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Hydraulic Logging Methods – A Summary and Field Demonstration in Conyers, Rockdale County, Georgia

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INTRODUCTION

Geophysical surveying techniques provide important information for ground-water investigations (Zohdy and others, 1974; Keys, 1997; Haeni and others, 2001). Subsurface-geophysical methods are used to delineate and characterize hydraulically active zones; the extent of contamination, and contaminant sources; identify geologic features; optimize monitoring well placement; and guide remediation efforts. Borehole-geophysical methods provide information about the physical, chemical, and hydraulic properties of rock, sediments, and fluids in the subsurface and provide important information on subsurface bedrock structures including lithology, rock fabric, location, orientation, and hydraulic properties of fractures (Keys, 1990).

Effective use of geophysical data requires that the data be interpreted in the context of known local and regional geology and hydrogeology. In addition, because of the complexity and heterogeneity of crystalline-rock aquifers, a suite of borehole-geophysical methods is used to determine the location, extent, and nature of fractures and other structural features in the bedrock aquifer. The geophysical data from each borehole and method are analyzed together to provide an integrated interpretation, thereby reducing the ambiguity that can occur by interpreting each geophysical log individually (Shapiro and others, 1999).

Previous work using borehole geophysics to characterize ground-water availability in crystalline-rock aquifers includes Chapman and Lane (1996), Mack and others (1998), and Johnson and others (1999). Other investigations that focused on contamination in fractured-rock aquifers used geophysical methods to relate highly transmissive features to structural features in the bedrock (Hansen and Lane, 1995; and Lane and others, 2002).

REVIEW OF LOGGING METHODS

Improvements in technology, portable computers, and data collection software have increased the potential for rapid, noninvasive, and cost-effective subsurface characterization through the application of geophysical methods. The logging methods demonstrated on this field trip are used to collect data on subsurface characteristics and properties, which are acquired with a personal computer, computer-driven software, a portable winch, and selected geophysical tools (fig. 1). The logging methods reviewed in this field trip include caliper, single-point resistance, normal and lateral resistivity, electromagnetic induction, fluid resistivity, fluid temperature, flowmeter under ambient and stressed conditions, camera and acoustic televiewer, and deviation. Information about these methods is summarized in table 1.

Caliper logging is used to generate a continuous profile of the borehole diameter measured in units of length with depth. The caliper tool is pulled up the borehole, allowing three spring-loaded arms to open or close as they pass borehole enlargements, or restrictions (Keys, 1990). Changes in the borehole diameter generally are related to fractures but also can be caused by changes in lithology or borehole construction or integrity. Fracture openings in the bedrock are easily distinguished from the changes that correspond to borehole enlargements as shown in the caliper log obtained from a crystalline-bedrock well in Lawrenceville, Gwinnett County, Georgia (fig. 2). The log can be collected relatively quickly and is one of the least expensive tools to run, process, and interpret data.

Single-point resistance logging measures the electrical resistance between a surface electrode (or mudfish) and an electrode in the down-hole probe. The measurement, which is highly influenced by

Table 1. Summary of selected geophysical logging methods

[Relative cost: 1–3 inexpensive to expensive; time: 1–3 fast to slow; relative difficulty: 1–3 easy to difficult]

Method	Purpose	Property measured	Cost	Time	Difficulty
Caliper	Generate continuous profile of borehole diameter	Borehole diameter	1	1	1
Single-point resistance	Delineate changes in lithology, porosity, and (or) clay content of surrounding formation or changes in porosity and total dissolved solids in the formation water	Resistance of formation, fluids in formation, and borehole fluids	1	1	1
Normal resistivity	Determine changes in resistivity of the fluids in the formation and (or) lithology	Resistivity of the formation; with additional data, true resistivity can be calculated	1	1	1
Electromagnetic induction	Delineate changes in rock type or in electrical properties of fluids in the rock formation; corroborate surface resistivity surveys	Bulk apparent conductivity of the formation and pore fluids surrounding the borehole	1	2	2
Fluid resistivity	Identify differences in concentration of total dissolved solids in borehole fluid; these differences typically indicate sources of water that have come from different transmissive zones	Electrical resistivity of borehole fluid, from which specific conductance is calculated	1	1	1
Fluid temperature	Identify where water enters or exits the borehole	Temperature of borehole fluid; differential temperature (rate of change of the temperature) is calculated	1	1	1
Heat-pulse, electromagnetic, and spinner flowmeter	Map fluid flow regime and transmissive fractures in the borehole	Direction and magnitude of vertical flow within the borehole	3	3	3
Camera	Characterize rock type, identify changes in rock type and small-scale geologic structures, locate and describe fractures, describe borehole construction, and identify problems with borehole integrity and (or) possible signs of contamination	Visual fish-eye view and side-looking view of borehole	2	2	2
Acoustic televiewer	Map location and orientation of fractures intersecting borehole and generate a high-resolution acoustic-caliper log	Amplitude and travel time of the reflected acoustic signal	3	3	3
Deviation	Three-dimensional geometry of the borehole	Azimuthal direction and the inclination of the borehole	2	2	2

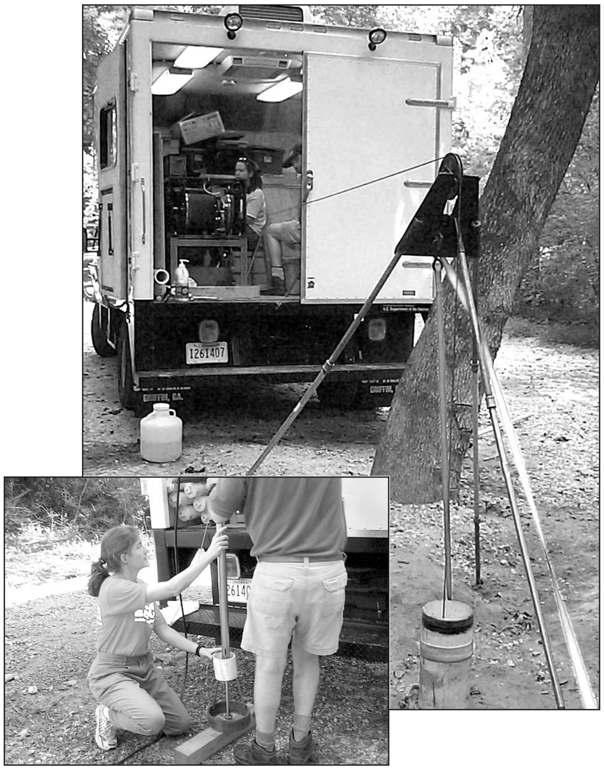

Figure 1. Logging a 6-inch-diameter crystalline-bedrock well in Lawrenceville, Georgia. Inset shows a 3-arm caliper tool being calibrated with a steel ring. Photographs by Lester J. Williams, USGS.

borehole diameter, includes the resistance of the formation, fluids saturating the formation, and fluids in the borehole. The resistance, which is recorded in ohms, is highly influenced by borehole diameter. Increases in borehole diameter typically are associated with a decrease in resistance. Single-point resistance can be used to delineate changes in lithology, clay content, porosity, and total dissolved solids in the formation water. The single-point resistance log can be collected relatively quickly and is one of the least expensive tools to run, process, and interpret data.

Long- and short-normal **resistivity logging** measures the apparent resistivity of the formation in ohmmeters. The tool applies a constant current across two electrodes while measuring the potential between two other electrodes. The volume of investigation is a sphere whose diameter is equal to twice the potential-electrode spacings, which are typically 16 or 64 inches. However, the shape and volume of investigation change depending on the resistivity of the formation. The apparent resistivity has to be corrected for borehole diameter, drilling mud invasion, and formation bed thickness to obtain true resistivity.

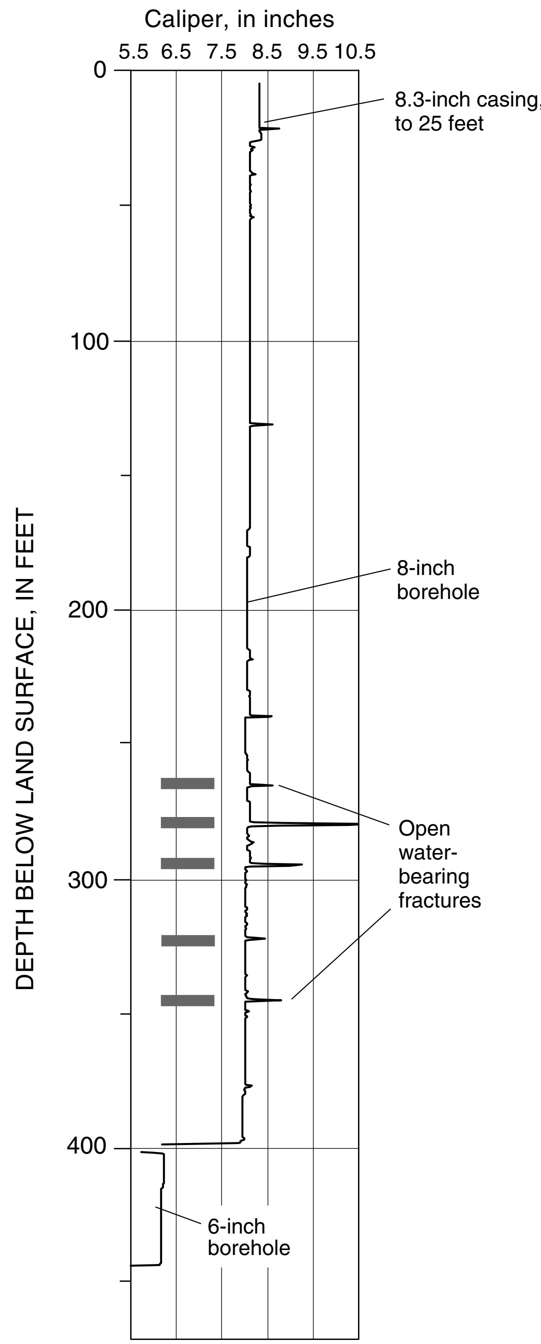

Figure 2. Caliper log from a crystalline-bedrock well in Lawrenceville, Georgia. Thick bars denote fracture openings. Hole is about 8 inches in diameter to 400 feet and 6 inches below that depth.

The apparent resistivity is helpful for corroborating results of two-dimensional surface-resistivity surveys and for determining changes in lithology and resistivity of the fluids in the formation. The normal resistivity can be calibrated by placing known resistors between the electrodes (Keys, 1990).

The lateral resistivity tool is similar to the normal resistivity tool in that it applies a current across two electrodes, while measuring potential across the other two electrodes. The potential electrodes are separated by 2.6 feet (ft). The current electrodes asymmetrically straddle the potential electrode pair with the upper electrode set 4.85 ft above the center point of the potential electrodes, which is considered to be the measurement point. Because the electrode spacing in the lateral resistivity tool is larger than the electrode spacing of the long- and short-normal resistivity tool, lateral resistivity measurements sample a larger volume of the formation. Because of the electrode geometry, lateral resistivity anomalies are nonsymmetrical. Best results are obtained when the bed thickness is twice the offset spacing (2 x 4.85 ft). Results are expected to be marginal in saline water and resistive rocks (Keys, 1990). Although lateral resistivity logs have not been used extensively for environmental applications, the tool has been used to identify fracture zones in crystalline rocks in the Lawrenceville area.

Resistivity logs are relatively cost-effective and easy to collect and interpret. Their most useful application in crystalline rocks is in regimes where the resistivity of the formation is too high for the induction conductivity meter to resolve. In hard, resistive crystalline bedrock, water-bearing zones typically are indicated by low resistivity. An annotated lateral resistivity log, shown in figure 3, easily distinguishes the water-bearing zones in a crystalline-bedrock well in Lawrenceville.

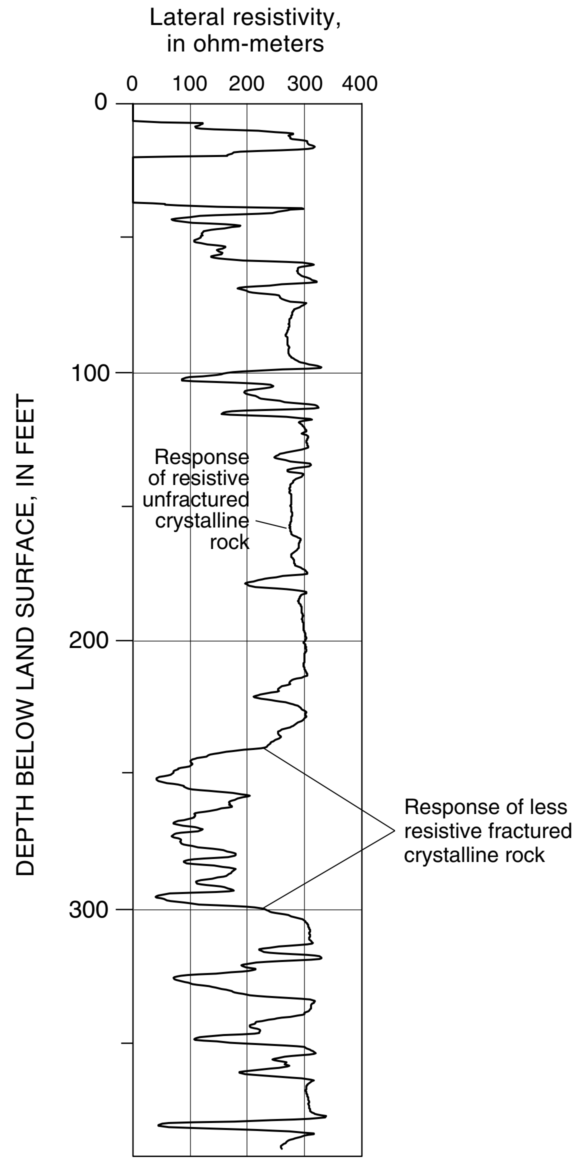

Figure 3. Lateral resistivity log from a crystalline-bedrock well in Lawrenceville, Georgia. Same well as shown in figure 2.

Electromagnetic (EM)-induction logging records the bulk electrical conductivity of the rocks and the fluids in the rocks surrounding the borehole (Williams and others, 1993). The tool uses an electromagnetic induction field to induce an electrical current in the surrounding formation. The induced current in the formation generates a secondary electromagnetic field. At low induction numbers (less than 100 millimhos/meter), the strength of the electromagnetic field is proportional to the formation conductivity. Changes in electrical conductivity are caused by variations in porosity, borehole diameter, dissolved concentration of the water in the rocks, and metallic minerals. The EM-induction probe is designed to maximize vertical resolution and radial penetration and to minimize the effects of the borehole fluid. The tool response is most sensitive to the bedrock and pore water approximately 1 ft away from the probe, and the tool has a vertical resolution of approximately 2 ft. In boreholes with diameters of 6 inches or less, the specific conductance of the borehole fluids has a negligible effect on the induction log response (Keys, 1990). The log is used to delineate changes in rock type or in electrical properties of water in the rock formation.

These logs are relatively inexpensive to collect. Field calibration is done with a calibration ring of known conductivity and with the tool held in low-humidity air for zero conductivity. In humid climates, high- and low-conductivity rings can be used for the calibration. Field calibration done with calibration rings may be time consuming but is important for collection of accurate data. Because the induction tool is temperature sensitive, it should be allowed to equilibrate to borehole conditions with tool power on for at least 20 minutes prior to logging.

Fluid logging methods measure properties of the water column in the borehole and commonly include the simultaneous measurement of fluid resistivity and temperature. Fluid logs are typically run first to measure an undisturbed water column that represents the ambient conditions in the borehole. The fluid logs can be collected again under stressed conditions (pumping or injection), and a comparison between ambient and stressed conditions can be used to identify the location of the contributing inflow zones. These logs are relatively easy and inexpensive to collect and interpret.

Fluid-resistivity logging measures the electrical resistivity of the borehole fluid from which its inverse, the specific conductance, is calculated. Changes in the specific conductance indicate differences in the concentration of the total dissolved solids in the borehole fluid (Williams and Conger, 1990). These differences typically indicate water that comes from different sources with contrasting chemistry, originating from different transmissive zones. The specific conductance is calibrated with standards or with two fluids of known specific conductance.

Fluid-temperature logging is used to identify where water enters or exits the borehole (Williams and Conger, 1990). In the absence of fluid flow in the borehole, the temperature gradually increases with the geothermal gradient, about 1° Fahrenheit per 100 ft of depth (Keys, 1990). Deviations from the expected geothermal gradient indicate possible transmissive zones in the borehole. Changes in the fluid temperature indicate water-producing and water-receiving zones. Intervals of vertical flow are characterized by little or no temperature gradient (Johnson and others, 1999).

The differential temperature log, which is calculated as the first derivative of the temperature log, can help identify changes in the slope of the temperature and deviations in the geothermal gradient. This log provides valuable information on the fluid in the borehole and may indicate flow dynamics of the borehole.

Flowmeter logging measures the direction and magnitude of vertical fluid flow within the borehole. Flowmeter measurements are collected at discrete locations, usually above and below fractures identified in the other geophysical logs, or as a continuous log in a trolling mode. Heat-pulse, electromagnetic, and spinner flowmeter methods are used to map the fluid flow regime and identify the transmissive fractures penetrated by the borehole.

The heat-pulse flowmeter uses a thermal trace to measure the direction and rate of vertical flow in a borehole (Hess and Paillet, 1990). It is used at stationary points along the borehole above and below fractures. Used in conjunction with other geophysical logs, individual fractures or fracture zones where water enters or exits the borehole can be identified.

The electromagnetic flowmeter can be used in a combination of stationary-mode and trolling-mode measurements to determine vertical flow in the borehole and identify inflow and outflow locations (Moltz and others, 1994). Electromagnetic flowmeter measurements that are collected at stationary locations can provide higher resolution measurements than under trolling conditions. The flow profiles collected under the trolling mode can be proportioned to the higher-resolution measurements made at points. The electromagnetic flowmeter concurrently measures temperature and fluid resistivity.

The spinner flowmeter measures vertical flow by recording the rotation rate of a 3- or 4-bladed impeller mounted with adjustable needle bearings on a freely rotating shaft. Frictional forces associated with shaft rotation must be overcome, and below this threshold velocity the tool does not respond. The threshold velocity of a typical spinner flowmeter is about 5 feet per minute (ft/min), which limits its use to higher flow conditions. Spinner flowmeters can be used in stationary and trolling modes.

Flowmeters can identify the most transmissive fracture in the borehole and other fractures with transmissivities within one or two orders of magnitude. Flowmeters typically are used with a flow diverter fitted to the nominal borehole diameter to channel flow through the measurement channel in the tool. The heat-pulse flowmeter with a flow diverter can measure flows as low as 0.01 +/- 0.005 gallons per minute (gal/min) and as great as 1.5 gal/min. The electromagnetic flowmeter with a flow diverter can measure flows between 0.1 and 15 gal/min. Greater flows (100 gal/min or more) can be measured with proper calibration of the flowmeters while using an underfit flow diverter that allows some of the vertical flow to bypass the tool (Paillet, 2000).

Under ambient conditions, differences in hydraulic head between two sufficiently transmissive fractures produce vertical flow in the borehole. Water enters the borehole at the fracture zone with the higher head and flows toward and out of the fracture with the lower head. Because vertical flow does not occur between transmissive zones with the same head, flowmeter logging also must be conducted under stressed conditions to identify transmissive fractures with the same head. The electromagnetic flowmeter log in figure 4 indicates the presence of multiple transmissive fractures with differing heads. Under ambient conditions water flowed from fractures with high hydraulic head into the borehole, upward through the borehole, and exited the borehole through fractures with lower head, just below the bottom of casing (fig. 4). In addition, water exited the borehole at the base of casing. Under pumping conditions of 50 gal/min, water entered the borehole at the transmissive fractures with high head and flowed upward in the borehole; however, the pumping did not reverse the ambient flow regime, and water continued to exit the borehole near the base of the casing (fig. 4, top arrows).

Flowmeter logging is expensive relative to the other methods presented in this field trip. The effort in data collection varies, depending on the number of fractures that are hydraulically active, and the flow regimes in the borehole. The time and difficulty of the interpretation also depends on the complexity of the flow regime. The interpretation of flowmeter data can be semi-quantitative or quantitative. The quantitative results can be verified with an iterative modeling approach described by Paillet (1998). Although the interpretation and modeling process is more time consuming, the quantitative results yield a unique solution providing information on the transmissivity and head of individual transmissive zones in the borehole.

Camera logging records both fish-eye and side-looking views of the borehole above and below the water and can provide a direct inspection of the borehole wall and details of the borehole construction.

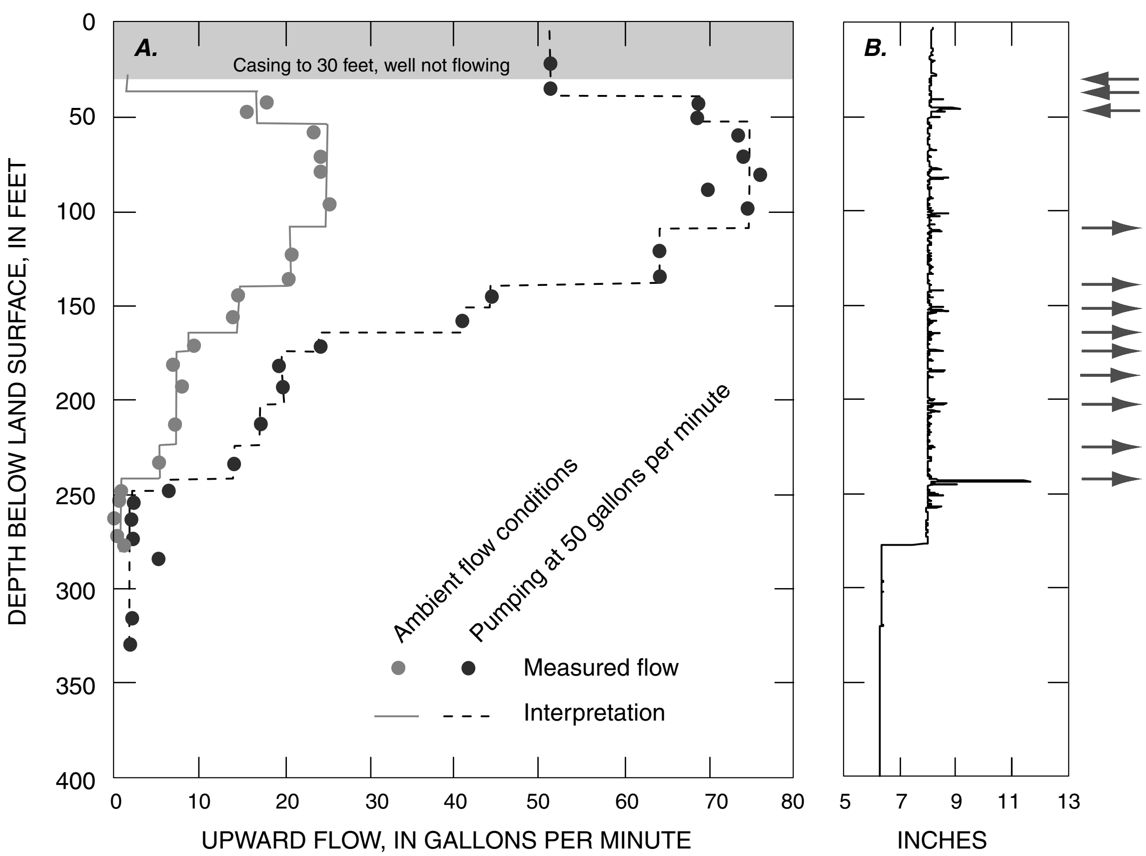

Figure 4. *(A)* Flowmeter logs from a crystalline-bedrock well in Lawrenceville, Georgia, showing ambient and pumping conditions. Top left facing arrows indicate fractures where water is flowing out of the borehole. Right facing arrows show water entering the borehole along artesian fractures between 100 and 250 feet. *(B)* Caliper log shown for reference. Survey conducted on December 4, 2001.

The color images, which are continuously labeled with depth, are collected and recorded on videotape. The images can be used to characterize rock type, identify changes in rock type and small-scale geologic structures, locate and describe fractures, describe the borehole construction, and identify problems with borehole integrity and (or) possible signs of contamination (Johnson and Dunstan, 1998). The images can be used in conjunction with other logs to help interpret anomalies observed in the other logs. This method of borehole imaging is relatively cost-effective, and logs can be collected quickly. However, detailed interpretation of the video logs can be time-consuming.

Acoustic televiewer (ATV) logging produces a high-resolution, magnetically oriented, digital image that is used to map the location and orientation of fractures that intersect the borehole (Williams and Johnson, 2000). The ATV tool emits a narrow acoustic beam that rotates 360° and is focused at the borehole wall. The acoustic wave moves through the fluid in the borehole and is reflected off the borehole wall and recorded by the tool. The log records the amplitude and travel time of the reflected wave, which can be displayed as a flattened 360° image of the borehole wall.

A fracture that intersects the borehole causes scattering of the acoustic wave and appears as a high contrast, low amplitude line (dark feature) on the acoustic amplitude log. On the acoustic travel-time log, a fracture is indicated by an increase in the one-way travel time of the wave, due to an increase in borehole diameter. The “acoustic caliper,” which is derived from the travel-time log, provides a much greater resolution measurement of borehole diameter than that collected with a 3-arm caliper. Interpretation of the magnetically oriented images in conjunction with other logs allows for the determination of transmissive fractures structures that may relate to the hydraulics of the aquifer.

The acoustic televiewer is a relatively expensive tool and data collection and interpretation can be time-consuming. Because of the high resolution of data collection, the recommended logging speed of about 5 ft/min is much slower than the logging speed of most other logs, which is 10–20 ft/min.

Deviation logging measures the borehole deviation by providing a record of the three-dimensional geometry of the borehole (Keys, 1990). The deviation log records the azimuthal direction (0–360°) and the inclination (0–90°) over the depth of the borehole. Borehole deviation tools generally indicate direction to within ±2° and inclination to within ±0.5°. Deviation logs are collected simultaneously with acoustic and optical images with the televiewer tools. The results of this log are used to correct the orientation of fractures determined from the acoustic and optical imaging tools.

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