Borehole geophysics is the science of recording and analyzing measurements of physical properties made in wells or test holes. Probes that measure different properties are lowered into the borehole to collect continuous or point data that is graphically displayed as a geophysical log. Multiple logs typically are collected to take advantage of their synergistic nature—much more can be learned by the analysis of a suite of logs as a group than by the analysis of the same logs individually. Borehole geophysics is used in ground-water and environmental investigations to obtain information on well construction, rock lithology and fractures, permeability and porosity, and water quality. The geophysical logging system consists of probes, cable and drawworks, power and processing modules, and data recording units. State-of-the-art logging systems are controlled by a computer and can collect multiple logs with one pass of the probe.

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Why log?

Borehole-geophysical logging can provide a wealth of information that is critical in gaining a better understanding of subsurface conditions needed for ground-water and environmental studies. Geophysical logs provide unbiased continuous and in-situ data and generally sample a larger volume than drilling samples.

Delineation of hydrogeologic units

The different hydrogeologic units found in the subsurface display a wide range of capabilities to store and transmit ground water and contaminants. Borehole-geophysical logging provides a highly efficient means to determine the character and thickness of the different geologic materials penetrated by wells and test holes. This information is essential for proper placement of casing and screens in water-supply wells and for characterizing and remediating ground-water contamination.

Definition of ground-water quality

The quality of ground water is highly variable and ground-water contamination may be caused by man-made or natural sources. Integration of borehole-geophysics logging with water-quality sampling provides a more complete picture, whether the objective is to develop a water-supply well or remediate a contaminated aquifer.

Determination of well construction and conditions

Wells are the access points to the ground-water system, and knowledge of their construction and condition are important whether they are being used for ground-water supply, monitoring, or remediation. The location and condition of casing and screen can be rapidly evaluated with geophysical logging.

What are the common geophysical logs and how are they used?

Common geophysical logs include caliper, gamma, single-point resistance, spontaneous potential, normal resistivity, electromagnetic induction, fluid resistivity, temperature, flowmeter, television, and acoustic televiewer.

Caliper logs record borehole diameter. Changes in borehole diameter are related to well construction, such as casing or drilling-bit size, and to fracturing or caving along the borehole wall. Because borehole diameter commonly affects log response, the caliper log is useful in the analysis of other geophysical logs, including interpretation of flowmeter logs.

Gamma logs record the amount of natural gamma radiation emitted by the rocks surrounding the borehole. The most significant naturally occurring sources of gamma radiation are potassium-40 and daughter products of the uranium- and thorium-decay series. Clay- and shale-bearing rocks commonly emit relatively high gamma radiation because they include weathering products of potassium feldspar and mica and tend to concentrate uranium and thorium by ion absorption and exchange.

Single-point resistance logs record the electrical resistance from points within the borehole to an electrical ground at land surface. In general, resistance increases with increasing grain size and decreases with increasing borehole diameter, fracture density, and dissolved-solids concentration of the water. Single-point resistance logs are useful in the determination of lithology, water quality, and location of fracture zones.

Spontaneous-potential logs record potentials or voltages developed between the borehole fluid and the surrounding rock and fluids. Spontaneous-potential logs can be used in the determination of lithology and water quality. Collection of spontaneous-potential logs is limited to water- or mud-filled open holes.

Normal-resistivity logs record the electrical resistivity of the borehole environment and surrounding rocks and water as measured by variably spaced potential electrodes on the logging probe. Typical spacing for potential electrodes are 16 inches for short-normal resistivity and 64 inches for long-normal resistivity. Normal-resistivity logs are affected by bed thickness, borehole diameter, and borehole fluid and can only be collected in water- or mud-filled open holes.

Electromagnetic-induction logs record the electrical conductivity or resistivity of the rocks and water surrounding the borehole. Electrical conductivity and resistivity are affected by the porosity, permeability, and clay content of the rocks and by the dissolved-solids concentration of the water within the rocks. The electromagnetic-induction probe is designed to maximize vertical resolution and depth of investigation and to minimize the effects of the borehole fluid.

Fluid-resistivity logs record the electric resistivity of water in the borehole. Changes in fluid resistivity reflect differences in dissolved-solids concentration of water. Fluid-resistivity logs are useful for delineating water-bearing zones and identifying vertical flow in the borehole.

Temperature logs record the water temperature in the borehole. Temperature logs are useful for delineating water-bearing zones and identifying vertical flow in the borehole between zones of differing hydraulic head penetrated by wells. Borehole flow between zones is indicated by temperature gradients that are less than the regional geothermal gradient, which is about 1 degree Fahrenheit per 100 feet of depth.

Flowmeter logs record the direction and rate of vertical flow in the borehole. Borehole-flow rates can be calculated from downhole-velocity measurements and borehole diameter recorded by the caliper log. Flowmeter logs can be collected under non-pumping and(or) pumping conditions. Impeller flowmeters are the most widely used but they generally cannot resolve velocities of less than 5 ft/min. Heat-pulse and electromagnetic flowmeters can resolve velocities of less than 0.1 ft/min.

Television logs record a color optical image of the borehole. In addition to being recorded on video-cassette-recorder tape, the optical image can be viewed in real time on a television monitor. Well construction, lithology and fractures, water level, cascading water from above the water level, and changes in borehole water quality (chemical precipitates, suspended particles, and gas) can be viewed directly with the camera.

Acoustic-televiewer logs record a magnetically oriented, photographic image of the acoustic reflectivity of the borehole wall. Televiewer logs indicate the location and strike and dip of fractures and lithologic contacts. Collection of televiewer logs is limited to water- or mud-filled open holes.

ADVANCES IN BOREHOLE GEOPHYSICS FOR GROUNDWATER INVESTIGATIONS

Detailed information on subsurface conditions is essential for the development and management of ground-water resources and the characterization and remediation of contaminated sites. Borehole geophysical techniques provide a highly efficient means for the collection of such information. Recent advances in methods and equipment have greatly increased the ability of geoscientists to obtain subsurface information in ground-water investigations through borehole geophysical techniques.

Portable geophysical loggers that are specifically designed for ground-water applications are available. The geophysical loggers are PC-based and have menu-driven software for the collection, display, and analysis of digital log data. Drawworks for shallow investigations are highly portable, and some have plastic-coated logging cables for easy decontamination. Many of the logging probes can be used in boreholes with a diameter as small as 5 centimeters. Many probes are capable of collecting multiple geophysical parameters with a single logging run, thereby greatly increasing the efficiency of the logging operation.

Electromagnetic-induction logging replaced normal-resistivity logging in the oil industry many years ago. Induction probes have been designed specifically for small-diameter monitoring wells. Induction logs can be collected in water-, air-, and mud-filled holes and through PVC casing. Major factors that affect induction-log response in sand-and-gravel aquifers are the concentration of dissolved solids in the ground water and the silt and clay content of the aquifer. Induction logs, which are commonly run in combination with gamma logs, are used to identify lithology and zones of electrically conductive contamination such as landfill leachate and saltwater intrusion.

High-resolution flowmeters that use heat-pulse and electromagnetic methods can measure extremely low vertical flow rates in boreholes. Conventional impeller flowmeters that are widely used in ground-water studies have a lower measurement limit of about 2 meters per minute, whereas the high-resolution flowmeters have lower measurement limits of less than 0.03 meters per minute. Flowmeters can be used to measure borehole flow under ambient as well as pumped conditions. Borehole-flow measurements made under ambient conditions can help to delineate transmissive fractures and other permeable zones and to indicate the direction of vertical hydraulic gradients; they also are useful in interpreting fluid-conductivity logs and borehole water-quality data. Borehole-flow measurements made under pumped conditions can be used to develop hydraulic-conductivity profiles of aquifers.

Television cameras commonly are used in ground-water studies to inspect the condition of well casing and screens; they also can be used to directly view (1) lithologic texture, grain size, and color; (2) water levels and cascading water; and (3) bedrock fractures. Television logs can be obtained in clear water and above the water level. The most sophisticated television systems are magnetically oriented and provide a 360-degree digital image of the borehole wall.

Acoustic televiewers provide a magnetically oriented, 360-degree, photographlike image of the acoustic reflectivity of the borehole wall. Televiewers have been used in the oil industry for many years and are being used increasingly in ground-water applications. Televiewer logs, which indicate acoustic transit time and reflected amplitude, can be obtained from water- or mud-filled holes. The newest digital televiewer systems allow interactive determination of fracture orientation.

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. 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, and cross-hole tomography can be used to delineate fracture zones between boreholes. The movement of a saline tracer through fracture zones can be monitored by borehole radar.

TRAINING AND TECHNOLOGY TRANSFER

A major component of the Office of Ground Water/Branch of Geophysical Application and Support program in geophysical training and technology transfer is based in the New York Water Science Center. The multi-faceted program includes demonstrations, field training, workshops, and courses at the project, Water Science Center, Region, and Survey-wide level. State-of-the-art geophysical equipment is used for training and demonstrations including borehole radar, electromagnetic induction, digital televiewer and television, heat-pulse flowmeter, and wireline packer.