Chapter 8
Geophysical Techniques

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8.1 Introduction

The use of geophysical techniques for the investigation of contaminated sites can provide rapid and cost-effective option for remedial activities. The information obtained from a geophysical investigation can be used to determine the subsurface conditions. Various geophysical techniques can be a tool in determining subsurface features such as hydrostratigraphic units, depth to bedrock, extent of concentrated ground water contaminant plumes, the location of voids, faults or fractures, and the presence of subsurface features, such as drums or utilities. Geophysical technique(s) used in the investigation, should be provided in the project workplan or QAPP.

Geophysical investigations are most effective when used in conjunction with a drilling or boring program and should not be considered a substitute for such programs. The information gained from a surface geophysical survey can be used to choose optimal locations for the placement of boreholes, monitor wells or test pits, as well as to correlate geology between monitor wells and boreholes. The information derived from a geophysical survey can also be used to reduce the risk of drilling into subsurface features, such as buried drums or utilities.

Each geophysical technique has its advantages and limitations. The combination of two or more techniques in an integrated interpretation results in a reduction of the degree of ambiguity. A geophysical investigation is generally most useful early in the investigation to provide guidance for other investigation activities.

In some instances, site conditions may preclude the successful use of most or all geophysical techniques. These conditions include the presence of factors that degrade the ability of the geophysical instruments to measure various physical parameters. For instance, the presence of strong electromagnetic fields at site may preclude the use of some geophysical techniques. Under such instances the use of geophysics may not be recommended. However, the application of geophysical methods should not be entirely dismissed until an experienced geophysicist evaluates the site. Although geophysical techniques may not be directly applicable onsite, a geophysical survey of the area surrounding the site may be useful to assist in the understanding of the hydrogeology of the impacted area.

Each site must be considered unique. The project geophysicist should therefore evaluate all material at their disposal prior to the implementation of a geophysical survey plan. In addition to visiting the site, an examination of recent aerial photography, Lidar surveys, existing geographical information system layers, geologic maps, well data, and other information is recommended. A “generic” approach to work plans should be avoided due to the wealth of available geophysical data in New Jersey.

Performance guidelines for surface geophysical techniques and borehole methods, are presented in this chapter. The surface methods included are ground penetrating radar (GPR), electrical resistivity, time, frequency-domain, electromagnetic spectral analysis (EM), very-low frequency (VLF), Seismic, and Borehole Geophysics Methods. Advances in some methods have made other methods obsolete for most uses. Time-domain EM replaced magnetic surveys and electrical resistivity replaced seismic. Other less common methods or emerging methods that are not in this Chapter; include spontaneous or self-potential (SP), controlled source audio-magneto tellurics (CSAMT), infrared (IR), surface wave methods, sonar, electromagnetic, and seismic methods, and airborne geophysical methods. The reader should consult the literature for more information on these methods.

Metal detectors are not included in this Chapter because most are essentially electromagnetic systems whose response is an audio or visual feedback that is rarely recorded. These instruments may be useful immediately prior to excavation to relocate some anomalous areas or mark underground utilities or metallic infrastructure. Although radiometric devices (scintillation counters and Geiger counters) and organic vapor analyzers can technically be considered geophysical instruments, they are more commonly referred to as health and safety monitoring devices and are therefore not included in this chapter.

The reader is advised to consult the literature if additional information on a particular method is needed. The use of new geophysical techniques or algorithms is encouraged if the investigation addresses the problem, and the work plan is within budgetary constraints.

The NJDEP maintains a library of guidance manuals on its website at https://www.nj.gov/dep/srp/guidance/. It is recommended the reader access the website and review the guidance manuals pertinent to the respective task. Additional guidance may also be found at websites of the EPA and the American Society for Testing and Materials (ASTM). Examples of some of the relevant guidance manuals pertaining to this chapter are:

Soil Investigation Technical Guidance https://www.nj.gov/dep/srp/guidance/#si_ri_ra_soils;

Ground Water Technical Guidance: https://www.nj.gov/dep/srp/guidance/#pa_si_ri_gw;

Ecological Evaluation Technical Guidance: https://www.nj.gov/dep/srp/guidance/#eco_eval;

Quality Assurance Project Plan Technical Guidance https://www.nj.gov/dep/srp/guidance/#analytic_methods;

Vapor Intrusion Technical Guidance https://www.nj.gov/dep/srp/guidance/#vi; and

OSHA: https://www.osha.gov.

8.2 Ground Penetrating Radar (GPR)

8.2.1 Fundamentals

The GPR method has been used for a variety of civil engineering, ground water evaluation and hazardous waste site applications. Of all geophysical techniques available, it is one of the most used. It provides subsurface information ranging in depth from several tens of meters to only a fraction of a meter. A basic understanding of the function of the GPR instrument, together with knowledge of the geology and mineralogy of the site, can help determine if GPR will be successful in the site assessment. When possible, the GPR technique should be integrated with other geophysical and geologic data to provide the most comprehensive site assessment.

The GPR systems uses a transmitter that emits pulses of high-frequency electromagnetic waves into the subsurface. The penetrating electromagnetic waves are reflected at changes in the complex dielectric permittivity, which is a property of the subsurface material dependent partially upon the bulk density, clay content and water content of the subsurface. The electromagnetic energy is reflected to the receiving antenna and is recorded as a function of time. Most GPR systems are monostatic (transmitter and receiver are close together and the separation is fixed). Bistatic GPR systems, where the transmitter and receiver are separated, are also available.

Depth penetration of GPR is severely limited by attenuation and/or absorption of the transmitted electromagnetic (radar) waves into the ground. Generally, penetration of radar waves is reduced by a shallow water table, high clay or salt content of the subsurface, and in areas where the electrical resistivity of the subsurface is less than 30 ohmmeters. Ground penetrating radar works best in dry sandy soil where the water table is deep. Under optimal conditions, depth penetration is between one and ten meters. Iron and steel are nearly perfect reflectors of, and no reflections are received from beneath a large piece of steel. But the strong reflection makes GPR ideal for finding subsurface steel, such as tanks.

The plot produced by most GPR systems is analogous to a seismic reflection profile; that is, the data are usually presented with the horizontal axis as distance units (feet or meters) along the GPR traverse and the vertical axis as time units (nanoseconds). The GPR profile should not be confused with a geologic cross section, which shows data as a function of horizontal distance versus depth. Some of the digital systems will present the data as a depth profile. Caution must be exercised when viewing data in this fashion as the equipment operator usually inputs conversion factors to view the data as a depth profile. Very high resolution (as great as ± 0.1 meter) is possible using GPR calibration of depth to recorded features with parabola matching, using reflectors that can be observed (such as a drainage pipe), or depth measurements from boreholes.

Under optimal conditions, GPR data can resolve changes in soil horizons, bedrock fractures, water-insoluble contaminants, geological features, man-made buried objects, voids, and hydrologic features such as the water table depth and wetting fronts.

8.2.2 Advantages

Most GPR systems can provide a continuous display of data along a traverse, which can often be interpreted qualitatively in the field. GPR can provide high-resolution data under favorable site conditions and is capable of operation over reinforced concrete. The real-time capability of GPR results in a rapid turnaround and allows the geophysicist to quickly evaluate subsurface site conditions.

8.2.3 Limitations

One of the major limitations of GPR is the site-specific nature of the technique. Another limitation is the cost of site preparation necessary prior to performing the survey. Most GPR antennas need to have good contact with the ground surface. Ideally, the ground surface should be flat, dry, and clear of any brush or debris. The quality of the data can be degraded by a variety of factors such as an uneven ground surface or various cultural noise sources. Because of the electrical properties of salt, salt is very effective at absorbing radar waves; therefore, GPR is not effective on surfaces treated with salt during the winter months. This is generally a permanent condition due to the retention of salt in the subsurface and annual reapplication.

The United States Department of Agriculture produces a GPR suitability map for the United States. The map for New Jersey is available at
https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053622.

8.2.4 Instrumentation

There are several manufacturers of commercially available GPR systems. The specifications of the instrument should be documented or referenced in the investigation report. The frequency of the transmitting antenna should be selected based on the desired depth of penetration or resolution where higher frequency antenna produce higher resolution and lower penetration and low frequency antenna produce lower resolution and deeper penetration. The size of the antenna increases as the frequency decreases. Some commercial systems allow for interchanging between antennas to have some flexibility of frequency. Most GPR systems used in the environmental field are midrange frequency systems. Because GPR systems are diverse and complex in construction, a detailed description of the instrumentation is not practical in the context of this review. The equipment used should be appropriate for the goal of the investigation and the site conditions.

8.2.5 Survey Design, Procedure and Quality Assurance

GPR traverses should be positioned appropriately to resolve and locate the target. Depending upon the nature of the survey, a network of intersecting traverse lines (grid pattern) or reconnaissance traverse lines should be employed. Generally, GPR surveys are task oriented, and anomalies of interest are marked in the field and the anomalies can be mapped based on site reference points. Most GPR systems have a display with instantaneous results for immediate interpretation. Features such as buildings, monitor wells, property lines, and sources of cultural interference should also be noted on the map. There should be a redundancy of data with parallel or intersecting traverses. The detection of a target should not rest solely on the interpretation of one traverse.

GPR systems can create three-dimensional representations of the subsurface. This is done by collecting equally spaced transverses into a file. The file is downloaded to a computer with appropriate software. This representation can be rotated, view as profiles, and as time slices. This method requires processing and is labor-intensive but is useful in complex environments.

Quality assurance is achieved by repetition of transverses over the areas where there were anomalies with small variations in location. Results can also be checked by varying data collection parameters such as gains (adjusting the strength of the graphical representation of the reflections). An operator should be able to recognize air wave reflections and signals from overhead wires. The instrumental analysis conditions should be documented in the field notes.

8.2.6 Data Reduction and Interpretation

GPR data is interpreted as it is collected, and data processing is done in real time. Adjustments to data collection parameters are done in the field and can be adjusted for the site. When three-dimensional representations are done, there are more options for processing the results to provide higher precision and relative depths. GPR profiles are qualitatively evaluated, although it is also possible to make depth estimates. Depth estimates can be made using a nominal speed-of-light for soil, adjusting the depth scale based on an anomaly of a known depth or parabola fitting for a well-defined hyperbola anomaly.

8.2.7 Presentation of Results

A site map should be developed showing permanent landmarks, areas covered with the GPR, inaccessible areas, and locations of anomalies. The report should also contain information pertinent to the instrumentation, field operations, and data reduction and interpretation techniques used in the investigation.

8.3 Magnetometer

8.3.1 Fundamentals

A magnetometer is an instrument which measures magnetic field strength in units of gamma or nanoteslas (1 gamma = 1 nanotesla = 0.00001 gauss). Local variations, or anomalies, in the earth’s magnetic field are the result of disturbances caused mostly by variations in concentrations of ferromagnetic material in the vicinity of the magnetometer’s sensor. A buried ferrous object, such as a steel drum or tank, locally distorts the earth’s magnetic field and results in a magnetic anomaly. The common objective of conducting a magnetic survey at a hazardous waste or ground water pollution site is to map these anomalies and delineate the area of burial of the sources of these anomalies.

Analysis of magnetic data can allow an experienced geophysicist to estimate the regional extent of buried ferrous targets, such as a steel tank, canister, or drum. Often, areas of burial can be prioritized upon examination of the data, with high priority areas indicating a near certainty of buried ferrous material. In some instances, estimates of depth of burial can be made from the data. Most of these depth estimates are graphical methods of interpretation, such as slope techniques and half-width rules, as described by Nettleton (1976). The accuracy of these methods is dependent upon the quality of the data and the skill of the interpreting geophysicist.

The magnetic method may also be used at a site to map various geologic features, such as igneous intrusions, faults, and some geologic contacts that may play an important role in the hydrogeology of a ground water pollution site.

8.3.2 Advantages

Advantages of using the magnetic method for the initial assessment of hazardous waste sites are the relatively low costs of conducting the survey, and the relative ease of completing a survey in a short amount of time. Little, if any, site preparation is necessary. Surveying requirements are not as stringent as for other methods and may be completed with a transit or Brunton-type pocket transit and non-metallic measuring tape. Very often, a magnetic investigation is a very cost-effective method for the initial assessment of a hazardous waste site where steel drums or tanks are suspected of being buried.

8.3.3 Limitations

There are certain limitations in the magnetic method. One limitation is the problem of "cultural noise" in certain areas. Man-made structures that are constructed using ferrous material, such as steel, have a detrimental effect on the quality of the data. Features to be avoided include steel structures, power lines, metal fences, steel reinforced concrete, surface metal, pipelines, and underground utilities. When these features cannot be avoided, their locations should be noted in a field notebook and on the site map.

Another limitation of the magnetic method is the inability of the interpretation methods to differentiate between various steel objects. For example, it is not possible to determine if an anomaly is the result of a group of steel drums or old washing machines. Also, the magnetic method does not allow the interpreter to determine the contents of a buried tank or drum.

8.3.4 Instrumentation

Several types of magnetometers are commonly used in hazardous waste site investigations. These include the total-field proton-precession magnetometer, the fluxgate magnetometer, and the magnetic gradiometer. The specific operation and construction of these various instruments may be found in the literature.

The type of magnetometer most used in hazardous waste site investigations is the total-field proton-precession magnetometer. The quantity measured by this instrument is a scalar quantity consisting of the sum of the earth's field, the anomaly caused by the magnetic source, if any, and the variations of the field caused by diurnal (daily) drift, magnetic storms and micropulsations.

There is no instrument drift associated with this type of magnetometer. The sensor must be oriented with one side towards the North, and it must be held stationary when the reading is being taken. The major advantages of the proton precession magnetometer are the ease of operation and the rapid cycling rate of the instrument. This rapid cycling rate allows the operator to take a reading of the magnetic field strength in about one to two seconds. Modern proton precession magnetometers have digital readouts, electronic data storage, and internal GPS units.

The fluxgate magnetometer is another type of magnetometer that may be used to locate buried ferrous objects. When used by a skilled operator, the fluxgate magnetometer can define the boundaries of regions of buried steel objects more precisely than the proton precession magnetometer. The fluxgate magnetometer can also be used in instances when a continuous record is needed. A fluxgate magnetometer can also be used to acquire readings at discrete locations. Unlike the proton precession magnetometer, the fluxgate magnetometer does not measure the absolute value of the earth's magnetic field. Also, the fluxgate magnetometer requires an exact orientation of the instrument and physically leveling the instrument requires more time and skill on the part of the operator. An additional disadvantage of the fluxgate is that it is subject to instrument drift.

Vertical magnetic gradiometers are magnetometers, which measure the vertical gradient, or difference, of the earth's total magnetic field. This differential magnetometer is usually a proton precession magnetometer with two or more sensors mounted on a staff. A constant distance vertically separates these sensors, usually one or one-half meter. A true gradiometer takes simultaneous readings from both sensors. Some instruments take readings from the upper and lower sensors sequentially. It is important that the sensor be held stationary during the cycling period.

Gradient measurements enhance the anomalies resulting from shallow magnetic sources. This feature may be important when conducting a survey in an area where steel drums are expected to be buried in a region underlain by ferromagnetically rich bedrock. Examples include igneous or certain types of metamorphic rocks. However, it is important that the site have little or no ferrous debris lying on the ground surface, because the signal from these surface features will also be amplified. The tendency of the gradiometer to enhance the effects of surface metal should be considered at sites where there is an abundance of surface metal which cannot be removed prior to the investigation.

8.3.5 Survey Design, Procedure and Quality Assurance

The importance of survey planning cannot be overemphasized. Often, the difference between a successful investigation and a disastrous one lies in the care given to the proper planning and design of the survey.

Magnetic data can be acquired in two configurations: 1) a rectangular grid pattern, or 2) along a traverse. Grid data consists of readings taken at the nodes of a rectangular grid; traverse data is acquired at fixed intervals along a line. Each configuration has its advantages and disadvantages, which are dependent upon variables such as the site conditions, size and orientation of the target, and financial resources. The survey configuration should be selected on a site-specific basis.

In both traverse and grid configurations, the station spacing, or distance between magnetic readings, is important. “Single-point” or erroneous anomalies are more easily recognized on surveys that utilize small station spacing. If large areas of buried drums or large steel tanks are the targets, the station spacing can be large, sometimes as much as 20 to 25 feet. If the target is a single 55-gallon steel drum, a small steel canister, or a steel munitions container, smaller station spacing is needed. In such instances, a station spacing of five to 10 feet is suggested.

In most instances involving the initial assessment of a site where drum burial is suspected, optimum station spacing is 10 to 15 feet. For a cost-effective initial assessment, magnetic data be acquired in a traverse configuration with a station spacing of approximately 15 feet and a distance between traverses of 25, 50, or even as much as 100 feet, depending on site conditions. If an anomaly is encountered, additional traverses can be placed between the existing traverses. Traverses are sometimes aligned in a northerly orientation to define the asymmetric anomaly usually associated with buried ferromagnetic material.

Grid or traverse coordinates must be surveyed from a known location, such as a property corner, building, or other point that can be recovered at a future date. In addition to features such as buildings, roads, monitoring wells, and property lines, sources of potential cultural interference should be noted on the map. Non-magnetic survey markers should be used to mark grid or traverse coordinates.

Provisions should be made for monitoring and/or correcting for diurnal variations. Various methods include recording the diurnal data with a base station monitor or looping back to a base location or base line. The magnetometer base station or loop reference point should be in an area that is free from cultural interference and away from any known ferrous material.

In the looping method, magnetic readings are taken at a base location with the field magnetometer during the survey. Because these readings are repeated at the same location, the magnetic readings should be relatively consistent over a short period of time. These readings represent the normal diurnal variation of the earth’s magnetic field. The diurnal correction assumes that the variation between the base location readings is linear. The magnetic survey data is corrected to the interpolations made from the base location readings. When the looping method is chosen instead of operating a base station magnetometer, effort should be made to loop back to a base location approximately every 30 minutes or less.

When a base station magnetometer is used, the diurnal is monitored more closely. The monitor can be programmed to record readings for various time intervals. Time intervals between readings can range from one to several minutes. The magnetic survey data is corrected for diurnal drift in a method similar to the looping method, except that the time interval between readings is usually less for the base station method. Thus, the base station method tends to allow for a more accurate correction.

Although the amplitude of typical diurnal variations does not approach the amplitude of anomalies associated with shallowly buried steel drums, monitoring the diurnal is a necessary quality assurance procedure. Large variations between readings taken at a base location may be indicative of magnetic storms, micropulsations, or instrument malfunctions. In such instances, the project geophysicist should recommend that the survey be suspended until the cause of the variations can be identified and eliminated.

The presence of cultural interference and surface metal, which cannot be removed from the site prior to the investigation, should be noted in the operator's field notes. Evaluation of the field notes by the geophysicist during the interpretation allows for a qualitative compensation for the effects of these features.

8.3.6 Data Reduction and Interpretation

The data should be corrected for diurnal variations of the magnetic field, if necessary. If the diurnal does not vary more than approximately 15 to 20 gammas over a one-hour period, corrections may not be necessary.

However, this variation must be approximately linear over time and should not show any extreme fluctuations.

After the data has been corrected for diurnal, the record should be plotted in profile form. Extraneous points that coincide with surface metal or cultural features must be noted. The geophysicist may decide to remove these extraneous data points from the record before producing a contour map.

After examination of the profile and contour map data, the geophysicist will outline areas of probable ferrous material burial. Examples of the typical magnetic response of a target source can be found in Redford (1964) and Breiner (1973).

It is sometimes possible to determine the approximate depth of burial of the material based on the magnetic data. Graphical and computer-modeling techniques for estimating the depth of burial can be found in the literature.

The geophysicist should indicate which anomalies might be the result of features other than buried ferrous material. The remaining anomalies should then be prioritized, with high priority anomalies representing areas most probable of containing buried steel objects. Test pits and/or boring locations can then be chosen to confirm the presence of buried ferrous material.

8.3.7 Presentation of Results

The final results will be presented in profile and contour map form. Profiles are usually presented in a north-south orientation, although this is not mandatory. The orientation of the traverses must be indicated on the plots. Areas of probable ferrous material burial, indicating a high, low, or medium priority will be indicated on the contour map, together with physical and cultural features. A listing of the magnetic data, including the diurnal monitor or looping data should be included in the report. The report must also contain information pertinent to the instrumentation, field operations, and data reduction and interpretation techniques used in the investigation.

8.4 Gravimetry

8.4.1 Fundamentals

The gravity method involves measuring the acceleration due to the earth's gravitational field. These measurements are normally made on the earth's surface. A gravity meter or gravimeter is used to measure variations in the earth's true gravitational field at a given location. These variations in gravity depend upon lateral changes in the density of the subsurface in the vicinity of the measuring point. Because density variations are very small and uniform, the instruments used are very sensitive. The acceleration due to the earth's gravity is approximately 980,000 milligal (the unit of measurement commonly used in gravity surveys). Many gravity meters have a sensitivity of 0.01 milligal. This allows the detection of a change of one part in 100 million of the earth's gravitational field. The gravity method is useful in delineating buried valleys, bedrock topography, geologic structure, and voids.

8.4.2 Advantages

An advantage of using the gravity method for site assessment is that gravity measurements are not as susceptible to cultural noise and hence data can be acquired in heavily populated areas. The main source of interference or noise that may affect gravity data are vibrations, which may be caused by vehicular traffic, heavy equipment, low flying aircraft and wind. Nevertheless, gravity readings can be taken in virtually any location, even indoors.

8.4.3 Limitations

A disadvantage of the gravity method is that each station must be precisely surveyed for elevation and latitude control. This could be costly and time consuming, especially in surveys covering large areas. The accuracy of vertical and horizontal positioning is directly related to the resolution capabilities of the gravity method.

Many computations are involved in the reduction and interpretation of gravity data. Also, there are two unknowns that must be determined for the interpretation: 1) the density contrasts between the underlying material, and 2) the depths of the contacts between areas of density contrasts.

Gravity meters are extremely sensitive mechanical balances in which a mass is supported by a spring. Another spring counterbalances the mass to null the instrument. Small changes in gravity move the weight against the restoring force of the spring. Recent developments in gravity meter technology have greatly increased instrument versatility. New designs enable instruments to be automatically leveled, read, and to electronically store the data.

Most land gravity meters have a precision as great as 0.01 milligal (1 milligal = 0.001 cm/sec^2). All readings of gravity meters are in arbitrary scale divisions, and calibration is necessary to express these scale divisions in milligal. The manufacturer usually does the calibrating of the gravity meter. Gravity meter springs are not perfectly elastic but are subject to a slow creep over long periods. Uncompensated temperature also affects the gravity meter. Spring creep, temperature compensation and earth tides cause variation of gravity readings with time. These temporal variations, known as drift, must be compensated for prior to interpretation.

8.4.4 Survey Design, Procedure and Quality Assurance

Gravity survey design depends on specific site conditions and survey objectives. Gravity data can be collected in a grid configuration or along a traverse. In some instances, the grid data may not be regularly spaced due to inaccessibility. Irregularly spaced areal data may be useful to delineate or establish the existence of buried valleys where a precise determination of the depth is not required. Data should be collected beyond the area of interest to determine the regional gravity field.

It is preferable to collect gravity data along a traverse if a quantitative interpretation of bedrock topography is the objective. Smaller station intervals and greater topographic surveying accuracy can improve the resolution of the interpretation. For an error of +0.1 foot in elevation and +40 feet in latitude the error in gravity is approximately +0.01 milligal.

Measurements at a gravity base station near the survey area should be repeated at intervals of two hours or less for regional surveys and one hour or less for detailed microgravity surveys to correct for instrument drift and tidal effects. The base station should be established by repeated loops from the nearest known gravity base station. A listing of established base stations throughout New Jersey is available from the New Jersey Geological Survey.

A gravity meter, capable of being read to the nearest 0.001 milligal, should be used to minimize measurement error. Gravity station elevation and latitude should be surveyed to an accuracy of ±0.1 foot and ±40 feet, respectively. It is recommended that the gravity stations be surveyed for elevation and latitude control as soon as gravity measurements are taken so the data can be immediately reduced and modification can be made to the survey design, if necessary. Accuracy of gravity readings should be maintained by taking consecutive observations at each station until satisfactory duplication is obtained.

8.4.5 Data Reduction and Interpretation

Gravity observations are reduced to simple Bouguer gravity anomalies. Dobrin (1976) and Telford and others (1976) give the formulas used to perform these calculations. Reduction of gravity data involves the correction for tidal effects, instrumental drift, latitude, elevation, and terrain.

The gravity readings at each station are converted to "observed gravity" by first correcting for tidal and instrumental drift. The theoretical gravity at sea level at each station is determined using the International Gravity Formula of 1930 (Dobrin, 1976) or the International Association of Geodesy Formula of 1967 (Telford and others, 1976). These formulas are used for latitude corrections. Latitude correction is applied where there are any appreciable north-south excursions of the stations.

The effect of the elevation of the station above sea level (or a reference datum) is determined by calculating the "free-air" and "Bouguer" corrections. The free-air correction compensates for the normal vertical gradient of gravity by applying a correction factor to the difference in elevation between the station and a reference datum. The free-air correction is added to the field reading when the station is above the datum and subtracted when below it. The Bouguer (pronounced 'boogay') or mass correction accounts for the gravity acceleration due to a mass of material between datum and station elevation. The Bouguer correction is subtracted from the gravity reading when the station is above the datum.

Terrain corrections are calculations that correct the gravity data to account for the deviation of topography from a horizontal surface. These corrections are required when the ground surface is very irregular in the vicinity of the gravity station; that is, hills rising above the gravity station and valleys lying below it. There are several graphical methods for calculating terrain corrections. The most commonly used are the Hammer (1939) template and tables. The terrain correction is added to the gravity reading. When the topography in the vicinity of the study area is gentle, terrain corrections are not required.

When all the corrections are made, the resulting gravity value is called the "Simple Bouguer Gravity Anomaly."

Gravity data can be analyzed using techniques that remove the regional gravity from the simple Bouguer gravity anomalies to obtain a residual gravity, which is more useful for gravity interpretation. There are various techniques to remove this regional gravity. Some techniques are graphical, and others are analytical. Commonly used analytical techniques include surface fitting (polynomial or Fourier series), frequency filtering, and downward continuation.

Residualization (removal of regional gravity) is one of the most important aspects in gravity interpretation and depends, to a large degree, on the experience of the interpreter. The residual gravity data is then used in the interpretation. For example, a trend of negative gravity anomalies may be due to a buried valley.

Modeling gravity data in profile form is useful in the calculation of the depth of various features and can be done by either forward or inverse algorithms. Software to model two-dimensional gravity data is available from various sources, such as Ballantyne and others (1981). Talwani and others (1959) have developed the algorithm, which is most widely used.

The interpretation of gravity data is non-unique because there are many possible models that would result in the same gravity anomaly. Constraints, such as depths to rock obtained from well information, rock densities, or other geophysical interpretations, are required during the modeling process to remove the ambiguity.

8.4.6 Presentation of Results

The final report should state the type of gravity meter, together with its accuracy and calibration requirements, used in the investigation. The accuracy of the topographic (elevation and location) surveying used should also be stated in the report. An explanation of the data reduction, modeling and interpretation programs or calculations used should also be presented.

The report should also include gravity profiles with the interpreted model, a Bouguer gravity anomaly map and a residual gravity map showing locations of various interpreted features. The profiles should show orientations and locations of gravity stations on a location map. A table of the gravity data should also be included. This table must contain station number, latitude, or north-south distance from base, longitude, elevation, observed gravity and simple Bouguer gravity anomaly of each station.

8.5 Electrical Resistivity

8.5.1 Fundamentals

The electrical resistivity method (electrical imaging) is used to map the subsurface electrical resistivity structure, which is interpreted by the geophysicist to determine geologic structure and/or physical properties of the geologic materials. The electrical resistivity of a geologic unit or target is measured in ohmmeters, and is a function of porosity, permeability, water saturation and the concentration of dissolved solids in pore fluids within the subsurface.

Electrical resistivity measures the bulk resistivity of the subsurface as do electromagnetic methods. The difference between the two methods is in the way that electrical currents are forced to flow in the earth. In the electrical resistivity method, current is injected into ground through surface electrodes, whereas in electromagnetic methods, currents are induced by the application of time-varying magnetic fields.

The method requires electrodes to be inserted into the earth at evenly spaced intervals. An electrical voltage is applied across a pair of electrodes and the resistance is measured across another pair. A series of permutations based on the method being used building an array of electrode distances and resistivities. Modeling converts the array into a pseudosection. The Schlumberger and dipole-dipole methods are the most commonly used in the field. The Wenner array was heavily used when curve-fitting was the interpretation method.

8.5.2 Advantages

A principal advantage of the electrical resistivity method is quantitative modeling can create detailed profiles of electrical resistivity. The resulting model is a cross section of resistivity where bedrock is more resistive than overburden, granite and basalt are more resistive than shales and mudstones. Voids are highly resistive, and fractures are less resistive. Electrical resistivity has largely replaced the seismic method for imaging the subsurface due to the relative ease in both processing and interpretation.

8.5.3 Limitations

Limitations of using the electrical resistivity method in environmental investigations are primarily due to site characteristics, rather than inherent limitations of the method. Typically, sites that are located in industrial areas contain an abundance of broad-spectrum electrical background noise. In conducting an electrical resistivity survey, the voltages are relayed to the receiver over long wires that are grounded at each end. These wires act as an antenna receiving the radiated electrical noise that in turn degrades the quality of the measured voltages.

Electrical resistivity surveys may require a large linear area, removed from power lines and grounded linear metallic structures such as metal fences, pipelines and railroad tracks. Issues related to these types of structures can be avoided by laying out the electrodes perpendicular to the feature and skipping electrodes near the feature. In paved areas, holes may have to be drilled for insertion of the electrodes. Electrode spacing and geometry or arrays (Schlumberger, Wenner, and Dipole-dipole) are discussed in detail in the section below entitled, *Survey Design, Procedure, and Quality Assurance*.

The maximum depth of penetration tends to be around 100 meters, and as with other types of geophysical methods resolution decreases with depth. To get deeper penetration, a wider electrode spacing is required, decreasing resolution. Close electrode spacing provides higher resolution at the expense of penetration.

Another consideration in the electrical resistivity method is that the fieldwork tends to be more labor intensive than some other geophysical techniques. A minimum of three crew members is ideal for the fieldwork.

8.5.4 Instrumentation

Electrical resistivity instrumentation systems consist of a transmitter and receiver, cables, and electrodes. The transmitter supplies a low frequency (typically 0.125 to 1 cycles/second or Hertz) current waveform that is applied across the current electrodes. Batteries supply power for the instrument. Most systems may require the field parameters to be input prior to collection of the data.

8.5.5 Survey Design, Procedure and Quality Assurance

Survey design depends on the specific characteristics of the site and the objective of the survey. The three most common modes of electrical resistivity surveying are vertical electrical sounding (VES), constant separation traversing (CST), and electrical resistivity tomography (ERT), each having its own specific purpose. If the purpose of the survey is to map the depths and thickness of stratigraphic units, then the electrical resistivity data should be collected in the sounding mode. Lateral electrical resistivity contrasts, such as lithologic contacts, can best be mapped in the profiling mode. In cases where the electrical resistivity is expected to vary both vertically and horizontally, such as in contaminant plume mapping, the preferred mode is profile sounding. However, with the advent of multi-core cables and multi-channel resistivity systems controlled by the software, most surveys done in the environmental field are almost always ERT.

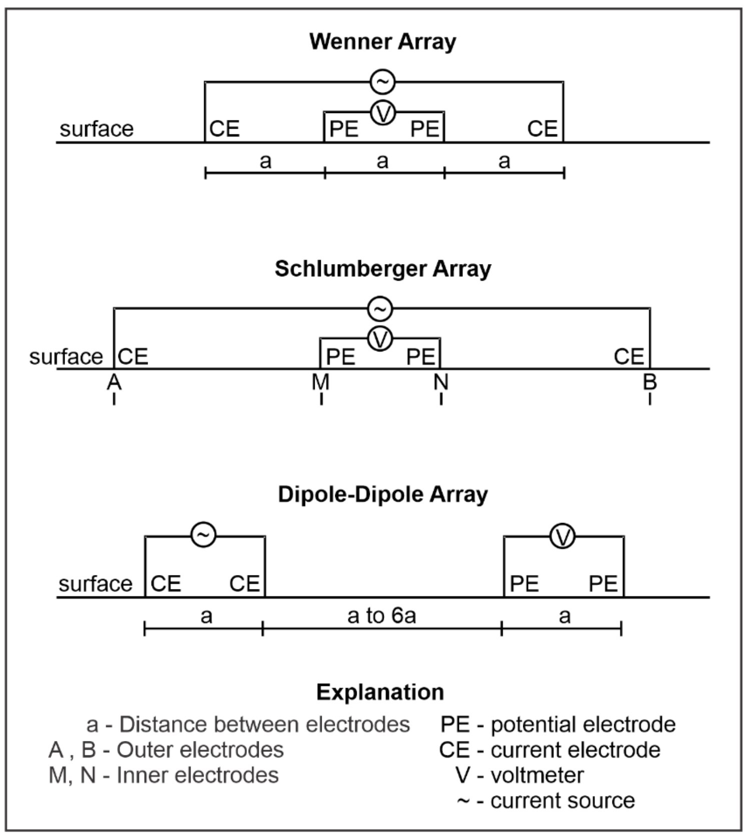

Figure 8.1 Some Common Arrays

8.5.6 Vertical Electrical Sounding (VES)

The two most common arrays for electrical resistivity surveying in the

VES mode are the Schlumberger and Wenner arrays. Electrode geometry for both arrays is shown in Figure 8.1. Increasing the separation of the outer current electrodes, thereby driving the currents deeper into the subsurface increases the depth of exploration.

8.5.7 Constant Separation Traversing (CST)

The two most common arrays for electrical resistivity surveying in the CST mode are the Wenner and dipole-dipole arrays. The electrode geometry for the Wenner array is the same as the VES mode. The difference is that in CST mode, the entire array is moved laterally along the profile while maintaining the potential and current electrode separation distances.

The electrode geometry for the dipole-dipole array is shown in Figure 8.1. In the CST mode, the distance between the potential and current dipoles (a dipole consists of a pair of like electrodes) is maintained while the array is moved along the profile.

8.5.8 Electrical Resistivity Tomography (ERT)

The Wenner, dipole-dipole, and pole-dipole arrays are the most common arrays used in the ERT mode. As the name implies, this mode is a combination of the VES and CST modes.

In the ERT mode, typically a 28 electrode to over 100 electrode multi-core cable are laid out and connected to a switching box and the resistivity meter. The data acquisition is controlled by a pre-programmed software packaged on the resistivity meter.

The most frequent source of inaccuracy in electrical resistivity surveying is the electrode contact resistance. Since resistivity methods rely on injecting current into the ground, if the resistance of the current electrode becomes too high the applied current may fall to zero and the measurement will fail. Common methods to overcome this are to wet the electrodes with water or salt water, or in extremely arid location (or in blacktop/concrete), to drill a small hole for the electrode and fill it with bentonite.

The second most common sources of error in electrical resistivity surveying are caused by the electrical noise generated by power lines or by large metallic objects near the survey site such as buried metal, fence posts, storm/sewer grates, and steel road barriers. It is sometimes possible to correct these problems after the data was collected. Since power line frequency is 60Hz, it is often possible to filter the data in post processing. A single or multiple electrodes can be removed in post processing if it had to be placed near a metallic object.

8.5.9 Resistivity Data Reduction and Interpretation

Reducing electrical resistivity data is a simple process in which the apparent electrical resistivity is calculated by dividing the measured voltages by the applied current. The quotient is then multiplied by the geometric factor specific to the array used to collect the data. Once the apparent electrical resistivities have been calculated, the next step is to model the data in order geologic structure.

The method used to model the apparent electrical resistivity data is specific to each data acquisition mode. Electrical resistivity data acquired in the VES mode, using either the Wenner or Schlumberger array, can be modeled using master curves or computer modeling algorithms. When using master curves, the interpreter attempts to match overlapping segments of the apparent electrical resistivity versus electrode separation plots with a succession of two-layer master curves. This modeling method provides coarse estimates of the model parameters, is time consuming, and requires skill on the part of the interpreter.

An alternative method of modeling sounding mode electrical resistivity data is to use readily available computer modeling software packages (Sandberg, 1990). There are a variety of different types of algorithms; some assume discrete electrical resistivity layers while others assume that electrical resistivity is a smooth function of depth. The discrete layer algorithms require input by the interpreter but allows for constraining model parameters to adequately reflect known geologic conditions. The continuous electrical resistivity algorithms are automatic, that is, they require no interaction on the part of the operator, and therefore geologic constraints cannot be incorporated into the models.

The modeling of CST and ERT mode data is much more involved than in the case of VES data. The ERT data reflects electrical resistivity variations in the lateral and vertical directions, resulting in a much more complicated computer simulation of the potential fields. The computer techniques capable of simulating these fields are finite difference, finite elements, and integral equation algorithms. PC based software is available to interpret these data, but caution should be exercised when using automatic interpretation routines: the inexperienced interpreter can make assumptions that will lead to a statistically accurate result, but not (necessarily) a correct geological interpretation. Generally, most ERT mode data is interpreted in a qualitative manner, with the accuracy of the interpretation being based solely on the experience of the geophysicist.

8.5.10 Presentation of Results

Listings of the electrode separations, current amplitudes, measured voltages and reduced apparent resistivities should be included in the report. Any specific information regarding the data, such as reduction method and model, should be outlined in the report. As with data interpretation, the final results are specific to the data collection mode.

8.5.10.1 Vertical Electrical Sounding (VES)

The electrical resistivity data collected in VES are presented as a bilogarithmic plot of electrical resistivity versus the distance from the current electrodes to the center of the array. If the data were modeled, the apparent electrical resistivities, as calculated from the model, should be presented on the bilogarithmic plot with the observed apparent electrical resistivities. In addition, the model should be presented in a section plot.

8.5.10.2 Constant Separation Traversing (CST)

Data collected in CST mode are presented in a plot of apparent electrical resistivity versus distance. Any modeling results, either using computer algorithms or by "rule-of-thumb" methods should be presented and include a legend indicating any parameter values.

8.5.10.3 Electrical Resistivity Tomography (ERT)

Data collected in ERT mode are presented in psuedosection format in which the apparent electrical resistivity is plotted as a function of position and electrode separation. Any modeling results presented using either computer algorithms or qualitative methods should include a legend indicating parameter values.

8.6 Induced Polarization (IP)

8.6.1 Fundamentals

The IP method is an electrical geophysical technique, which measures the slow decay of voltage in the subsurface following the cessation of an excitation current pulse. Basically, an electrical current is imparted into the subsurface, as in the electrical resistivity method explained elsewhere in this chapter. Water in the subsurface geologic material (within pores and fissures) allows for certain geologic material to show an effect called "induced polarization" when an electrical current is applied. During the application of the electrical current, electro-chemical reactions within the subsurface material takes place and electrical energy is stored. After the electrical current is turned off the stored electrical energy is discharged which results in a current flow within the subsurface material. The IP instruments then measure the current flow. Thus, in a sense, the subsurface material acts as a large electrical capacitor.

The IP method measures the bulk electrical characteristics of geologic units; these characteristics are related to the mineralogy, geochemistry, and grain size of the subsurface materials through which electrical current passes.

IP measurements are taken together with electrical resistivity measurements using specialized IP instruments. Although the IP method historically has been used in mining exploration to detect disseminated sulfide deposits, it has also been used successfully in ground water studies to map clay and silt layers which serve as confining units separating unconsolidated sediment aquifers.

8.6.2 Advantages

IP data can be collected during an electrical resistivity survey, providing the proper equipment is used. The addition of IP data to a resistivity investigation improves the resolution of the analysis of resistivity data in three ways: 1) some of the ambiguities encountered in resolving thin stratigraphic layers while modeling electrical resistivity data can be reduced by analysis of IP data; 2) IP data can be used to distinguish geologic layers which do not respond well to an electrical resistivity survey; and 3) the measurement of another physical property (electrical chargeability) can be used to enhance a hydrogeologic interpretation, such as discriminating equally electrically conductive targets such as saline, electrolytic or metallic-ion contaminant plumes from clay layers.

8.6.3 Limitations

The IP method is more susceptible to sources of cultural interference (metal fences, pipelines, power lines, electrical machinery and so on) than the electrical resistivity method. Like electrical resistivity surveys, IP surveys often require a large area, far removed from power lines and grounded metallic structures such as metal fences, pipelines, and railroad tracks.

8.6.4 Instrumentation

IP instruments are similar to electrical resistivity instruments. There are two different types of IP systems. Probably the most common type of IP instrument is the "time-domain" system. This instrument transmits a constant electrical current pulse during which time the received voltage is sampled for an electrical resistivity measurement, acting like a conventional electrical resistivity system. The electrical current is then shut off abruptly by the system, and after a specified time delay (several milliseconds) the decaying voltage in the subsurface is sampled at the IP receiver, averaging over one or more "time windows" or "time gates." The units of measurement are in millivolt-seconds per volt.

The second type of IP instrument is the "frequency-domain" system. In this type of system, transmitted current is sinusoidal at a specified frequency. Since the system is always on, only an electrical resistivity measurement can be collected at a particular frequency. To collect IP data, two frequencies are used, and a percent change is apparent electrical resistivity from measurements collected at the two frequencies is calculated. This number is called the "percent frequency effect" or "PFE," and the units are dimensionless in percent. Two frequencies commonly used are 0.3 and 3.0 Hertz, representing low and high frequency responses, respectively.

Many modern electrical resistivity systems have IP capability, and it is often integrated into the resistivity box and software. Electrical resistivity surveys and IP surveys can then be run at the same time and with the same equipment setup, greatly reducing field time.

Other types of IP may be encountered, although not commonly in environmental applications. These include "spectral IP," "complex resistivity," and "phase" systems.

8.6.5 Survey Design, Procedure and Quality Assurance

IP survey design depends on the specific characteristics of the site and the objective of the survey. Like electrical resistivity investigations, the three most common modes of IP surveying are profiling, sounding, and profiling-sounding, each having its own specific purpose.

If the purpose of the survey is to map the depths and thickness of stratigraphic units, then the IP data should be collected in the sounding mode concurrently with an electrical resistivity investigation. Lateral contrasts in electrical properties of the subsurface, such as litho-logic contacts, can best be mapped in the profiling mode. In contaminant plume mapping, where subsurface electrical properties are expected to vary both vertically and horizontally, the preferred mode is profile sounding.

8.6.6 Vertical Electrical Sounding (VES)

The two most common arrays for induced polarization/electrical resistivity surveying in the sounding mode are the Schlumberger and Wenner arrays. Electrode geometry for both arrays is shown in the "Electrical Resistively" section of this chapter.

Increasing the separation of the outer current electrodes, thereby driving the currents deeper into the subsurface increases the depth of exploration.

8.6.7 Constant Separation Traversing (CST)

The two most common arrays for induced polarization/electrical resistivity data collection in the profiling mode are the Wenner and dipole-dipole arrays. The electrode geometry for the Wenner array is the same as the sounding mode. The difference is that in profiling mode the entire array is moved laterally along the profile while maintaining the potential and current electrode separation distances.

The electrode geometry for the dipole-dipole array is shown in the "Electrical Resistivity" section of this chapter. In the profiling mode, the distance between the potential and current dipoles (a dipole consists of a pair of matching electrodes) is maintained while the array is moved along the profile.

8.6.8 Electrical Resistivity Tomography (ERT)

As in the profiling mode, the Wenner and dipole-dipole arrays are the most common arrays used in the profiling-sounding mode. As the name implies, this mode is a combination of the profiling and sounding modes.

In the Wenner array, the typical field procedure is to collect the data in a succession of profiles, each having a different electrode separation. The resulting data therefore contains information about the lateral and vertical electrical properties of the subsurface.

In the dipole-dipole array, the typical field procedure is to transmit on a current dipole while taking measurements. When the data collection is completed, the entire array is moved one dipole separation and the process is repeated.

8.6.9 Data Reduction and Interpretation

IP data values obtained in the field indicate the bulk chargeability of the subsurface. Therefore, induced polarization data, represented either in millivolt-seconds/volt or PFE (percent frequency effect), require no data reduction.

When data are collected in the profiling or profiling-sounding modes, electrical resistivity and chargeability data form the Wenner and dipole-dipole arrays are most often merely plotted in profile form. The geophysicist plots the chargeability values on a pseudosection. The data of this pesudosection or "electric vertical section" are then contoured and qualitatively evaluated.

Similar to electrical resistivity data, complex computer modeling software can be used to interpret dipole-dipole data. However, due to the complications involved with such an interpretation, profile-sounding mode data are usually interpreted in a qualitative manner, with the accuracy or the interpretation being based solely on the skill and experience of the interpreting geophysicist.

IP and electrical resistivity data acquired concurrently in the sounding mode can be simultaneously modeled using layered-earth modeling software (Sandberg, 1990). Alternatively, the data can be compared to layered-earth master curves for induced polarization data for analysis.

8.6.10 Presentation of Results

Listings of electrode separation, current amplitude, and chargeability should be included in the report. Any specific information regarding the manner in which the data were reduced or modeled should outlined in the report. As with data interpretation, presentations of the final results are specific to the mode of data collection.

A site map showing location(s) of the electrical soundings and/or profiles and physical features of the site (buildings, wells, and so on) should be included in the report. If the data are modeled an electrical section plot should be included, together with the modeling results, and a legend indicating the parameter values.

Data collected in the profiling-sounding mode should be presented in appropriate format.

8.7 Electromagnetics

8.7.1 Fundamentals

The electromagnetic method is a geophysical technique based on the physical principles of inducing and detecting electrical current flow within geologic strata.

While the term electromagnetics encompasses most geophysical methods including GPR and electrical resistivity, the term, as used in geophysics, refers to currents being induced in the subsurface by the application of time-varying magnetic fields. The frequency-domain electromagnetic method measures the bulk conductivity (the inverse of resistivity) of subsurface material beneath the instrument's transmitter and receiver coils in millimhos/meter. Time-domain electromagnetics measures the electrical response in millivolts over different time gates as the signal decays in milliseimens/meter. An older and now obsolete unit was millimhos/meter (1 millimho = 1 milliseimen). A "mho" is the reciprocal of an ohm.

Electromagnetics can be used to locate pipes, utility lines, cables, buried steel drums, trenches, buried waste, and concentrated contaminant plumes. The method can also be used to map shallow geologic features such as lithologic changes, clay layers, and fault zones.

8.7.2 Advantages

Most electromagnetic equipment used in ground water pollution investigations is lightweight and easily portable. Measurements can be collected rapidly and with a minimum number of field personnel. The electromagnetic method is a technique commonly used environmental investigations.

Most electromagnetic instrumentation now commonly integrates GPS data for easier mapping of results and locating anomalies of interest.

8.7.3 Limitations

The main limitations of the frequency-domain electromagnetic method are cultural noise. Sources of cultural noise can include large metal objects, buried cables, pipes, buildings, and metal fences. However, some of these objects, which are considered sources of interference when an electro-magnetic investigation is used for hydrogeologic mapping, can be successfully delineated with this method. Electromagnetics can be used to map buried steel drums, tanks, pipelines and so on, although the presence of these objects will effectively mask the more subtle response of most geologic features.

Lateral variability in the geology can also cause conductivity anomalies or lineations. These features can easily be misinterpreted as a contaminant plume.

8.7.4 Instrumentation

The most common type of electromagnetic system used in environmental investigations consists of coplanar transmitter and receiver coils with fixed separation. Typically, increasing the coil separation increases the depth of exploration. Most systems have only a few discrete allowable coil separations to internally process the data for the output to be in conductivity units (millisiemens/meter). Some systems produce an output in units of secondary field as a percentage of the primary field.

Electromagnetic equipment commonly used in environmental investigations operates in the frequency domain, where the current flowing in the transmitter coil is sinusoidal with time, running at a fixed frequency. Most electromagnetic equipment allows measurement of both the "in-phase" (or "real") component and 90º "out-of-phase" (or "quadrature") components of the induced magnetic field.

Another type of electromagnetic equipment used more for regional ground water studies, minerals exploration, and geologic mapping is called "transient" or "time-domain" electromagnetic (TEM, or TDEM) equipment. This equipment operates in the time-domain, where a transmitted current is kept on long enough to create a steady-state magnetic field in the earth and is then shut off. Currents, which are thereby induced to flow in the ground, then dissipate with time. The secondary magnetic field associated with these dissipative currents is sampled at a remote receiver as a function of time after transmitter shut-off.

Most systems are integrated this a GPS receiver, where the data collection is synchronized with the collection of location data.

8.7.5 Survey Design, Procedure and Quality Assurance

Preparation for an electromagnetic investigation, the appropriate instrument should be chosen; time-domain versus frequency-domain and coil separation. Time-domain for searching for subsurface metal and frequency-domain for geological information. Frequency-domain can also be used to locate subsurface metal. The in-phase measurement is used to locate metal, where the quadrature component measures the conductivity of the subsurface. Both components are collected simultaneously.

When electromagnetic data are collected for the purpose of modeling the data for a geologic model of two or more layers (as opposed to locating shallow clay layers, plumes, buried drums or other metallic objects) readings should be collected at a single station for at least three different coil separations. Meaningful quantitative depth determinations cannot be obtained using a single frequency, coil separation, or orientation.

8.7.6 Data Reduction and Interpretation

Instrument readings in milliseimens/meter need no further data reduction because they are already in units corresponding to the bulk conductivity of the subsurface. Data can be interpreted using two-layer master curves or computer algorithms. It should be noted that layer determinations require a different field procedure than profiling or areal mapping. A detailed description of these procedures can be found in the literature. Profile or traverse data can be qualitatively interpreted by comparison to published modeling results or computer modeling programs (Sandberg, 1988).

Depth of penetration is less in the vertical coplanar (horizontal dipole) configuration than in the horizontal coplanar (vertical dipole) configuration. The horizontal coplanar configuration is more commonly used and is recommended to compare results with other geophysical survey results. Depth of penetration is roughly considered to be one-half the coil separation, whereas in actuality, it is a complex function of conductivity structure, coil separation and orientation, and transmitter frequency.

8.7.7 Presentation of Results

Data should be presented on a contour map, showing the contour interval and the scale of the profile plots. Traverse data should be presented in profile form and include the scale of the plots. Location of the contour map should be indicated on a site map. Features of interest, such as utilities, tanks, buried drum or contaminant plumes, indicating a high, low, or medium priority, should also be indicated on the contour map, together with physical and cultural features. The report should also contain information pertinent to the instrumentation, field operations, and data reduction and interpretation techniques used in the investigation.

8.8 Very-low Frequency (VLF) Electromagnetics

8.8.1 Fundamentals

The VLF electromagnetic method detects electrical conductors by utilizing radio signals in the 15 to 30 kiloHertz (kHz) range that are used for military communications. The VLF method is useful for detecting long, straight electrical conductors, such as moderate to steeply dipping water-filled fractures or faults.

The VLF instrument compares the magnetic field of the primary (transmitted) signal to that of the secondary signal (induced current flow within the subsurface electrical conductor). In the absence of subsurface conductors, the transmitted signal is horizontal and linearly polarized. When a conductor is crossed, the magnetic field becomes elliptically polarized and the major axis of the ellipse tilts with respect to the horizontal axis (McNeill, 1988). The anomaly associated with a conductor exhibits a crossover. As with other frequency domain electromagnetic systems, both the in-phase (“real” or “tilt-angle”) and the out-of-phase (“imaginary,” “ellipticity,” or “quadrature”) components are measured.

A number of VLF transmitting stations operated by the military are located worldwide; the most commonly used in North America are Annapolis, Maryland (21.4 kHz), Cutler, Maine (24.0 kHz), and Seattle, Washington (24.8 kHz) stations. Commercially available VLF systems utilize one or more of these transmitting stations for survey applications.

8.8.2 Advantages

The VLF method is very effective for locating zones of high electrical conductivity, such as mineralized or water-filled fractures or faults within the bedrock. Structures such as these often act as conduits along which ground water and contaminants flow. The information from a VLF investigation can be used to optimally locate monitor and/or treatment wells to intercept these hydrologic conduits.

Another advantage of VLF is that data collection is fast, inexpensive and requires a field crew of only one or two people.

8.8.3 Limitations

The VLF method is affected by all electrical conductors, including those that are man-made (power lines, wire fences, pipes, and so on).

VLF transmitting stations often shut down for scheduled and unscheduled maintenance. If this happens, another transmitting station may have to be used or data collection may have to be halted until the transmitting station resumes operation. Care must be taken to make sure that the antenna of the VLF receiver is correctly and consistently oriented (always oriented in the same direction for all stations of a traverse).

8.8.4 Instrumentation

VLF instruments have historically fallen into two types. Early instruments were hand-held and measured the tilt-angle of the major axis of the magnetic field polarization ellipse. This angle is obtained by rotating the instrument until a null is obtained (indicated audibly through a speaker); then, the angle is read from an inclinometer mounted on the instrument case. Some instruments of this type also could provide reading indicating the magnitude of the maximum in-phase component.

More recent instruments are either belt or backpack mounted due to the increased weight of batteries needed for microprocessors which control these devices. These instruments measure both in-phase and quadrature components of the ratio of horizontal-to-vertical magnetic field. Some instruments have real-time interpretive capability for use while still collecting data.

In either case, the measured quantity is such that variations in the source field over time (from atmospheric fluctuations or actual signal-strength changes) are normalized out and the resulting information is repeatable hour-to-hour or day-to-day.

A hand-held compass is useful to ensure the antenna is oriented in the correct direction. A GPS receiver provides the location of the data points. If GPS is being used, it should be operated by a second crew member.

8.8.5 Survey Design, Procedure and Quality Assurance

VLF data are normally collected along traverses, and anomalies are correlated from traverse to traverse. When planning a VLF survey, every effort should be made to avoid putting traverses in areas that contain cultural features that may mask anomalies associated with the intended target. Consideration must also be given to which transmitting stations are available for use during the survey.

When designing a survey, several traverses should be placed parallel to one another and close enough (25 to 50 feet apart) so that anomalies can be correlated from traverse to traverse. It is crucial that traverses are long enough that the entire anomaly caused by the target is covered and the readings return to a background level. Data can be collected on a grid; however, the antenna must be oriented in the same direction regardless of the direction of the transverse. Station spacing should be close enough together that the entire form of the anomaly can be observed (15 to 30 feet).

Each traverse must be accurately located on a map and related to a point or landmark that can be recovered later. Using a GPS receiver simplifies mapping traverses.

During data collection, care must be taken to properly orient the VLF receiver antenna and to consistently collect data with the antenna facing the same direction. Careful field notes should be kept while collecting data, noting the location of any cultural features (including buried pipes, wire fences, power lines, fieldstone, or concrete walls, and building foundations). Keeping careful and observant field notes will save time when interpreting the data.

If the transmitter stops transmitting during data collection, another transmitter may have to be used. If this happens, the entire traverse should be read again using the new transmitter station. In this instance, data collection will have to cease until the transmitter station resumes operation. It is best if the same transmitter station can be used during the entire survey, because strength and orientation of different transmitters can lead to slightly different shaped anomalies, making the data more difficult to interpret.

8.8.6 Data Reduction and Interpretation

Most commonly used VLF interpretation methods are qualitative. Data collected in the field can be interpreted when using a data logger that plots the results as the data is collected. Commercial programs are available to calculate and plot data using the Karous-Hjelt filter. Using such a program, current density can be plotted with respect to depth and gray-tone plots can be created to further aid in interpretation.

To determine the strike direction of a fracture, it is necessary to have at least two traverses close enough to one another so that the same anomaly can be correlated from one traverse to the other. By collecting data on a grid, the strike is detected from a second angle adding accuracy to the strike direction. By mapping sets of profiles, it is then possible to correlate fractures or conductive zones across the entire survey area. Once the strike direction of a fracture has been determined, the fracture can be projected along strike to determine if it intersects any areas of interest. Projecting fracture zones along strike can also aid in determining where to place monitor and/or treatment wells, or where contaminants can migrate in a fracture-flow system.

More quantitative methods of interpretation include curve matching. Vozoff and Madden (1971) developed several interpretive curves that can help in the interpretation of VLF data. Simple, numerical forward modeling can be accomplished done using formulas found in Telford and others (1976). It must be emphasized that when modeling, assumptions are made, some of which may be incorrect in a given situation.

If enough parallel traverses are collected it is possible to contour the data to further aid in identifying zones of increased conductivity. If the data is to be contoured, filtered data should be used so that the zones of increased conductivity correspond to "highs" on the contour map.

8.8.7 Presentation of Results

The report should explain the methods and the reasoning behind the methods used for data collection. Explanations for what transmitting station was used, the traverse station spacing, and field procedures should be discussed in the report. Any problems encountered during data collection (such as a transmitting station shutting down or excessive atmospheric interference) should be noted.

The most common way to present VLF data is to plot the "real" and "imaginary" component values on the y-axis and distance along a traverse on the x-axis of a plot. Plots for each traverse should appear in the appendix of the report. All the plots should be drafted at the same vertical and horizontal scales for consistency and ease of comparison. The location of cultural features, as well as areas interpreted as fracture zones should also be indicated on annotated plots.

The locations of the traverses should be shown on a base map. It is also useful to identify anomalies interpreted as fracture zones on the map. The correlation of anomalies from traverse to traverse should also be indicated on the map, to delineate the continuation of interpreted fractures.

8.9 Seismic

8.9.1 Fundamentals

Surface seismic techniques used in ground water pollution site investigations are largely restricted to seismic refraction and seismic reflection methods. The equipment used for both methods is fundamentally the same and both methods measure the travel-time of acoustic waves propagating through the subsurface. In the refraction method, the travel-time of waves refracted along an acoustic interface is measured. In the reflection method, the travel-time of a wave which reflects off an interface, is measured. See Figure 8.2. The advantages, limitations, and other details of each method are discussed separately below.

The interpretation of seismic data will yield subsurface velocity information, which is dependent upon the acoustic properties of the subsurface material. Their acoustic properties or velocities can categorize various geologic materials. Depth to geologic interfaces can be calculated using the velocities obtained from a seismic investigation. The geologic information gained from a seismic investigation can then be used in the hydrogeologic assessment of a ground water pollution site and the surrounding area. The interpretation of seismic data can indicate changes in lithology or stratigraphy, geologic structure, or water saturation (water table). Seismic methods are commonly used to determine the depth and structure of geologic and hydrogeologic units (for example, depth to bedrock or water table), estimate hydraulic conductivity, detect cavities or voids, determine structure stability, detect fractures and fault zones, and estimate rippability. The choice of method depends upon the information needed and the nature of the

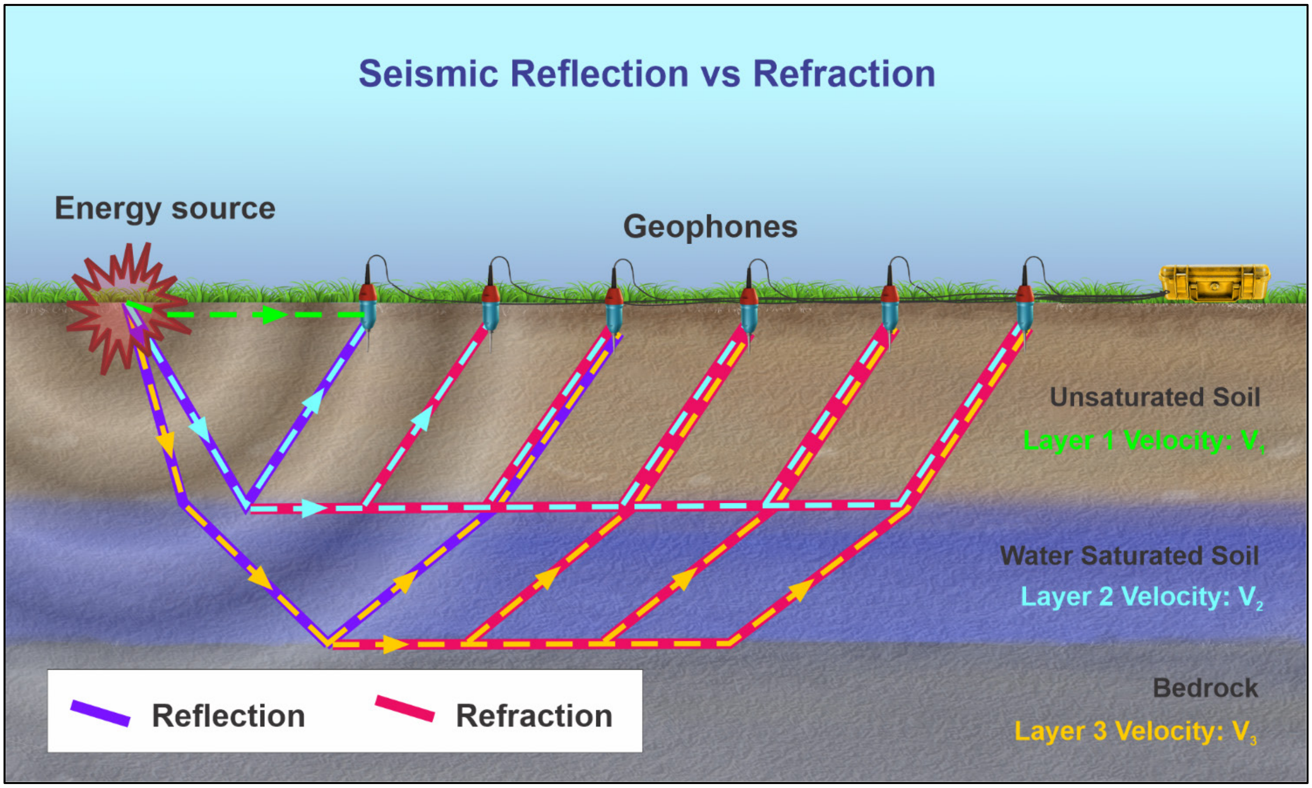

Figure 8.2 Seismic Reflection vs Refraction

study area. A geophysicist who is experienced in both methods, aware of the geologic information needed by the hydrogeologist, and aware of the environment of the study area, must make this decision.

8.9.2 Instrumentation

Both refraction and reflection data are acquired using a seismograph. A seismograph records the arrival of reflected and refracted seismic waves with respect to time. These waves are detected at the surface by small receivers (geophones), which transform mechanical energy into electrical voltages. The voltages are relayed along cables to the seismograph, which records the voltage output versus time, much like an oscilloscope.

There are a variety of seismographs used in the industry. Engineering seismographs are the most common types of seismographs used in ground water pollution site investigations. Each seismograph has different capabilities to handle data that is dependent on the number of “channels” in the seismograph. Seismographs are available with one, six, twelve, twenty-four or forty-eight channels, or as many channels as desired (usually the number of channels is a multiple of six). Each channel records the response of a geophone or array of geophones. Other capabilities of a seismograph may include analog or digital recording, frequency filters, electronic data storage, and signal enhancement hardware.

On multichannel systems, geophone stations are located at established distances along the seismic cable; on single channel systems, the geophone is moved to the next station after each shot.

Geophones are coupled to the ground, usually by a small spike attached to the bottom of the geophone. Care must be taken in the placement of geophones; each geophone gives the best response when the axis of the geophone element is positioned vertically with the attached spike driven firmly into the ground. Geophones are manufactured at different natural frequencies depending upon the desired result. High natural frequency geophones (usually greater than 30 hertz) are used when collecting shallow reflection data and lower natural frequency geophones are used in refraction surveys. More details on this can be found in Dobrin (1976).

There are many types of seismic sources used to impart sound into the earth. The most common type of source in seismic investigations for ground water pollution studies is a sledgehammer and strike plate. Other sources include explosives, shot gun shells detonated in shallow auger holes, and various mechanical devices that shake the ground or drop large weights. The types of sources used are dependent on the signal versus noise ratio in the survey area. Noise can come from vehicular traffic, people or animals walking near the geophones, electrical current in the ground (electromagnetic interference which affects the geophone cables), low-flying aircraft, or any sound source. Generally, the noise can be overcome by using a larger source, which effectively increases the signal. Filtering on the seismograph can also reduce noise.

8.9.3 The Seismic Refraction Method

Seismic refraction is most used at sites where bedrock is less than 500 feet below the ground surface. Seismic refraction is defined as the travel path of a sound wave through an upper medium and along an interface and then back to the surface, as shown in Figure 8.2. A detailed discussion of the seismic refraction technique can be found in Dobrin (1976), Telford and others (1985), and Musgrave (1967).

8.9.3.1 Seismic Refraction Advantages

The seismic velocity of a geologic horizon can be determined from a seismic refraction survey, and a relatively precise estimate of the depth to different acoustic interfaces (which may be related to a geologic horizon) can be calculated.

Seismic refraction surveys can be useful to obtain depth information at locations between boreholes or wells. Subsurface information can be obtained between boreholes at a fraction of the cost of drilling. Refraction data can be used to determine the depth to the water table or bedrock. Refraction surveys are useful in buried valley areas to map the depth to bedrock or thickness of overburden. Sites in the northern portion of New Jersey are generally well suited for the seismic refraction method.

The velocity information obtained from a refraction survey can be related to various physical properties of the bedrock. However, rock types have certain ranges of velocities, and these velocities are not always unique to a particular rock type. For instance, some dolomites and granites have similar seismic velocities. However, seismic velocity data can allow a geophysicist to differentiate between certain units with divergent seismic velocities, such as shales and granites.

8.9.3.2 Seismic Refraction Limitations

The seismic refraction method is based on several assumptions. To successfully resolve the subsurface using the refraction method the conditions of the geologic environment must approximate these assumptions. These conditions include the following:

- the seismic velocities of the geologic layers increase with depth;
- the seismic velocity contrasts between layers is sufficient to resolve the interface;
- the geometry of the geophones in relation to the refracting layers will permit the detection of thin geologic layers, and
- the apparent dip of the units or layers is less than ten to fifteen degrees.

If these conditions are not met, accurate depth information will not be obtained.

There are several disadvantages to collecting and interpreting seismic refraction data. Data collection can be labor intensive. Also, large line lengths are needed. Generally, the distance from the shot, or seismic source, to the geophone stations (or geophone “spread”) must be at least three times the desired depth of exploration.

8.9.3.3 Seismic Refraction Survey Design, Procedure and Quality Assurance

Survey design is site dependent and must be planned so that the geometry of the geophone spread will allow the target to be resolved. A primary limitation of the refraction method on many sites is that long refraction traverses are sometimes required. The spacing of the geophone stations within the spread can vary from several feet to tens of feet, depending on the depth of the geologic layer and required resolution. A closer spacing of geophones within the spread is chosen when a higher resolution of a shallow target is the objective. Shotpoints should extend along the entire traverse length and show a redundant sampling of the resolved interfaces. Care must be taken to maintain quality control on distance measurements. Small differences in horizontal displacements can cause a considerable change in the interpretation.

The geophone stations should lie along as straight a line as possible (for profile data). Deviations from a straight path will result in ray path projection inaccuracies. This will affect the accuracy of the survey. Also, deviations in elevations will cause errors in the calculations. Shotpoint and geophone elevations must be surveyed using a level or transit if variations in elevation occur along the traverse. These elevations are used in the static elevation corrections of the refraction data. Elevations to the nearest half-foot are adequate for most purposes.

A diligent field procedure will result in optimum results and will eliminate problems when processing and interpreting data. The geophysicist must be aware of any problems encountered during the survey, which may degrade the quality of the data. Modification of the original survey plan may become necessary if problems are encountered in the field. The field geophysicist should fill out an “observers log” listing pertinent information. An example of an observer’s log is shown in Figure 8.3.

8.9.3.4 Seismic Refraction Data Reduction and Interpretation

Static elevation corrections must be made when there are significant changes in topographic relief along the traverse. Failure to make elevation corrections will simply transfer those differences in elevation to the interpreted results or otherwise cause errors in the interpreted results. The geophone and shotpoint elevations obtained from the leveling or surveying are used to compensate for travel-time differences caused by the changes in shotpoint and geophone elevations. Corrections should also be made when the geophone stations deviate from a straight line.

Seismic refraction data can be interpreted graphically or with the aid of a computer. There are multitudes of interpretation schemes for seismic refraction data, depending upon the method and desired results. A detailed description of each interpretation algorithm is beyond the scope of this manual but an overview of many of the methods can be found in Musgrave (1967) and other literature cited in the References section of this chapter.

8.9.3.5 Seismic Refraction Presentation of Results

The interpretation should be presented in profile form and in contour map form when a grid of data is collected. The contour map should include all information pertinent to the site, including locations of buildings, property lines, roads, and other cultural and physical features. Locations of the traverses should also be indicated on the site map. Traverse sections or profiles should include details showing fixed positions, labeled interpretations, surface landmarks intersected by the traverse, areas of poor data quality, and a vertical time/depth scale.

Coordinates System

Observer's Log

File # ____________________

Line # ____________________
Shotpoint # ____________________
Geophone ____________________ Hz
Source: ☐ Hammer
☐ Explosives (lb.)
☐ Dynasource
☐ Buffalo Gun

Refraction __________/__________
Reflection
☐ CDP
☐ Wide Angle
☐ Common Offset
☐ VSP
Well # ____________________

County ____________________
Project ____________________
Date ____________________

Quad Sheet ____________________
Latitude ____________________
Longitude ____________________
Field Personnel ____________________
____
____
____

Weather ____________________

Shot point Offset ____________________ ft.
Sweep Time ____________________ ms.
Delay Time ____________________ ms.
Filters HP ____________________ ms.
LP ____________________
Notch ____________________
Program Gain ____________________ ms.

	SP →	1 →	2 →	3 →	4 →	5 →	6 →	7 →	8 →	9 →	10 →	11 →	12
Elevation Geophone													
Geophone gains													
# enhancements													
# EX													
polarity													

Trace Interval
Enter S.P. (*) location & distance to first geophone

O---O---O---O---O---O---O---O---O---O---O---O---O---O---O---O---O---O---O---O

Remarks ____________________
____
____

Figure 8.3 Observer's Log

A listing of the seismic data, including the elevation data, time-picks (where applicable), and the respective layer velocities should be included in the report. A brief description of the survey procedure, instrumentation, and data reduction and interpretation procedures should also be included in the report. If the original survey plan has been altered, the reasons for the alteration should also be explained in the text. Thorough reports will contain the positive results of the investigation and will detail the limitations and negative results encountered during the investigation.

8.9.4 The Seismic Reflection Method

In the seismic reflection method, a sound wave travels down to a geologic interface and reflects back to the surface, as shown in Figure 8.4. Reflections occur at an interface where there is a change in the acoustic properties of the subsurface material (V_1, V_2).

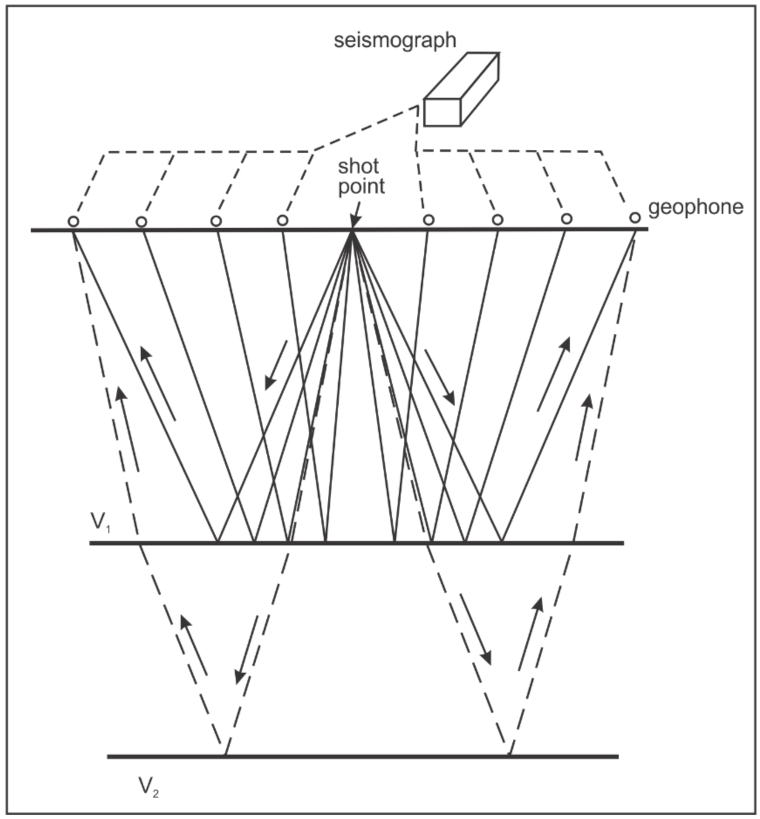

Figure 8.4 Seismic Reflection

8.9.4.1 Seismic Reflection Advantages

The seismic reflection method yields information that allows the interpreter to discern between fairly discrete layers. The reflection method has been used to map stratigraphy.

Reflection data is usually presented in profile form, and depths to interfaces are represented as a function of time. Depth information can be obtained by converting time sections into depth from velocities obtained from seismic refraction data, sonic logs, or velocity logs. The reflection technique requires much less space than refraction surveys. The long offsets of the seismic source from the geophones, common in refraction surveys are not required in the reflection method. In some geologic environments reflection data can yield acceptable depth estimates.

8.9.4.2 Seismic Reflection Limitations

The major disadvantage to using reflection data is that a precise depth determination cannot be made. Velocities obtained from most reflection data are at least 10% and can be 20% of the true velocities.

The interpretation of reflection data requires a qualitative approach. In addition to being more labor intensive, the acquisition of reflection data is more complex than refraction data.

The reflection method places higher requirements on the capabilities of the seismic equipment. Reflection data is commonly used in the petroleum exploration industry and requires a large amount of data processing time and lengthy data collection procedures. In most cases, the data must be recorded digitally or converted to a digital format, to employ various numerical processing operations. The use of high-resolution reflection seismic methods is very labor intensive, in terms of computer capacity, data reduction and processing programs, resolution capabilities of the seismograph and geophones, and the ingenuity of the interpreter. These factors should be carefully considered before a reflection survey is recommended.

8.9.4.3 Seismic Reflection Survey Design, Procedure, And Quality Assurance

Because the seismic reflection method is extremely dependent upon the geology and physical conditions of the site, a thorough evaluation of the survey area, including a site visit and review of all available geologic data, is necessary.

There are many different seismic energy sources, geophone and shotpoint array configurations, and survey plans that may be used in a particular investigation. However, there is no "best" survey plan. Due to the many variables in site conditions and reflection survey parameters, each site must be evaluated separately. Only a geophysicist with substantial experience in high-resolution reflection seismology is able to prepare such a site-specific survey plan. Experience can be substantiated by the presentation of case histories where reflection has been used successfully.

Several generalities with respect to instrumentation and field procedure should be followed. The seismograph should be able to record data digitally, and signal enhancement and filtering capabilities are often necessary. The geophysicist should choose a seismic source that not only imparts a sufficient signal, but also generates a minimum airwave. The seismic sources used in reflection surveys are the same as those used in refraction work. A comparison of various high-resolution seismic reflection sources can be found in the literature (Miller and others, 1986).

Shotpoint and geophone locations should be surveyed for elevation control. Elevations should be surveyed to the nearest half-foot. As mentioned in the *Seismic Refraction* section, the geophone stations should lie along a straight line, with the geophones properly coupled to the ground.

A complete discussion of survey design and field procedures would be too lengthy to include in this report. A good discussion of these parameters can be found in Coffeen (1978).

The field geophysicist should be able to make changes to the initial survey plan if necessary. These changes should be discussed in detail with the State geophysicist prior to implementation.

8.9.4.4 Seismic Reflection Data Reduction and Interpretation

Seismic reflection must be corrected for static elevation and normal moveout. In some instances, dip moveout corrections can be applied. Dip moveout corrections are applied in areas where the dip of the reflecting layer is several degrees from horizontal. A complete discussion of the many methods of data reduction and interpretation is beyond the scope of this outline, but can be found in Dobrin (1976), Coffeen (1978), and Telford and others (1985). The final report should present the results of the investigation.

8.10 Borehole Geophysical Methods

8.10.1 Introduction

There are various borehole tools, probes, or sondes that can be used for logging wells. Most borehole methods are based on the same principles as surface geophysical methods. It is recommended that borehole geophysics be done on all wells drilled and kept as a permanent record. Natural gamma ray and resistivity logs have been widely used, along with other traditional logging methods, in the water well industry for many years. In the past 20 years, additional advanced methods, including borehole imaging and measurement of in-borehole flow, have become standard elements of bedrock hydrogeologic studies, providing quantitative data to support water supply and environmental site remediation projects.

8.10.2 Advantages

Borehole methods supply an abundance of subsurface information. Information on the stratigraphy, hydrogeology and contamination of ground water at a site can often be derived from the borehole logs. In addition to the initial assessment of the subsurface conditions at a site, borehole information can sometimes be used to monitor the remediation of a site.

When correlation of borehole geophysical logs can be established among multiple holes at a site, a geologic framework can be created to map stratigraphic units, and potentially, to identify specific transmissive fractures or zones, evidence for which may be absent using other investigative methods. Application of borehole geophysics in existing wells (open-hole or cased) can often provide new understandings of site hydro-stratigraphic conditions, without the need for additional drilling. Borehole geophysics provides results that are objective and repeatable, less subject to variations of individual interpretations than descriptions of soil or rock cuttings or core. Generally, borehole geophysical records provide continuous, full coverage of the logged interval, including in fractured or weathered intervals of particular interest for groundwater studies and which can be poorly recovered by coring methods. Advanced methods, when applied with proper quality control measures, can provide abundant quantitative information on rock structure and fracture orientations, and flow conditions that is often otherwise unavailable (e.g., due to lack of surface exposure of geologic units, cost of applying other methods such as packer testing and pumping tests).

8.10.3 Limitations

Borehole logging can be expensive. Information from borehole logs only comes from a limited radius around the well (no more than 1 to 3 feet); if subsurface conditions vary between wells, discrepancies may have to be qualitatively evaluated. In addition, some geophysical logging tools must be used in uncased or ungrouted wells. Certain logging tools require different borehole conditions. The advantages, limitations, and requirements of each borehole method must be considered when planning the investigation. The site/case manager should therefore request the assistance of a geologist or geophysicist with experience in borehole methods throughout the investigation. Likewise, a responsible party or consultant proposing to perform borehole geophysics should include specific details of the proposed method(s) in the work plan submitted to the appropriate site/case manager in the Site Remediation Program.

8.10.4 Types of Borehole Investigation Tools

Geophysical logging tools can be categorized into six major types:

1) Natural gamma ray
2) Self-potential
3) Resistivity/induction
4) Porosity/density
5) Mechanical
6) Acoustic/optical/radar

Types 1, 2, 3, and 4 have historically been more commonly seen in ground water studies because they are relatively inexpensive and easily handled. Porosity/density tools (category 3) can sometimes yield more information, but they are generally expensive, and some require careful handling due to the radioactive sources required for their operation. Type 6 logging methods capture a 360-degree image of the inside of the borehole and provide extremely useful information in the groundwater industry. Each of the six types of investigative tools will be discussed briefly below.

8.10.4.1 Gamma Ray

A natural gamma ray (scintillation) detector contains a sodium iodide crystal that gives a flash of light when struck by a gamma ray. The results of a gamma ray log are in counts per second. Nearly all natural gamma rays in the earth come from potassium isotope 40 and decay products of uranium and thorium. Natural gamma rays are usually highest in shales and clays. A typical gamma ray log from the New Jersey Coastal Plain will often show peaks at the clay layers. Natural gamma logs are key elements of sedimentary bedrock hydrogeologic studies such as those conducted for site remediation in the Newark Basin, where site-wide correlation of the logs, which regularly with rock layering, provides the initial basis for understanding the physical framework of the Leaky, Multi-unit Aquifer System (LMAS) default conceptualization embraced in NJDEP's Ground Water Technical Ground Water Technical Guidance: Site Investigation Remedial Investigation Remedial Action Performance Monitoring.

However, a small amount of clay or sand can sometimes yield a high response. This may be due to feldspar, glauconite or mica in the sand or sandstone, which will increase the count rate. In addition, the gamma ray log cannot easily distinguish between interbedded sequences of thin clays and sands and silty or clayey sand. Thus, a quantitative estimate of the amount of clay or sand in a layer cannot be obtained from a natural gamma ray log by itself. The interpretation of natural gamma ray logs is strictly qualitative and information from other logging tools (and soil and rock samples) should be considered along with the gamma ray results.

Gamma ray tools can be used in uncased, steel-cased, PVC-cased holes, and above or below the water table. This enables evaluation and correlation of rock or sediment units within the aquifer system stratigraphic template, using data that can be quickly collected from existing well networks. A common approach is to log all of the deepest wells (which provide the fullest vertical record) in each well nest or cluster. Frequently, even in bedrock settings, the deepest well is of PVC construction, which is highly amenable to collection of a representative, correlatable natural gamma record. It should be noted that casing shields some of the gamma rays, most notably in steel-cased portions of boreholes, thus, lowering the count rate compared to that in uncased holes. Additionally, the larger-diameter borehole present around the cased interval places the logging tool further from the borehole wall than in the lower, open-hole portion (where the probe typically rides along the "low side" of the borehole), which can also contribute to lower gamma response. While the numerical gamma count result is rarely important for groundwater studies, the diminished responses can otherwise distinct log characteristics and thereby complicate log correlation efforts. In this case, correction factors based on known casing pipe and borehole dimensions can be applied to data from the affected portion of the logging run, and reported as an additional "corrected" log, with appropriate description in the logging report. Likewise, water in the borehole can shield some of the gamma rays and both the water level and the casing (e.g., in an open-hole bedrock well) can be discerned with the gamma log.

8.10.4.2 Self Potential (SP)

Self-potential or SP tools measure a voltage difference between a fixed surface electrode and a probe in the borehole. The voltage difference is usually caused by electrochemical action between two electrolytes of different concentrations. Such a condition will occur when the borehole probe passes between porous sand and clay. The boundary between the two layers occurs at the inflection point on the log curve. SP data cannot be quantified and shows a relative response. SP tools cannot be used in either PVC or steel-cased holes. They also cannot be used above the water table, i.e., in air-filled boreholes.

8.10.4.3 Electrical Resistivity and Induction

There are several different kinds of logging tools that will be discussed in this category:

1) Resistance
2) Fluid conductivity
3) Normal
4) Lateral

5) Laterolog

6) Induction tools

For the most part, normal and lateral resistivity logs are commonly used in ground water studies. Resistance logs may be seen in some older reports. Induction and laterologs have been used in the mining and oil industry, but these tools are generally too large (length and width) and too expensive to be applicable to ground water studies. However, electromagnetic induction tools have recently been developed for groundwater applications. Induction tools do not require a fluid- filled hole, as resistivity tools do. Single point resistance and normal resistivity logs are frequently used as stratigraphic evaluation tools complementary to natural gamma logs, in both consolidated and unconsolidated settings. Where high-gamma responses are due to the presence of clays, the high water saturated porosity that accompanies such lithology causes correspondingly low responses in the single point resistance and normal resistivity. Except where sands rich in potassium-feldspar are present, it is common for the gamma and electrical logs to present "hourglass" pattern, in sand/clay, sandstone/mudstone sequences. The same pattern may also be evident within vertical assemblages of predominantly fine-grained sediments or rocks, where textural variations are more subtle.

Electrical resistance logs or single-point resistance logs measure the electrical resistance between an electrode in the borehole and one on the surface. Resistance logging has a small radius of investigation and essentially measures the electrical resistance at the in-hole electrode. The method is most useful in locating fractures. However, this method can give variable data on different logging runs due to oxidation and reduction on the in-hole electrode that changes the resistance across the surface of the electrode. The electrode configuration is the same as a SP tool and data are normally acquired while running a SP tool.

Fluid conductivity or resistivity tools measure the electrical resistivity of the borehole fluid. These tools are called conductivity logs to avoid confusion with resistivity logs. Even though they measure resistivity, resistivity is the inverse of conductivity (see 8.5 *Electrical Resistivity* or 8.7 *Electromagnetics*). The tool measures the voltage drop across two closely spaced electrodes. Conductivity logs are most useful when correlated to other electrical logs to obtain a true resistivity of a formation. Conductivity gradients may also be directly correlated to water quality measurements or recharge areas. The fluid conductivity or fluid resistivity tools and the temperature tools are logged down hole to preserve the stratification in the fluid.

Normal resistivity tools are constructed as shown in Figure 8.5. The principle of operation and physics are similar to surface resistivity measurements. It must be understood that the electrode spacings are built into tools or sondes, resulting in a fixed distance of investigation. There are two types of normal resistivity tools: long-normal (64 inches between the “A” and “M” electrodes), and short-normal (16 inches between the “A” and “N” electrodes). The short-normal sonde yields information about the borehole and the drilling mud invaded zone of the borehole, and the long-normal yields information further into the formation. This log is also run with a SP tool.

Lateral resistivity tools are constructed as shown in Figure 8.6. The configuration of the electrodes is different from that of normal resistivity tools, but the potential is still measured between “M” and “B” electrodes. The lateral sonde has one additional electrode that acts as an electrical ground and assists in noise rejection. The lateral sonde allows for resistivity to be measured further into the formation. The distance of investigation beyond the side of the borehole is roughly equal to the A-O spacing as shown in Figure 8.7. Thin, high resistivity beds are difficult to detect and the true resistivity is difficult to determine from this log, but it can be estimated.

Laterologs (focused current tools) are similar to the normal device except the current is focused into the formation by two extra electrodes as seen in Figure 8.5. This tool is generally designed to work best in 8-inch boreholes and when the ratio between the true resistivity and resistivity of the mud is greater than 100 to one. The best feature of the tool is that it gives a sharp response at layer boundaries and is often used for thin-bed resolution. Laterologs are not used extensively in ground water investigations.

Induction tools are discussed with electrical resistivity tools in this outline even though induction tools are electromagnetic devices. The principle of operation is similar to surface electromagnetic methods. The tools use high-frequency electromagnetic energy (see Figure 8.7), and measure the conductivity of the formation. For the principle of operation, see the section on surface geophysical methods dealing with electromagnetics. Induction tools can be run in either dry or fluid-filled holes, and they can also be used in PVC-cased holes. Until recently, induction tools were primarily used in the petroleum industry. A smaller tool is now available with a total length of 36 inches as opposed to six- to eight-foot-long tools used in the past. Single point resistance and normal resistivity logs are frequently used as stratigraphic evaluation tools complementary to natural gamma logs, in both consolidated and unconsolidated settings. Where high-gamma responses are due to the presence of clays, the high water saturated porosity that accompanies such lithology causes correspondingly low responses in the single point resistance and normal resistivity. Except where sands rich in potassium-feldspar are present, it is common for the gamma and electrical logs to present "hourglass" pattern, in sand/clay, sandstone/mudstone sequences. The same pattern may also be evident within vertical assemblages of predominantly fine-grained sediments or rocks, where textural variations are more subtle.

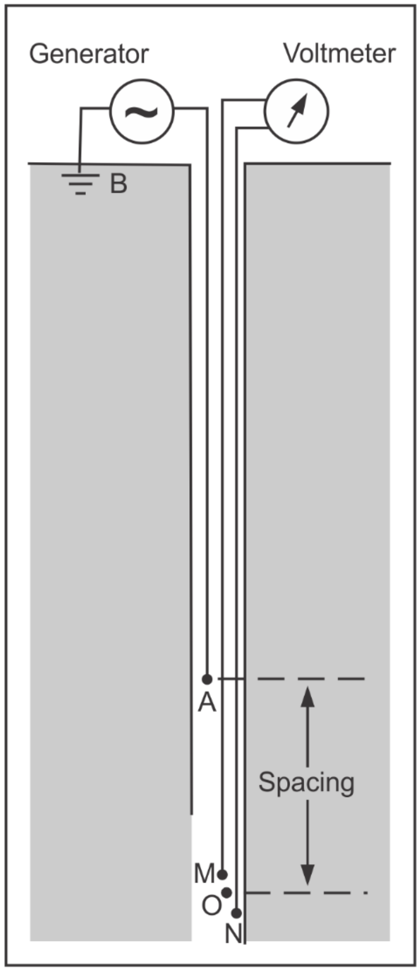

Figure 8.5 Normal Resistivity Sonde

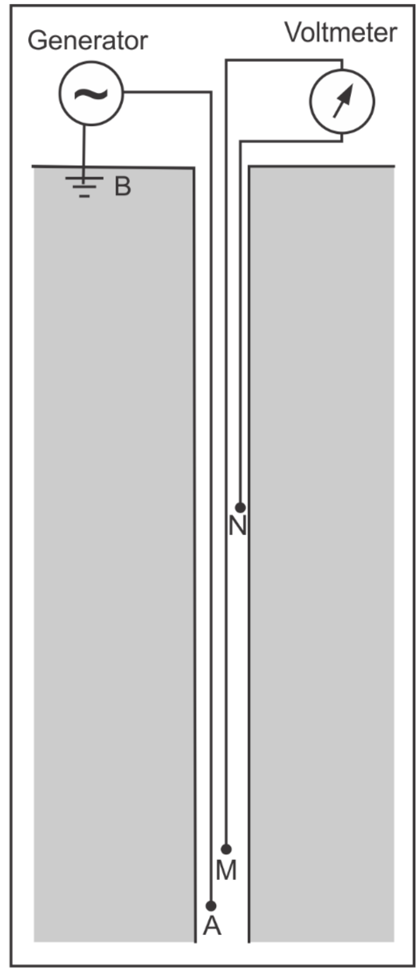

Figure 8.6 Lateral Resistivity Sonde

8.10.4.4 Porosity/Density

This category includes sonic, gamma-gamma (density), and neutron logs. These tools are not used as extensively in ground water studies as the methods previously outlined, but they can provide an abundance of subsurface information, when used with other logs, including determining the lithology and type of fluid in the formation (water versus hydrocarbons), as well as porosity.

Velocity or sonic logs measure the transit time of elastic waves for a short distance, usually one-foot. The unit of measurement is referred to as “Delta T” or DT [(DT) = microseconds per foot = velocity in 1 x 10^{-6} feet/second]. There is a relationship between DT and the density, lithology, and porosity of the geologic material. Usually, higher DT values indicate that the sound wave is traveling slower, and this implies a less dense formation. This could indicate an increase in formation porosity or change in lithology. In some instances, fractures and/or vuggy porosity can be determined. Vuggy porosity is a type of pore space in rocks that is not interparticle, but rather small cavities in a rock or vein. Vuggy porosity is visible to the naked eye and can form major conduits for ground water flow, especially in carbonate rocks. A basic sonic system involves one transmitter and two or three receivers, as shown in Figure 8.8. The transmitter emits elastic sound waves, and pulses at a constant amplitude and frequency. The transmitter pulses 15 times per second. As with surface seismic methods, rocks can be categorized by the velocities. Density is an important factor controlling velocity, and density is influenced by porosity. Sonic logs can be used in cased holes to locate areas of poor cement bond to the casing (cement bond logs).

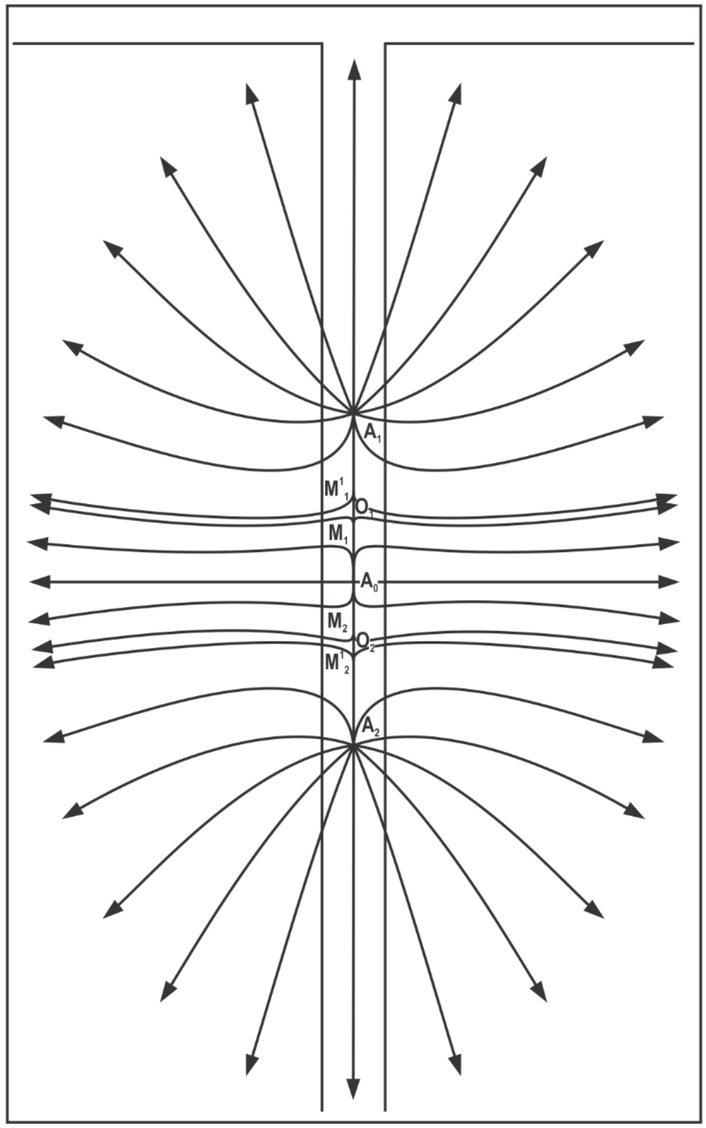

Figure 8.7 High Frequency Electromagnetic Energy

Gamma-Gamma Ray logs or "density" logs are not commonly used in ground water studies. However, these logs may be seen on some investigations. The tool is similar to the natural gamma ray tool because it also detects gamma rays, but the gamma-gamma ray tools use a radioactive source (Cesium 137) to generate gamma rays. Count rates are inversely proportional to bulk electron density, therefore, the higher the count rate, the lower the bulk density. The tool consists of one source and two detectors. If there is a mudcake on the side of the borehole, the short detector and the long detector will exhibit different counts. The gamma-gamma tool only measures on one side of the borehole and in one direction. If the density varies across the borehole, a variation will result in the data from subsequent logging passes. These tools can be used in cased holes but are more effective in open holes. However, they can be used effectively to evaluate the integrity of cement and bentonite grouts in cased holes.

Neutron logs are essentially hydrogen-ion detectors. Because water is partially composed of hydrogen, neutron logs can be used to locate water-bearing zones or water-filled fractures. These tools also require a radioactive source to operate, and are not commonly used in ground water investigations. The radioactive source in the tool is a combination of americium and beryllium. A neutron device radiates neutrons into a formation. The neutrons collide with other particles and the more they collide, the slower they travel. The greatest loss of energy of the neutron will occur when it strikes a hydrogen ion, because their masses are almost identical. Once the neutron has lost some energy, it will reach a thermal energy level. At the thermal energy level, the neutron will gain as much energy as it loses. However, the neutron is easily captured in this state, and once captured (absorbed), the neutron gives off a high- energy gamma ray to maintain a steady state of energy. Neutron tools may detect fast neutrons, with energies at just about the thermal level, thermal neutrons, gamma rays, or a combination of all these. Hydrogen is the main absorber of neutrons. Therefore, a neutron tool is essentially a hydrogen-ion detector. High concentrations of hydrogen occur in water and hydrocarbons. Therefore, the neutron log has potential for identifying whether free and/or residual product is present in an aquifer. There are many types of neutron tools, and some can be used in cased holes, others only in open holes, depending upon the detector.

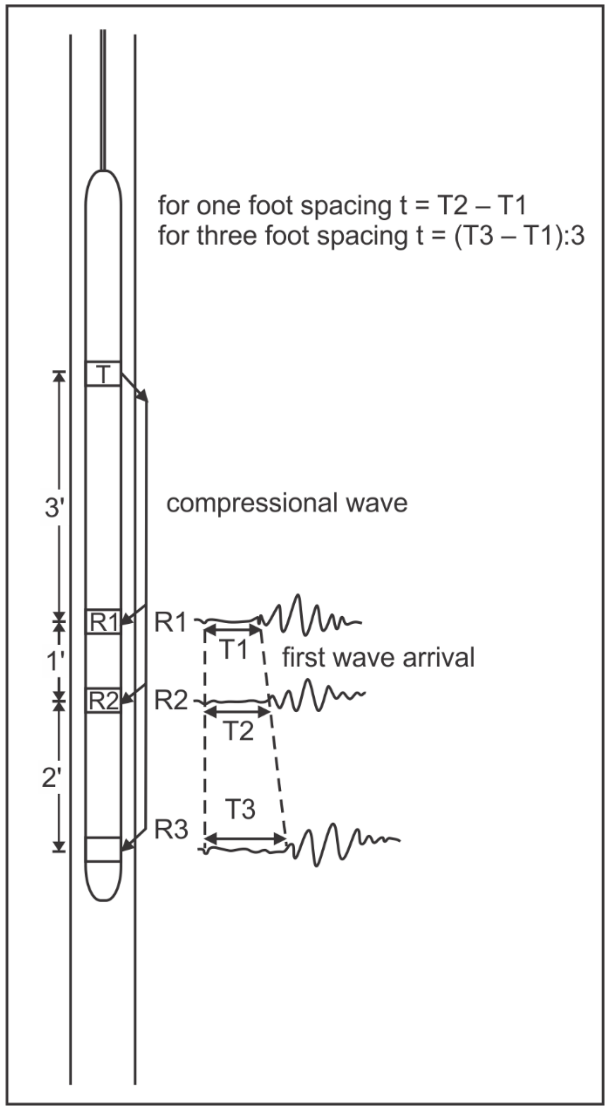

Figure 8.8 Basic Sonic System

8.10.4.5 Mechanical Devices

This category includes caliper, dipmeter, flowmeter, and temperature logging tools.

A caliper tool is a simple device that measures the diameter of the borehole by using a spring-loaded arm that applies constant pressure to the side of the borehole as the tool is brought up the hole. This tool can indicate sections of the borehole where cave-ins and washouts occur. It is necessary to know the open-hole diameter when running other geophysical tools. In most cases, a geophysical tool will yield a different response when the borehole is widened.

A dipmeter is a magnetically oriented tool (oriented with respect to magnetic north) that consists of four or more caliper arms with micro-conductivity electrodes that are pressed against the borehole. The data are used to collect information on the orientation (e.g., strike and dip) of planar features (e.g., bedding planes, cross-bedding, fractures, faults, etc.) encountered in the borehole. The method was developed and is primarily used in the petroleum industry. The dip meter log includes a presentation of dip angle and direction of the feature with respect to depth (e.g., tadpole plots). The data can also be plotted as rose diagrams of azimuth frequency.

"A flowmeter measures the vertical movement of fluid in the borehole. The flowmeter can be used to detect hydraulic head differences between two aquifers, or can be used to determine if an artesian system exists. In fractured bedrock settings such as the Newark Basin rocks in New Jersey, the pattern and magnitude of in-flow and out-flow conditions, which can be interpreted from flow meter profiling of borehole crossing aquifer sub-units, aids the understanding of key transmissive fractures.

Traditional "spinner" type tools employ a rotor or impeller to directly measure fluid movement. These devices typically have lower measurement limits of about 2 meters per minute for static measurements. Sensitivity can be increased by running spinner tools while "trolling" up and down the borehole at known cable speeds.

More advanced flow meters are available, with lower measurement limits of less than 0.03 m/min. These include heat-pulse, or thermal, flow and electromagnetic flow meters. These flow meters can be used under static water-level conditions and pumping conditions to develop hydraulic-conductivity profiles of aquifers. Heat-pulse flow meters have been widely adopted for fractured bedrock remediation site characterization. These tools employ special divertors to channel ambient or pumping induced flow through the tool body, where the response time is measured, and used to calculate a flow rate in galls/min. Where borehole conditions are favorable and a good seal is accomplished with the flowmeter divertors, lower measurement limits of 0.03 galls/min are achievable with the heat-pulse flow meter tool."

Temperature logs are used to relate temperature differences in the borehole to fluid movement. This tool, along with the fluid conductivity or fluid resistivity tools, are designed to log the hole on the trip down the borehole rather than up the borehole. This tool should be run several days (preferably weeks) after the water in the hole has been disturbed by pumping or other logging tools. Disturbing the water will cause large changes in the temperature gradient. Temperature gradients can be correlated to water flowing into and out of wells. Temperature logging has been effectively used for mapping fractures.

8.10.4.6 Acoustic, Radar and Optical

Acoustic tools include velocity/sonic tools (discussed above under porosity/density tools), cement-bond logs and acoustic televiewer tools. All acoustic tools must be used in fluid-filled boreholes as the fluid in the borehole allows propagation of the sound waves.

Cement-bond logs use sound to measure the acoustic travel time and reflected amplitude of sound waves in the borehole emitted by the cement-bond log tool. These are used to evaluate the integrity of the cement-to-casing and cement-to-formation bond. The method was developed in the petroleum industry.

The acoustic televiewer provides a magnetically oriented, 360-degree, photograph-like image of the acoustic reflectivity of the borehole wall. Televiewer logs, which indicate acoustic transit time and reflected amplitude (like cement-bond logs), can be obtained from both water- and mud-filled boreholes. Like dipmeter logs, they can be used to determine fracture and bedding orientation as shown in Figure 8.9 and dip angle and direction data can be plotted with respect to depth (tadpole plots) and in azimuth frequency diagrams.

Borehole radar provides a method to detect fracture zones at distances as far as 30 meters or more from the borehole in electrically resistive rocks. Fracture zones with electrical properties that differ from the surrounding non-fractured rock are excellent radar reflectors. Radar measurements can be made in a single borehole (transmitter and receiver in same borehole) or by cross-hole tomography (transmitter and receiver in separate boreholes). Single-hole, directional radar can be used to identify the location and orientation of fracture zones. Cross-hole tomography including radar velocity and attenuation can be used to delineate fracture zones between boreholes. The movement of a saline tracer through fracture zones can also be monitored by borehole radar.

Optical methods include conventional video logs and optical televiewer logs. Video logs have been used to inspect sewer lines and, in recent years, have been used to inspect monitor wells and open-hole bedrock formations.

Optical televiewers are similar to acoustic televiewers in that they provide a magnetically oriented, 360-degree image of the bore-hole wall. The information is recorded digitally which allows evaluation of the strike and dip of planer features in the same way that acoustic data are evaluated (see Figure 8.10). An advantage of the optical televiewer over the acoustic televiewer is the higher resolution of the recorded images. However, use of the optical televiewer is limited to situations where rather clear water is present in the borehole. High turbidity levels can reduce the resolution of the images. In these situations, use of the acoustic televiewer is necessary, as it can be used in both

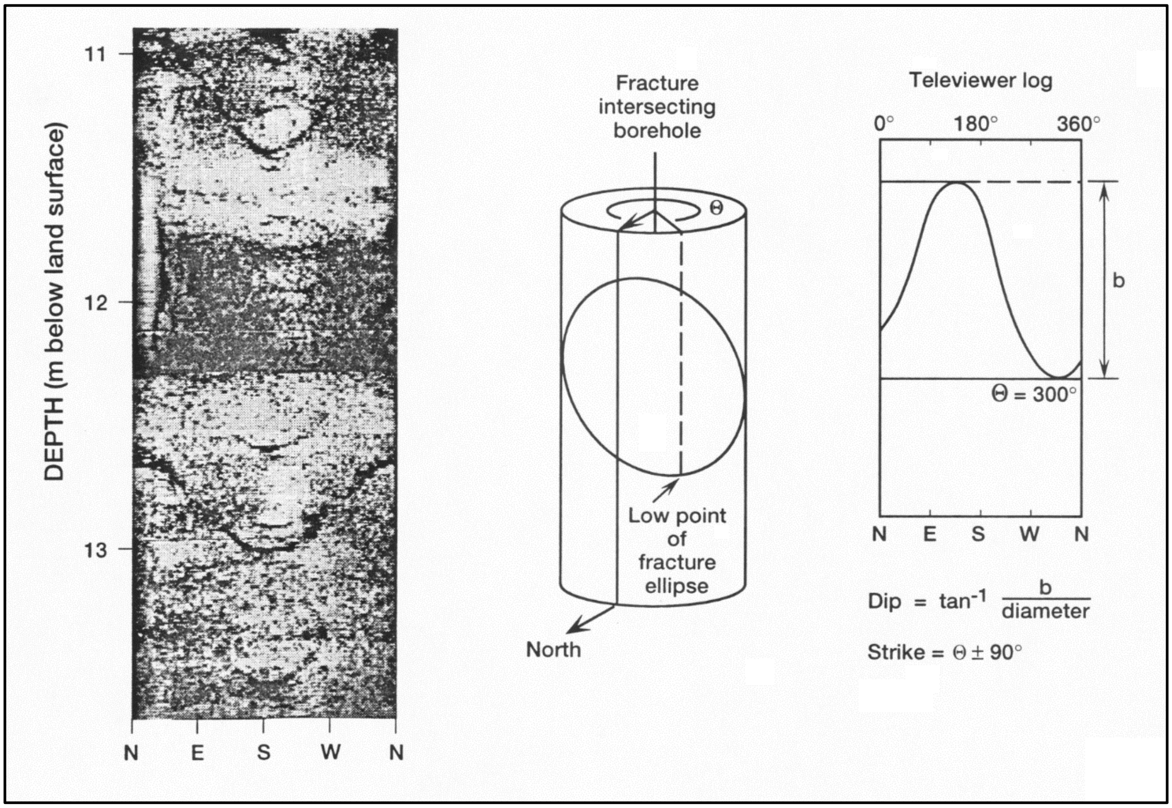

Figure 8.9 Magnetically oriented, acoustic-amplitude image of borehole wall generated from an acoustic televiewer. Fracture strike and dip are determined from depth scale and magnetic orientation. Source: Morin et. al., 1997.

water- and mud-filled boreholes. In addition, some optical televiewers have limits on their effectiveness in large-diameter boreholes (e.g., greater than nine inches). An advantage of the use of the optical televiewer is that an oriented "virtual core" can be viewed (see Figure 8.10). This information can be used to supplement the collection of actual rock core, negate the need to collect oriented rock core, or may even be used in place of collecting rock core, reducing the cost of the bedrock investigation.

In practice, the acoustic and optical televiewers often provide a complementary data set. Imaging of sedimentary bedding layers, important in bedrock such as the Leaky, Multi-unit Aquifer System of the Newark Basin, is best done with an optical televiewer. The optical televiewer can also reveal the presence of features such as NAPL staining or mineral precipitates indicating vertical flow directions at fractures. Acoustic televiewer data can show fractures through turbid water, which may exist within only a portion of the borehole (allowing optical televiewer to be used in the remainder). Acoustic televiewer data can identify some fractures not evident by optical televiewer, even in clear sections. Acoustic televiewer data may reveal correlatable sections of harder rock which are not evident based upon texture or color seen in the optical televiewer log.

8.10.5 Quality Assurance

Certain logging tools require different borehole conditions. The requirements of the logger must be discussed with the driller during the planning of the drilling program. Topics, which must be discussed, include depth and width of the hole, casing material, and cementing or grouting of the hole.

Well-logging equipment is generally expensive and can be complicated to use. Consequently, only a few companies own or operate equipment. Except for temperature, fluid conductivity or resistivity, and video logging, well logging should be done coming up the borehole and not on the downward trip. There is the possibility that the tool may get caught on the sides of the borehole and slack the lines if logging is done going down the hole.

Electrical tools, such as SP, resistivity, and induction logging tools, are generally susceptible to the same types of interference as those methods used for surface geophysics. Buried cables, high-tension lines and cathodically protected tanks and pipelines cause electrical current to be shown on the logs. Usually, the current frequency is 60 cycles and at the same regular frequency which can be seen as an overprint on the curves. Generally, useful information can be extracted from the curves even though there is a 60-cycle overprint because the 60-cycle noise is of much higher frequency than the desired curve. The surface electrode should be kept as far away as possible (at least 100 feet) from the borehole to avoid electrode geometry effects.

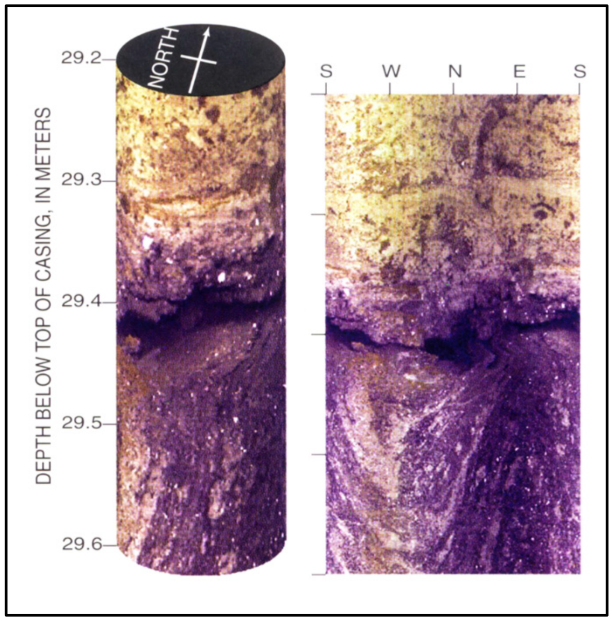

Figure 8.10 "Virtual core" wrapped (left) and unwrapped (right) images of a bedrock fracture at a depth of 29.4 meters collected with a digital television camera. The images show that the fracture is at the contact between pegmatite and gneiss. Source: USGS, 1998.

Sonic, neutron, and gamma-gamma ray logs are susceptible to "wash-outs" in the open hole (e.g., detectors may receive radiation directly from a nuclear source in a rough hole). These logs should be correlated to a caliper log to determine the hole diameter. An anomalous response seen on the density/porosity logs could be erroneous due to variations in the borehole diameter.

Structural interpretations based upon acoustic and optical televiewers logs are sensitive to conditions such as borehole deviation and variations in diameter. Correction should therefore be made during log processing, utilizing deviation measurements collected by orientation sensors within the OTV probe.

Generally, geophysical logging is recommended at all sites and for every well drilled. Geophysical logs are a consistent standard (assuming that the logging tools are calibrated regularly), as opposed to a driller's (lithology) log, which can vary depending upon the person who describes the samples of the well.

8.10.6 Presentation of Results

The geophysical logging professional should prepare a report including, at minimum, a copy of the logs from each run, displayed at a common vertical scale useful for the purposes intended. Each paper log record should show the name and location of the well or test boring in latitude and longitude, the date that the logging was performed, the company and individual(s) performing the logging, log headings showing the types of probes employed, equipment settings, and scaling. Locations of the wells or borings that were logged should be documented on a site map. For projects that involve more than simple plotting of raw, uncorrected data recorded by the logging equipment, a written report should accompany the logs. The report should include descriptions of the purposes, scope, implementation, and results of the geophysical logging work; including the bases for and methods used for any interpretive aspects of the project, classification schemes employed, problems encountered, and solutions applied.

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