Chapter 14

BOREHOLE GEOPHYSICAL AND WIRELINE SURVEYS

Introduction

Wireline surveys determine physical properties in and beyond the wall of a borehole by devices attached to a cable, or wireline. Subsurface geologic conditions and engineering characteristics can be derived directly or indirectly from the wide variety of measurable properties available by wireline surveying. Wireline logging techniques commonly are classified by the kind of energy that is input (active systems) or received (passive systems), including electric, seismic or acoustic, nuclear, magnetic, gravity, or optical. Logging tools are also classified according to whether they are for use in open holes or cased holes. Data from several methods are often combined to evaluate a single geologic or engineering characteristic. This chapter describes the methods and discusses the application of borehole wireline surveying to geotechnical exploration and investigation.

Electric Logging Techniques

An electric log is a continuous record of the electrical properties of the fluids and geologic materials in and around a borehole. Electric logging is performed in the uncased portion of a borehole by passing electric current through electrodes in the logging device, or sonde, and out into the borehole and the geologic medium. Other electrodes located on the surface or in the borehole complete the circuit to the source and recording device. Electric logging surveys are efficient and cost effective because the process is automated and several electrical properties are measured simultaneously by combining several electrode configurations in the same tool.

Electric logging techniques can be used in geotechnical investigations to assess the variation with depth of geologic materials and associated fluids. Electric logs from two or more boreholes are used to correlate and determine the continuity of geologic strata or zones that have similar electrical properties. Since the electrical properties depend on physical characteristics, the porosity, mineral composition, water content (saturation), water salinity, lithology, and continuity of the bedding can often be deduced. Borehole electric logs are also the best source of control for surface electrical surveys by providing subsurface layer resistivities. Electric log correlation of continuous layers from borehole to borehole is relatively simple. The interpretation of physical properties from electric logs can be ambiguous and complicated. Different combinations of water content, salinity, mineralogy, porosity, and borehole peculiarities can produce similar electric logs.

Spontaneous Potential (SP) Log

The spontaneous potential or SP logging device records the difference in potential in millivolts between a fixed electrode at the surface and an electrode in a borehole (figure 14-1). The measured potential difference changes as the electrical potential between the borehole fluid and the fluids in the various strata opposite the sonde changes. The spontaneous potential device commonly is incorporated into the multiple-electrode resistivity sonde so that resistivity and SP logs are acquired simultaneously. Figure 14-2 illustrates a typical SP resistivity log. The recording is a relative measurement of the voltage in the borehole. Readings opposite shales or clays are relatively constant and form the shale baseline, or "shale line." The SP curve typically deflects to the left or right opposite permeable formations depending on the salinity of the drilling mud. Sandstone and other porous

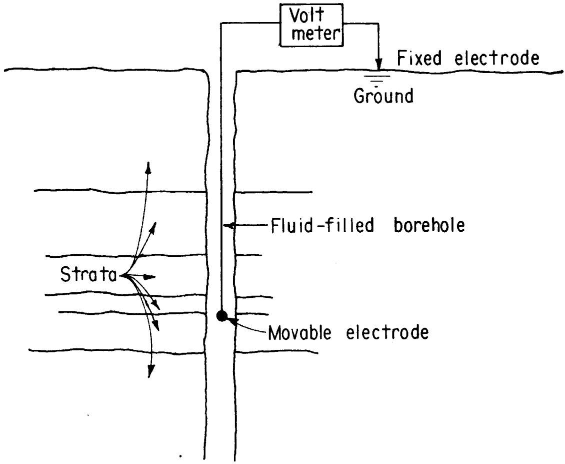

Figure 14-1.—Spontaneous potential survey elements.

and permeable strata allow the different fluids to mix and produce salinity of the pore fluid with respect to the borehole fluid and the clay content of the strata. The SP peaks are commonly displayed to the left of the shale line because negative potentials are more commonly encountered. In fresh water, SP anomalies are typically inverted (i.e., they appear to the right of the shale baseline).

SP logs are used in combination with resistivity logs to define strata boundaries for correlation and to infer the lithology of the strata as a function of permeability and resistivity. The shape of the SP curve depends on the drilling mud used and the geologic strata encountered. For example, the SP curve for a shale bed would indicate zero deflection (the shale line in figure 14-2), and the

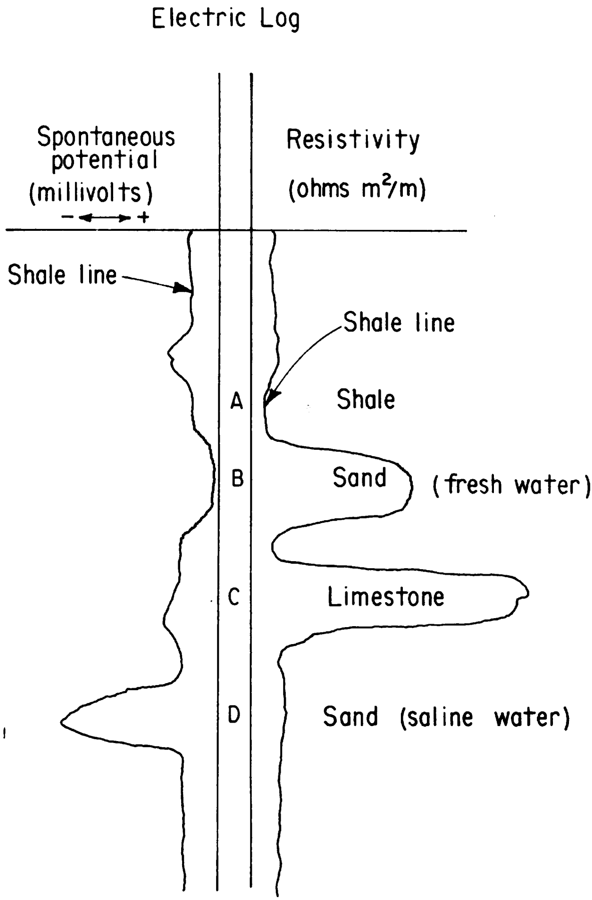

Figure 14-2.—Electric log showing SP and resistivity in different beds.

resistivity curve would indicate low resistivity because of bound water in the clay and trapped water in the shale. Generally, the SP and resistivity curves converge opposite shale strata (A in figure 14-2) and diverge opposite permeable fresh water sands (B in figure 14-2). A limestone bed, which usually is highly resistive but develops little spontaneous potential, would produce a large resistivity deflection but a subdued SP peak (C in figure 14-2). A permeable sand bed with pore water of high salinity typically would produce little resistivity deflection but a large negative SP peak (D in figure 14-2). The determination of lithologies from SP logs should be done cautiously because many factors contribute to the magnitudes and directions of the curve deflections. The SP log is best used with resistivity and other logs to detect strata boundaries and to correlate strata between boreholes. The SP log is also used to determine formation water resistivities.

Single-Point Resistance Log

Single-point resistance loggers are the simplest electrical measuring devices. A current can flow between a single electrode placed in a borehole and another electrode at the ground surface (figure 14-3). The earth between the electrodes completes the circuit. Single-point resistance logs are not commonly used in modern logging operations but illustrate the principal of down-hole electric logging. The resistance, R, of the circuit (electrodes plus earth) can be calculated from Ohm's Law, $R = V/I$, where V is the measured voltage drop and I is the current through the circuit. The resistance of a circuit is determined by the conductor's size, shape, and resistivity, p, an intrinsic property of a material. Resistance of the conductor (the earth) is a convenient and useful property determined by pore fluid content, pore fluid composition, lithology, and continuity of strata. The resistivity of the measured

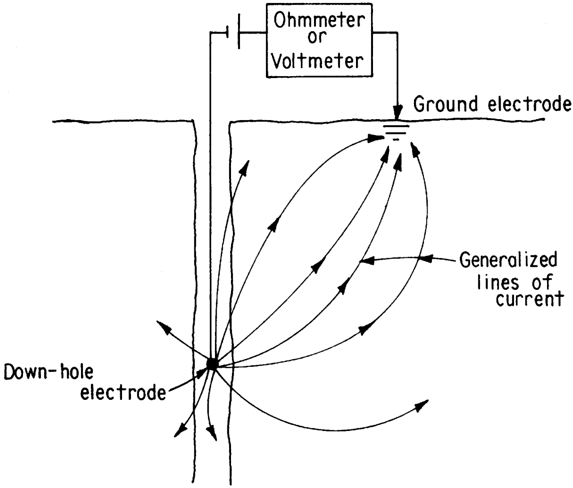

Figure 14-3.—Single-point resistivity array.

section of earth is determined from $p = KR$, where K is a geometric factor which differs for different electrode configurations and R is the measured resistance V/I. A single point resistance log measures an apparent resistance of a section made up of borehole fluid and the various individual strata between the borehole and the ground surface electrode. The multiple electrode arrays discussed below are designed to narrow and better define the measured sections so that individual strata are represented more accurately by the logs.

Multiple Electrode Array Log

Wireline electrical systems using multiple electrode arrays in the borehole provide better resolution of resistivity and associated properties of individual strata within the subsurface than can be achieved with the single-point array. Multiple electrode arrays include the short- and long-normal array, lateral array, and focused-current or guard logging systems. Current electrodes usually are designated A and B, and potential electrodes are designated M and N. "Normal" arrays place the in-hole current electrode far away, at effective infinity (figure 14-4A). "Lateral" devices place the two potential electrodes close together with respect to the in-hole current electrode (figure 14-4B). Conventional modern logging systems use a sonde made up of two normal devices and one lateral device to produce three resistivity logs and the SP log simultaneously.

The normal resistivity arrays (figure 14-4A) are called short normal or long normal depending on the spacing of the in-hole current (A and B) and potential (M and N) electrodes. The industry standard AM electrode spacing is 16 inches (in) for the short normal and 64 in for the long normal. The normal arrays measure the electrical potential at the in-hole electrode M. The greater the spacing between the current and measuring electrodes, the greater the effective penetration (effective penetration distance = ½ AM) of the device into the surrounding geologic medium.

The lateral resistivity array is shown in figure 14-4B. The actual positions of the electrodes may vary from the circuit shown, but the resistivity measurements are the same. The lateral array spacing is measured from the A current electrode to the center (0) of the potential electrode configuration and is called the AO spacing. The lateral array measures the potential difference, or gradient, between the two in-hole potential electrodes and is also called the gradient array. The influence of the

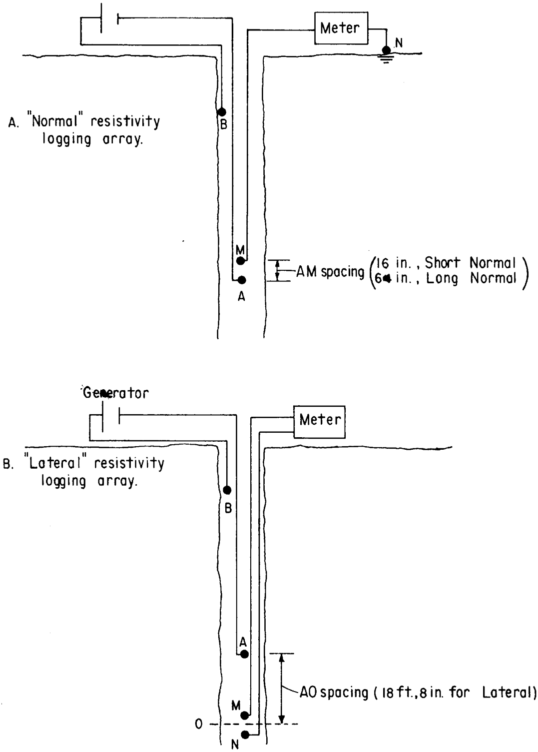

Figure 14-4.—Multiple-electrode resistivity arrays. (A and B are current electrodes. M and N are potential electrodes.)

geologic medium away from the borehole (the effective penetration of the system) is greatest for the lateral array with an 18-foot 8-in spacing and least for a 16-in short normal array.

The focused-current, or guard, resistivity device is a modified single-electrode array in which "guard" current electrodes are placed above and below a central current electrode and two pairs of potential electrodes (figure 14-5). Current in the central and guard electrodes is adjusted so that zero potential exists between the potential electrodes and the current is thus forced or focused to flow out into the geologic medium in a narrow band. The device then measures the potential between the sonde electrodes and a reference electrode at the ground surface. Focusing the current into a band of predetermined thickness gives the focused array much greater thin bed and stratum boundary resolution than the other arrays.

Geotechnical applications for multiple-electrode resistivity arrays include apparent resistivity and an approximation of true resistivities of individual strata or zones. Resistivity data aid in the interpretation of surface electrical surveys, which generally are less expensive to conduct than down-hole surveys and can be applied over large areas. Since the depth of penetration of the measuring circuit into the geologic medium varies with the electrode spacing, logs of the various arrays (short- and long-normal and lateral) can be analyzed collectively to evaluate the effects of bed thickness, borehole fluids, drilling mudcake, variations in fluids, and permeabilities of strata at various distances from the borehole. The curve shapes of the logs for several boreholes permit correlation of strata and zones from borehole to borehole. Normal devices produce better boundary definition of thick strata than do lateral devices, but lateral logs are more effective in delineating thin strata and thin, highly resistive zones. The focused logs discriminate more sharply between different strata, define strata boundaries better, and give a better approximation of true stratum resistivity than do normal or lateral logs. Porosity and

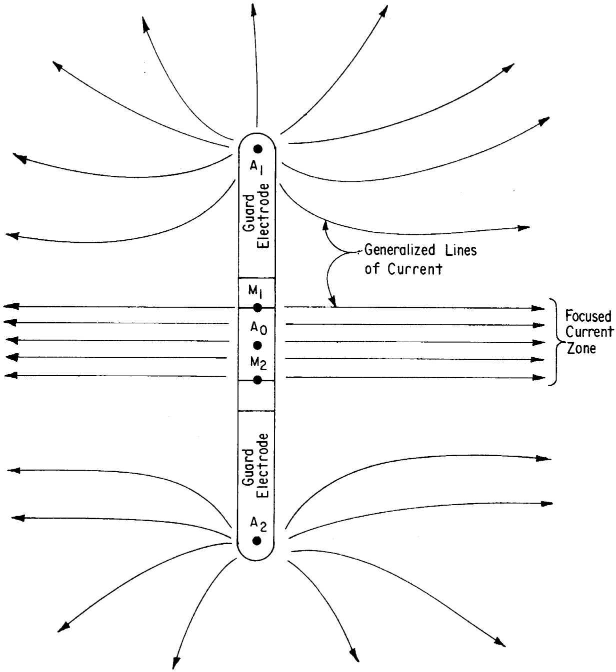

Figure 14-5.— Focused current, or guard, resistivity array.

water content of strata and salinity of pore fluids can be calculated from the logs if sufficient information is obtained.

Microlog

Special purpose electric logging devices are available to supplement or, in some cases, replace standard resistivity logs. The microlog (also called contact log, microsurvey, and minilog) records variations in resistivity of a narrow, shallow zone near the borehole wall. The microlog sonde is equipped with three closely spaced electrodes placed on a rubber pad which is pressed against the borehole wall (figure 14-6). Microlog electrode spacings are about 1 to 2 in (2.5 to 5 centimeters [cm]). Depth of investigation for the microlog is about 3 in (7.5 cm) from the borehole wall. Normal, lateral, and guard arrays can be configured in the microlog survey. Porous permeable zones allow the mud cake to penetrate the strata, and the resulting microlog will indicate resistivities close to that of the mud.

Induction Log

Induction logging is performed in dry boreholes or boreholes containing nonconducting fluids. Induction logging can be done in holes cased with polyvinyl chloride (PVC) casing. The induction logger is housed in a sonde that uses an induction coil to induce a current in the geologic medium around a borehole. The induction logger is a focused device and produces good thin-bed resolution at greater distances from the borehole than can be achieved with normal spacing devices. A primary advantage over other devices is that the induction logger does not require a conductive fluid in the borehole.

Nuclear Radiation Logging Techniques

A nuclear radiation log is a continuous record of the natural or induced radiation emitted by geologic materials near the borehole. Nuclear radiation logging is performed by raising a sonde containing a radiation detector or a detector and a radioactive source up a borehole and recording electrical impulses produced by a radiation detector.

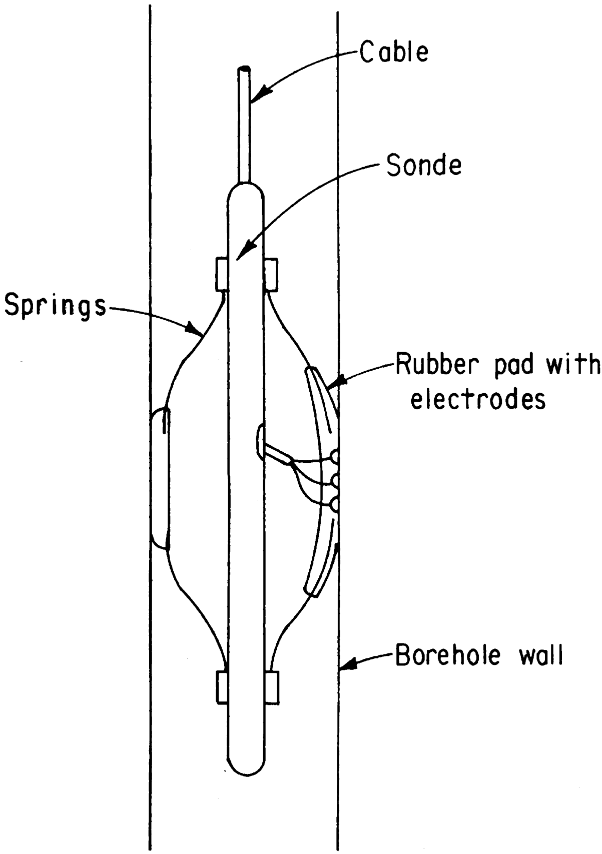

Figure 14-6.—Microlog resistivity logging device.

Nuclear radiation logging can be used in geotechnical investigations to correlate strata between boreholes, aid in determining lithology, and derive or measure directly many physical parameters of the subsurface materials, including bulk density, porosity, water content, and relative clay content. Most nuclear radiation logging systems can be operated in cased boreholes, giving them an advantage over electrical wireline logging systems. Nuclear logs can also be run in old boreholes, which are more likely to be cased than recent boreholes. The logs are among the simplest to obtain and interpret, but the calibrations required for meaningful quantitative interpretations must be meticulously performed. Nuclear radiation logging tools should be calibrated in controlled calibration pits. Under favorable conditions, nuclear borehole measurements approach the precision of direct density tests of rock cores. The gamma-gamma density log and the neutron water content log require the use of isotopic sources of nuclear radiation. Potential radiation hazards necessitate thorough training of personnel working around the logging sources.

Three common wireline nuclear radiation systems are the gamma ray or natural gamma logger, the gamma-gamma or density logger, and the neutron logger. The gamma-gamma and neutron devices require the use of a radioactive source material. The gamma ray device is a passive system and does not use a radioactive source. All the systems employ an in-hole sonde containing the source and detector. Most devices require a borehole diameter of at least 2 in (5 cm) and investigate a zone extending 6 to 12 in (15 to 30 cm) from the borehole. Applications differ for the three systems and depend on the properties measured.

Gamma Ray (Natural Gamma) Log

The gamma ray or natural gamma radiation device provides a continuous record of the amount of natural gamma radiation emitted by geologic materials near the sonde. The gamma-ray detector converts incoming gamma radiation to electrical impulses proportional to the number of rays detected and sends the amplified electrical impulses to the surface. Gamma ray logs generally reveal the presence of shale or clay beds because clay minerals commonly contain the potassium isotope K^{40} ,which is the primary source of natural gamma radiation in most sediments. Shales and clays usually produce a high gamma ray count, or a peak on the log.

The relative density of a stratum is also indicated by natural gamma ray logs because gamma radiation is absorbed more by dense materials than by less dense materials. Gamma ray logging can be conducted in cased boreholes and is sometimes used in place of SP logging to define shale (clay) and non-shale (non-clay) strata. The natural gamma ray and neutron logs are usually run simultaneously from the same sonde and recorded side-by-side. The gamma ray log also infers the effective porosity in porous strata with the assumption that high gamma counts are caused by clay filling the pores of the strata. Gamma ray logs are used to correct gamma-gamma density logs. Gamma ray logs are standard in radiation logging systems.

Natural Gamma Spectral Log

Spectral logging permits the identification of the naturally occurring radioactive isotopes of potassium, uranium, and thorium which make up the radiation detected by the natural gamma ray detector. Spectral logging technology allows the detection and identification of radioactive isotopes that contaminate water resources, or are introduced as tracer elements in hydrologic studies.

Density or Gamma-Gamma Log

The gamma-gamma or density logging device measures the response of the geologic medium to bombardment by gamma radiation from a source in the sonde. Electrons in the atoms of the geologic medium scatter and slow down the source gamma rays, impeding their paths to the detector. Figure 14-7 illustrates the operation of the gamma-gamma device. Since electron density is proportional to bulk density for most earth materials, strata with high bulk densities impede the source gamma rays more than low density strata and produce correspondingly lower counts at the detector. The primary use of the gamma-gamma log is determining bulk density. If bulk density and grain density are known from samples and if fluid density can be determined, the porosity can be calculated. Gamma-gamma logs can also be used for correlation of strata between boreholes.

Gamma-gamma logging is best conducted in uncased boreholes using decentralizing devices to keep the sonde

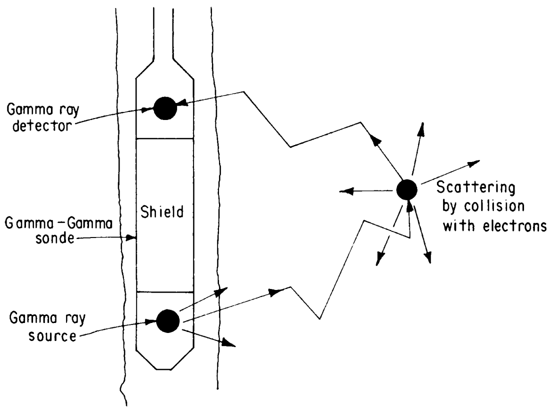

Figure 14-7.—Gamma-gamma logging sonde.

against the borehole wall. The system is affected by borehole diameter and wall irregularities and must be carefully calibrated for the effects of hole diameter, decay of the strength of the radioactive source, natural gamma radiation in the geologic medium, and borehole fluid density. A caliper log is commonly run to permit calibration for hole diameter. Some logging systems simultaneously display the gamma ray count on one side of the log and bulk density on the other side, with the bulk density log automatically corrected for the effects of mud cake and wall irregularity.

Neutron Log

Neutron logging is an active system that measures the response of the geologic medium to emission of neutron radiation from a source located in the sonde. Neutrons emitted by the source are captured by certain atoms, especially hydrogen nuclei, in the strata near the sonde. Figure 14-8 illustrates the operation of the neutron logging device. Collision of neutrons with atoms of the geologic medium causes secondary emission of neutrons and gamma rays, a portion of which are picked up by the detector. A high concentration of hydrogen atoms near the source captures a greater number of neutrons and produces a smaller counting rate at the detector.

Neutron detectors may detect gamma (neutron-gamma) or neutron (neutron-neutron) radiation. Water and hydrocarbons contain high concentrations of hydrogen atoms. If the fluid in the strata is assumed to be water, the neutron log is an indicator of the amount of water present. Determination of volumetric water content (weight of water per unit volume measured) is a principal use of neutron logging. In saturated materials, the neutron log can be an indicator of porosity, the ratio of the volume of void space to the total volume. Bulk densities from gamma-gamma logs, grain densities from samples, caliper

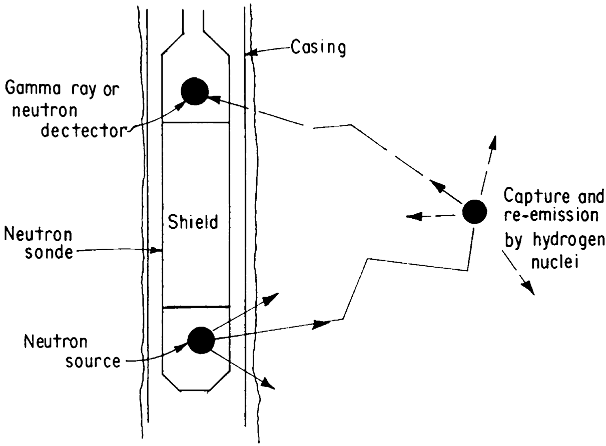

Figure 14-8.—Neutron logging sonde.

log data, and natural gamma log information can be combined with the volumetric water contents from neutron logs to calculate the more commonly used geotechnical parameters of water content by weight, wet and dry density, void ratio, porosity, saturation, and lithology.

Neutron logs and natural gamma radioactive logs can be obtained through thick borehole casing and are usually run together. Figure 14-9 illustrates the format of the tandem logs and typical responses for several lithologies. The response of different lithologies to the natural gamma and neutron devices is controlled directly by the amount of radioactive material present (especially the clay content) and the fluid content and indirectly by the porosity and bulk density of the material. For example, the saturated sand of figure 14-9 absorbs neutron radiation, produces a correspondingly low neutron log count, and produces a low natural gamma count because of the lack of clay in its pores.

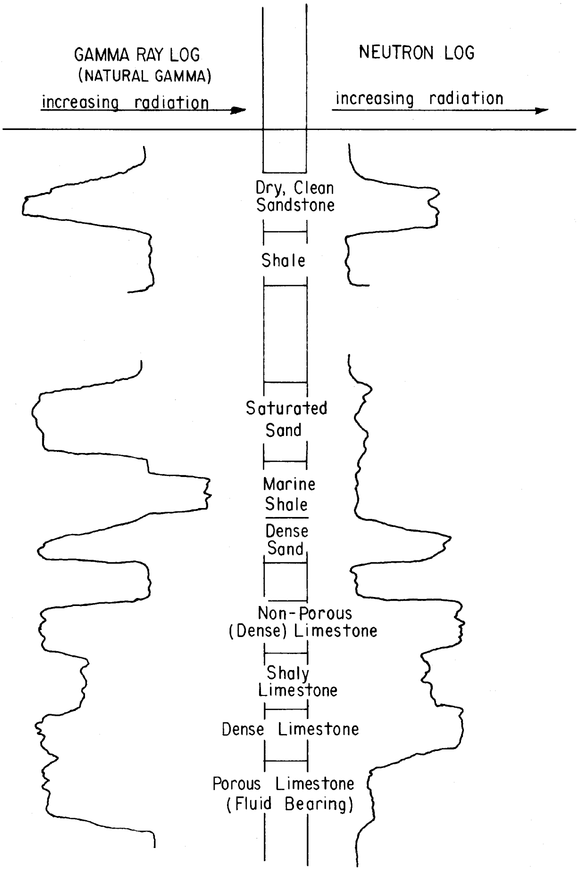

Figure 14-9.—Typical curve responses for nuclear radiation logs.

Neutron activation or spectral logs provide spectral analyses of the geologic medium near the borehole to detect the presence of certain elements. The spectral logging sonde activates a neutron source in bursts of short duration and activates the gamma ray detector only during the source bursts. As a result, only certain radiation ("prompt" gamma rays) is detected. The system produces a plot of counts versus gamma ray energy. Peaks on the energy/count plot identify specific elements, for example carbon, silicon, magnesium, or chlorine. Spectral logs may have application to groundwater quality investigations.

Neutrino Log

Neutrino logs are not necessarily a borehole log, but the method can and often is performed in drill holes. Neutrino sources are located throughout the universe with the closest and most useful source being the sun. Using the sun as a neutrino source eliminates the need for a special source, and there are no handling and licensing problems that are often associated with other nuclear logs. Neutrinos penetrate the earth with little to no impediment, so neutrino logs can be run at any time of day or night. Logging tools generally consist of strings of widely spaced photomultiplier tubes (PMT) placed into the borehole. High-energy neutrinos passing through the rock will occasionally interact with the rock and create a muon. These muons emit Cherenkov light when passing through the array and are tracked by measuring the arrival times of these Cherenkov photons at the PMTs. Resolution is high because the source (Sun) only subtends half a degree at this distance (93 million miles from Earth). Neutrino logging is particularly useful in cased holes and when fluid in the hole is not a factor. New or old holes can be logged no matter what the hole contains. These logs are often used for tomography. Tomography is particularly useful and convenient because, as the Earth rotates, the source penetrates a full 360 degrees, similar to CAT scan or Magnetic Resonance Imaging. A drawback is that 24 hours is required to run a complete neutrino tomography log.

Acoustic/Seismic Logging Techniques

Wireline acoustic/seismic logging systems use medium- to high-frequency acoustic (sonic) energy emitted from a sonde to image the borehole wall or to obtain seismic velocities of the geologic material in the wall or in the formation away from the borehole. Acoustic systems use sonic energy generated and propagated in a fluid such as water. Seismic systems use sonic energy propagated through the ground in geologic materials. The three systems discussed in this section are the acoustic velocity logger, an acoustic and seismic energy system; a borehole imaging device, an acoustic system; and the cross-hole seismic technique, a seismic technique.

The borehole imaging and acoustic velocity systems are used in geotechnical investigations to evaluate geologic conditions including attitude and occurrence of discontinuities and solution cavities and in determining the effective porosity and elastic properties of rock. The down-hole systems also supply subsurface information for interpreting surface-applied geophysical surveys. The frequency of the energy pulse produced by the sonde's transducer determines whether the energy penetrates the borehole wall for acoustic/seismic velocity surveys. Medium frequencies are used in acoustic/seismic velocity surveys. The energy is reflected from the wall for imaging surveys. High frequencies are used in acoustic/seismic velocity surveys. Borehole imaging velocity devices generate compressional (P-wave) energy. The acoustic velocity device generates primarily compressional energy but also generates shear (S-wave) energy if the shear wave velocity exceeds the fluid velocity. The cross-hole seismic technique generates P- and S-wave energies and determines their velocities.

Acoustic Velocity Log

The continuous acoustic velocity (sonic) logger measures and records the velocity of acoustic energy (seismic waves) in the material adjacent to the borehole. A transmitter located at one end of the sonde generates an electro-mechanical pulse that is transmitted through the bore-hole fluid into the borehole wall and by refraction to a receiver located at the other end of the sonde (figure 14-10). The propagation velocities of the seismic waves can be calculated by travel times and distance traveled from transmitter to receiver. The devices must be operated in a fluid-filled borehole. Compressional wave oscillations set up by the sonde's transmitter in the borehole fluid set up, in turn, oscillations in the borehole wall. Compressional, shear, and surface waves propagate in and along the wall and then, as compressional waves, back through the borehole fluid to the receiver. Compressional waves have the highest velocity and arrive first, followed by the shear waves and the surface waves. Devices with two receivers cancel the borehole fluid travel times so that only the refracted wave paths through the borehole wall are measured. Single-receiver devices require the borehole fluid acoustic velocity and borehole diameter for calculation of seismic velocities. The acoustic pulses generated at the transmitter are in the lower ultrasonic range around 20 kilohertz (kHz).

The simplest acoustic logging devices display a single graphical trace or waveform of the arrival of each pulse

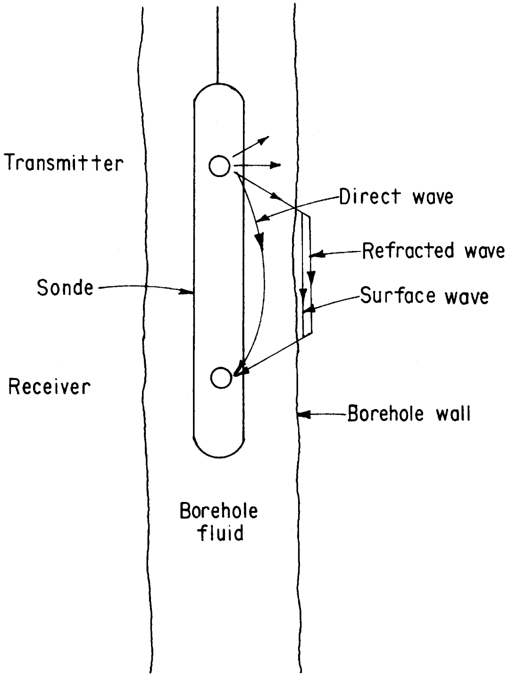

Figure 14-10.—Elements of a simple wireline acoustic velocity device.

and are called amplitude-modulated devices. Intensity-modulated acoustic logging devices record the entire continuous acoustic wave (see figure 14-11). Intensity-modulated, or three-dimensional (3-D), devices express wave frequency by the width of light and dark bands and

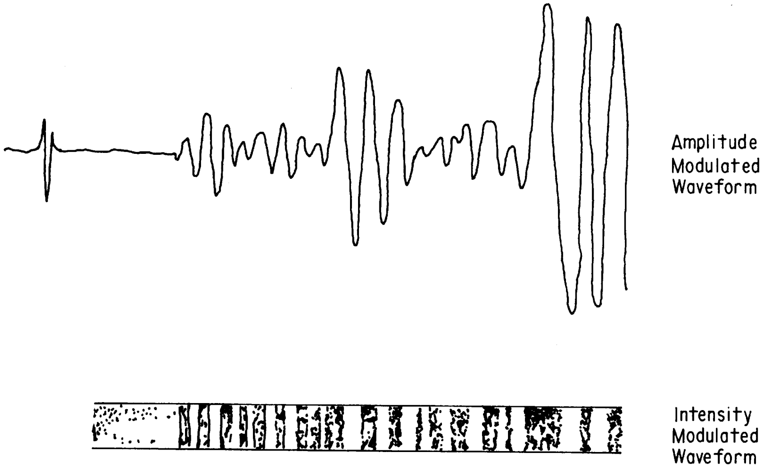

Figure 14-11.—Acoustic log presentations. The intensity modulated waveform wave frequency by the width of the band, amplitude by the shading intensity of the band.

amplitude by the degree of light or dark shading (figures 14-11 and 14-12). The P-wave, S-wave, and surface wave arrivals can be discerned on the 3-D records. Strata or zones of different seismic velocity produce contrasting signatures on the 3-D log. The phyllite zones in figure 14-12 represent softer materials of lower seismic velocity than the metabasalts and produce correspondingly later arrival times. Fractures or other discontinuities can often be seen as disruptions in the bands.

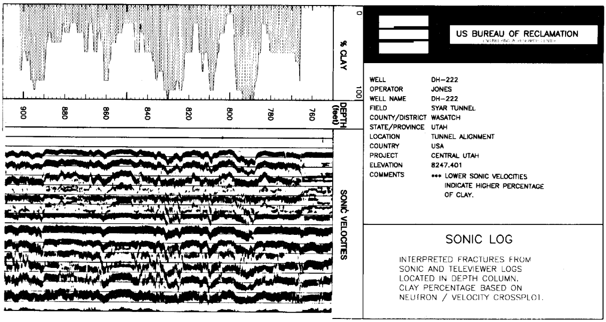

Figure 14-12.—Sample of intensity modulated acoustic log. Lithologies from core samples.

In addition to determining seismic velocities to aid interpretation of seismic surveys, 3-D logs show lithologic contacts, geologic structure, and solution features. The P- and S-wave velocities can be used directly to calculate the dynamic elastic properties of rock, including Poisson's ratio, Young's modulus, and bulk and shear moduli. For example, Poisson's ratio is calculated using:

$$\mu = \frac{1/2\,\boldsymbol{V}_p^2 - \boldsymbol{V}_s^2}{\boldsymbol{V}_p^2 - \boldsymbol{V}_s^2}$$

where V_p and V_s are the compressional and shear wave velocities, respectively. The effective porosity of the strata can also be evaluated.

Acoustic velocity devices require a borehole diameter of 3 in or greater. The in-place geologic materials must have compressional wave velocities higher than the velocity of the borehole fluid (approximately 4,800 feet per second [ft/sec] [1,450 meters per second (m/sec)] for water) for the waves to be refracted and detected. Soils generally do not have sufficiently high seismic velocities for acoustic velocity logging. The wave train (trace) type velocity loggers often are equipped with a radiation logging device and caliper on the same sonde for simultaneous acoustic and natural gamma ray logging and borehole diameter measurement.

Acoustic Borehole Imaging Log

The acoustic borehole imaging device uses high-frequency acoustic waves to produce a continuous 360-degree image of the borehole wall. Physical changes in the borehole wall are visible as changes in image intensity or contrast. Proprietary trade names for the acoustic borehole imaging device include "Televiewer" and "Seisviewer." Figure 14-13 illustrates the operation of an acoustic borehole imaging device. A piezoelectric transducer and direction indicating magnetometer are rotated by a motor inside the tool housing at approximately three revolutions per second (rps). The transducer emits pulses of acoustic energy toward the borehole wall at a rate of about 2,000 pulses per second at a frequency of about 2 megahertz (MHz). The high-frequency acoustic energy does not penetrate the borehole wall, and the acoustic beams are reflected from the borehole wall back to a transducer. The intensity of the reflected energy is a function of the physical condition of the borehole wall,

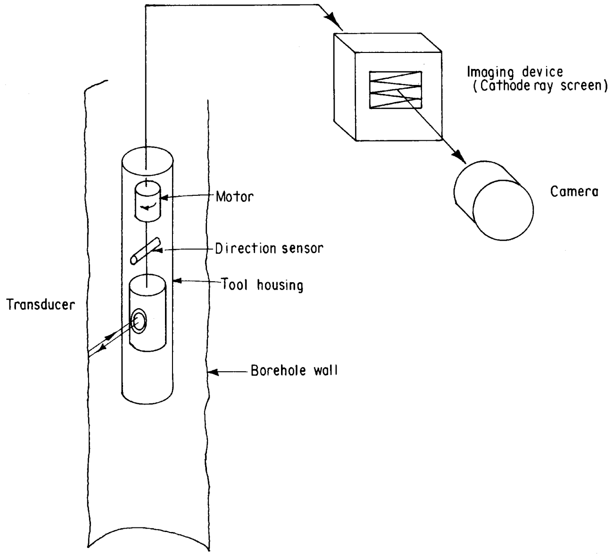

Figure 14-13.—Acoustic borehole imaging system.

including texture (rough or smooth) and hardness (a function of the elasticity and density of the material). The image is oriented to magnetic north with every revolution of the transducer. Fractures, cavities, and other open discontinuities produce low-amplitude acoustic reflections and are readily discerned in their true orientation, width, and vertical extent on the image.

The acoustic borehole imaging device can detect discontinuities as small as 1/8 in (3 millimeters [mm]) wide and

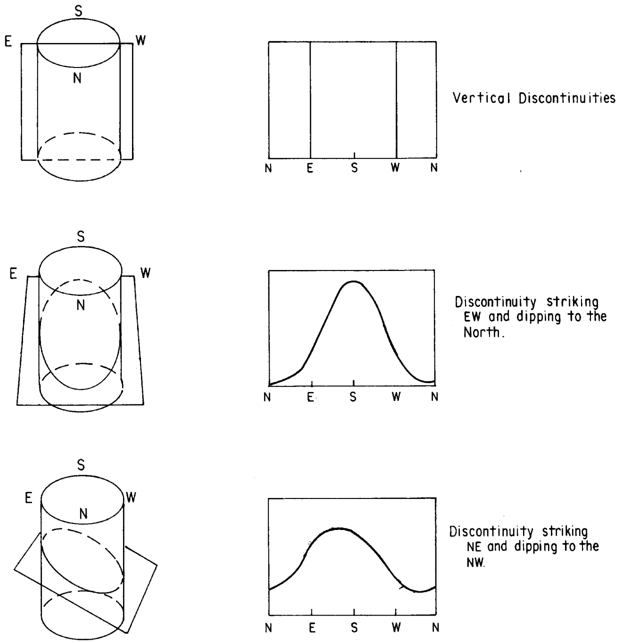

Figure 14-14.—Traces of planar discontinuities intercepting the borehole (left) as they appear on the acoustic borehole imaging record (right).

can sometimes distinguish contrasting lithologies. Discontinuities, contacts, and other linear features intercepting the borehole at an angle other than 90 degrees produce a characteristic sinusoidal trace that can be used to determine the strikes and dips of the features. Figure 14-14 shows how planar discontinuities of different orientations appear on the acoustic imaging log. Vugs and solution cavities are displayed as black areas, and their traces can be analyzed to determine their size (in two dimensions) and percentage of the borehole. The device can also be used to inspect casing and well screens for defects. The acoustic imaging device must be operated in a fluid-filled borehole.

Cross-Hole Seismic Test

Cross-hole tests are conducted by generating a seismic wave in a borehole and recording the arrival of the seismic pulse with geophones placed at the same depth in another (receiver) borehole. Source and geophones are placed at several regular depth intervals in the boreholes to determine seismic wave velocities of each material. Compressional and shear wave velocities can be determined with the cross-hole test. Figure 14-15 illustrates the essential features of a cross-hole seismic test. The seismic source may be either an explosive or a mechanical device. A vertical hammer device, clamped to the borehole wall, is the typical source arrangement. Cross-hole geophones configured in triaxial arrays are used because directional detectors are necessary to identify the S-wave arrival. Two or more receiver holes are sometimes used.

The raw data of cross-hole tests are the times required for P- and S-waves to travel from the seismic source in one borehole to the detectors in the receiver hole or holes. The corresponding P- and S-wave arrival times can be used to calculate seismic velocities as the ratios of distance to travel time, assuming the arrivals are direct (non-refracted) arrivals. If refraction through a faster zone occurs, true velocities must be calculated, similar to surface refraction seismic calculations.

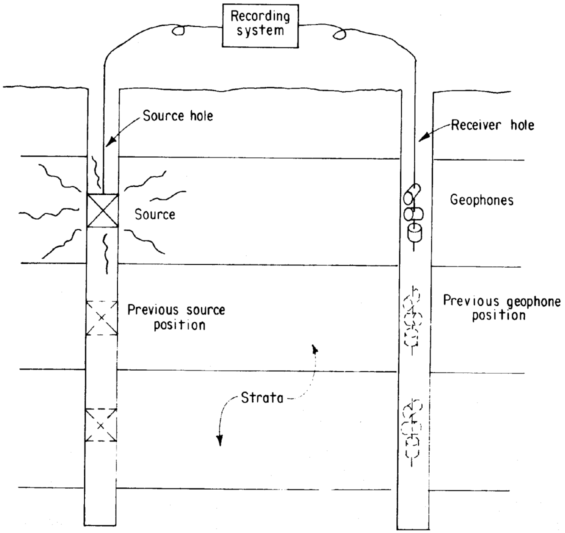

Figure 14-15.—Cross-hole seismic test.

Borehole spacing (distance) is critical in cross-hole tests. Generally, spacing should be no greater than 50 feet (ft) (15 meters [m]) or less than 10 ft (3 m). Borehole deviation surveys should be conducted prior to testing to determine precise spacing between holes at each shotpoint depth.

Cross-hole tests have several applications in engineering geology. S-wave cross-hole tests provide data on material properties for static and dynamic stress analysis. In addition to providing true P- and S-wave velocities at different depths, cross-hole surveys can detect seismic anomalies such as zones of low velocity underlying a zone of higher velocity or a layer with insufficient thickness or velocity contrast to be detected by surface refraction tests.

Seismic Tomography

Tomography is a method of constructing an image of some physical property inside an object from energy sent through the object in many directions. Much like medical tomography (such as a CAT scan) is used to create images of features inside the human body; geophysical tomography is used to create images of features beneath the ground or within engineered structures. There are several types of geophysical tomography. Cross-hole seismic tomography is one of the most common types of geophysical tomography. Cross-hole seismic tomography involves sending seismic energy from one borehole to another. A transmitter is lowered into one borehole, and the transmitted seismic energy is recorded by a string of receivers located in the second borehole. The positions of the transmitter and receivers are varied so that the seismic energy is transmitted between the two boreholes over a large depth range and at many different angles. The arrival times of the transmitted seismic energy are used to construct an image of seismic P-wave velocity of the geologic materials between the two boreholes. In addition, the amplitudes of the transmitted signals may sometimes be used to construct an image of the apparent attenuation of the geologic materials. Attenuation is a measure of the amount of energy loss of the seismic signal and is related to such factors as material type, degree of compaction or cementation, porosity, saturation, and fracturing. Cross-hole seismic tomography may be used to image geologic features such as solution cavities, fracture zones, and lithologic contacts. Tomography may also be used to evaluate engineered structures such as concrete cut-off walls, grout curtains, and concrete dams.

Borehole Optical Systems

Borehole optical logging systems include borehole film-recording cameras and borehole television cameras. Optical logging systems permit viewing and recording visible features in the walls of dry or water-filled boreholes, wells, casing, pipelines, and small tunnels.

Borehole cameras are an important supplement to geotechnical drilling and sampling programs because the cameras show geologic and construction features in place and in relatively undisturbed condition. The aperture (opening), true orientation (strike and dip), and frequency (number per foot of borehole) of discontinuities in the rock mass can be determined with optical logging systems. The effective or fracture porosity associated with open discontinuities can be derived also. The occurrence and size of solution cavities, the rock type from visual examination of rock and mineral textures and color of the borehole wall, and the location of stratigraphic contacts can be determined. Other geotechnical applications include inspecting contacts of rock or soil against concrete and of the interior of rock or concrete structures. Optical logging systems permit viewing soft or open zones in rock that may be overlooked in normal drilling and sampling operations. Zones of poor sample recovery or of drilling fluid loss can be investigated.

Borehole Television Camera.—Borehole television systems provide real-time viewing of the interior of a dry or water-filled borehole. The typical system (figure 14-16) consists of a down-hole probe and surface-mounted cable winch, control unit, power supply, television monitor, and video tape unit. The down-hole probe contains a television camera facing vertically downward toward a partially reflecting mirror inclined 45 degrees to the axis

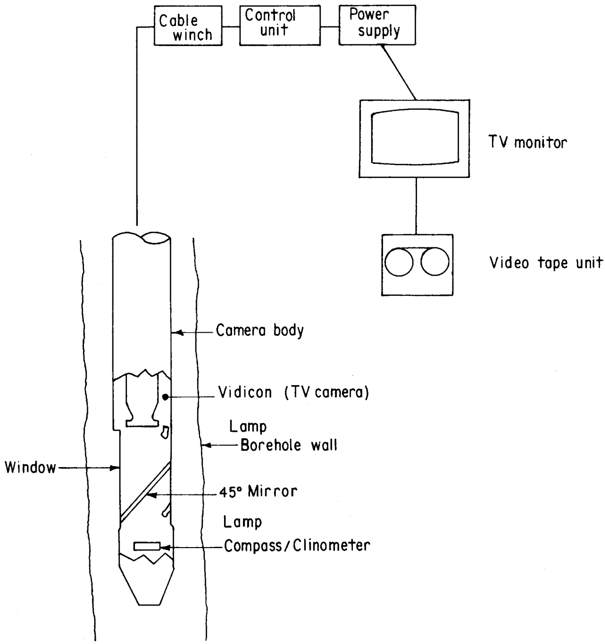

Figure 14-16.—Borehole television logging system.

of the probe. A compass/clinometer used to determine the orientation of features in the borehole wall and the inclination of the borehole can be viewed selectively through the mirror by varying the relative intensities of lamps located above and below the plane of the mirror. A motor within the probe rotates the camera and mirror assembly (or the mirror only) 380 degrees in a reciprocating fashion (clockwise, then counterclockwise) as the probe is lowered or raised within the hole. The operator controls the motion and logging speed of the probe. A full image of the borehole wall is obtained with each rotation.

A viewing head can be attached to the probe to allow axial viewing of the hole directly ahead. The probe ascent or descent and camera rotation can be slowed or stopped for examination of borehole features. The entire viewing sequence is usually videotaped.

Borehole television systems are commonly used to inspect large concrete structures and rock for defects, determine the effectiveness of grouting operations, check the condition of concrete joints, estimate the volume of cavities within a rock or soil mass, and inspect the screens of water wells. Television images can be used to determine attitudes of discontinuities but are less effective for complete borehole mapping than the borehole film camera systems that portray the borehole walls as discrete, full-color, separate images more suitable for detailed study and measurement.

Borehole Film Camera.—The borehole film camera produces consecutive, over-lapping, 16-mm color still photographs of 360 degree, 1-in (25-mm) sections of the walls of NX or larger boreholes. The system consists of a down-hole probe and surface- mounted lowering device, metering units, and power supply. Figure 14-17 illustrates the down-hole probe. The probe consists of a 16-mm camera mounted in line with the probe axis and facing a truncated conical mirror, which is surrounded by a cylindrical quartz window. A film magazine and film drive mechanism are mounted above the camera in the probe housing. A ring-shaped strobe illuminates the borehole wall in synchronization with the camera's film advance. Film advance, probe movement, and strobe lighting are synchronized to expose a frame every 3/4 in

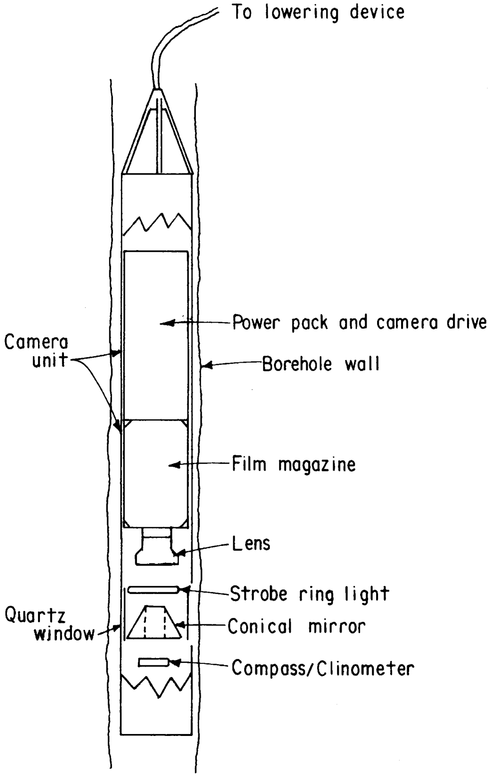

Figure 14-17.—Borehole film camera.

(20 mm) along the hole, so that a photograph with 1/4-in (6-mm) overlap of every 360-degree, 1-in (25-mm) section is taken. The truncation of the conical mirror allows the camera simultaneously to photograph a compass/clinometer located directly beneath the mirror. Photographs produced by the camera are viewed individually (still frame) using a special projector. The image of the mirror face is projected onto a flat film plane. The outer ring of the image "doughnut" represents the base, and the inner ring is the top of the 1-in section of the borehole wall. Planar discontinuities intersecting the borehole wall produce a trace on the image like the shaded curve of figure 14-18 (top). In a vertical borehole, the outer and inner rings of the image "doughnut" are horizontal traces. Points of intersection of planar discontinuities with a ring thus define the strike of the feature in vertical boreholes. The compass area in the center of the image of figure 14-18 shows the bearing of intersecting planes. The dip of the feature can be determined graphically by counting the number of successive frames in which the feature appears. A steeply dipping plane intersects several frames, a gently dipping plane only a few frames, and a horizontal plane intersects one frame. The thickness or width of the discontinuity can also be measured directly from the image. Data from inclined boreholes must be corrected to true strike, dip, and width. The NX borehole film camera is a proven tool for supplying subsurface data in difficult drilling and sampling situations and for providing complete quantitative information on discontinuities and borehole anomalies. Strike can be measured accurately to about 1 degree, dip (or inclination) to about 5 degrees, and thickness or width of discontinuities to a hundredth of an inch (0.1 mm) or better.

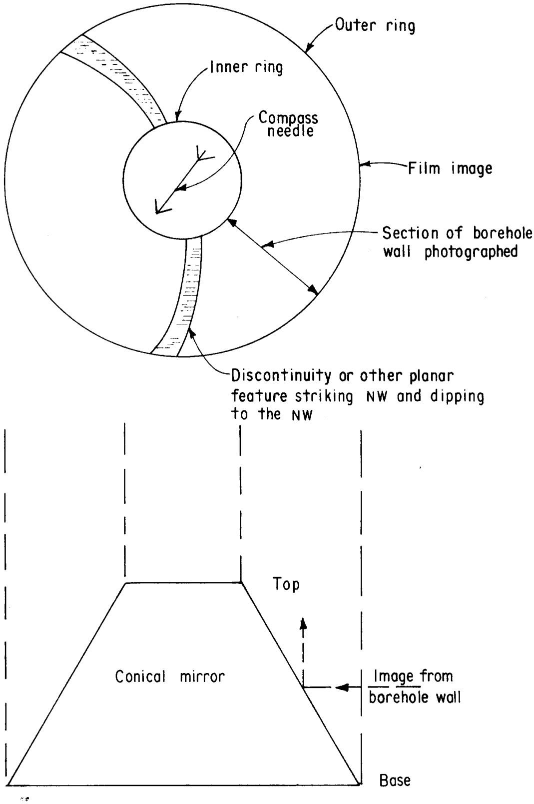

Figure 14-18.—Projection of borehole wall image into the film plane from the conical mirror of the borehole film camera.

In operation, the borehole film camera probe is lowered to the bottom of the hole and raised by a hand-cranked winch at a logging speed of between 5 and 10 feet per minute (ft/min). A single load of film can photograph 75 to 90 ft of borehole. Since the camera has no shutter or light metering capability, the aperture must be preset to satisfy lighting requirements of hole diameter and reflectivity of the borehole wall. The lens aperture ranges from f 2.8 for dark rock to f 22 for light colored rock. The maximum range (depth of field) is about 12 in. Boreholes larger than NX require centering of the probe in the hole.

Borehole Image Processing System (BIPS)

The Borehole Image Processing System (BIPS) uses direct optical observation of the borehole wall in both air and clear-fluid filled holes. The BIPS tool has a small fluorescent light ring that illuminates the borehole wall. A conical mirror in a clear cylindrical window projects a 360-degree optical slice of borehole wall into the camera lens. The tool also contains a digital azimuth sensor that determines the orientation of the image. The optical images are digitized and stored.

The BIPS analysis provides color images of the borehole wall. In a two-dimensional (2-D) projection, planar features that intersect the borehole wall appear as sinusoids. Processing allows the borehole wall to be viewed like a core, regardless of whether core was actually recovered. Strike and dip of planar features intersecting the borehole wall are determined during processing.

Other Wireline Systems

This section discusses wireline devices that are available for supplementary or special purpose applications. These systems include the borehole caliper log, directional surveys, borehole temperature log, borehole gravity log, magnetic log, and flowmeter log.

Borehole Caliper Log

The borehole caliper log provides a continuous record of changes in borehole diameter determined by a probe equipped with tensioned mechanical arms or an acoustic transducer. Caliper or borehole diameter logs are one of the most useful and simple of all logs obtained in borehole geophysics. Caliper logs provide the physical size of a drill hole and should be run in all borings in which other geophysical logging is anticipated. Caliper logs provide indirect information on subsurface lithology and rock quality. Borehole diameter varies with the hardness, fracture frequency, and cementation of the various materials penetrated. Borehole caliper surveys can be used to accurately identify washouts or swelling or to help determine the accurate location of fractures or solution openings, particularly in borings with core loss. Caliper logs can also identify more porous zones in a boring by locating the intervals in which excessive mud filter cake has built up on the walls of the borehole. One of the major uses of borehole caliper logs is to correct for borehole diameter effects. Caliper logs also can be used to place water well screens, position packers for pressure testing in foundation investigations for dams or other large engineering structures, and help estimate grout volumes in solution or washout zones.

Mechanical calipers are standard logging service equipment available in one-, two-, three-, four-, or six-arm probe designs. Multiple-arm calipers convert the position of feelers or bow springs to electrical signals in the probe. The electrical signals are transmitted to the surface through an armored cable. Some caliper systems average the movement of all the arms and record only the change in average diameter with depth, and others provide the movements of the individual arms as well as an average diameter. The shape or geometry of the borehole cross section can be determined with the individual caliper arm readings. A six-arm caliper capable of detecting diameter changes as small as 1/4 inch in 6-in to 30-in diameter boreholes produces a record like that shown on figure 14-19. The six arms are read as three pairs so that the diameter in three directions is recorded in addition to the average diameter.

Mechanical calipers are lowered to the bottom of the bore-hole in closed position, the arms are released, and the tool is raised. The calipers must be calibrated against a known minimum and maximum diameter before logging.

The acoustic caliper measures the distance from an acoustic transducer to the borehole wall. Individual diameter readings for each of four transducers mounted 90 degrees apart are obtained and also the average of the four readings. A special purpose acoustic caliper designed for large or cavernous holes (6 ft to 100 ft in diameter) uses a single rotating transducer to produce a continuous record of the hole diameter.

Directional Surveys

In some situations, borehole deviation must be accurately determined. Several methods of accomplishing this have been devised. Borehole survey instruments initially consisted of single or multiple picture (multishot) cameras that photographed a compass and plumb bob at selected locations in the borehole. Depths were based on the length of cable in the borehole. The camera was retrieved from the hole, and the film developed and interpreted.

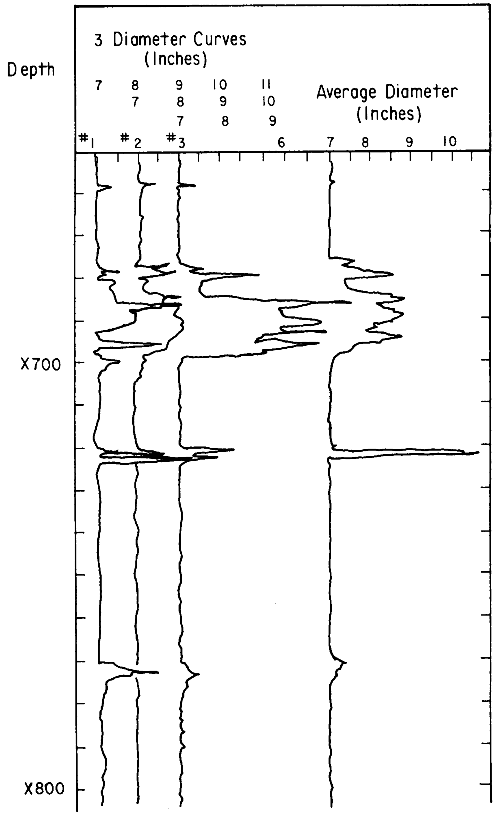

Figure 14-19.—Log of six-arm mechanical caliper.

A fluxgate compass or gyroscope is commonly used today to measure azimuth and an inclinometer to measure deviation from vertical. The information is then electronically transmitted to the surface via a cable. This method provides a continuous survey of the hole and not just checks at intervals. Systems are also available that use accelerometers and gyroscopic sensors to survey boreholes and provide real time data via a cable or ultrasonically via the mud.

Borehole Fluid Temperature Log

The standard borehole fluid temperature logging device continuously records the temperature of the water or drilling fluid in an open or cased borehole as a sonde is raised or lowered in the borehole. The standard, or gradient device uses a single thermistor (thermal resistor) that responds to temperature variations in the fluid. A small change in temperature produces a large change in resistance, which is converted to a change in electrical current. A differential device is sometimes used to record differences in temperature between two positions in the borehole by the use of two thermistors or one thermistor and a memory unit within the control module. The log produced by the temperature device shows temperature as a function of depth.

Temperature logging is usually performed before standard geophysical logging operations to permit correction of other logs (e.g., the resistivity logs) for the effects of borehole fluid temperature. Temperature logs can also be used to locate the source and movement of fluids into or out of the borehole and identify zones of waste discharge or thermal pollution in groundwater. Grouted zones behind casing can be located by the cement heat of hydration.

The temperature probe must be calibrated against a test fluid of known temperature immediately before temperature logging. Borehole fluids must be allowed to reach a stable temperature after drilling operations before logging can be conducted. Open boreholes take longer to stabilize because of the differences in thermal conductivity of the various materials encountered.

Borehole Gravity Log

A borehole gravity meter (or gravimeter) detects and measures variations in the force of gravity. The device determines the bulk density of a large volume of soil or rock between a pair of measuring stations in the borehole (figure 14-20). The bulk density (ρ) is proportional to the measured difference in gravity (G) between the two stations and inversely proportional to the vertical distance (Z) between the stations:

$$\Delta \boldsymbol{G} = \boldsymbol{G}_1 - \boldsymbol{G}_2 \quad \rho = \frac{\Delta \boldsymbol{G}}{\Delta \boldsymbol{Z}}$$

The borehole gravity meter has been used primarily by the oil industry to determine the porosity (especially porosity because of fractures and vugs). Porosity is calculated using standard equations relating bulk density, fluid density, and specific gravity of solids (matrix density). Although density and porosity are also provided by the gamma-gamma density logger (see "Nuclear Radiation Logging Techniques"), because of the large volume and radius of investigation, gravity meter data are less affected by borehole effects such as mudcake and irregular hole diameter. Gravity meter density determinations are more representative of the geologic medium away from the borehole than are gamma-gamma logs. The radius of investigation of the gravity meter is an estimated five times the difference in elevation between the measuring stations (see figure 14-20).

The borehole gravity meter is not a continuous recording instrument. The tool must be positioned at a preselected measurement station, allowed to stabilize, and then a

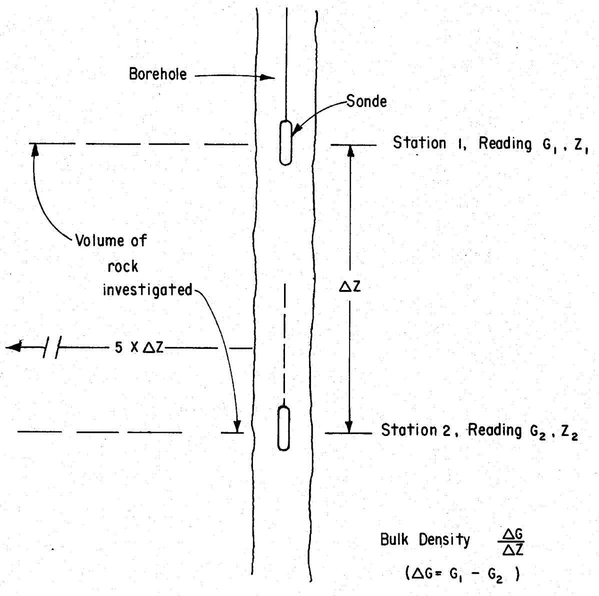

Figure 14-20.—Elements of borehole gravity logging.

measurement taken. Instrument readings are converted to gravity values using a conversion table. Bulk density is then calculated using the difference in gravity values and depth between the two stations. Usually two or three traverses are made in the hole at repeated stations and the values averaged. The precision of the method increases with decreasing distance between measuring stations.

Surveys may be conducted in cased or uncased holes. Several corrections to the data are necessary, including corrections for earth-moon tides, instrument drift, borehole effects, subsurface structure, gravity anomalies, hole deviation from vertical, and the free-air vertical gravity gradient. The instrument should be calibrated to correct for drift and tides. The borehole gravity logger is available commercially but is not a standard log. An apparent advantage over other bulk density/porosity logging methods is the reduction of borehole effects and the greater sample volume.

Magnetic Log

The magnetic field in an uncased borehole is the result of the Earth's magnetic field and any induced or remnant magnetism. These fields can be directly measured. Magnetic susceptibility is the degree that a material is effected by a magnetic field and is the basis for the logging technique. Susceptibility logs measure the change of inductance in a coil caused by the adjacent borehole wall. The magnetic susceptibility is proportional to the amount of iron-bearing minerals in the rock.

Flowmeter Log

A flowmeter measures fluid flow in boreholes. A flowmeter log provides information about locations where fluid enters or leaves the borehole through permeable material or fractures intersecting the borehole.

Conventional flowmeters employ a spinner or propellor driven by fluid moving through the borehole. High resolution flowmeters such as the heat pulse flowmeter can measure very low flow rates. Heat pulse flowmeters have a heating element that heats borehole fluid. The flow rate and direction of the heated fluid pulse is measured by detectors located above and below the heat element. Electromagnetic flowmeters induce a voltage in electrically conductive borehole fluid moving at a right angle through a magnetic field. The induced voltage is proportional to the velocity of the conductive borehole fluid.

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