in controlled velocity environments, and the meter must be rechecked if any significant wear or damage is suspected and if quantitative results are needed. The technique may not give good results in small diameter (2- to 3-inch) holes. If used in large diameter holes, a skirt should be attached to concentrate the flow past the impeller or sensors. Caliper logging of uncased holes is highly recommended prior to running in-hole flow tests, as not making diameter corrections may cause velocity errors to exceed 40 percent (Schimschal, 1981).

Trace ejector logging may provide reliable results at somewhat lower velocities, but this technique is difficult to use to investigate long sections of borehole. Both methodologies require relatively simple instrument controls and operator training.

Borehole flow logging is more time consuming than most other downhole logging.

## 8.3-4 FORMATION PENETRATING METHODS

### 8.3-4.1 Resistivitv Techniques

#### 8.3-4.1.1 Principles of Operation

Resistivity measuring devices (normal, single point and induction/EM probes) measure the electrical resistance of a volume of material around the borehole. These active techniques involve applying a current (AC or DC) to the formation and measuring the resulting potential field. The use of normal and/or single point techniques requires that the borehole be uncased and filled with a conductive fluid. The induction probe, which applies an electromagnetic field to induce currents in the formation, is employed when a current cannot be applied directly, such as in air-filled or PVC-cased holes.

The single-point resistance probe is the most commonly used resistivity device. It consists of a single lead electrode connected to a power source and voltage meter (Figure 8.3-6). A constant current is applied to the electrode and the voltage between the electrode and surface ground, which basically varies with earth resistance, is measured in the same manner resistance is measured with a volt-ohm meter. The actual property measured with the single-point device is resistance, in ohms. Resistivity is a volumetric quantity expressed in ohm-meters.

The normal device, also called the two electrode system, employs the use of two electrodes on a probe, spaced a selected distance apart (see Figure 8.3-6). The lower electrode is used to apply a constant current to the formation. The upper electrode is used to measure the potential field at that point. The electrode spacing determines the depth of investigation of the normal tools. The depth of investigation into the rocks surrounding the borehole is approximately equal to about half the electrode spacing. Common spacings are 16, 32, and 64 inches. Closer spacings may be used to advantage in slotted PVC casing, with minor adjustments.

When borehole conditions (i.e., air or foam filled holes or in holes cased with PVC) prevent a current from being applied directly to the formation, as is the case for normal and single-point methods, an electromagnetic probe, also known as the induction technique, may be used. The induction probe is essentially the same as the surface terrain conductivity instrument described in Section 6. A lower transmitter coil produces an electromagnetic field that generates a ground loop (circular currents around the borehole). The secondary field created by the ground loop in the rocks and fluids surrounding the borehole is measured by the upper coil, and is proportional to the conductivity of the material between the coils.

### 8.3-4.1.2 Applications

Resistivity logs are used to determine:

- o Water saturation
- o Porosity (when the conductivity of formation water is known)
- o Clay presence
- o Basic water quality (i.e.. conductivity due to salts - when the formation porosity is generally known)

Generally, when these parameters are to be determined, a log suite consisting of gamma ray, SP, acoustic velocity (to be explained later in this section) and resistivity is run. Also, the resistivity and induction method can often be used to identify contaminated zones, if the contaminants have an electrical conductivity significantly higher or lower than the hydrogeologic environment and an adequately high concentration is present.

### 8-3-4.1.3 Equipment

The downhole equipment for single-point resistance and resistivity logging includes a probe with lead or copper electrodes connected to the logging cable. The uphole equipment includes a winch, electronic control circuits, power supply, and recorder. Single-point resistance logging, which utilizes only one probe electrode, requires that a grounding electrode or stake be driven into the ground at least 25 feet from the borehole.

Two induction instrumentations are available for groundwater investigations, with slightly different configurations. A stand-alone portable unit is commercially available which focuses the electromagnetic field into the formation beyond the walls of the borehole. This unit includes a two-coil probe; a 9-mm diameter, seven conductor logging cables; uphole electronics module; power supply (12 VDC); and an analog or digital recorder. The other configuration for the induction logging equipment is a standard multi-conductor probe that is compatible with truck-mounted logging equipment.

### 8.3-4.1.4 Field Procedures

Field procedures for electrical logging follow the same rules as most logging. The probe is lowered to the bottom of the hole and logs are made as the probe travels up the borehole. When making a single-point resistance log, it is important to have an effective ground electrode. In very hard or dry material it may be necessary to saturate the ground with water or electrolyte so that a good electrical connection exists between the electrode and the surface material. The logging cable must be electrically insulated for a distance of 5 times the electrode spacing when running normal resistivity logs. Logging speeds can be as high as 3 feet per minute for electric logs without losing log quality.

A variable-resistance decade box should be used during each day of field logging to calibrate the system's response output in ohm-meters.

8.3-4.1.5 Interpretation

Resistivity measurements can be used qualitatively to interpret porous water-filled zones or fracture zones. Usually, these zones have lower resistivities than adjacent non-porous or non-fractured zones. After these low resistivity zones are identified, they should be compared to the SP and gamma-ray logs to verify that they are not clay zones which also have low resistivity. The single-point resistance probe is especially sensitive to individual open fractures with apertures greater than about 0.1 foot.

Porosity can be estimated from resistivity logs if the resistivity of the formation water is known. Formulas to calculate formation porosity can be found in Keys and MacCary (1971). For example, formation porosity for sandstone can be determined graphically from Figure 8.3-7.

Qualitative estimates of water quality can be made from resistivity logs in clay-free zones. As specific conductance increases, the resistivity will decrease, assuming the porosity and lithology are constant. Thus, brackish and salt-water aquifers will show lower resistivity than fresh-water aquifers of similar porosity and lithology. Keys and Maccary (1971) and Rwader (1982) describe methods of estimating water quality from electric logs. The methods employ the use of mathematical expressions or cross-plots to relate properties such as formation resistivity factor, fluid resistivity, porosity, cementation factor, specific conductance, and dissolved solids.

When used with the SP and gamma-ray logs, the resistivity log can give valuable information concerning lithology, water content, and groundwater quality. Because electrical current passes through soil by way of water in the pores, it is possible to locate the top of the saturated zone using this method. If a single-point or small-spacing resistivity probe is used, the capillary fringe can often be identified.

Resistivity values are not unique for specific lithologies. However, clays usually have low resistivities and most non-fractured, unweathered igneous and metamorphic rocks have high resistivities. Fresh-water saturated sands normally have resistivities significantly greater than clays. Fine-grained sands and silts commonly have lower resistivities than coarser sands and gravels. In coastal environments, the resistivity log is used to discriminate the higher resistivity fresh-water aquifer from the lower resistivity brackish or saline sea-water aquifer.

8-3-4.1.6 Advantages and Disadvantages

Borehole electrical methods are rapid, repeatable and well documented techniques that require simple equipment and all can be run in two-inch ID holes. They are effective methods for determining the presence of clay layers and water quality.

The primary disadvantage of the electrical methods is that (with the exception of induction/electromagnetic techniques) they require water-filled uncased boreholes.

Another disadvantage is that these methods generally require a fracture with an aperture greater than 0.1 foot.

The induction/electromagnetic probe is effective in low to moderate resistivity formations, and provides resistivity data under conditions where other techniques cannot be applied (air-filled boles and PVC-cased holes). A disadvantage of the induction/electromagnetic technique is that it has poor vertical resolution (cannot resolve layers less than 2-3 ft thick) and gives unreliable data in high resistivity formations.

Resistivity and SP measurements are very sensitive to the resistivity of the drilling fluid. If drilling fluid is highly resistive and the borehole diameter relatively large, thin beds and more resistive beds will not be detected, as most of the current is forced to travel along the borehole walls (Kwader, 1982).

In glacial terrain, boreholes must be cased with PVC or steel. Use of these materials usually precludes single-point, normal resistivity and SP methods, although they can be run in the screened interval of PVC-cased wells. Care should be taken to ensure the integrity of the borehole so that expensive logging probes are not lost by collapsing sections of the borehole.

Electrical methods provide calibrated, quantified results in low to moderate resistivity, water-saturated rocks and soil, such as clays and saturated sand and gravel. Electrical methods give only qualitative to semi-quantitative results in high resistivity materials, such as unfractured granite or dense silty till.

### 8.3-4-2 Acoustic (Sonic) Methods

#### 8.3-4.2.1 Principles of Operation

Acoustic borehole methods are a group of active techniques that use sound waves to measure the acoustic properties of the soil, rock, and fluid near the borehole. The velocity with which sound propagates through the materials, and/or the strength of the signal at the receiver, are evaluated in conjunction with other geophysical techniques (i.e., SP, Resistivity) to determine the type of the material penetrated. The techniques include:

- Velocity logging
- Amplitude logging
- Wave-form analysis
- Acoustic televiewer

The most common of these techniques is velocity logging. The acoustic methods can be used in open or cased holes. A fluid-filled hole is usually required to transmit the sound wave to the formation. Dry hole acoustic probes are available, but have limited applications. A discussion of basic acoustic logging methods can be found in Labo (1987) or Key and MacCary (1971). More detailed information on the acoustic televiewer can be found in Paillet (1980) and Zemanek and others (1968).

In its simplest form, the acoustic velocity logging technique uses a sound-wave source generator and a receiver mounted on a probe at a fixed distance from the generator (Figure 8.3-8). The generated sound wave is propagated through the borehole fluid and refracted into the formation. A portion of this acoustic energy travels parallel to the borehole and is refracted back to the receiver. Electrical circuits are used to measure the transit time for the sound waves to travel from source to receiver. These data are presented on the log as travel time, recorded in microseconds per foot. Many acoustic velocity logging systems are designed with two or more receivers and two sound-wave generators to minimize the following borehole effects:

- Travel time through borehole fluid

- Irregularities in borehole size (indicated by caliper logs run in uncased holes)

- Orientation of the probe in the hole

Multiple-receiver probes (see Figure 8.3-8) measure travel time by taking the difference between the first arrival of the sound wave from the near and far receivers. Some logging systems are also equipped to record the strength, or amplitude, of the first arrival, usually in millivolts. These acoustic logging systems contain an oscilloscope which allow the entire wave train to be observed while logging. The wave train can also be photographed or recorded digitally so that a complete analysis of all portions of the wave may be performed.

The acoustic televiewer is an elaborate probe that contains one or more sound-wave source generators and receivers mounted radially on an internal rotating mechanism (Figure 8.3-9). The rotating mechanism is powered by a small electric motor and contains a magnetic orientation device used to tie the acoustic measurements to compass directions. As it rotates, high frequency sound waves are generated and reflected off the borehole and back to the probe. Receivers, located coincident with the sound-wave generators, measure the amplitude of the reflected wave and send the information uphole. The wave amplitude data is combined with the simultaneously collected probe orientation and depth information to produce an uncoiled 360-degree acoustic image of the borehole (Figure 8.3-10).

8.3-4.2.2 Applications

Acoustic velocity measurements can be used to determine

- o Porosity (for known lithology)
- o Lithology (determined in conjunction with other logs)
- o Rock strength
- o Fracture location
- o Validity of seismic refraction interpretations

Porosity can be determined from the acoustic velocity log if the formation compensation is known and is clay-free, consolidated (grains cemented together) and fluid-bearing. The porosity is calculated from the relationship established by Wyllie (1963), which involves transit times through the rock and the pore fluids.

The accuracy of the calculated porosity is dependent on the accuracy of the matrix identification. Because the acoustic travel time varies with porosity and rock composition it is a non-unique response. Lithology can only be confirmed if other logs such as the neutron, gamma-gamma or natural gamma are used for verification. The acoustic travel-time log can be used to verify seismic model layers determined by the seismic refraction method (Section 3).

Matrix travel times for sedimentary rocks (shale, sandstone and limestone) are well documented and vary within known limits. Matrix travel times for igneous and metamorphic rocks vary considerably and are not well defined by the present literature. For this reason it is recommended that the interpretation of the acoustic velocity log be limited to identification of relative changes in porosity in igneous and metamorphic rocks, unless detailed information concerning rock type or seismic velocities are available. Dobrin (1976) provides a table of velocities for various sedimentary, igneous and metamorphic rocks (Table 8.3-2).

Relative rock strength can be estimated from acoustic travel-time data in zones of similar rock type. Increases in travel-time can indicate zones of weathering, alteration or fractures, which also have higher porosity than rock outside such zones.

The acoustic amplitude log can be used as an indication of conditions at the edge of the borehole, such as cement bonding quality between steel casing and the formation. If there is a good bond, the acoustic amplitude is high. However, if there is a gap caused by partial grouting, the signal from the formation will be weak (attenuated) and show as a low-amplitude zone. Low amplitude can also be an indication of fractures, unconsolidated or soft material, weathering, or mineral alteration in uncased holes.

The full waveform acoustic log records the complete acoustic wave so that various components of the wave may be identified. These components include the arrival times and amplitudes of:

- o Compressional waves
- o Shear waves
- o Tube waves

Shear- and tube-wave data can be used to locate fractures and estimate permeability. The shear-wave and tube-wave information also is used to calculate engineering properties used in the design of remedial structures or systems. These engineering properties are:

- o Bulk modulus
- o Shear modulus
- o Poisson's ratio
- o Young's modulus

The reader is referred to Dobrin (1976) for a complete discussion of the calculation of these properties from seismic and acoustic log data.

The acoustic televiewer is used primarily to identify and measure the strike and dip of fractures. However, it can also be used to identify other borehole and rock conditions such as hole enlargements, hole obstructions, rock breakouts, foliation, and zones of weakness due to weathering or alteration.

8-3-4.2.3 Equipment

Acoustic logging methods require relatively complex electronic systems and instrument controls to produce acoustic logs. Sophisticated timing and measuring circuits are used to pulse the sound-wave generators and turn the receivers on and off. An oscilloscope is used to visually inspect the quality of the sound wave as it is transmitted and received. All of these components are contained in the surface electronics package. The probe contains the sound-wave generators and receivers. A specially designed camera may be necessary to record the full waveform acoustic log.

8.3-4.2.4 Field Procedures

The acoustic televiewer logs must be run at very slow probe speeds, commonly four feet per minute. Calibration of acoustic surface electronics is generally performed internally by passing a reference signal through the circuits. There are no calibrations needed for acoustic probe electronics apart from the surface system calibration. For quantitative velocity determination, it is best to calibrate the system by correlation with velocities determined by core tests or a seismic refraction survey.

### 8.3-4.2.5 Interpretation

The porosity value calculated from the acoustic velocity log represents the primary (intergranular) porosity only. Secondary porosity created by vugs, dissolution, and fractures is not detected by the acoustic velocity method because the sound wave travels along the fastest path, which is through the rock rather than the fluid. If the total porosity from the density or neutron log is compared to the primary porosity from the acoustic velocity log, the amount of porosty due to vugs and fractures can be determined.

When the amplitude of the received sound wave is low due to inhomogeneities in the rock (fractures, vugs), the first arrival of the sound wave may not be detected because it is below the detection limit of the probe. Later arrivals with higher amplitudes trigger the detector and show as very long travel time on the log. This phenomenon is called "cycle skipping." The log usually looks very spikey and irregular when cycle skipping occurs. Cycle skipping may indicate vugs, fractures or weak rock.

Acoustic travel times for specific depths can be plotted against gamma-gamma, neutron, or natural gamma count rates at corresponding depths to define rock-type groups (Figure 8.3-11). This technique, called cross-plotting, is very informative, especially when combined with core or other geologic data.

Full acoustic waveform interpretation is similar to vertical seismic profiling (VSP) interpretation; therefore the reader is referred to Section 8.3-4.4 for a more complete discussion.

Interpretation of acoustic televiewer images (logs) is somewhat subjective unless borehole wall character is evidenced on other logs. The basic premise is that strong signals from smooth borehole walls of competent rock appear as bright areas on the log, whereas fractures, soft seams and weathered rock appear as dark areas.

### 8.3-4.2.6 Advantages and Disadvantages

The acoustic probes are advantageous because they provide perhaps the most accurate information concerning fracture location, geometry and characterization, and need not require confirmation by other log types for some purposes.

The primary disadvantage of acoustic velocity techniques is their relatively high cost and complexity, and their limited value in cased holes penetrating unconsolidated materials. The acoustic tools must be run in water-filled holes so that the sound wave is effectively transmitted to the borehole walls. However, special receivers are available for use in dry holes, but they must be clamped to the side of the borehole, thus preventing continuous logging of the hole.

The acoustic televiewer is not readily available among geophysical contractors, because it is an expensive, relatively specialized probe. Furthermore, the quality of the log, and thus reliability of interpretation, depends strongly on the operator's experience and ability to set the proper acoustic focus. As major changes in the borehole diameter occur, refocusing is commonly required.

The reader is referred to Zemanec and others (1969 and 1970) or Taylor (1983) for a complete discussion of the interpretation of the technique.

## 8.3-4.3 Nuclear (Radiation) Methods

### 8-3-4.3.1 Principles of Operation

Nuclear logging methods include both passive (natural gamma-ray) and active (gamma-gamma and neutron) techniques. These techniques are used primarily for the determination of porosity and lithology. Most nuclear methods employ the use of geiger tubes or scintillation crystals to detect the intensity of radioactivity. The detector emits photons (flashes of light) when struck by radioactive particles (neutrons and gamma-rays). The photons are converted to electrical pulses and sent uphole to counting and timing circuits, where a surface electronics module converts these pulses into counts per second. All nuclear logs can be run in open or cased holes, and in dry or water-filled holes.

#### 8.3-4.3.1.1 Natural Gamma-ray Log

The natural gamma-ray log is a measure of the naturally occurring gamma radiation in the formation. Natural gamma radiation is produced by the radioactive decay of potassium, thorium (Th) and uranium (U) atoms. Clay minerals show high gamma ray readings because they commonly contain potassium in their chemical structure. Clay minerals also promote the adsorption of positive ions, such as Th+ and U+, because of their open crystal lattice structure and net negative charges. Thus, the natural gamma log serves as a reliable clay indicator in those environments where non-clay beds do not contain radioactive minerals. However, some granites and their weathering products are also rich in radioactive minerals, and also will give high gamma-ray counts.

#### 8.3-4.3.1.2 Gamma-gamma Log

Gamma-gamma logging uses a solid, encapsulated radioactive source (generally cesium-137 or cobalt-60) mounted 10 to 35 inches from the detector to bombard the formation with medium-energy gamma-rays. The gamma-rays are scattered as they collide with the electrons of the material in the formation. With each collision, an individual gamma particle will lose some of its energy until it reaches a low energy state and is absorbed by an electron. The probe measures the number of gamma rays that are reflected back to the detector. The number of electrons detected by the instrument is inversely proportional to the density of the formation evaluated. Therefore, very dense formations, which have high electron densities and will reduce gamma energy quickly, will cause fewer gamma rays to reach the detector, while less dense formations will exhibit higher gamma count rates. If the formation lithology (and density) are known, variations of density measured can be attributed to changes in porosity.

### 8.3-4.3.1.3 Neutron-epithermal-neutron Log

The neutron-epithermal-neutron log is used to determine porosity as a function of formation hydrogen content. The basic assumption in the calculation of porosity using this method is that all pore (void) spaces in a formation are water filled. This survey method can be employed below the water table to measure porosity and above the water table to indicate relative moisture content in the unsaturated zone.

The neutron probe is similar in design to the gamma-gamma probe, except an americium-241 beryllium radioactive source is installed. This source emits fast neutrons, which collide with atoms in the formation and are slowed down. The most effective atom in slowing down fast neutrons (because of its similar atomic mass) is the hydrogen atom, which is a major constituent of water. When neutrons reach a very low energy level, they are captured primarily by hydrogen atoms, and gamma energy is released. Detectors are designed to detect (count) either neutrons or gamma photons released by neutron collisions. The counting rate for both types of detectors is inversely proportional to the hydrogen content of the formation. The instrument detection results are converted to porosity.

Although a neutron log cannot be used for measuring porosity above the water table, it is very useful for measuring changes in the moisture content.

### 8.3-4.3.2 Applications

Nuclear techniques are used primarily to identify the presence of clay, correlate lithologies, and determine porosity. These techniques are most valuable if the probes are calibrated with appropriately constructed field standards of known properties, and, therefore, accurate densities and porosities can be determined. The gamma-gamma and neutron radiation logs provide a record of count rate, which must be scaled with a calibration rating curve after dead-time corrections are applied (moderate to high count rates only) to provide porosity values.

Natural gamma and neutron logs can aid in the identification of perched aquifers, especially when used with a resistivity technique. Opposite a perched aquifer the resistivity is low; the neutron log would show increased water content, and the natural gamma should confirm the perched zone to be non-clayey materials. As the resistivity and neutron probe responses may be similar for clay and water-saturated sands due to water molecules bound to the structure of clay minerals, the natural gamma log is critical for correct interpretation.

8.3-4.3.3 Equipment

The three nuclear techniques use very similar surface and downhole equipment. While a few nuclear logging systems use the same probe and detector for all three methods, with only the source and source-to-detector spacings changed, most logging systems employ the same probe for natural gamma and gamma-gamma, but a different probe for neutron. The uphole electronics consists of a counting and timing circuit for recording data in counts per second. A more complex electronics package is required for directly recording porosity during gamma-gamma or neutron logging.

The gamma-gamma and neutron methods require the use of a solid, encapsulated, chemical radioactive source. Although these sources are relatively small, they present a safety concern for the operators of the equipment. The sources are regulated by the Nuclear Regulatory Commission (NRC) and must be licensed. Use of licensed sources is limited to those persons who have proper training and have obtained NRC certification in nuclear materials handling and safety. These sources are transported and stored in locked, shielded carrying cases and are secured to the probe only during actual logging.

Another aspect of safety is the use of active sources in uncased, loose formations. The potential for getting a probe stuck in the hole often is significant when borehole walls consisting of unconsolidated soils are unstable. It is recommended that no probe with a radioactive source be run in an uncased hole in an unconsolidated formation.

8-3-4.3.4 Field Procedures.

Nuclear logging methods follow the same general field procedures as other logs. One notable difference is that radioactive sources used with the density and neutron techniques are installed using a site-specific field routine that minimizes radiation doses to the operator. Also, log quality and repeatability are enhanced if a probe decentralizer is used in hole diameters of 8 inches or greater. Probes are calibrated at the site using either a source of known strength (field standard) to check detector response or a piece of material with known physical properties to check total probe response.

For uncased holes in competent rock, a caliper probe is always run before the nuclear probes because of the serious consequences of getting a radioactive source stuck in the hole.

Radiation probes are generally run at a slower speed (10-15 ft/min) than most other probes so that the count rates can be averaged over a longer period of time, thus reducing the statistical variability and making the logs more repeatable.

8.3-4.3.5 Interpretation

None of the radiation logs have a unique count rate response to individual lithologies (see Figure 8.3-12); however, within a single geohydrologic environment, any given geohydrologic unit (layer) generally shows a consistent response. This aspect gives these logs much value in correlating lithology between well sites.

Natural gamma logs respond primarily to the amount of potassium, and secondarily to the amount of thorium and uranium isotopes in the formation. As potassium is a major component of most clay minerals, the natural gamma log is generally considered to be a clay-content log.

Other minerals that can cause high gamma counts include:

- o Feldspars (high potassium) - found in many granites and other light-colored igneous and metamorphic rocks
- o Micas (high potassium; may contain thorium) - found in granites
- o Hornblende (can contain thorium and uranium) - a common accessory mineral in granites and some metamorphic rocks
- o Uranium minerals in granites and sands

Sometimes, a natural gamma log will show high radioactivity opposite fractures or fractured zones in bedrock. These spikes are usually due to uranium-rich mineral precipitates lining the fracture walls, but small excursions on the log may represent clay-filled fractures.

Natural gamma log responses should be cross-examined with the SP and one of the resistivity log types to confirm rock type. Fractures can usually be identified with the single-point resistance log.

Neutron logs will respond to water bound in the crystal structure as if it were pore water. It is important to check for the presence of clay with SP or natural gamma when using the neutron log to determine porosity. The neutron probe is affected by borehole enlargements and high chloride content. Under these conditions, the neutron log should be used only as a general indicator of porous zones.

Rocks and glacial sediments show an extremely wide range of bulk densities (the combined density of rock, fluid, and air). If the lithology is known, a reasonable estimate of porosity can be made by using published relationships.

The density log can also be used to detect voids and channeling in grout behind casing. Voids and channels in grout may provide pathways for transport of water and contaminants between layers.

When analyzed together, the gamma-gamma and neutron logs commonly indicate zones of formation washout that exist behind the well casing, caused by the drilling process. Washouts and aquifers may give a similar response on these logs, and commonly the natural gamma log must be consulted.

### 8.3-4.3.6 Advantages and Disadvantages

Nuclear techniques work well in a wide variety of borehole environment including cased (PVC or steel) and uncased holes in saturated and unsaturated formations. Their primary advantage is that, when properly calibrated, these logs give estimates of porosity and lithology that are consistent with independent field and laboratory test results. The porosity and lithology measurements are made in-situ at accurately known depths, thus reducing cost and time involved in comparison to core sampling and aquifer test pumping.

Most of the probe response in nuclear logging is from the first six inches to one foot of the formation surrounding the borehole. Sometimes this zone may be very disturbed, due to drilling and completion procedures that may force drilling fluids into pore spaces near the borehole or alter the compaction of loose materials. If large augers are used and a small diameter well is installed, most of the radiation response is from the gravel pack (filter sand) or backfilled material. In such cases a false indication of formation properties may be obtained. The best hole conditions result from driving casing or open-hole drilling in competent rock.

Hole diameter variation and rugosity of the borehole walls affect all nuclear logs to some degree, depending on source strength and the chosen spacing between source and detector. Gamma-gamma density logs made with a weak radiation source and short spacing may be severely affected, misrepresenting true formation density. Neutron probes have a lesser sensitivity to the same conditions, while natural gamma logs generally are not significantly affected unless a large void or washout is present. Caliper logging in open holes provides data for correcting radiation logs for hole diameter variations. However, quantitative determination of density and porosity opposite washouts in cased wells is not possible.

Radioactive sources are regulated by the NRC and must be licensed. The use of geophysics tools employing radioactive sources is restricted to only those persons who have NRC certification. The consequences of losing a radioactive-source (i.e., by being unable to retrieve a downhole source/probe) is serious and costly.

### 8.3-4.4 Vertical Seismic Profiling (VSP)

### 8.3-4.4.1 Principles of Operation

Vertical Seismic Profiling (VSP) is a borehole seismic survey method used to detect and characterize open fractures within rock. The VSP method was developed in the petroleum industry and has recently been applied to hydrogeologic characterization for environmental studies. This method provides a three-dimensional image of subsurface velocities and geologic structure, utilizing an array of seismic borehole geophones (motion sensitive sensors) or hydrophones (pressure sensitive sensors) placed in a borehole at the depths of interest. The technique is illustrated schematically in Figure 8.3-13.

The VSP technique uses a seismic source, placed at the surface some distance away from the borehole to generate seismic waves, which travel through the ground and are detected by the geopbones in the borehole. These waves consist of compressional waves (P waves) and shear waves (S waves). Figure 8.3-13 shows a schematic representation of the seismic wave received by the geophones.

When a fluid-filled fracture, which intersects the borehole, is squeezed by compression from a seismic wave, a pressure pulse known as a tube wave is generated in the borehole. The tube wave is detected by the geophones as the pressure pulse is propagated upward and downward in the borehole. The size (amplitude) of tube waves generated by a permeable fracture depends on the hydraulic conductivity of the fracture, elastic properties of the rock, fluid properties, and borehole radius. High permeability fractures yield large amplitude tube waves. Tube wave amplitudes are generally much larger than those of compressional waves (see Figure 8.3-13).

### 8.3-4.4.2 Applications

A particular application of this technique is the detection of open, water-filled fractures that are intersected by a borehole (Levine and others, 1985). Compressional, shear, and tube waves can be used to characterize the fractures in terms of depth, attitude, and hydraulic conductivity.

When the formation and fluid properties are known, tube wave amplitudes can be used to determine the hydraulic conductivity (K) of a fracture. The K value is determined through the comparison of compressional wave pressure amplitude to that of the tube wave as measured by the hydrophone positioned closest to the fracture depth. The use of the nearest hydrophone removes the effects of the source as well as the recording system response.

If desired, the lateral extent of the fracture can be delineated by moving the surface source away from the borehole and observing changes in the transmitted and reflected compressional and shear waves (see Figure 8.3-14). Because the compressional and shear waves scatter, attenuate, reflect, and refract at a fracture zone, computer ray-tracing methods can be used to image the geometry of the fracture. Of particular note is the significant attenuation of shear wave energy through a fracture zone or other low velocity zone.

### 8.3-4.4.3 Equipment

A string of hydrophones or undamped geopbones are used in the borehole to detect the tube waves. The hydrophone responses are transmitted to a surface recording unit. This surface unit should consist of digital recording instrumentation capable of timing in the range of tens of microseconds and with playback capability for later analyses.

The VSP technique generally uses conventional seismic sources (e.g., weight drop, explosives, Betsy seisgun) placed on the ground surface at appropriate locations or within nearby shallow borings. The energy source with the highest frequency content consistent with the attenuation characteristics of the earth materials at that location should be used.

### 8.3-4.4.4 Field Procedures

The following field procedures allow fracture characteristics, primarily depth, length, and orientation, to be determined.

Surface energy sources are arranged in a radial pattern around the bole and placed at various distances from the borehole. Receivers are placed within the uncased bedrock segment of the borehole. Each source location is detonated individually, with data being stored digitally for each geophone for each shot. After all seismic recordings are made, the sensor array may be raised or lowered in the borehole to span deeper or shallower unmonitored segments. Sensor spacings are directly related to the degree of accuracy with which individual fractures or fracture zones need to be defined. Wide sensor spacings (25 to 50 feet) are useful in identifying depths to zones of fractures; closer sensor spacings (5 to 10 feet) may identify individual fractures. Additional data are recorded until the entire water-filled section of the borehole has been surveyed.

The data are stored on magnetic tape or disk for further computer processing, such as amplitude, frequency and particle motion analysis. A complete display of VSP data from the top to the bottom of a borehole can also be made using the stored data.

### 8.3-4.4.5 Interpretation

Tube waves indicative of permeable fracture zones are often readily apparent on the seismic recordings. By using an appropriate X-Y data display (individual sensor seismograms with time along one axis and depth along the other axis), the depth at which the tube waves originate can be determined within a few feet if closely spaced sensors are employed. The orientation of the fracture can be approximated by analysis of the tube-wave to compressional-wave amplitude ratio. Geophone records from energy sources located at the same distance, but different angles, around the borehole are used for this analysis. Because of the qualitative nature of the analysis, results are presented in terns of shallow-, moderately-, or steeply dipping fractures. Analysis of the amplitude ratios will define the strike of steeply dipping fractures to within ±10 degrees, and that of moderately dipping fractures to within ±15 to 20 degrees. The more data available from different azimuths, the better is the fracture orientation definition.

The continuity and extent of fractures can best be determined if multiple boreholes are investigated. If a fracture intersects two boreholes, the continuity of the fracture can be determined through computer modeling and imaging. Borehole-to-borehole seismic methods can also be used to establish fracture continuity through the use of guided wave technology (i.e., energy generated in the vicinity of permeable fractures in one borehole and high-amplitude, high-frequency seismic waves recorded in an adjacent borehole).

The tube-wave amplitude is generally influenced by the hydraulic conductivity of the fracture. Other factors such as the physical properties of the medium surrounding the borehole, the frequency of the seismic waves, the properties of the fluid filling the borehole, and the radius of the borehole may also affect the amplitude. The amplitude ratio (tube-wave to P-wave) versus frequency is the key relationship used to establish the hydraulic conductivity of a fracture zone. A set of curves can be generated showing amplitude ratio versus frequency for different hydraulic conductivity values. A set of such curves is shown on Figure 8.3-15. The determination of hydraulic conductivity values by the VSP technique has been verified through correlation with permeability test data.

### 8.3-4.4-6 Advantages and Disadvantages

Vertical seismic profiling yields clear and definitive results for identifying permeable fractures intersecting a borehole. As numerous studies have shown, some fractures detected by other logging techniques, such as acoustic logging, borehole televiewer, electrical and caliper logging, are not permeable and are not fluid conductive.

The VSP technique has been used in all types of rock with varying degrees of success. The greatest successes for fracture and hydraulic conductivity objectives have been achieved in igneous and competent metamorphic rocks, which appear to have rather distinctive faulting and fracturing zones. Its use in sedimentary rocks and weathered metamorphic rocks, which may have extensive zones of permeable materials, has been less successful.

VSP results away from the borehole are limited to the seismic-ray paths from the seismic source to the detectors. This procedure may, or may not, be sufficient to determine the lateral extent of a fracture away from the borehole and provide control on the attitude of any permeable fractures identified.

The VSP technique requires relatively sophisticated equipment when compared with many of the other borehole techniques. It is also time-consuming and, thus, relatively expensive.

## 8.3-5 GLOSSARY

Active technique - A technique in which a stress is applied to the material under study and the resultant response is measured. Stresses can include electrical current, sound waves, or neutron or gamma ray bombardment.

Calibration - The process wherein the zero and sensitivity of the logging circuitry is set so that the recorded measurements will be accurate with reaped to industry-standard units of measurement for a specific log-type (i.e., grams/cubic centimeter for rock density).

Dead time - In radioactive logging, the length of time (usually measured in microseconds) required by a logging system to recover from counting one disintegration event in order to count (record) the next event. Events occurring during dead time are not counted.

Formal depth-registered log - A geophysical log recorded on graph paper or digitally in which accurate downhole depths are simultaneously and systematically registered opposite corresponding log responses, and detailed logging run information is recorded in a log header.

Lithology - The physical character and composition of a rock, implying a specific rock or soil type.

Measuring point - The point, on a probe, where the reading is taken (e.g., the tips of the caliper arms; the detector on a gamma-ray probe).

Non-unique response - Response that is not unique to a specific rock characteristic. As examples, several different rock types exhibit low gamma-ray counts; or water-filled fractures and clay layers both have low resistivity values.

Passive techniques - A technique that measures properties inherent to the material. Examples include SP, gamma-ray, temperature.

Probe - The downhole electronics and detecting/measuring apparatus of the logging system, usually encased in a stainless steel jacket.

Radioactive decay - The transformation of an unstable isotope into an isotope of another element, resulting in a loss of energy and the emission of radiation (e.g., alpha or beta particles, neutrons and/or gamma rays).

Reference elevation - The aboveground elevation, which is designated as a common point for referencing all measurements for correlative purposes (commonly, ground surface or top of casing).

Resolution (vertical) - The capability of a logging system to distinguish geophysical changes between closely spaced (thin) lithologic units.

Rugosity - The degree of roughness or irregularity of the borehole wall, which affects some log types.

Total depth (TD) - The deepest point in the boring as determined by accurate measurement, in this instance geophysical logs. Discrepancies commonly occur between total drilling depth and total depth from geophysical logs, due to filling of the bottom of the borehole from caved material or to cable stretch (very deep holes only).

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# SECTION 8.3
# BOREHOLE GEOPHYSICS
# LIST OF FIGURES

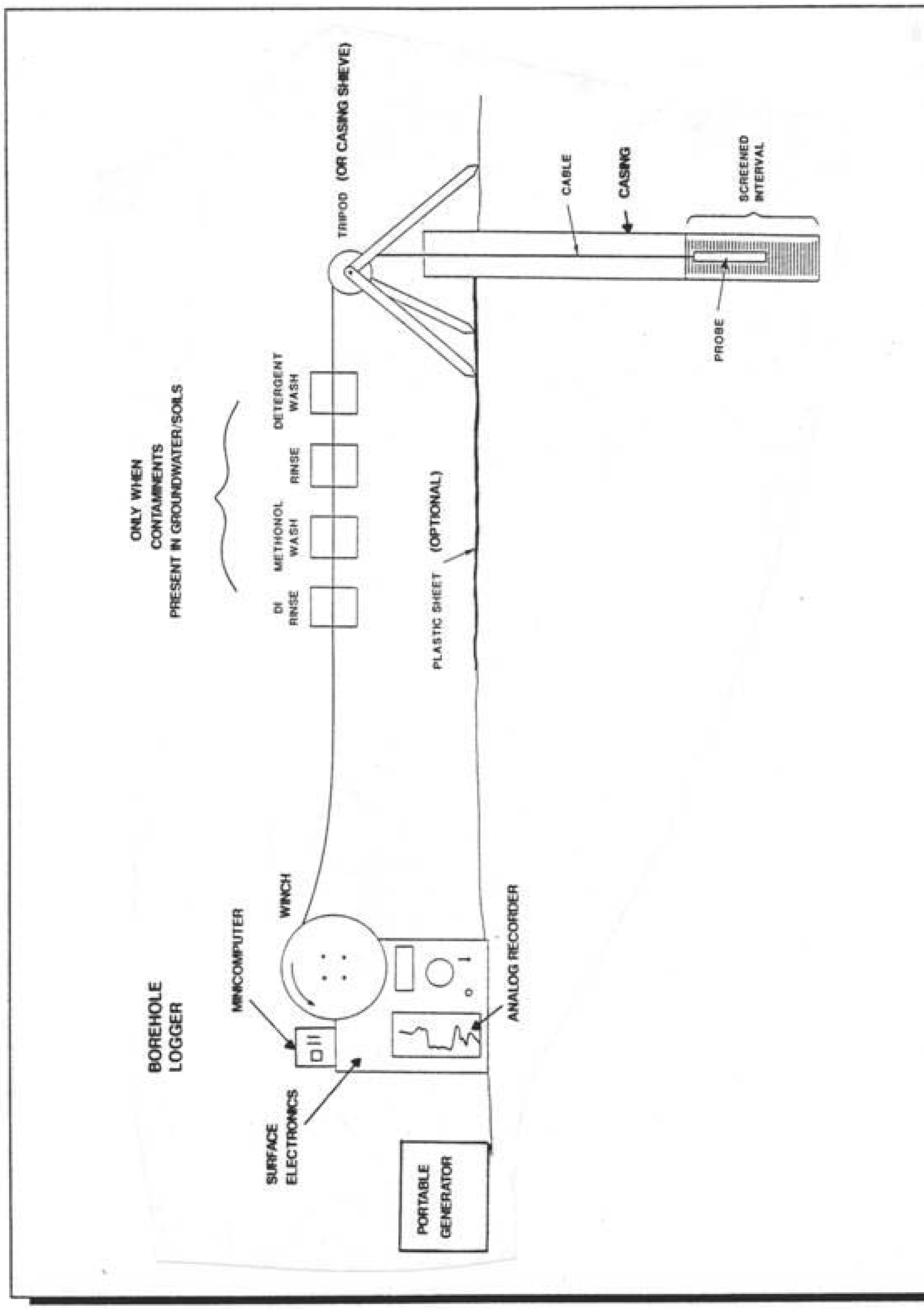



Figure 8.3-1
Typical Geophysical Logging Setup

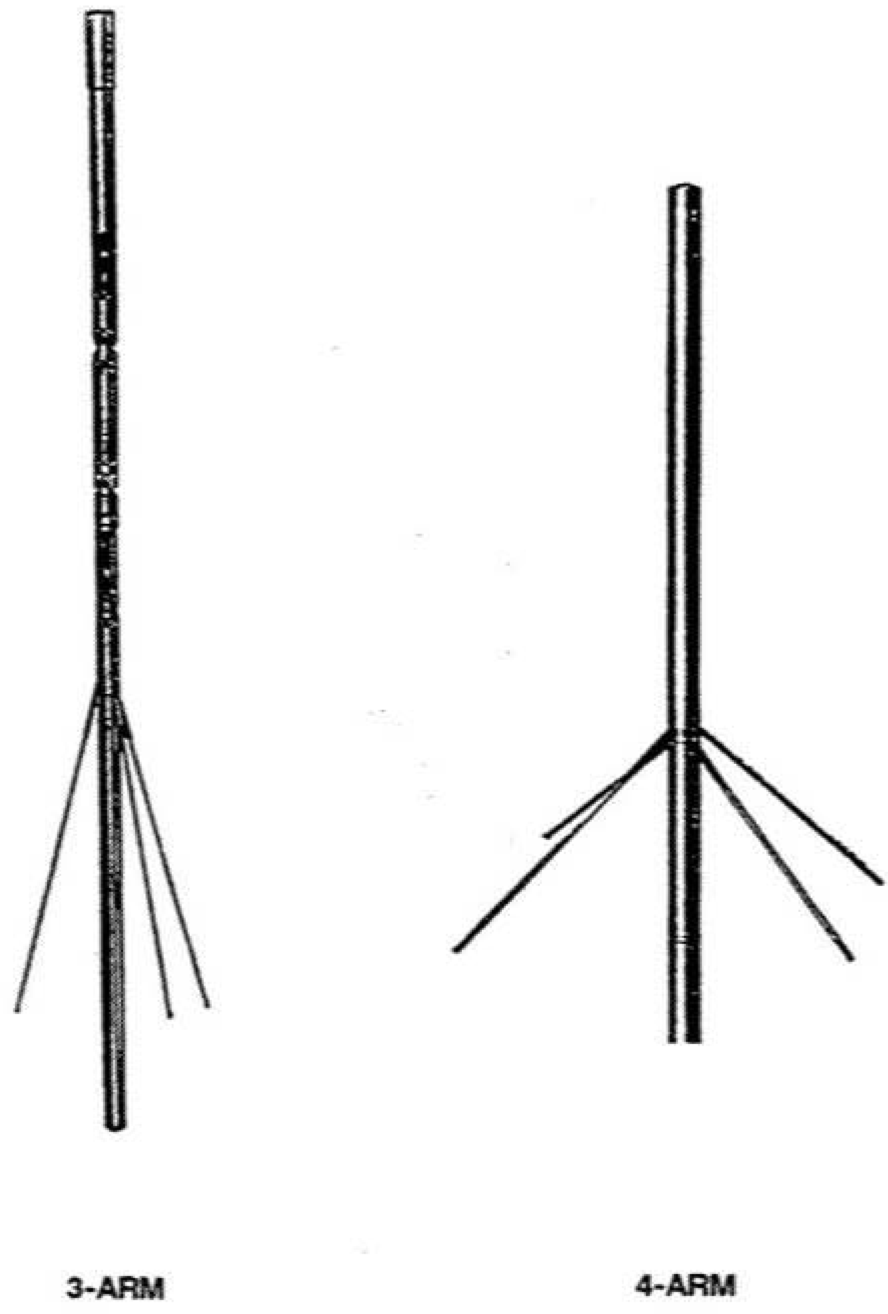
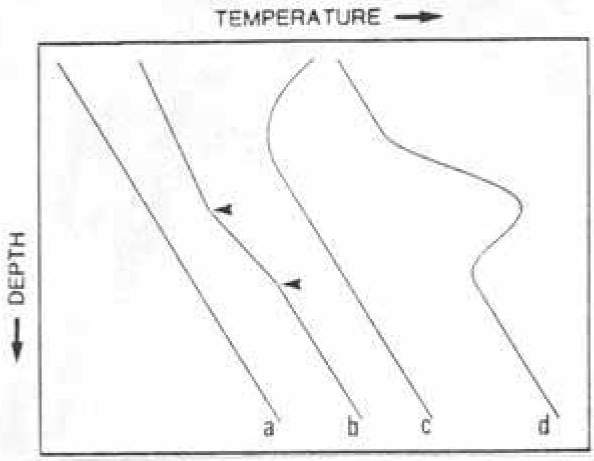


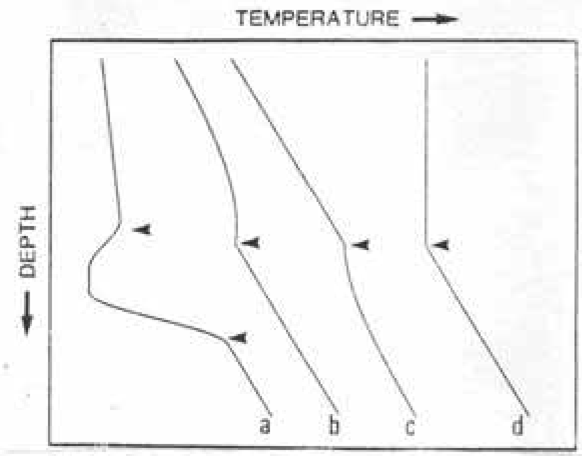

Figure 8.3-2

Caliper Probes



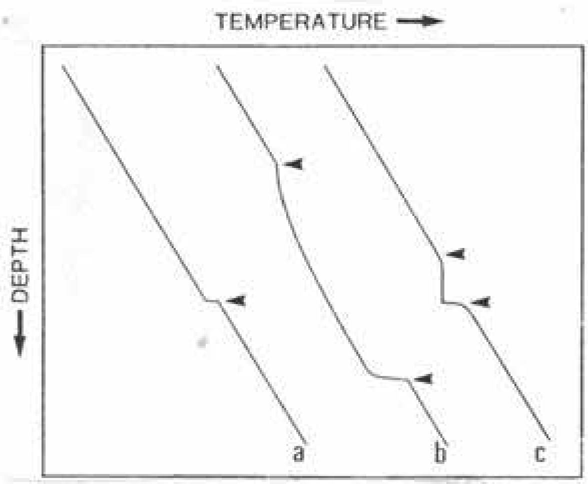

## Geologic Controls

**Figure A** - *Curve a* shows a temperature survey in a thermally stable borehole through a uniform, homogeneous formation. There are no disturbances of any kind. *Curve b* shows a log through three different parallel, homogeneous formations having three different thermal resistivities. The bed boundaries are indicated by the two arrows. *Curve c* shows what the effect of a warming trend on the surface of the ground might be. *Curve d* shows the effect of the exothermic reaction involved in fresh cement setting behind the casing.




## Groundwater Controls

**Figure B** - *Curve a* shows how a permeable zone can appear on a temperature log in a borehole after a period of circulation of liquid colder than the rock in that region. The permeable zone is bracketed by the two arrows. The thermal gradient in the upper portion of the borehole has be changed a great deal by the circulating liquid, and the permeable zone where circulation was lost stands out as an anomalous low-temperature region. *Curve b* shows the effect of liquid entering the borehole at the arrow and flowing upward. The effect of the liquid flowing in the borehole can be manifested in the temperature log in many ways depending on flow rate, flow direction, properties of the rock, and number and nature of the zones of entry and exit of the liquid. *Curve c* shows the effect of liquid entering the borehole at the arrow and flowing downward. *Curve d* shows the same condition as Curve b, but with the liquid flowing much faster.




## Special Conditions

**Figure C** - *Curve a* shows liquid entering the borehole at the bottom and flowing upward, exiting at the arrow. *Curve b* shows liquid entering the borhole at the upper arrow and flowing downward to exit at the lower arrow. *Curve c* shows what might happen if the tool hangs up on the way down the hole, and then drops free after a short period of time.

From: Conaway (1987)

**Figure 8.3-3**

**Interpretations of Borehole Temperature Profiles**

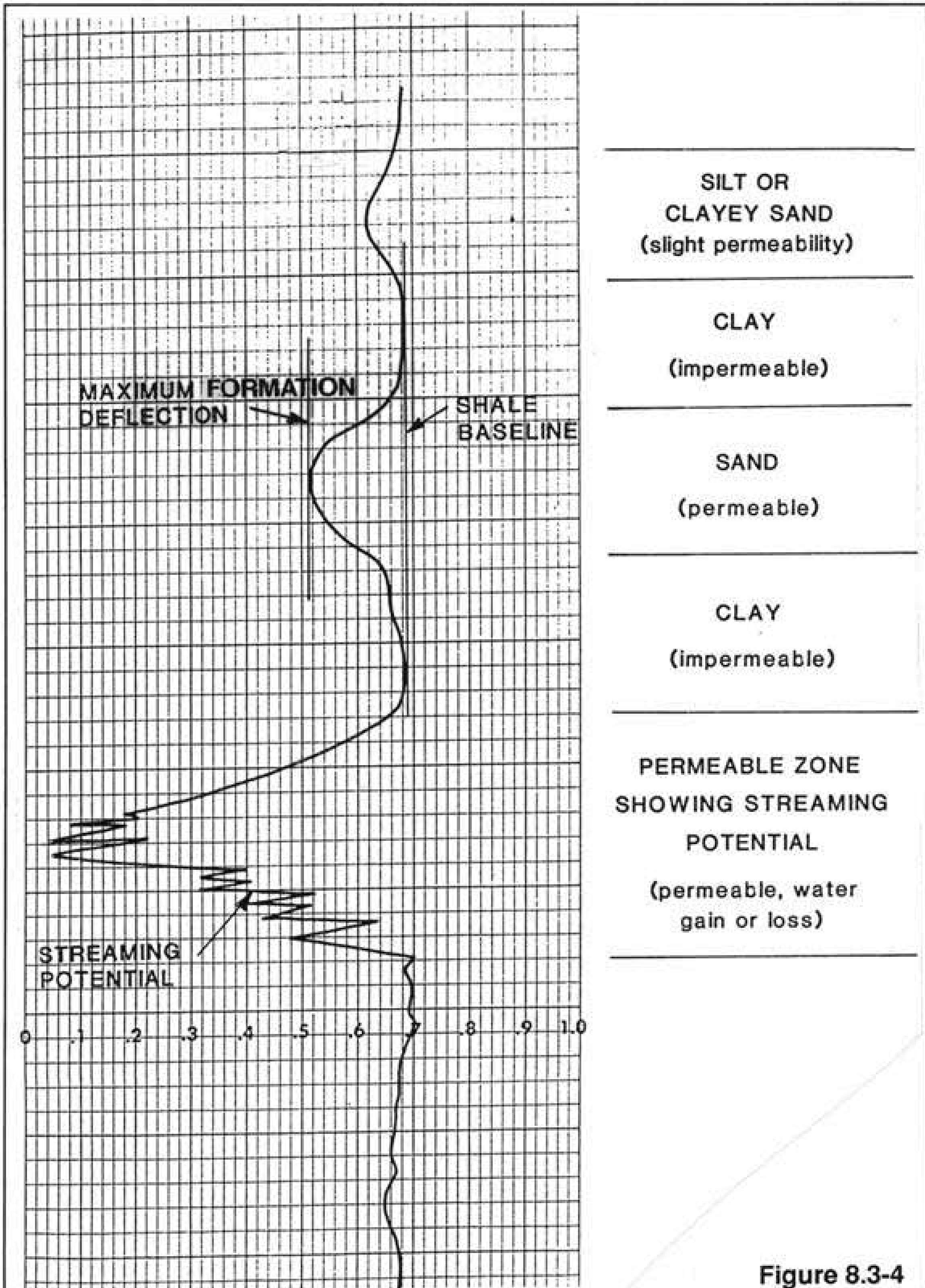
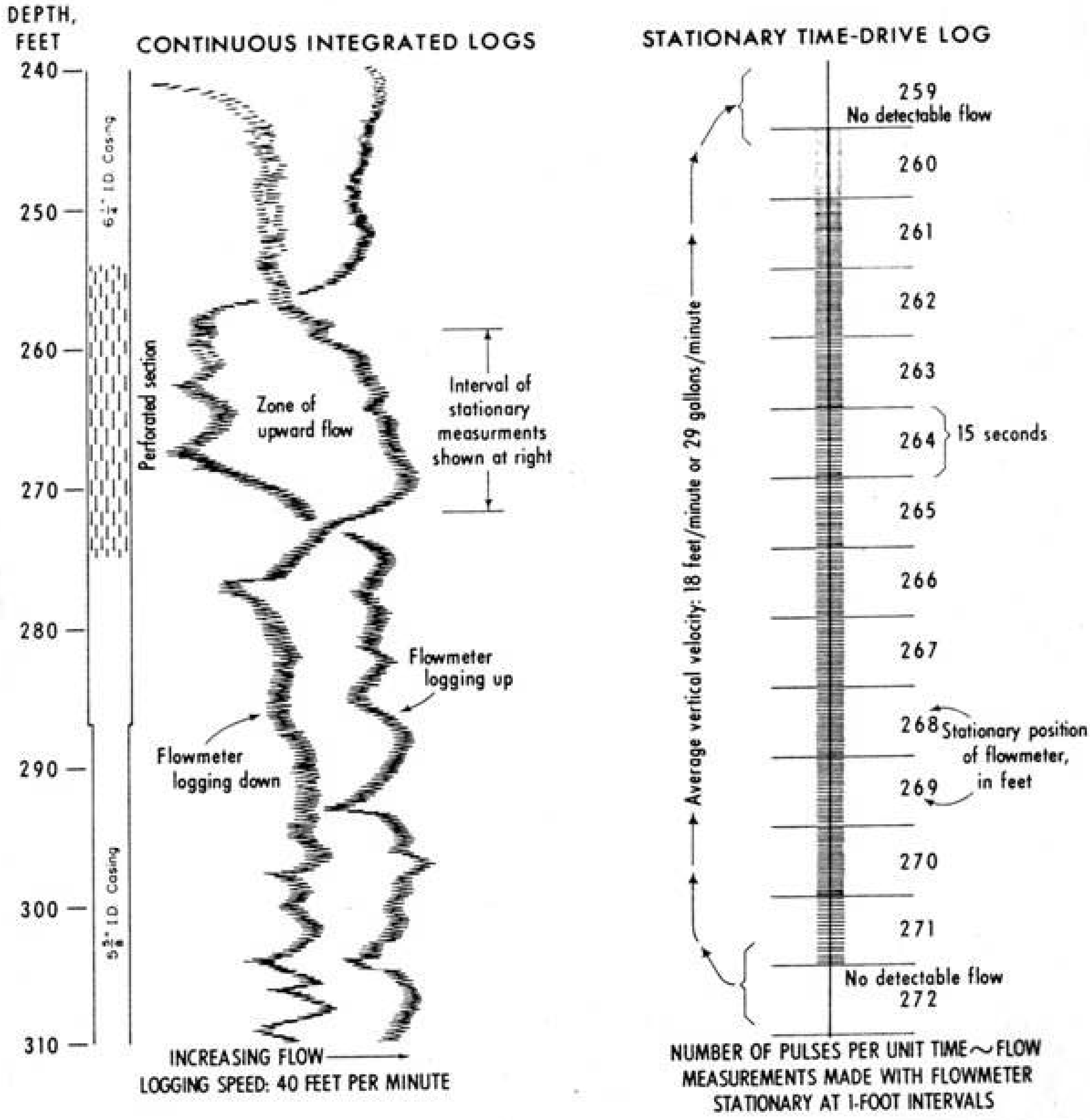



**Figure 8.3-4**

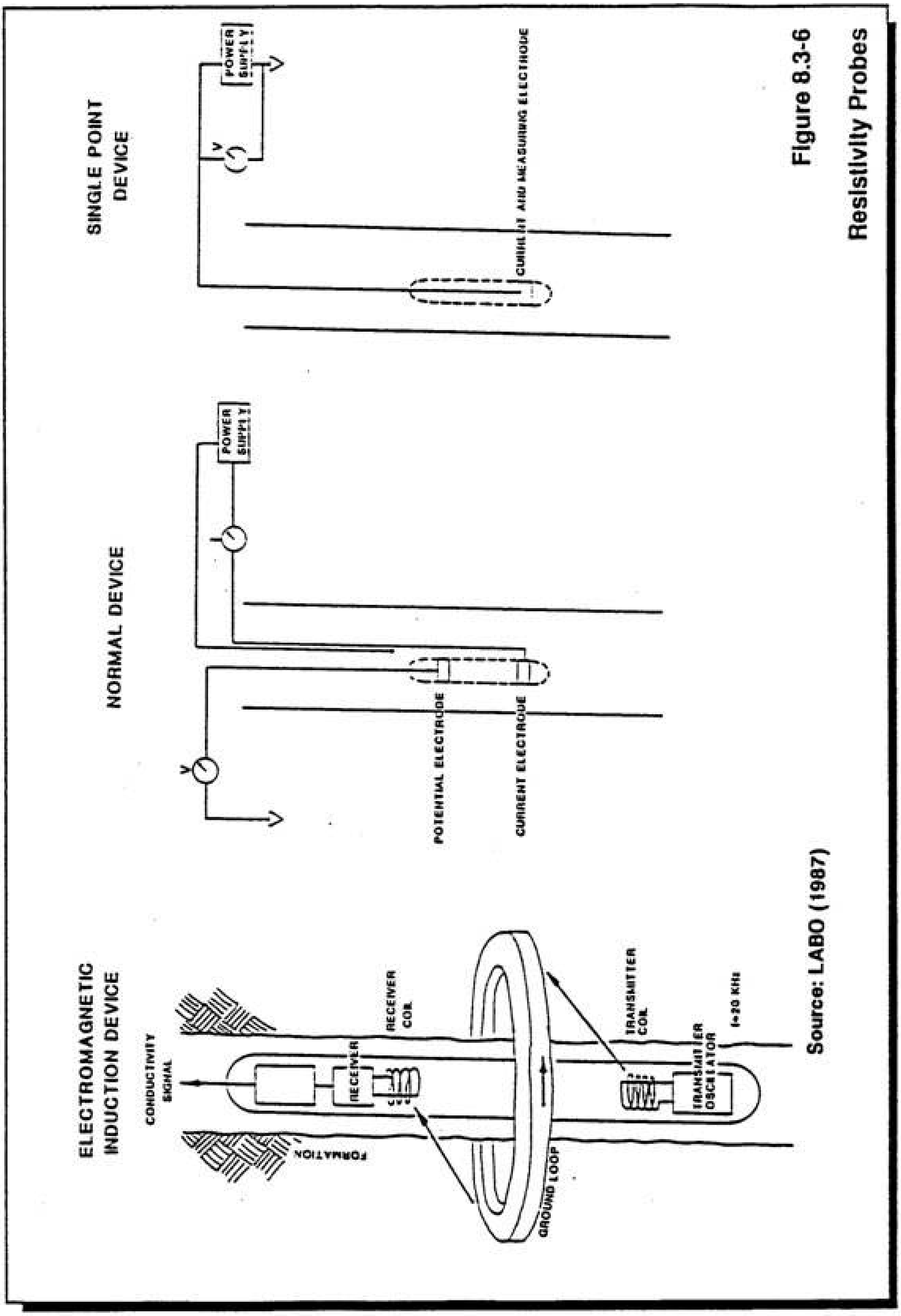
**SP Log Example**




Source:
Keys and MacCory (1971)

**Figure 8.3-5**

**Example of Flowmeter Log**




Source: LABO (1987)

**Figure 8.3-6**
**Resistivity Probes**

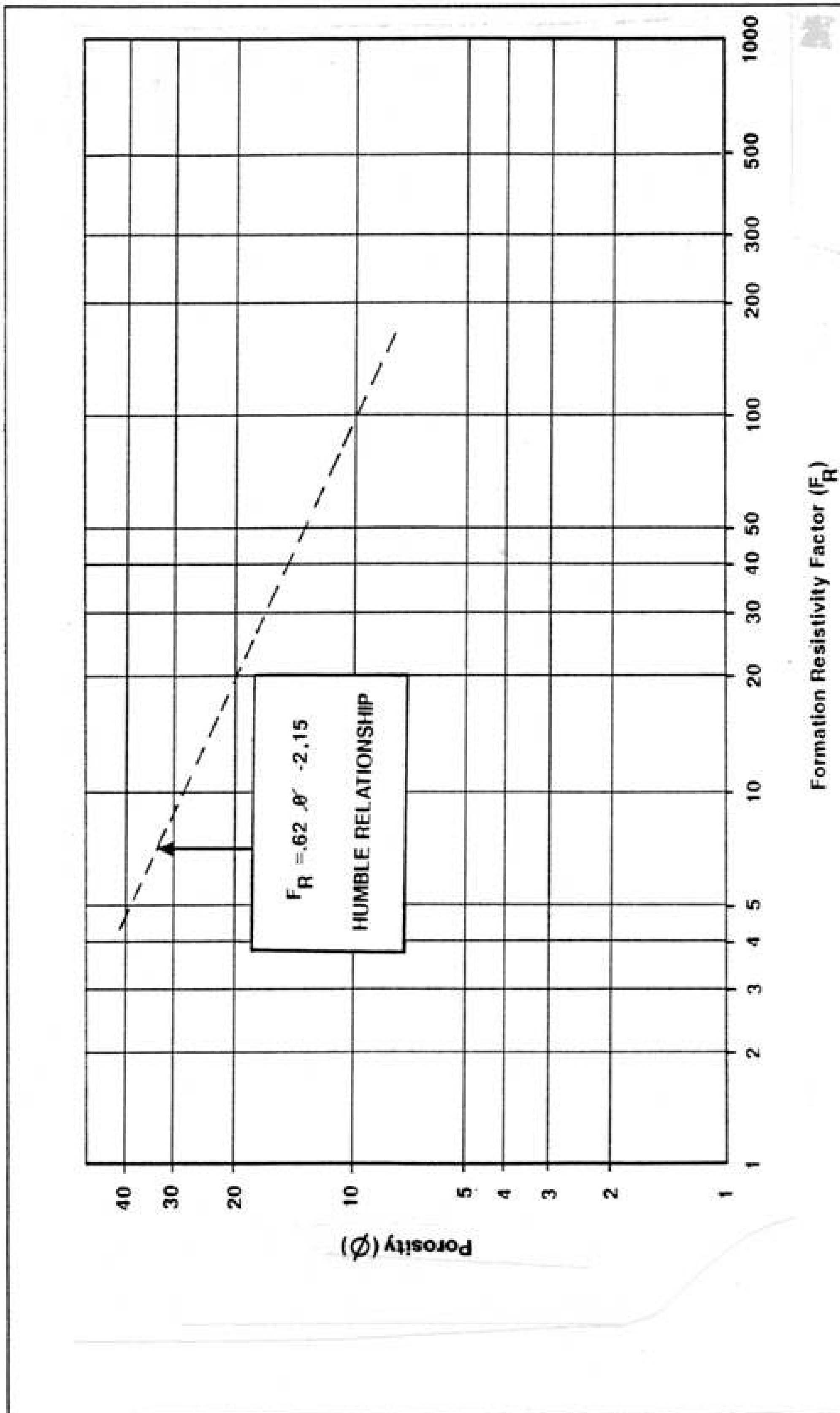
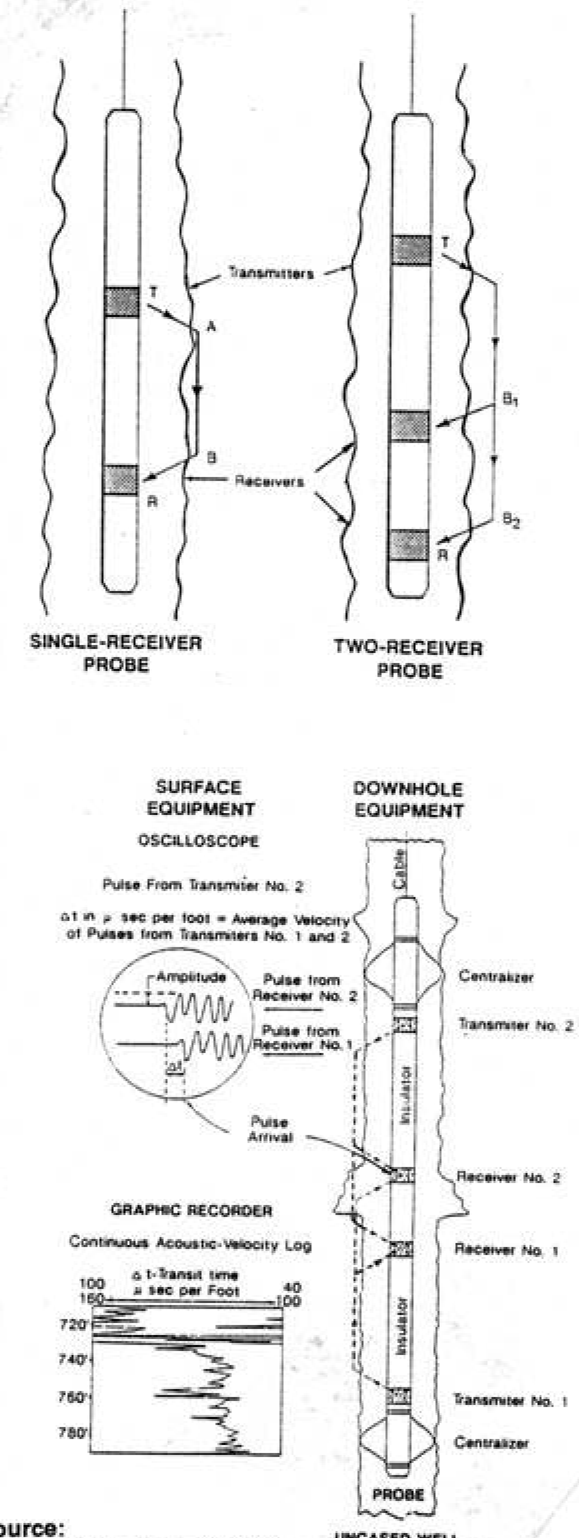



**Figure 8.3-7**

**F Versus o Plot for Sandstones**

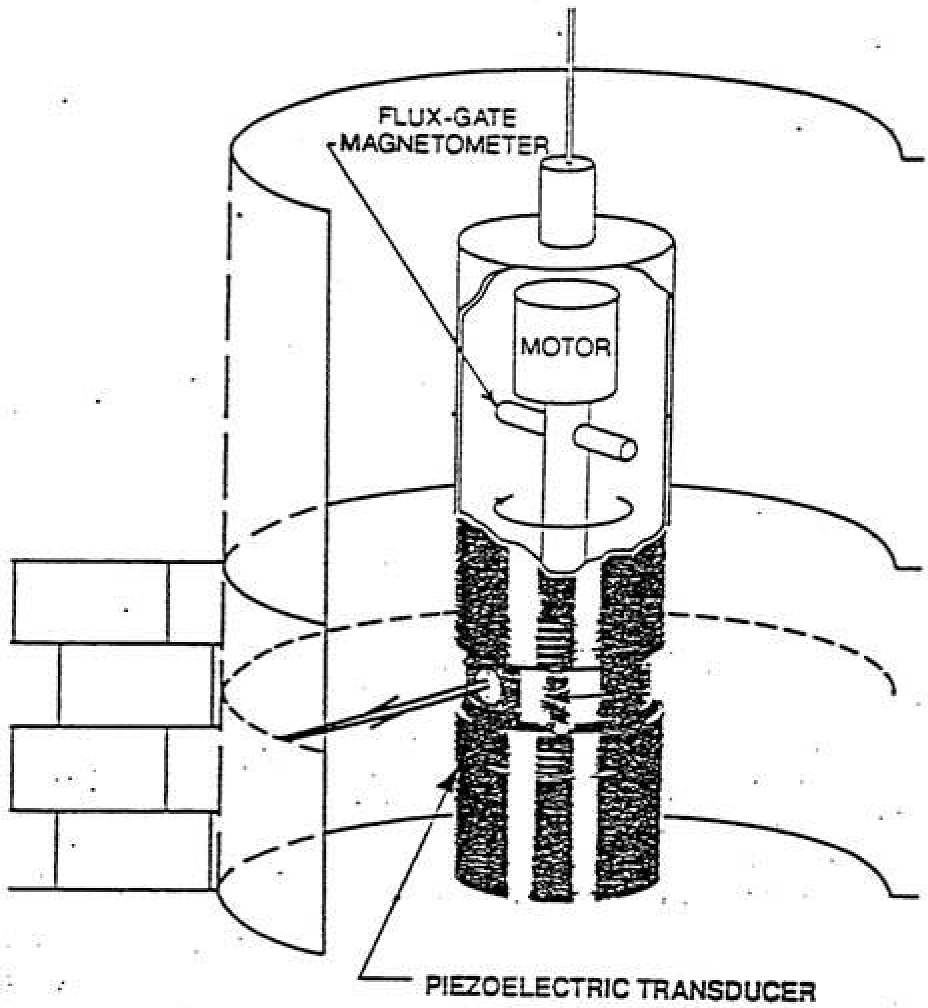
**Source: Simplified from Hilche (1978)**




Source:
Keys and MacCary, (1971)

**Figure 8.3-8**

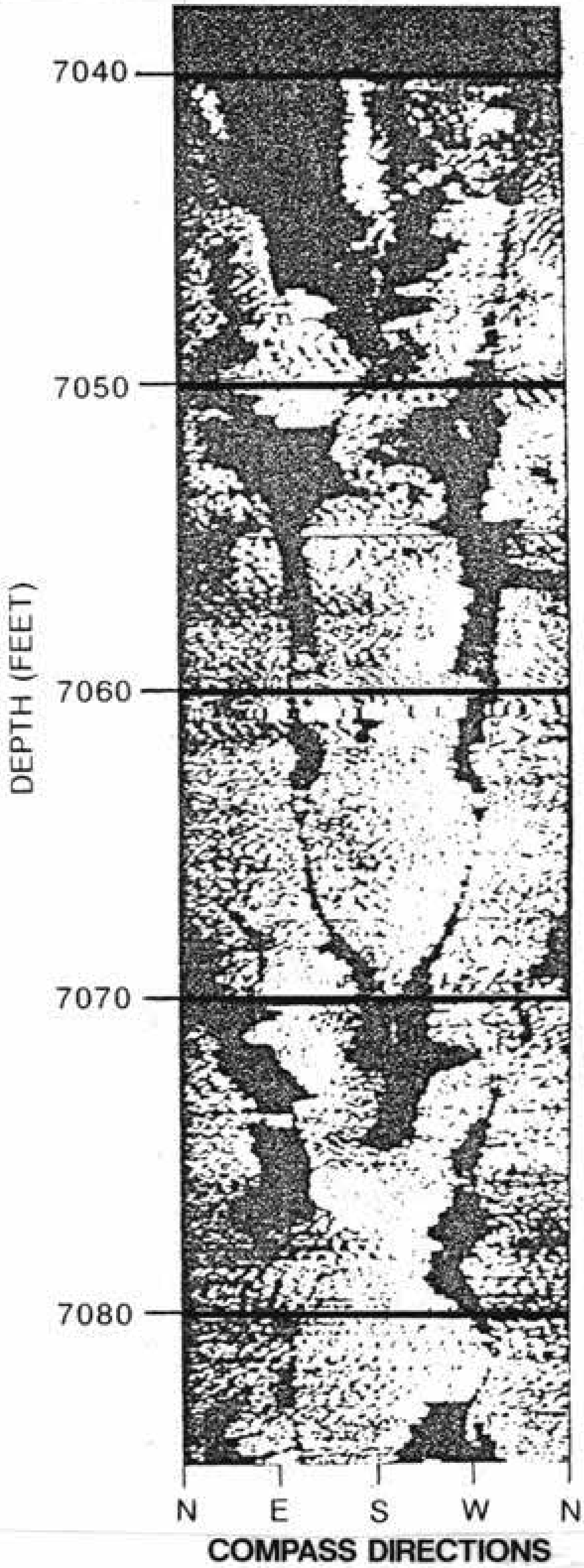
**Acoustic Velocity Logging**




Source:
Zemanek et al. , (1970)

Figure 8.3-9

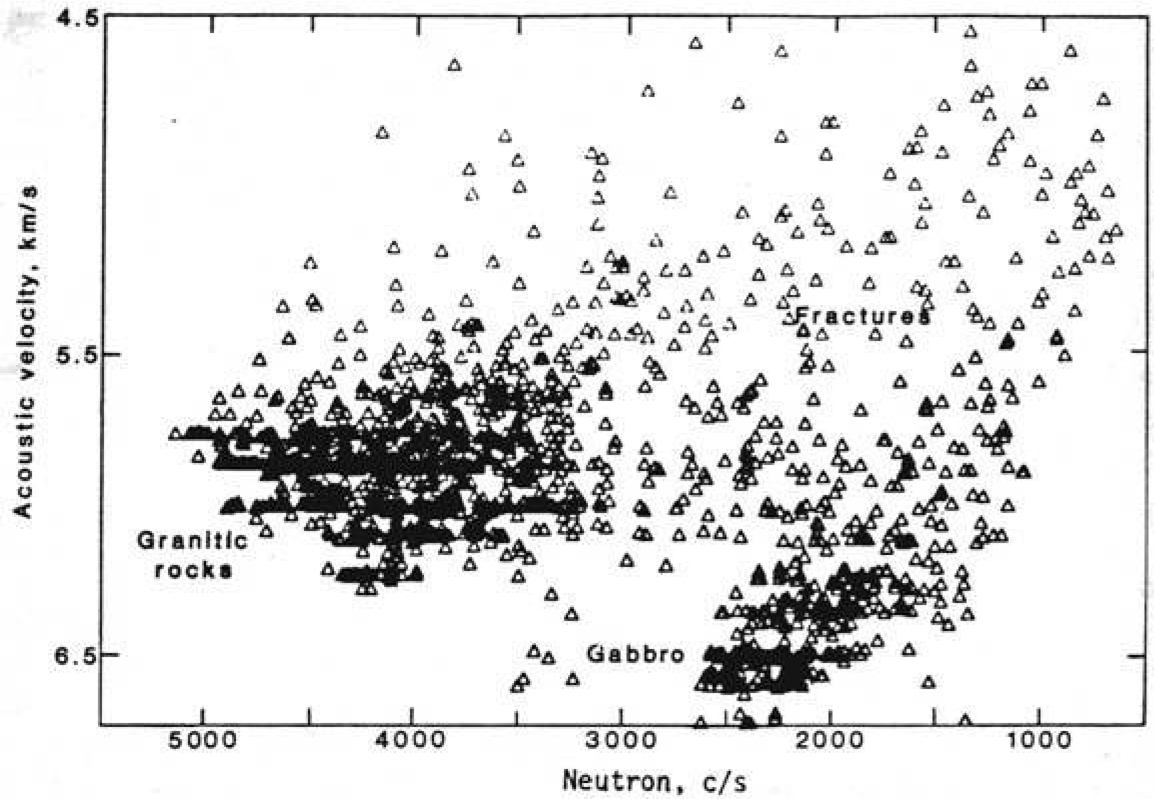
Acoustic Televiewer Diagram




Source:
Zemanek et al. , (1970)

Figure 8.3-10

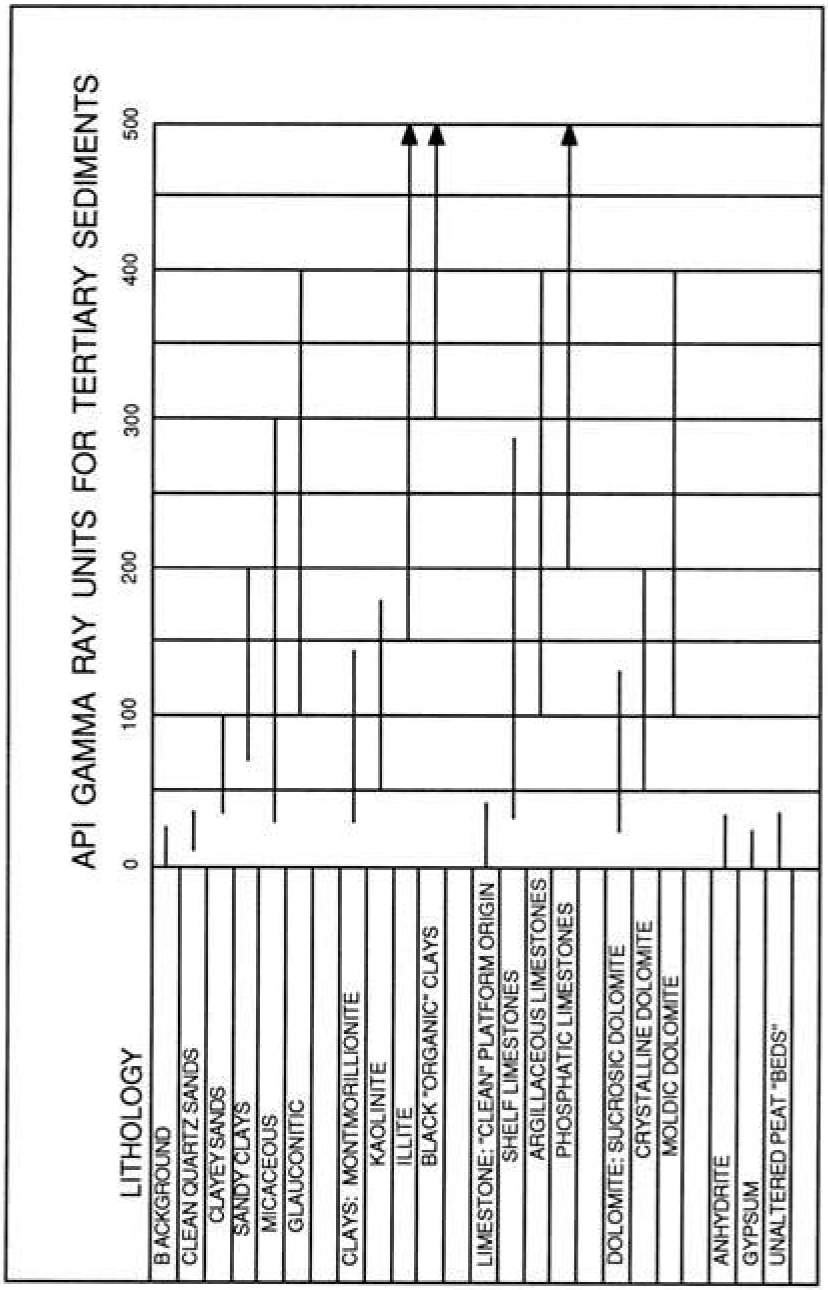
Example of Acoustic Televiewer Image




Source:
Davison et al. , (1982)

**Figure 8.3-11**

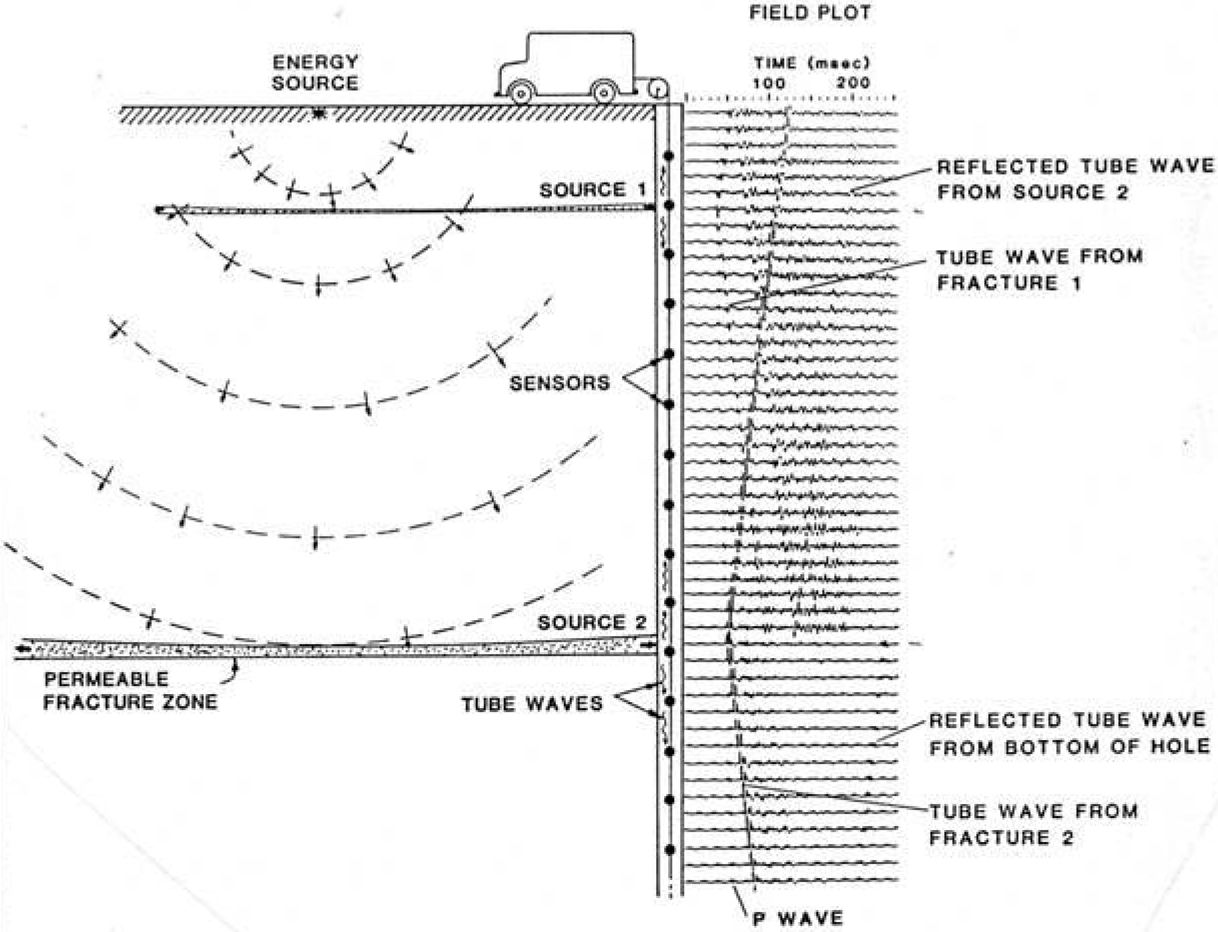
**Example of Cross-plot of Acoustic Velocity and Neutron Logs with Geologic Interpretation**




Source:
Kwader, (1982)

**Figure 8.3-12**

**API Gamma Ray Units for Various Tertiary Sediments**




Source:
Levine et al., (1985)
Modified by Weston Geophysical (1988)

**Figure 8.3-13**

**Tube Waves Generated by Seismic Energy Incident on Permeable Fracture Zones**

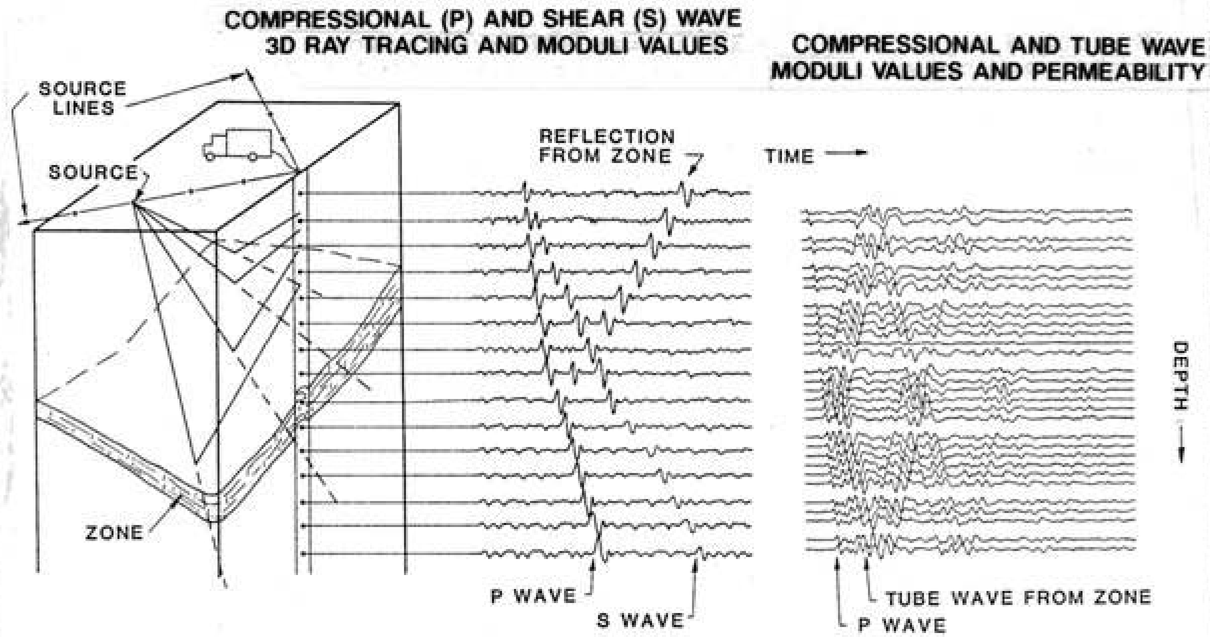
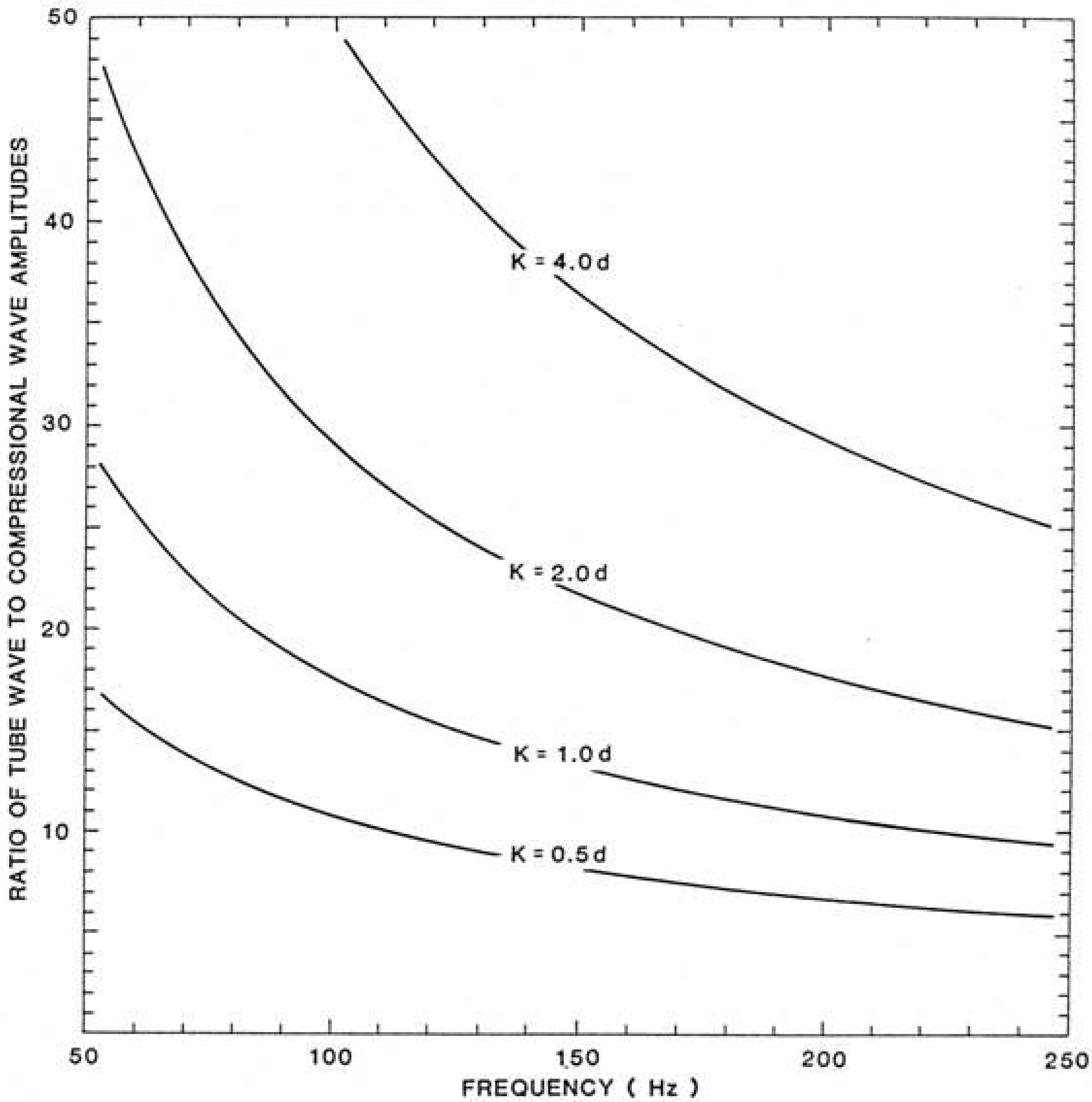



**Figure 8.3-14**

**VSP to Determine 3D Geometry of Strata, Moduli Values and Permeability**




Source:
Levine et al., (1985)

**Figure 8.3-15**

**Relationship Between Hydraulic Conductivity and Ratios of Tube Waves to P Wave Amplitudes as a Function of Frequency**

# SECTION 8.3
# BOREHOLE GEOPHYSICS
# LIST OF TABLES

## GEOPHYSICAL TECHNIQUES

| APPLICATION / INFORMATION DESIRED \ MEASUREMENTS-METHOD | Acoustic Amp. and △ T | Acoustic Waveform | Spontaneous Potential (SP) | Single Point Resistance | Short Normal (16") Res. | Long Normal (64") Res. | | | Fluid Resistivity | | Induction Electromagnetic | | Natural Gamma | Focused G-G Density | | Neutron-Thermal Neutron | Temperature | Caliper | | | Flowmeter |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Borehole Fluid Quality | | | | ● | | | | | ■ | | | | | | | | ■ | | | | |
| Casing Features | ■ | ■ | | ■ | | | | | ■ | | | | | △ | | | ■ | □ | | | ■ |
| Cement Features or Bond | ■ | ■ | | | | | | | | | | | | △ | | △ | ■ | ○ | | | |
| | | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | |
| Densities | ● | ● | | | | | | | | | | | | △ | | △ | | ○ | | | |
| Depositional Environment | ● | ● | ● | ● | ● | ● | | | | | * | | □ | △ | | △ | | ○ | | | |
| | | | | | | | | | | | | | | | | | | | | | |
| Fluid Flow | | | ● | | | | | | | | | | | | | | ■ | | | | ■ |
| Formation Water Res. (Rw) | ● | | ● | | | ● | | | ■ | | * | | □ | △ | | △ | | ○ | | | |
| Formation Res. (Rt) | | | | | | ● | | | ● | | * | | | | | | | ○ | | | |
| Fracture Detection | ● | ● | | | ● | ● | | | | | | | | | | △ | ■ | ○ | | | |
| Geologic Structure | ● | ● | ● | ● | ● | ● | | | | | * | | □ | △ | | △ | | ○ | | | |
| Geotechnical Studies | ● | ● | ● | ● | ● | ● | | | | | * | | □ | △ | | △ | | ○ | | | |
| Hazardous Waste Studies | ● | ● | ● | ● | ● | ● | | | ■ | | * | | □ | △ | | △ | ■ | ○ | | | ■ |
| | | | | | | | | | | | | | | | | | | | | | |
| Lithology - Stratigraphy | ● | ● | ● | ● | ● | ● | | | | | * | | □ | △ | | △ | | ○ | | | |
| Mineral Identification | ● | | ● | | | | | | | | | | □ | △ | | △ | | ○ | | | |
| Permeability Estimates | ● | ● | ● | | ● | ● | | | | | | | □ | △ | | △ | ■ | ○ | | | ■ |
| Porosity | ● | ● | | | ● | ● | | | | | | | □ | △ | | △ | | ○ | | | |
| | | | | | | | | | | | | | | | | | | | | | |
| Rock Properties | ● | ● | | | ● | ● | | | | | | | □ | △ | | △ | | ○ | | | |
| Shaliness Evaluaton | ● | | ● | | ● | ● | | | | | | | | △ | | △ | | ○ | | | |
| Hydrocarbon Investigation | ● | ● | ● | | ● | ● | | | ● | | * | | □ | △ | | △ | | ○ | | | |
| | | | | | | | | | | | | | | | | | | | | | |
| Water Investigations | ● | | ● | ● | ● | ● | | | ● | | * | | □ | △ | | △ | ■ | ○ | | | ■ |
| Water Saturation | ● | ● | | | ● | ● | | | ● | | * | | | △ | | △ | | ○ | | | |

○ Open Hole Only

● Open Fluid Filled Hole Only

+ Steel Casing Only

□ No Restriction on Hole

■ Cased or Open Fluid Filled Hole

△ Active Nuclear Log to be Run Only in Stabel or Cased Holes Only

* Open or Non-Steel casing Only - Dry or Fluid Filled

Source:
Adopted from Keys, (1971) and Colog, Inc. (unpublished)

Table 8.3-1

Common Borehole Logging Techniques

| Material and Source | Compressional velocity m/s | Compressional velocity ft/s | Shear velocity m/s | Shear velocity ft/s |
|---|---|---|---|---|
| Granite: | | | | |
| Barriefield, Ontario | 5640 | 18,600 | 2870 | 9470 |
| Quincy, Mass. | 5880 | 19,400 | 2940 | 9700 |
| Bear Mt., Tex. | 5520 | 17,200 | 3040 | 10,000 |
| Granodiorite, Weston, Mass. | 4780 | 15,800 | 3100 | 10,200 |
| Diorite, Salem, Mass. | 5780 | 19,100 | 3060 | 10,100 |
| Gabbro, Duluth, Minn. | 6450 | 21,300 | 3420 | 11,200 |
| Basalt, Germany | 6400 | 21,100 | 3200 | 10,500 |
| Dunite: | | | | |
| Jackson City, N.C. | 7400 | 24,400 | 3790 | 12,500 |
| Twin Sisters, Wash. | 8600 | 28,400 | 4370 | 14,400 |
| Sandstone | 1400–4300 | 4620–14,200 | | |
| Sandstone conglomerate, Australia | 2400 | 7920 | | |
| Limestone: | | | | |
| Soft | 1700–4200 | 5610–13,900 | | |
| Solenhofen, Bavaria | 5970 | 19,700 | 2880 | 9500 |
| Argillaceous, Tex. | 6030 | 19,900 | 3030 | 10,000 |
| Rundle, Alberta | 6060 | 20,000 | | |
| Anhydrite, U.S. Midcontinent, Gulf Coast | 4100 | 13,530 | | |
| Clay | 1100–2500 | 3630–8250 | | |
| Loose sand | 1800 | 5940 | 500 | 1,650 |

Source: Clark (1966)

**Table 8.3-2**

**Compressional and Shear Velocities in Rocks**