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Techniques of Water-Resources Investigations of the United States Geological Survey

Chapter E2

BOREHOLE GEOPHYSICS APPLIED TO GROUND-WATER INVESTIGATIONS

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Book 2

COLLECTION OF ENVIRONMENTAL DATA

11. To determine porosity from a gamma-gamma log, one must have
    a. Data for grain density.
    b. Calibration data for a similar lithology.
    c. Data for fluid density.
    d. Data for borehole-diameter corrections.
12. When compensated neutron and gamma-gamma logs are calibrated in limestone,
    a. The porosity for dolomite indicated on the neutron log will be less than that indicated on the gamma-gamma log.
    b. The two logs will indicate the same porosity for sandstone.
    c. The porosity for shale indicated on the neutron log will be less than that indicated on the gamma-gamma log.
    d. The two logs will indicate the same porosity for limestone.

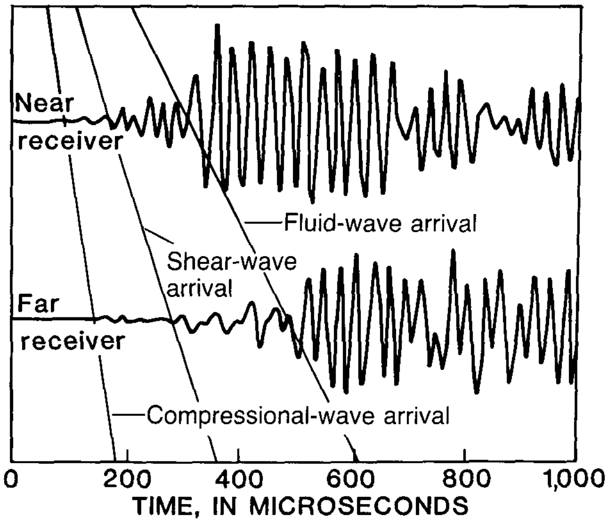

Figure 73.—Acoustic wave forms for a two-receiver system and arrival times of compressional, shear, and fluid waves (modified from Paillet and White, 1982).

Acoustic Logging

Acoustic logging includes techniques that use a transducer to transmit an acoustic wave through the fluid in a borehole and the surrounding rocks. Several types of acoustic logs are used; they differ in the frequencies used, the way the signal is recorded, and the purpose of the log, but all require fluid in the borehole to couple the signal to the surrounding rocks. Four types are described here: acoustic velocity, acoustic wave form, cement bond, and acoustic televiewer. Acoustic logs can provide data on porosity, lithology, cement, and the location and character of fractures.

Acoustic-velocity logging

Acoustic-velocity logs, also called sonic logs or transit-time logs, are a record of the traveltime of an acoustic wave from one or more transmitters to receivers in the probe. The acoustic energy travels through the fluid in the borehole and through surrounding rocks at a velocity that is related to the matrix mineralogy and porosity of the rocks. Sonic logs are used extensively in the petroleum industry to identify lithology and measure porosity; sonic-logging equipment is now installed on some water-well loggers.

Principles and instrumentation

The principles and instrumentation required to make acoustic logs are complex, and the reader is referred to Guyod and Shane (1969) for a more complete description than can be provided here. Most acoustic-velocity probes use magnetostrictive transducers to convert electrical energy to acoustic energy. Most of the transducers are pulsed 10 or more times per second, and the acoustic energy emitted has a frequency in the range 10 to 35 kHz. Probes are constructed of low-velocity materials, so that the fastest travel path for the acoustic pulse will be through the borehole fluid and the adjacent rocks, which transmit acoustic energy faster than does the borehole fluid. Acoustic probes are centralized with bow springs or rubber fingers, so the travel path to and from the rock will be of consistent length. Some of the energy moving through the rock is refracted back to the receivers, which may be piezoelectric transducers. The receivers reconvert the acoustic energy to an electrical signal, which is transmitted up the cable. At the land surface, the entire signal may be recorded for acoustic-wave-form logging, or the transit time may be recorded for acoustic-velocity logging. The amplitude of parts of the acoustic wave also may be recorded; that technique is described later in the section on acoustic-wave-form logging.

Acoustic energy transmitted in borehole fluid and adjacent rocks is divided into several components; the most important for this discussion are compressional waves and shear waves. Standard acoustic-velocity logs are based on the time the compressional wave arrives at the receivers. Compressional and shear waves at near and far receivers, along with the fluid waves that are transmitted through the borehole fluid, are shown in figure 73 (Paillet and White, 1982). The optimum frequency range for excitation of compressional and shear waves depends in a complicated way on borehole diameter and rock properties but usually is 10 to 25 kHz. Most acoustic-velocity probes have paired receivers located 1 ft apart; some probes have several pairs of receivers with different spacing; the pair that is to be used may be selected from the land surface. Some compensated probes have two transmitters and two pairs of receivers. Transmitter to near-receiver distance generally is greater than 2 ft. Compressional waves, or P waves, are propagated by movement of particles in an elastic medium in the direction of propagation. P waves have a faster velocity and a lower amplitude than shear waves, or S waves. S waves have a velocity about one-half that of P waves and are characterized by particle movement perpendicular to the direction of wave propagation. S waves are not transmitted directly by borehole fluid, but by means of an intermediate P wave. Fluid waves are slower and have higher amplitude than P and S waves.

The signals shown in figure 73 are typical of those displayed on an oscilloscope at the surface. Acoustic-velocity logging modules contain a tracking circuit that detects the arrival of the P wave when the wave amplitude exceeds a threshold selected by the operator. The amplitude of the transmitted signal and the received signal, along with the height of the detection threshold, can be controlled from the land surface. A circuit is used to convert the difference in arrival time at the two detectors to transit time (delta *t*), in microseconds per foot. Acoustic-velocity logs are recorded with interval transit time increasing from right to left; porosity also increases to the left, as it does on neutron and gamma-gamma logs. On many logs, two scales show interval transit time, in microseconds per foot, and porosity, in percent, assuming a specified rock type.

For rocks having uniformly distributed intergranular-pore spaces, porosity usually is derived from the time-average equation. This equation is based on the theory that the path of an acoustic wave through saturated rock consists of two velocities in series, the velocity in the fluid, *Vf*, in feet per second, and the velocity in the rock matrix, *Vm*, in feet per second. The method assumes that the length of the path in the fluid is equal to the porosity (ϕ), and that the length of the path in the rock matrix is equal to $1/\phi$. The time-average equation is expressed as

$$\text{delta } t = 1/VL = \phi/Vf + (1 - \phi/Vm) \qquad (10)$$

where *VL* is the velocity in the rock, in feet per second, determined from a log. To calculate porosity, the time-average equation is converted to the form

$$\phi = (\text{delta } t \text{ log} - \text{delta } t \text{ matrix}) / (\text{delta } t \text{ fluid} - \text{delta } t \text{ matrix}) \qquad (11)$$

Table 6.—Compressional-wave velocity and transit time for some common rocks and fluids

[Single values are averages]

Rock or fluid type	Velocity (feet per second)	Transit time (microseconds per foot)
Sandstone		
Slightly consolidated	15,000-17,000	58.8–66.7
Consolidated	19,000	52.6
Shale	6,000–16,000	62.5–167.0
Limestone	19,000–21,000+	47.6–52.6
Dolomite	21,000–24,000	42.0–47.6
Anhydrite	20,000	50
Granite	19,000–20,000	50.0–52.5
Gabbro	23,600	42.4
Freshwater	5,000	200
Brine	5,300	189

Velocities and transit times for some common rocks and fluids are provided in table 6. Note that the range can be very large; laboratory measurements or experience in logging specific types of rock may be needed to calculate porosities accurately.

The data in figure 74 can be used to convert transit times from logs to approximate porosity values when matrix transit times are not accurately known. More information on determining porosity is included in the sections on calibration and interpretation.

Calibration and standardization

The interval transit-time scale on most acoustic-velocity logs has a resolution of 1 s/ft and a somewhat lesser accuracy; however, the scale should be checked if possible. The difference in arrival times of the P wave at two receivers can be read directly from a calibrated oscilloscope, which is an essential part of any acoustic-logging system. Because transit time is a direct measurement of a physical property, it usually is not subject to operator errors, although operator

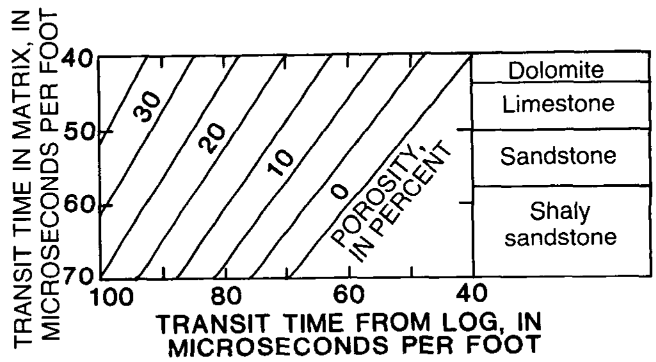

Figure 74.—Conversion of transit time from acoustic-velocity logs to porosity of various rock types.

adjustment of the triggering of the arrival of the first compressional wave can affect measurement accuracy.

Most calibration pits are not specifically designed for acoustic-velocity probes; however, they may be used if velocity analyses are available and if the use of probe centralizers will not damage the pit. Calibration also can be accomplished using core samples analyzed in the laboratory for acoustic velocity and porosity.

The response of an acoustic-velocity probe can be checked onsite with a piece of steel pipe cut in half lengthwise. The probe can be laid horizontally in the pipe and dams made at both ends with flexible caulking, so that half of the transmitters and receivers can be covered with water. Steel pipe has an acoustic velocity variously reported to be 17,000 to 20,000 ft/s, so the probe can be checked for that range of values. It is possible to make the same check in a borehole that contains free-hanging steel pipe; however, if the pipe is cemented in with good bonding, first arrival might be through the rock if it has a faster acoustic velocity.

Some logging systems have several built-in calibration signals that can be used to check uphole circuits and to place values on logs; however, such signals do not check the transmitted or received signal or the triggering circuits. An oscilloscope is essential for checking the operation of these components.

Volume of investigation

The radius of investigation of an acoustic-velocity probe is reported to be about three times the wavelength (Pirson, 1963). The wavelength is equal to the velocity divided by the frequency. At a frequency of 20 kHz, the radius of investigation theoretically ranges from about 0.75 ft for completely unconsolidated materials or freshwater having an acoustic velocity of 5,000 ft/s up to about 3.75 ft for hard rocks having an acoustic velocity of 25,000 ft/s. A lower transmitter frequency will increase the volume of investigation, but it will decrease the resolution of small features, such as fractures.

Extraneous effects

One of the most obvious problems on acoustic-velocity logs is cycle skipping caused by the amplitude of the first compressional-wave cycle being too low for detection or by prearrival noise of sufficient amplitude to be detected. If the first cycle is detected at the near receiver and the second cycle is detected at the far receiver, the resulting transit time will be much too long and the log will show a sharp deflection. Often the amplitude of the received signal will vary from greater than to less than the detection level, which causes rapid fluctuations in the log trace that are easily recognized as cycle skips (fig. 75). Cycle skipping frequently is blamed on gas in the borehole fluid; however, any condition that causes the amplitude of the compressional wave to be less than the detection level at one of the receivers will produce cycle skipping on the log. Causes include improper adjustment of signal gain or detection level, fractures or solution openings, rocks that attenuate the signal, and gas in the borehole fluid. Cycle skipping can be used to locate fractures in some boreholes, but corroborating evidence is necessary.

Borehole enlargements or cavities may produce cycle skips or errors in transit time when the receiver pair is opposite the top or bottom of a cavity. When the edge of a cavity is between receivers, the travel path may be of different length to the receivers, causing the transit time to be erroneous. Some borehole-compensated probes contain transmitters located both above and below two pairs of receivers and record the average of the two transit times. These probes may decrease the effect of cavities somewhat, but they do not ensure an error-free log.

Acoustic velocity in porous media is dependent on such lithologic factors as the type of matrix, the density, size, distribution, and type of grains and pore spaces, and the degree of cementation. Acoustic velocity is also dependent on the elastic properties of the interstitial fluids (Jenkins, 1960). The commonly used time-average equation does not account for most of these factors, but it has been determined to produce reasonably correct porosity values under most conditions. Because correction for all of these listed factors is impossible, some core analyses are needed for checking porosity values recorded on acoustic-velocity logs in each new geologic environment.

Interpretation and applications

Acoustic-velocity logs are useful for providing information on lithology and porosity under a fairly wide range of conditions. They usually are limited to consolidated materials penetrated by uncased, fluid-filled boreholes. A hypothetical, but typical, response of an acoustic-velocity log in a series of sedimentary rocks and in granite is shown in figure 75. The response can be compared with other logs in these same lithologic types in figure 7. The hypothetical response of an acoustic-velocity log compared with other logs in a series of igneous and metamorphic rocks is shown in figure 8. In figure 75, cycle skips are caused by solution openings and probably also by fractures in the arkose and granite. Solution openings and fractures also are indicated by the caliper log. Transit times decrease, or acoustic velocities increase, with greater depth and with increase in rock hardness or cementation. In addition, acoustic velocities may vary with confining pressure for several hundred feet below the

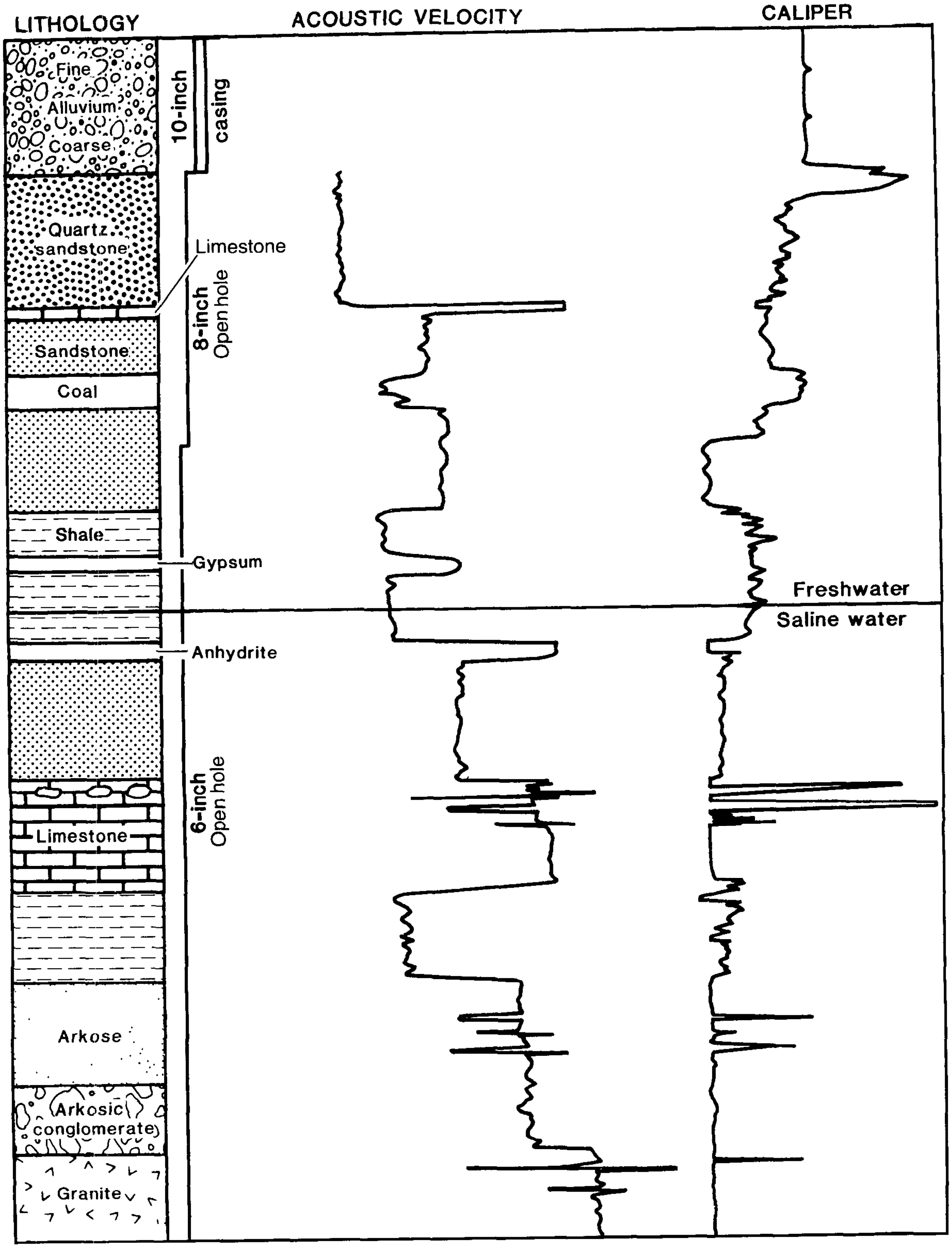

Figure 75.—Typical responses of acoustic-velocity and caliper logs to a sequence of sedimentary rocks.

land surface. This effect is most evident in slightly consolidated materials, but it also has been noted in crystalline rocks. Resolution of thin beds is good when 1-ft receiver spacing is used; contacts generally are marked by sharp deflections. Changes in diameter of the bit used to drill the borehole, as shown in figure

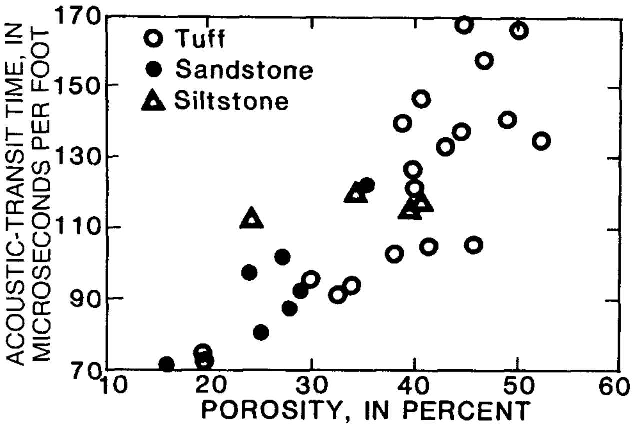

Figure 76.—Relation of acoustic-transit time to porosity for tuff, sandstone, and siltstone, Raft River geothermal reservoir, Idaho.

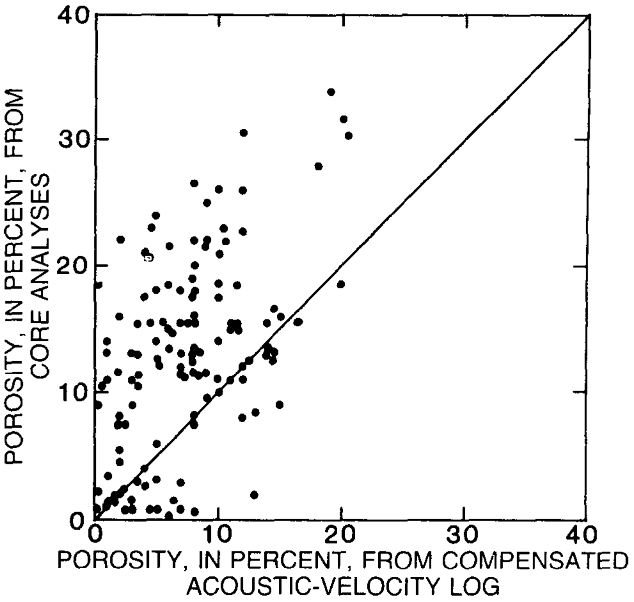

Figure 77.—Porosity from core analyses versus porosity from a compensated acoustic-velocity log, Madison Limestone test well 1, Wyoming.

75, do not cause substantial shifts on an acoustic-velocity log made with two or more receivers.

Many of the rock types logged will be characterized by a limited range of transit times; therefore, acoustic-velocity logs will provide diagnostic information on lithology as well as porosity. Some porosity values measured on core plotted against transit time obtained from an acoustic-velocity log, for a sequence of basin-fill sedimentary and volcanic rocks in Idaho, are shown in figure 76. The correlation coefficient for the core and log data from this well is 0.87, and the log could be used to estimate porosity in this hole. Note that the siltstone had a small range of acoustic-transit times, even though the porosity of the siltstone had a large range. The sandstone had a larger, but still diagnostic, range of acoustic-transit time and porosity, whereas the tuff had an undiagnostic range of acoustic-transit time and porosity, probably because of its diverse lithologic character.

A computer plot of porosity from core analyses versus values from an acoustic-velocity log that was calibrated in terms of porosity is shown in figure 77. The scatter of data points is large, and errors in deriving porosity from this log would be substantial. The value of having some core analyses for evaluation of these log data is obvious. In figure 77, some data points plot on the line where the core and log porosity values are equal; however, many data points indicate that the log porosity values are too small. The main reason for this error is the presence of secondary porosity, which was not detected by the acoustic-velocity log. Secondary porosity is not detected by acoustic-velocity logs because the first acoustic wave to arrive travels the fastest path around solution openings. In addition, the logging operator used a limestone matrix lithology for calculating the porosity curve, whereas dolomite was more prevalent in the rocks penetrated by the well. An example of how cross plots can be used to correct porosity for matrix lithology is shown in figure 11. Some borehole enlargements also are present that may have caused erroneous log values.

In some geohydrologic environments, especially those consisting of carbonate rocks, porosity from an acoustic-velocity log and from a neutron log or gamma-gamma log or core can be cross plotted to identify intervals of secondary porosity. Many of the data points above the calibration line in figure 77 represent intervals of large secondary porosity. A computer-generated cross plot of the neutron log versus the acoustic-velocity log for Madison Limestone test well 1 also was used to characterize the most permeable intervals in the rocks penetrated by the well (Keys, 1986). In the permeable intervals, identified on flowmeter logs, many porosity values on the acoustic-velocity log were smaller than the corresponding values on the neutron log or determined from core analyses, because of secondary porosity.

Acoustic-wave-form logging

Considerable information on lithology and structure is available through analyses of the various components of a received acoustic signal. Analyses may include amplitude changes, ratios of the velocities of various components of the wave train, and frequency-dependent effects. Cement-bond logs are included in this section because acoustic-wave-form data are needed to increase the accuracy of interpretation of these logs. Acoustic wave forms can be recorded digitally, photographs can be taken of the display on an oscilloscope, or a variable-density log can be made. The variable-density log, or three-dimensional velocity log, is recorded photographically, so that variations in darkness of the record are related to changes in amplitude of cycles in the wave form. Troughs in the wave form produce dark bands on the log; peaks produce light bands. A digitized acoustic-wave-form log is the most useful type, because the data can be analyzed quantitatively. Velocities and amplitudes of all parts of the recorded wave form can be measured from a digital record. Acoustic-wave-form logs have not been used extensively in ground-water hydrology; however, the potential for obtaining useful information is significant, and the equipment is available commercially.

The elastic properties of rocks can be calculated from the velocities of compressional and shear waves, and from corrected bulk density from a gamma-gamma log. The elastic properties, or constants, that can be determined are Poisson's ratio, Young's modulus, shear modulus, and bulk modulus. Guyod and Shane (1969) discussed the relations among these constants, and Helander (1983) discussed equations for calculating the constants from log data. These constants have their greatest application in mining and civil engineering; potential hydrologic applications include predicting the subsidence and fracturing characteristics of rocks. Taylor (1968) used acoustic logs to estimate the vertical compressibility of an artesian aquifer. The compressibility values then were used to plot the effects that changes in net stress had on the storage coefficient of the aquifer.

Because of the potential for obtaining information on aquifers from acoustic-wave-form data, the U.S. Geological Survey is studying the application of acoustic-wave-form analysis to ground-water hydrology; a number of reports have been published. Paillet and White (1982) described the relation of modes of acoustic-wave propagation to rock properties. Paillet (1980, 1981) and Davison and others (1982) described the characterization of fractures by various acoustic techniques. A significant finding was a correlation between the attenuation of tube-wave amplitude in crystalline rocks and the permeability of fractures determined by packer-isolation tests in small-diameter boreholes. Thus, tube-wave-amplitude logging has potential for predicting the relative flow through fractures in hard rocks. The tube wave is part of the fluid wave propagated along the borehole under certain conditions; it apparently is attenuated where water in the borehole is free to move in and out of fractures or when pressure oscillations in the borehole produce viscous losses by forcing water flow in permeable pore spaces.

Cement-bond logging systems commonly use a single transmitter and a single receiver to obtain information on the quality of the bond between the casing and the cement and between the cement and the borehole wall. Most cement-bond logs are a measurement of only the amplitude of the early arriving signal from the casing; however, to improve the accuracy of interpretation, the full acoustic wave form is needed for study. Although a small proportion of the total acoustic energy may be received from the rock when the casing is free to vibrate, this signal usually is not detectable. The amplitude of the signal from the casing is decreased by the following: good bonding of cement to casing, larger area of casing surface bonded, increased thickness of cement, and longer curing time (Guyod and Shane, 1969). When the casing is well bonded to the borehole wall by cement, acoustic-velocity logs of the rocks can be obtained.

Detection of channeling through cement in the annular space is one of the main objectives of cement-bond logging, yet even an expert analyst of cement-bond logs probably will not accurately locate all channels. A basic problem derives from the fact that the signal is averaged around the circumference of the borehole so an open vertical channel 10° wide is a small part of the total signal. When the bonding to hard rocks is good, the casing signal will be obscured by the arrival of compressional waves from the rock, and the amplitude may not indicate the presence of channels. Although interpretation of cement-bond logs may seem simple, it is qualitative and best performed by the expert. Newer cement-bond logging systems plot the ratio of amplitudes in the casing time window to the formation time window.

Acoustic-televiewer logging

An acoustic televiewer (ATV) is a logging device that can provide high-resolution information on the location and character of secondary porosity, such as fractures and solution openings. An ATV also can provide information on the strike and dip of planar features, such as fractures and bedding planes. Because an ATV also is called a borehole televiewer, it occasionally is confused with borehole television. Borehole television is not discussed in detail in this report because the probes currently available cannot be operated on standard logging cable and because the light required for television limits application to boreholes that contain clear water and have clean walls. A few commercial firms offer ATV-logging services, and the equipment to make logs can be purchased. ATV logging has been applied to ground-water studies in the United States and several foreign countries, but it is not yet used extensively, partly because of the cost and complexity of the equipment.

Principles and instrumentation

The standard ATV probe uses a rotating 1.3-MHz transducer that functions as both transmitter and receiver (Zemanek and others, 1969). Lower frequencies may be used for better mud penetration. The piezoelectric transducer is rotated at 3 r/s and is pulsed approximately 800 times per second. The high-frequency acoustic energy is reflected from, but does not penetrate, the borehole wall. A trigger pulse is transmitted to the recording equipment at the land surface from a flux-gate magnetometer each time the transducer rotates past magnetic north. This pulse triggers the sweep on an oscilloscope; each sweep represents a 360° scan of the borehole wall. The brightness of the oscilloscope trace is proportional to the amplitude of the reflected acoustic signal, somewhat analogous to a rotating depth finder in a boat. The probe must be centralized accurately with bow springs so the signal will reflect from the borehole wall perpendicularly and return along the same path to the transducer. The sweeps are moved across the oscilloscope or other type of graphic recorder by a depth-related signal derived from the cable measuring sheave. If the log is recorded at speeds greater than 5 ft/min, small horizontal features may not be detected. A camera or graphic recorder, using continuous light-sensitive paper, is used to make a record of the intensity of the sweeps, thus producing a continuous image. If a Polaroid camera is used to record the acoustic image, the photographs can be taped together to form a continuous log. An ATV system requires at least four-conductor logging cable.

An ATV log can be thought of as a cylinder that has been opened along the north side and flattened, as illustrated in figure 78. In the three-dimensional drawing on the left of this figure, an open fracture dipping to magnetic south is shown intersecting a borehole. The hypothetical ATV log on the right shows the fracture as it might appear, as a dark sinusoid with the low point oriented toward magnetic south. The transducer rotates clockwise, as viewed looking down the borehole; hence, compass directions are in the order shown at the bottom of the ATV log in figure 78. This figure is discussed further in the section on interpretation.

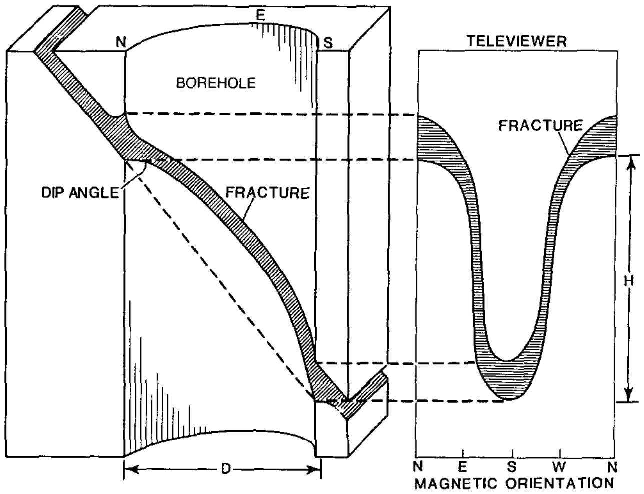

Figure 78.—Three-dimensional view of a fracture intersecting a borehole and appearance of the same fracture on an acoustic-televiewer log. D is the borehole diameter from a caliper log, and H is the length of intercept at the fracture in the borehole.

Fractures and other openings in the borehole wall or in the casing appear as dark areas for several reasons. Increasing borehole diameter means that the acoustic signal must travel farther and that it will be more attenuated by the fluid in the borehole. In addition, where part of the surface of fractures and other openings is not at right angles to the incident acoustic signal, little of the signal will be reflected back to the transducer.

Because of the large number of equipment adjustments that must be made to produce a quality ATV log, an experienced operator is needed. A second oscilloscope also should be available to monitor the incoming signal so adjustments can be made as required. The acoustic signal can be taped on a modified videocassette recorder simultaneously with graphic recording; the taping allows the log to be enhanced by later playback, using different adjustments of uphole equipment, if necessary. It also is possible to digitize the acoustic signal and to use image-enhancement computer programs to improve the log.

Modifications to ATV equipment permit recording an acoustic-caliper log, which consists of four high-resolution traces. The use of a lower frequency transducer will provide better penetration of casing, and the ATV probe can be used to examine cement in the annular space. Broding (1984) demonstrated the ability of a lower frequency probe to locate voids and channels in cement that were not detected by other logging methods. ATV logs made in steel casing or in the presence of large concentrations of magnetic minerals will not be oriented correctly because the magnetometer does not work reliably under these conditions. Under such conditions, a switch in the ATV probe can be used to trigger the sweep relative to the probe instead of the magnetometer; as a result, compass orientation will be lost but an unoriented log may be obtained.

Calibration and standardization

Magnetometer orientation and recording scales need calibration and occasional standardization onsite. If possible, the magnetometer should be checked with a compass to determine if it triggers on magnetic north within 1°; this can be accomplished by using a narrow reflective object in a plastic bucket filled with water. The lower set of centralizers usually are removed for this procedure. If an acoustic-caliper log is to be made, borehole-diameter response should be checked. Although the time-distance relation can be calculated by using the calculated velocity of sound in the borehole fluid, an onsite check is occasionally needed. To make this check, the probe is carefully centered in nonmagnetic rings of different sizes immersed in a water-filled bucket. Checking orientation and borehole-diameter response also provides a prelogging check of probe operation. Both horizontal and vertical scales are checked with a ruler on the analog record, before and during logging, because drift is not uncommon. Logging speed should be checked frequently with a stopwatch because logging speed changes as the probe moves up the borehole, and because the analog meters used to display logging speed are not accurate at slow rates.

Volume of investigation

The concept of volume of investigation does not apply to the ATV in a strict sense because, with the typical high-frequency transducer, most of the signal is received from the wall of the borehole. Even if the frequency is decreased to half the usual value, rock penetration is small, although mud penetration is increased. However, ATV probes have mechanical and electronic limits to the diameter of the well that can be logged. The operating range of borehole diameter for most 1⅞ in ATV probes is 3 to 16 in. Adjustment of the electronic-gating circuits might allow some increase in borehole diameter, but the centralizers need to be designed to do an effective job in a large-diameter borehole.

Extraneous effects

Although interpretation of ATV logs ought to be relatively straightforward, it is complicated by a number of extraneous effects. Most significant are inadequate centralization, incorrect gain settings, errors caused by vertical deviation of the borehole, and aberrations in the magnetic field. The effect of several of these problems is illustrated in figure 79. The commercial acoustic-televiewer log on the right was made with gain settings that were too low to accurately resolve the numerous solution openings in this dolomite, particularly in the depth range 3,000 to 3,010 ft. Many more features can be seen in the ATV log on the left. The black streak down the left side of the commercial log was caused by inadequate centralization, probably because the well is not circular. The effect is much more obvious on the commercial log because the gain settings were too low. Continuous monitoring of the signal displayed on an oscilloscope will allow an experienced operator to make the proper gain adjustments.

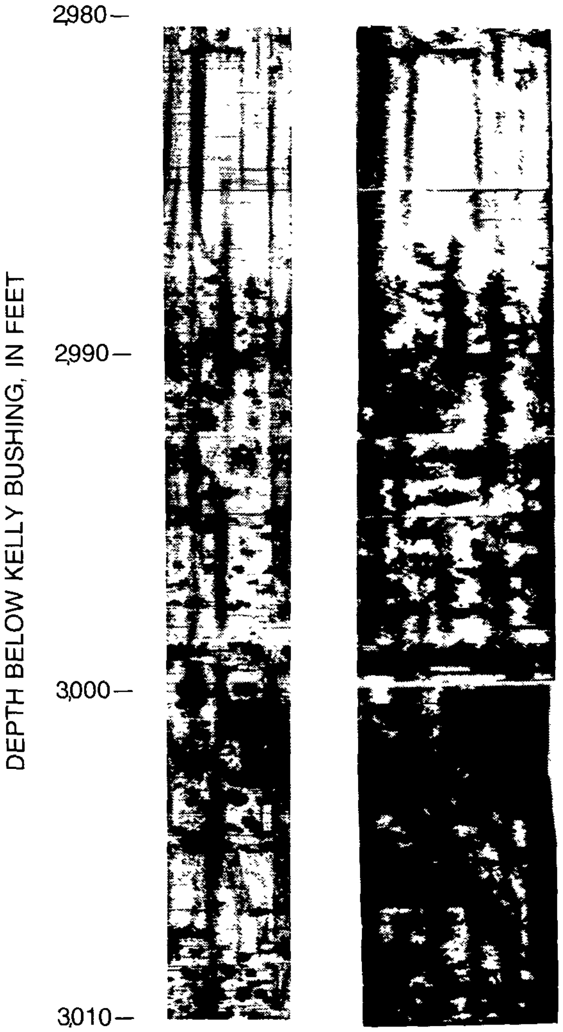

Figure 79.—Acoustic-televiewer logs made by the U.S. Geological Survey (left) and a commercial service company (right), Madison Limestone test well 1, Wyoming.

Substantial deviation from vertical is common in deep boreholes, and this introduces several errors on ATV logs. In addition to the obvious error in the measured vertical depth, corrections must be made to dip and strike calculated from ATV logs made in deviated boreholes. Another orientation error is related to the effect of the vertical component of the Earth's magnetic field on the tilted magnetometer. Kierstein (1984) has developed computer programs for correcting the data and solutions that use a stereographic projection, and has described the orientation problems in detail. A borehole-deviation survey must be made if errors from this source are to be recognized and corrected. Steel casing or drilling equipment lost in the borehole, as well as magnetite, will result in misorientation or missing sweeps, making the ATV log difficult to interpret. Where the presence of magnetic materials is suspected, a rerun of the log using the mechanical switch for triggering, rather than the magnetometer, may eliminate the problem. Such triggering problems have been used to locate magnetite concentrations that have been substantiated by the examination of core.

Interpretation and applications

An acoustic televiewer provides a record of the location, character, and orientation of any features in the casing or borehole wall that alter the reflectivity of the acoustic signal. These include diameter and shape of the borehole, roughness of the borehole wall that may be caused by drilling procedures or lithology, differences in rock hardness, and structural features such as bedding, fractures, and solution openings. In addition to providing a photographlike image that can be interpreted in terms of the character of these features, an ATV log also permits calculation of orientation of fractures and bedding planes. The smallest feature that can be resolved on an ATV log depends on a number of factors, such as borehole diameter and borehole-wall roughness. Under ideal conditions, features as small as 1/32 in, or possibly even smaller, can be identified.

Figure 80.—Acoustic-televiewer log of producing zone A in a geothermal well, Roosevelt Hot Springs, Utah.

An acoustic-televiewer log of a producing fracture zone in a geothermal well at Roosevelt Hot Springs, Utah, is shown in figure 80. Acoustic- and mechanical-caliper logs of this producing zone are shown in figure 81. These logs were made at temperatures as high as 260 °C (Keys, 1979). The producing interval shown in figure 80 is about 4 ft thick; this interval apparently is the result of alteration and solution along a series of subparallel fractures. The fracture at the top of the interval appears, on the basis of the ATV log, to be about 6 in wide; probably it is much less. Rock adjacent to fractures tends to be broken out during

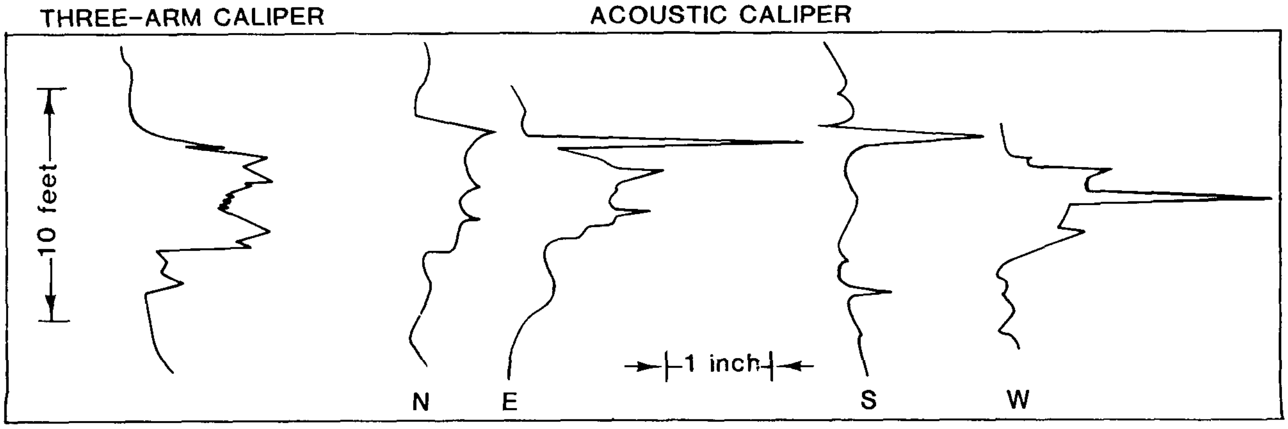

Figure 81.—Mechanical- and acoustic-caliper logs of producing zone A in a geothermal well, Roosevelt Hot Springs, Utah.

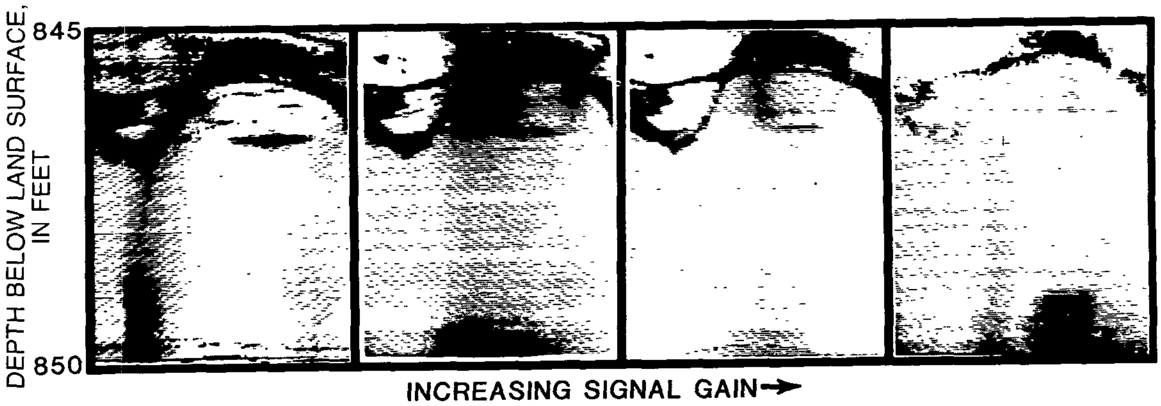

Figure 82.—Acoustic-televiewer logs of a 5-foot interval at four different gain settings, borehole CR-6, Ontario, Canada.

drilling, and the broken edges further increase the apparent thickness of the fractures on the ATV log by refracting the acoustic signal. This is particularly evident at the top and bottom of the sinusoid on steeply dipping fractures, as shown in figure 78. The open fracture in the producing zone in figure 80 is paralleled by one fracture above, and probably six fractures below, which produced a brecciated, and probably altered, permeable zone. The effect of drilling technique and lithology on the interpretation of fracture character from ATV logs has been discussed by Paillet and others (1985). Log quality generally is not as good where the wall of the borehole is rough, or where rocks are soft.

To calculate the strike and dip of fractures or bedding, the following information is needed: (1) the vertical intercept distance on the ATV log, H, as shown in figure 78, (2) the direction of dip from the ATV log, and (3) the borehole diameter, D, from a caliper log. The same units should be used for H and D. The angle of dip, in degrees, is equal to the arc tangent of H/D. If the average H for the fractures in figure 80 is 12 in and the borehole diameter is 6 in, the dip would be 63°; if the borehole diameter is 12 in, the dip would be 45°. Direction of dip usually can be measured to the nearest 5°, using a 360° scale constructed to fit the width of the ATV log. The average direction of dip of the fractures in figure 80 is slightly south of west. Errors in measuring strike and dip are much greater for slightly dipping features than for steeply dipping features. All calculations of orientation must be corrected for hole deviation and magnetic effects, as explained by Kierstein (1984).

The orientation of the stress field can be determined from an analysis of ATV logs made in wells where fractures have been induced hydraulically, either intentionally or accidentally, by drilling (Wolff and others, 1974; Keys and others, 1979). Hydraulic fractures are oriented perpendicular to the direction of least principal stress. Breakouts are increases in borehole diameter oriented at right angles to the maximum principal horizontal stress. They are easily recognized on ATV logs and have been discussed in detail by Zoback and others (1985) and Paillet and Kim (1987). Breakouts appear as two vertical dark bands with irregular margins located about 180° apart on the log. Breakouts also can be identified and oriented with four-arm directional mechanical- or acoustic-caliper logs, which may help to distinguish them from the dark bands caused by a decentralized ATV probe.

Interpretation of ATV logs is complicated by many factors, one of the most significant being gain adjustment. Four ATV logs recorded at different gain settings are shown in figure 82. Based on the log on the left, the intersecting fractures appear to be quite open and permeable; however, increasing the gain indicates that the fractures were widened artificially near the borehole. The interpretation that these fractures were almost closed or filled with clay a short distance from the borehole wall was substantiated by an isolation-packer test that indicated minimal permeability for the interval containing the fractures (Davison and others, 1982).

The relation between ATV-log response and single-point-resistance, caliper, neutron, and gamma logs is illustrated in figure 83. Bedding in the Tertiary Monterey Shale, Calif., is shown by the horizontal bands across the ATV log. Beds of hard, silicified shale appear white on the ATV log, and they are indicated

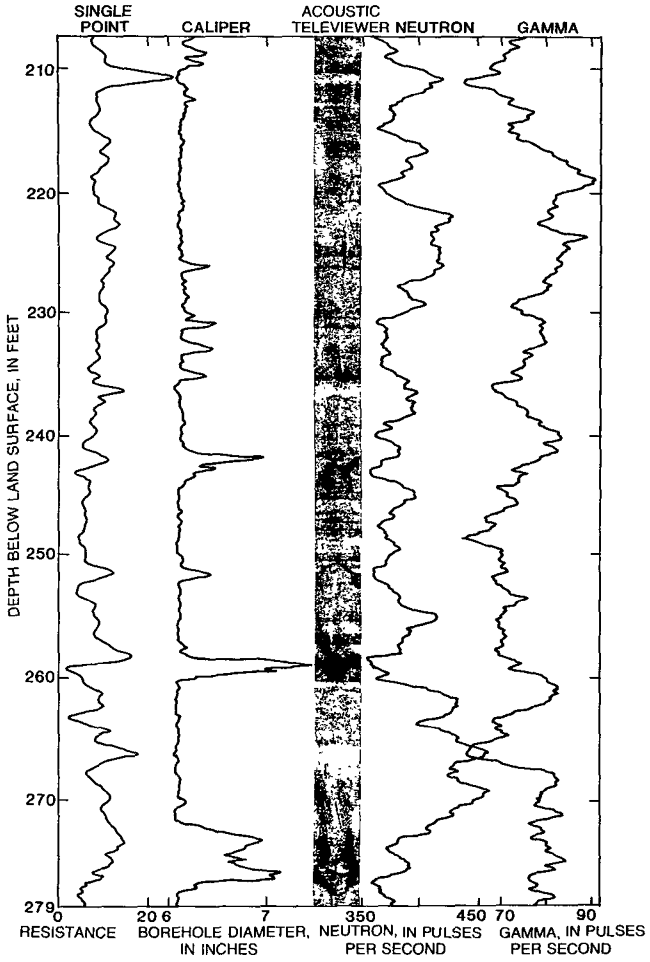

Figure 83.—Single-point-resistance, caliper, acoustic-televiewer, neutron, and gamma logs of a borehole penetrating the Monterey Shale, Calif.

clearly by substantial resistance on the single-point-resistance log, minimal apparent porosity on the neutron log, and minimal radioactivity on the gamma log. Natural fractures are shown clearly on the ATV log at depths of 242, 252, 258, and 276 to 278 ft. Although these fractures are shown as borehole enlargements on the caliper log, and several produce anomalies on the single-point-resistance log, the relative width and orientation cannot be determined from these logs. The dark vertical bands located 180° apart just above the deepest fractures probably are breakouts. Note the numerous horizontal bedding planes in the softer shale. In another borehole in the same rocks, an inflatable packer left impressions in the shale that could be identified on the ATV log. It is common in softer rocks to identify grooves in the wall of the borehole caused by probe centralizers or by caliper arms.

The ATV also can be used to examine casing for damage and to locate joints in pipe and well screens; borehole television might be better for these purposes if the water is clear and the walls are clean. Borehole television must be used above water level because the ATV will not operate there. A comparison of fractures located by the ATV, television, and logging the core in a borehole penetrating crystalline rocks has been published (Davison and others, 1982). Core logging identified the largest number of fractures; however, fractures not detected by the ATV log probably were closed so tightly that they would not transmit water. In this example the smallest number of fractures was identified by borehole television. Borehole television in dark rocks will not locate many fractures seen on an ATV log. Use of borehole television is limited further by borehole depths and temperature; another factor limiting use is that it cannot be operated through standard logging cable.

Caliper Logging

Caliper logs provide a continuous record of borehole diameter and are used extensively for ground-water applications. Changes in borehole diameter may be related to both drilling technique and lithology. Caliper logs are essential in interpreting other logs, because most of them are affected by changes in borehole diameter. Caliper logs also provide information on well construction, lithology, and secondary porosity.

Principles and instrumentation

Many different types of caliper probes have been described in detail by Hilchie (1968). The most common type of probe used for logging water wells has three arms, each approximately the diameter of a pencil, that are spaced 120° apart and mechanically coupled together. Arms of different lengths can be attached to this type of probe to optimize sensitivity for the borehole-diameter range expected. Mechanical caliper probes have been used to measure a maximum borehole diameter of 42 in. A typical water-well caliper probe has arms that are connected together to move a linear potentiometer so changes in resistance, transmitted to the land surface as voltage changes, are proportional to average borehole diameter. In some probes, the voltage changes are converted to a varying pulse rate to eliminate the effect of changes in resistance of the cable. Three-arm averaging and single-arm caliper probes will operate on single-conductor cable; however, probes having multiple independent arms may require more conductors.

Single-arm caliper probes commonly are used to provide a record of borehole diameter while another type of log is being made. The single arm also may be used to decentralize another probe, such as a side-collimated gamma-gamma probe. Some single-arm decentralizing caliper probes use a pad or wide arm that does not allow borehole roughness to be resolved. A single-arm caliper probe has an advantage in that the arm generally follows the high side of a deviated hole. A three-arm averaging caliper probe does not function properly in highly deviated boreholes, because the weight of the tool forces one arm to close, which closes the other two arms.

Bow springs or bow springs with pads are used on some commercial probes to provide a caliper log; however, the log does not have the resolution that can be achieved with small fingers or arms. The data from bow-spring or single-arm devices sometimes are used in real time to correct another log made simultaneously for borehole-diameter effects. The corrected log will therefore be no better than the borehole-diameter data that are transmitted to the correction circuits.

High-resolution caliper-logging probes generally have three or four independent arms; these arms are sometimes compass oriented. The difference in resolution between logs made with a four-arm probe and the more common types is shown in figure 84 and is described in the section on interpretation. Vertical resolution is a function of the length of the contact surface at the end of the arm as well as the response of the mechanical and electronic components in the system. Horizontal resolution, which provides accurate borehole-diameter measurement regardless of borehole shape, is related to the number of independent arms. Although four arms are typical for a high-resolution probe, some have more.

Acoustic calipers may use the time-of-travel data from an acoustic televiewer (ATV) to provide compass-oriented high-resolution logs. The reflected signal usually is averaged for about 5° of transducer rotation. This type of caliper log will show minute openings, but it is limited to the maximum borehole diameter that the ATV can log. Most ATV systems are designed to operate in wells as large as 16 inches in diameter, but they can be modified to operate in larger diameter wells. A sonar caliper probe that emits low-frequency acoustic energy has been designed to measure the cross section of extremely large diameter wells and gas-storage caverns (Dawson-Grove, 1969). The transducer in this probe is rotated similarly to the acoustic televiewer; however, it may be tilted up or down to scan a cavity. Sonar caliper probes have a range of measurement of 1.5 to 1,000 ft.

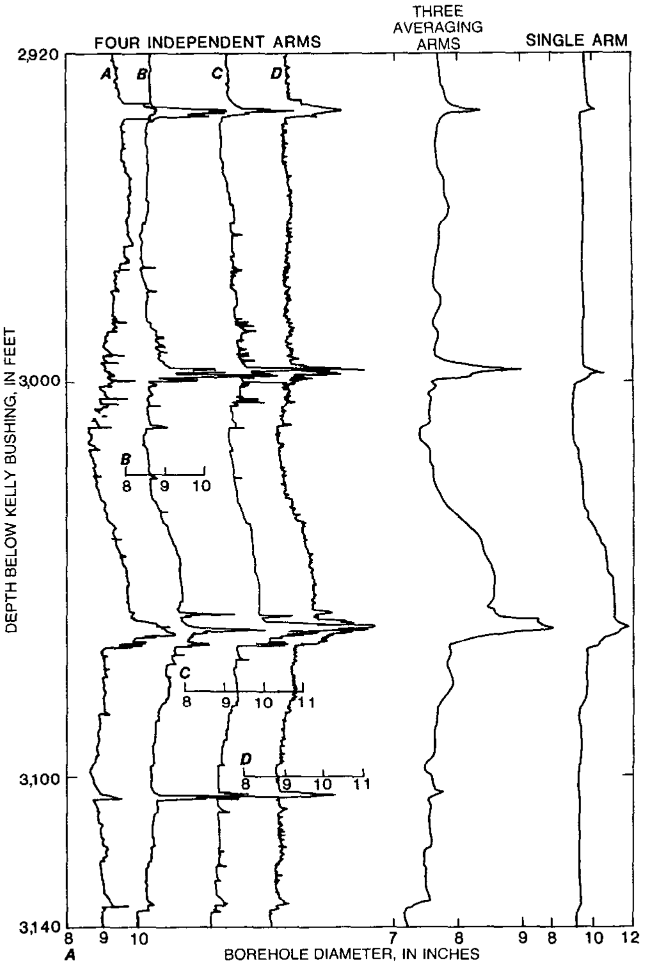

Figure 84.—Caliper logs from probes having four independent arms, three averaging arms, and a single arm, Madison Limestone test well 1, Wyoming.

Calibration and standardization

Calibration of caliper probes is done most accurately in cylinders of different diameters. Because large cylinders occupy considerable space in a logging truck, it is common practice to use a metal plate for onsite standardization of three-arm averaging or single-arm probes. The plate is drilled and marked every inch or two and machined to fit over the body of the probe. One arm is placed in each of the appropriate holes for the range to be logged. The pen location is labeled on the analog chart and a digital value is recorded, if applicable, for each of the known diameter measurements. Because values obtained with a calibration plate are not as accurate as those obtained with a cylinder, the log scale generally is checked using casing of known diameter logged in the borehole. A common horizontal scale used for water-well logs is 1 in of chart for 1 in of borehole diameter. With this scale, changes in average hole diameter of 0.1 in are easily detected. Some caliper systems are capable of detecting much smaller changes; the horizontal scale can be expanded 10 times, if necessary; however, noise may become significant at this sensitivity.

Volume of investigation

The concept of volume of investigation does not apply to caliper logs, because they are designed to measure changes in distance to the borehole wall, not into the rock. For the types of caliper probes described here, the radius of investigation varies from a few inches within the borehole to 1,000 ft within gas-storage caverns. Under some conditions, data on borehole shape can be obtained through casing and cement using an ATV with lower than normal frequency or a gamma-gamma probe.

Extraneous effects

Most extraneous effects on caliper logs are caused by instrument problems, rather than by the borehole. Occasionally, heavy drilling mud will prevent caliper arms from opening fully, and thick mud cake may prevent accurate measurement of drilled diameter. A typical three-arm averaging caliper probe used for logging water wells will not be lowered into the heavy mud that is common in the bottom of wells, because it may not open. If the lack of pen deflection indicates that the arms have not opened, this problem may be corrected by lifting the probe out of the heaviest mud or by bouncing it up and down. Packing the external mechanical mechanism and grooves for the arms with viscous grease will decrease the incidence of arms failing to open.

Electrical leakage of cable and grounding problems may cause spurious responses on caliper logs. Some caliper probes are subject to temperature drift, but this problem usually occurs only if the temperature range is extreme. Checking the scale in casing of known diameter and checking the calibration immediately after logging will indicate any changes that might have occurred during logging. Two of the arms on a three-arm averaging probe may need to be removed to produce a valid log in a markedly deviated hole. A subsequent caliper log in the same borehole may not repeat exactly because the probe may rotate, causing the arms to follow slightly different paths.

Interpretation and applications

A valid caliper log is essential to interpretation of the many different types of logs that are affected by changes in borehole diameter, even those logs that are labeled "borehole compensated." Substantial differences in the responses of gamma-gamma logs in two closely spaced boreholes, differences almost entirely the result of differences in borehole diameter, are illustrated in figure 59. Caliper logs of these two boreholes are shown in figure 20. Because the lithologies penetrated by the boreholes are nearly the same, the differences in borehole diameter are related almost entirely to drilling technique. In general, circulation of large volumes of drilling fluid and a large number of trips in and out of a borehole with the drill string cause an increase in borehole diameter. The shallower part of a borehole generally has a larger diameter than the deeper part because it has been affected by more drilling activity. Drill bits also may become smaller with use; changes in drill-bit size will be obvious on a caliper log, as will casing of different size. Couplings, welds, and screens may be located using a high-resolution caliper log.

Because a caliper log is needed to interpret many other logs, it should be made before casing is installed in a borehole that is in danger of caving. When borehole conditions are questionable, the first log made generally is the single-point-resistance log, because it will provide some lithologic information; also, the probe is relatively inexpensive, and will constitute a relatively small loss if it is lost. If no serious caving problems are detected during the running of the single-point-resistance log, a caliper log should be made before casing is installed so it can be used to aid in analysis of nuclear logs made through the casing. Data for extremely rough intervals of borehole wall, with changes in diameter of several inches, cannot be corrected on the basis of caliper logs; data for these intervals should be eliminated from quantitative analysis.

Caliper logs can provide information on lithology and secondary porosity. Examples of the response of caliper logs to lithology and structures in sedimentary and igneous rocks are provided in figures 7 and 8. Boreholes drilled in hard rocks such as limestone will have a smaller diameter than in adjacent shale. The presence of thin beds may result in an irregular trace. Secondary porosity, such as fractures and solution openings, may be obvious on a caliper log; however, the character will not be uniquely defined, as it would be on an acoustic-televiewer log. Four traces from an acoustic-caliper log and one trace from a mechanical-caliper log for a producing-fracture zone in a geothermal well at Roosevelt Hot Springs, Utah, are included in figure 81. An ATV log of this interval is shown in figure 80. The oriented traces of the acoustic caliper clearly show the apparent openness of the fractures and the direction of dip of the larger fracture at the top of the zone. These traces also demonstrate that the borehole is not symmetrical or circular, which is a typical, rather than an unusual, situation. An elliptical cross section is particularly common in deviated boreholes. Note that the mechanical-caliper log, made with a three-arm averaging probe, does not indicate the actual irregularity of the fractured and altered zone. The average borehole diameter probably was increased in this interval by drilling because the rocks were softer and because numerous fractures permitted spalling into the borehole.

The differences that can occur between three of the most common types of caliper logs made in the same well are illustrated in figure 84. The high-resolution logs on the left were made with a probe having four independent arms. The log for the three-arm averaging probe is typical of that recorded in many water wells. The log for the single-arm caliper probe was recorded during the running of a compensated gamma-gamma log. The resolution of these logs decreases from left to right. The numerous sharp excursions on curves A, B, C, and D may appear to have resulted from noise; however, they are valid, as they repeated on subsequent logs. ATV logs indicate that these excursions were caused by solution openings in the carbonate rocks. Some of these openings are shown on the ATV log in figure 79. Flowmeter logs indicate that most of the water flowing from this well under artesian pressure was produced from the interval below a depth of about 3,000 ft, where the high-resolution caliper logs indicate the maximum number of solution openings. Note that the single-arm caliper log and, to a degree, the three-arm caliper log give a false impression as to the character of solution openings intersecting this well. For example, in figure 84, a significant solution opening just below a depth of 3,100 ft is not indicated on the single-arm caliper log and is indicated by only a small anomaly on the three-arm averaging caliper log, but is clearly indicated on the four-independent-arm caliper logs.

Open fractures are detected readily by three-arm averaging caliper probes; however, as illustrated in figures 8 and 83, the true character of the fractures may not be correctly interpreted from the log. If an open fracture is dipping at an angle such that the three arms enter the opening at different depths, the separate anomalies produced indicate three fractures, rather than one.

Caliper logs have been used to correlate major producing aquifers in the Snake River Plain in Idaho (Jones, 1961). Vesicular and scoriaceous tops of basalt flows, cinder beds, and caving sediments were identified with three-arm caliper logs. In the basalt of the Quaternary Snake River Group, caliper logs also were used to locate the optimum depth for cementing and to estimate the volume of cement that might be required to fill the annulus to a preselected depth (Keys, 1963). Similarly, a caliper log can be used to calculate the volume of gravel pack needed and to determine the size of casing that can be set to a selected depth. Caliper logs are particularly useful for selecting the depths for inflating packers. Packers can be set only in those intervals of a borehole that are within a specified range of borehole diameters, and packers may be damaged if they are set in rough or irregular parts of a borehole. Packers set under these unfavorable conditions may explode; in addition, if they are set on an open fracture, they may explode or be bypassed by flow. Caliper logs are useful for determining what other logs can be made and what range of borehole diameters will be accepted by centralizers or decentralizers. Borehole-diameter information is essential for calculation of volumetric rate from flowmeter logs.

Mud cake, mud rings, and clay squeezes can be identified with caliper logs. Clay squeezes are caused by a gradual hydration of clay; they may result in a borehole closing entirely, with the resultant loss of a logging probe. A sequence of caliper logs has been used to identify intervals that were freezing inward in permafrost, which eventually resulted in the borehole closing. The more rapid freezing rate probably was the result of greater thermal conductivity of the sedimentary units in these intervals. A series of caliper logs also may show increases in borehole diameter over time caused by reaction of acidic wastes with carbonate rocks; the logs identify the intervals accepting most of the waste (Keys and Brown, 1973).

Test 4.—ACOUSTIC AND CALIPER LOGGING

1. Acoustic-velocity logs are distinguished from acoustic-televiewer logs by their
    - a. Use of a lower frequency.
    - b. Much greater depth of rock penetration.
    - c. Use of two or more transducers.
    - d. Use of centralizers.
2. Acoustic-velocity logs measure
    - a. Transit time, in microseconds per foot.
    - b. Transit time of the shear wave.
    - c. Velocity of the tube wave, in miles per second.
    - d. Transit time of the compressional wave.
3. An acoustic televiewer can be used to determine
    - a. Location of perforations in casing.
    - b. Strike and dip of bedding.
    - c. Location and orientation of fractures.
    - d. Size of some solution openings.
4. Acoustic-wave-form logs
    - a. Can be made with an acoustic-velocity probe.
    - b. Can be used to locate open fractures.

    c. Require a different recording system than that used for acoustic-velocity logs.
    d. Are used commercially to evaluate cement bond.
5. Acoustic-televiewer logs
    a. Can be recorded quite rapidly.
    b. Are affected by the presence of magnetic materials.
    c. Cannot be recorded in steel casing.
    d. May require several logging trips to optimize results.
6. Porosity can be determined from acoustic-velocity logs
    a. Made in dry holes.
    b. By using the equation ϕ=delta t log−delta t matrix/delta t liquid−delta t matrix.
    c. By calibration with core samples.
    d. In fractured and vuggy limestone.
7. The acoustic caliper has the following advantage(s) over a three-arm averaging mechanical caliper:
    a. Greater resolution can be obtained.
    b. It can be used under more varied borehole conditions.
    c. The traces are oriented.
    d. The equipment is less expensive.
8. Caliper logs can be used for
    a. Distinguishing crystalline-rock types.
    b. Correcting other logs.
    c. Calculating cement volumes.
    d. Locating packer seats.
9. Borehole-diameter changes may be caused by
    a. Lithology.
    b. Drilling technique.
    c. Fractures and solution openings.
    d. Mineral solution after drilling.
10. Markedly deviated boreholes are a problem for acoustic probes and some calipers because
    a. The transducers do not work properly when they are not vertical.
    b. Properly centering acoustic probes is difficult.
    c. Coupled arms on three-arm averaging caliper probes may be forced closed.
    d. Orientation corrections are needed for the acoustic televiewer.
11. A cement-bond log
    a. Can be readily interpreted by any log analyst.
    b. Is the best method for locating channels through cement.
    c. Can indicate the quality of bonding between cement, casing, and the borehole wall.
    d. Will record "formation" signal through casing under some conditions.

Fluid Logging

Fluid logging includes techniques that measure characteristics related to the fluid column in the borehole; no direct signal is derived from the surrounding rocks and their contained fluids. The fluid logs that are described here are temperature, conductivity, and flow. Fluid logs are unique in that the recorded characteristics of the fluid column may change rapidly with time and may be altered by the logging process.

Temperature

Temperature logs can provide useful information on the movement of water through a borehole, including the location of depth intervals that produce or accept water; thus, they can provide information related to permeability distribution and relative hydraulic head. Temperature logs can be used to trace the movement of injected water or waste, to locate cement behind casing, and to correct other logs that are sensitive to temperature. Although the temperature sensor responds only to the temperature of the water or air in the immediate vicinity, recorded temperatures may indicate the temperature of adjacent rocks and their contained fluids. Rock temperature may be indicated if no flow exists in the borehole and if equilibrium exists between the temperature of the fluid in the well and the temperature of the adjacent rocks. Temperature logs may have been the first type of geophysical log recorded, and they have been extensively used in ground-water hydrology for many years (see fig. 3). For many oil wells, the only temperature data available are bottom-hole temperatures obtained by taping maximum-reading thermometers to logging probes.

Principles and instrumentation

Most temperature probes used in ground-water studies use a glass-bead thermistor mounted in a tube that is open at both ends to protect it from damage and to channel water flow past the sensor. The thermistor may be enclosed in a protective cover, but the cover should be made of materials of substantial thermal conductivity and minimal specific heat to permit fast response time. Response time is fastest, about 1 s, when the glass-bead thermistor is exposed to the fluid, but without the cover breakage is more likely. The thermistor is thermally insulated from the body of the logging probe.

A small electrical current is conducted through the glass-bead thermistor to measure changes in resistance that occur as a function of temperature. The changes in resistance of the thermistor are converted to a varying pulse rate to eliminate the effect of

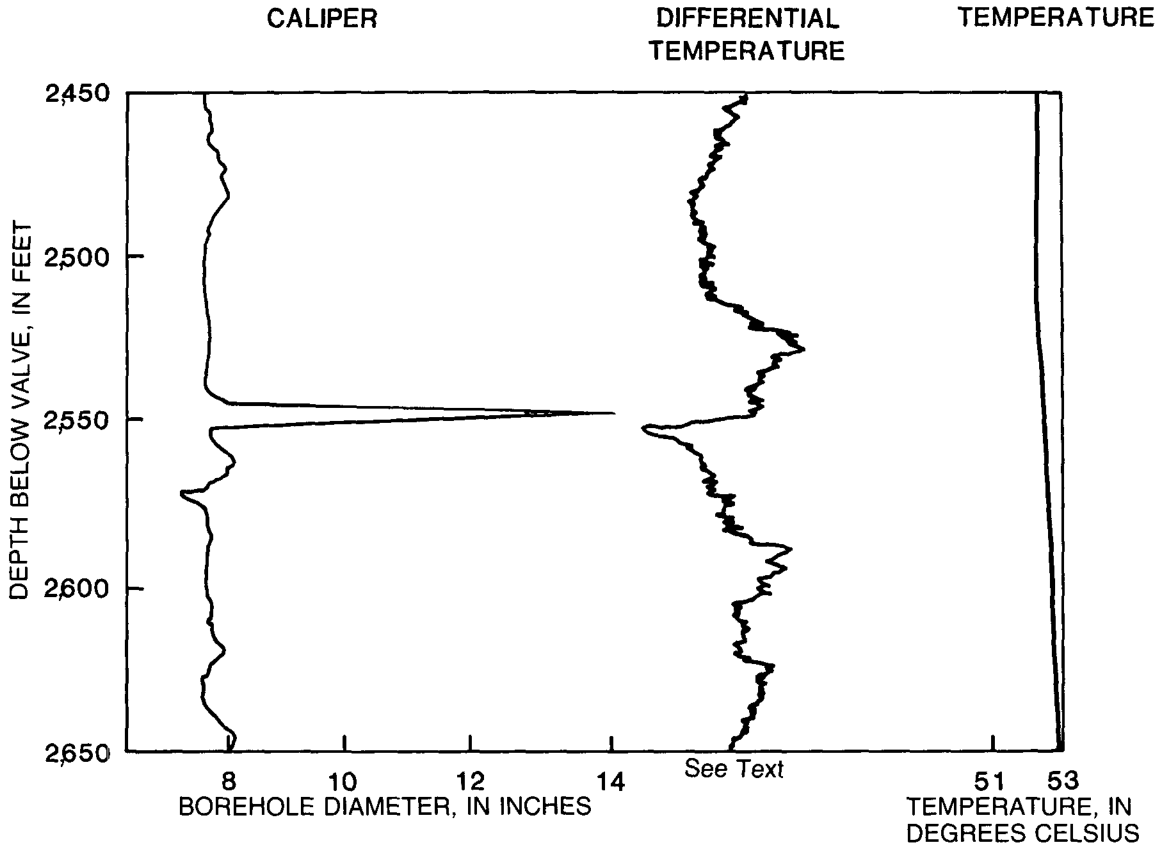

Figure 85.—Caliper, differential-temperature, and temperature logs for an interval in Madison Limestone test well 1, Wyoming.

changes in resistance of the logging cable. Electronic components in the probe that might change output because of thermal drift are placed in a constant-temperature oven that maintains a temperature higher than the ambient temperature. Thermistor-type temperature probes used by the U.S. Geological Survey have an accuracy, repeatability, and sensitivity of about 0.02 °C. They are stable for long periods, but they have the disadvantage of a nonlinear temperature response. If desired, the nonlinear curve can be replotted on a linear scale by a computer. Low-temperature measuring systems for water have been described in detail by Stevens and others (1975). For high-temperature logging in geothermal wells, platinum resistor sensors may be used; they have an accurate, stable, and linear response but a much longer response time. In a simple version of a geothermal-well probe, the probe contains no electronics; therefore, changes in electrical leakage in the logging cable can introduce an error.

Two general types of temperature logs are commonly made. One type, called simply a temperature log, is a record of temperature versus depth. The other type, the differential-temperature log, is a record of the rate of change in temperature versus depth. A differential-temperature log is more sensitive to changes in temperature gradient. The greater sensitivity of a differential-temperature log is illustrated in figure 85. The anomaly on the differential-temperature log clearly correlates with an anomaly on the caliper log, which is caused by a large solution opening in the carbonate rock. Most differential-temperature logs do not use a scale; if a scale is used, it is in degrees per foot. A differential-temperature log can be considered the first derivative of a temperature log; it can be obtained by two different types of logging probes or by computer calculation from a temperature log.

One type of differential-temperature probe measures the difference in temperature between two sensors that are placed one to several feet apart along the vertical axis of the probe (Basham and Macune, 1952). The other type of differential-temperature probe uses one sensor and an electronic memory so that the temperature at one time can be compared with the temperature at a selected previous time (Johns, 1966). When the latter type of probe is used, logging speed must be maintained accurately. With either type of probe, the recorder can be set at a reference gradient, which will plot as a straight line. Departures from the reference gradient will be recorded as deflections on the log. The same result can be derived from computer analysis of a digitized temperature log; such analysis has the advantage that the spacing or delay can be varied in the computer to provide maximum sensitivity. All differential-temperature logs reproduced as figures in this manual were produced by a computer with theoretical spacings of 1 to 3 ft.

Calibration and standardization

Calibration of temperature probes should be done in a constant-temperature bath using accurate mercury thermometers. The bath and probe should reach thermal equilibrium before a calibration value is established. For calibration of geothermal-logging probes, an oil having a high burning temperature, such as peanut oil, may be used. Periodic recalibration is needed to establish the stability of any temperature-logging system; if long-term stability has been proved, onsite standardization may be sufficient.

Onsite standardization cannot be done with great accuracy because no portable substitute exists for a constant-temperature bath. The only temperature that can be achieved and maintained for sufficient time to permit a valid calibration is 0 °C, in an ice bath. An approximate check of system response can be made at other temperatures, but the temperature of water in a bucket will change constantly; further, a thermometer reading of the water temperature immediately surrounding the sensor is difficult to make. Some probes incorporate a fixed resistor that can be switched into the measuring circuit in place of the thermistor to check system response onsite. A resistance-decade box can be substituted for the resistance temperature sensor to check response of all of the logging system except the sensor.

Volume of investigation

The sensor in a temperature probe responds only to the fluid in its immediate vicinity. Therefore, in an interval in which fluid is moving, measured temperature may be different from the temperature in adjacent rocks. Under these conditions, a thermal gradient will exist from the borehole wall outward. Only in a borehole in which no fluid movement has occurred for sufficient time to permit thermal equilibrium to be established does a temperature log reflect the geothermal gradient in the rocks. Thus, the concept of volume of investigation does not apply to temperature logs.

Extraneous effects

Errors on temperature logs can be caused by such instrument problems as thermal lag, drift of the electronics, and self-heating of the thermistor. None of these factors is significant in a well-designed probe. A number of borehole conditions may cause misinterpretation of a temperature log. Drilling, testing, and cementing a borehole cause significant perturbations of the thermal system, and thermal equilibrium may not be reestablished for many years. Predicting the return of thermal equilibrium between the borehole and adjacent rock after drilling or injection of fluids or under conditions of natural vertical circulation is difficult. A theoretical method for calculating true formation temperature under these conditions has been described by Sanyal and others (1980). Movement of the logging probe disturbs the thermal profile in the fluid column. Unless rapid flow is occurring, each temperature log will be different. The degree of disturbance caused by any type of logging probe is related to speed of logging and to the diameter of the probe in relation to the diameter of the borehole. Fast logging speed and large-diameter probes will cause the greatest disturbance. The most accurate temperature log is made before any other log is made; the temperature log is recorded while moving slowly down the borehole. Logging speed is a function of response time of the probe; a speed faster than 25 ft/min seldom produces an accurate temperature log.

Convection is a major problem in interpretation of temperature logs, particularly in large-diameter wells and in areas of substantial thermal gradient. Convective cells in large-diameter wells can cause major temperature anomalies unrelated to ground-water movement. Krige (1939) developed an expression for the critical temperature gradient above which convection occurs:

$$Cvk/g\alpha a^{4}+g\alpha T/cp \qquad (12)$$

where

C=a constant, which is 216 for most boreholes;
v=kinematic viscosity, in square centimeters per second;
k=thermal conductivity, in square centimeters per second;
g=acceleration of gravity, in centimeters per second squared;
α=coefficient of thermal expansion of water, in inverse degrees kelvin;
a=radius of the borehole, in centimeters;
T=absolute temperature, in degrees kelvin; and
cp=specific heat at constant pressure, in inverse degrees kelvin.

Sammel (1968) plotted critical thermal gradients as functions of temperature, concentration of dissolved solids, and borehole diameter. He concluded that convection may cause temperatures of water in the upper interval of deep boreholes to be substantially different from true temperatures in the rocks penetrated. Because of the effect of convective movement, small-diameter boreholes provide more useful temperature logs under most conditions.

Interpretation and applications

Temperature logs can aid in the solution of a number of ground-water problems if they are properly run under suitable conditions and if interpretation is not oversimplified. If there is no flow in or adjacent to a borehole, the temperature gradually will increase with depth, as a function of geothermal gradient. Typical geothermal gradients range between 0.47 and 0.6 °C per 100 ft of depth; they are related to the thermal conductivity or thermal resistivity of the rocks adjacent to the borehole and the geothermal heat flow from below. Conaway (1977) developed a computer program for correcting digitized temperature data and computing temperature gradients to be plotted as differential-temperature logs. The resulting logs of a cased well were determined to correlate well with measurements of thermal resistivity on core and to resolve stratigraphic units as thin as 1.5 ft, where thermal-resistivity contrast was adequate (Conaway and Beck, 1977). Thus, temperature logs can be used to obtain lithologic information, which is not a common use in ground-water studies because water movement commonly obscures temperature changes caused by lithology. Schneider (1972) has reported that prolonged pumping of an aquifer may cause a substantial distortion of the natural geothermal field by inducing upward flow of warm water or downward flow of cold water, or both.

If rapid vertical flow of water occurs in a well, the temperature log through that interval will show little change. Vertical flow, up or down, is common in wells that are completed through several aquifers or fractures that have different hydraulic head, although the flow rate is seldom fast enough to produce an isothermal log. An example of a temperature log of a geothermal well that indicates the intervals of producing fractures is given in figure 86. Much of the water was entering the well at a depth of 2,900 ft, but there are additional producing fractures below a depth of 3,000 ft. Although the production rate was rapid in this well, the upward-flowing water cooled markedly, because the well had not been flowing for a long period and because the shallow rocks had not yet been heated substantially.

The identification of fractures that are producing water from Triassic sedimentary rocks near Raleigh, N.C., is illustrated in figure 87. The temperature log on the left indicates several changes in temperature gradient that are clearly defined by the computer-derived differential-temperature log. The caliper log indicates that the water production may come from fractures, and this interpretation is substantiated by the acoustic-televiewer logs on the right. Differential-temperature logs usually display sharper anomalies that are easier to identify than the subtle changes in gradient in a temperature log.

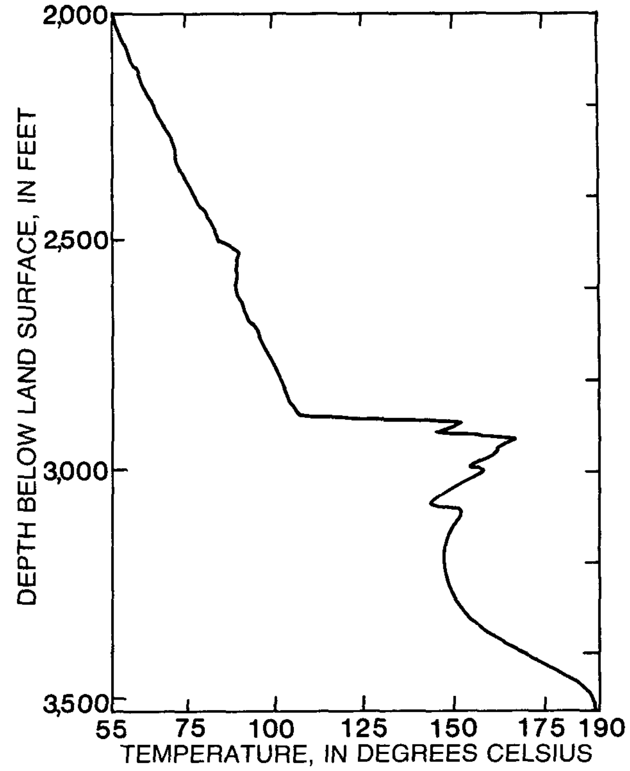

Figure 86.—Temperature log of a producing geothermal well, Roosevelt Hot Springs, Utah.

A radial differential-temperature probe has been described that can be used to detect flow behind casing (Cooke and Meyer, 1979). Two sensors are extended to contact the casing; the temperature difference between the two sensors is recorded as they rotate. The temperature of fluid or gas flowing in a channel in cement usually is somewhat different than the temperature of cement where channels are not present. Detection can be improved by injecting water of different temperature into the borehole.

Many temperature logs are recorded at a relatively insensitive scale to decrease off-scale deflections and the necessary repositioning of the trace. Commercial temperature logs generally are recorded at a sensitivity that makes the resolution of 1-°C changes difficult. Commonly, water wells are logged at a scale of 1 °C per 1 in of paper; scales can be expanded to 10 times that sensitivity, if necessary. Because the most accurate temperature log is made on the first logging trip down a well, the temperature range is not known beforehand; the tendency may be to decrease sensitivity to keep the record on scale. One way to record

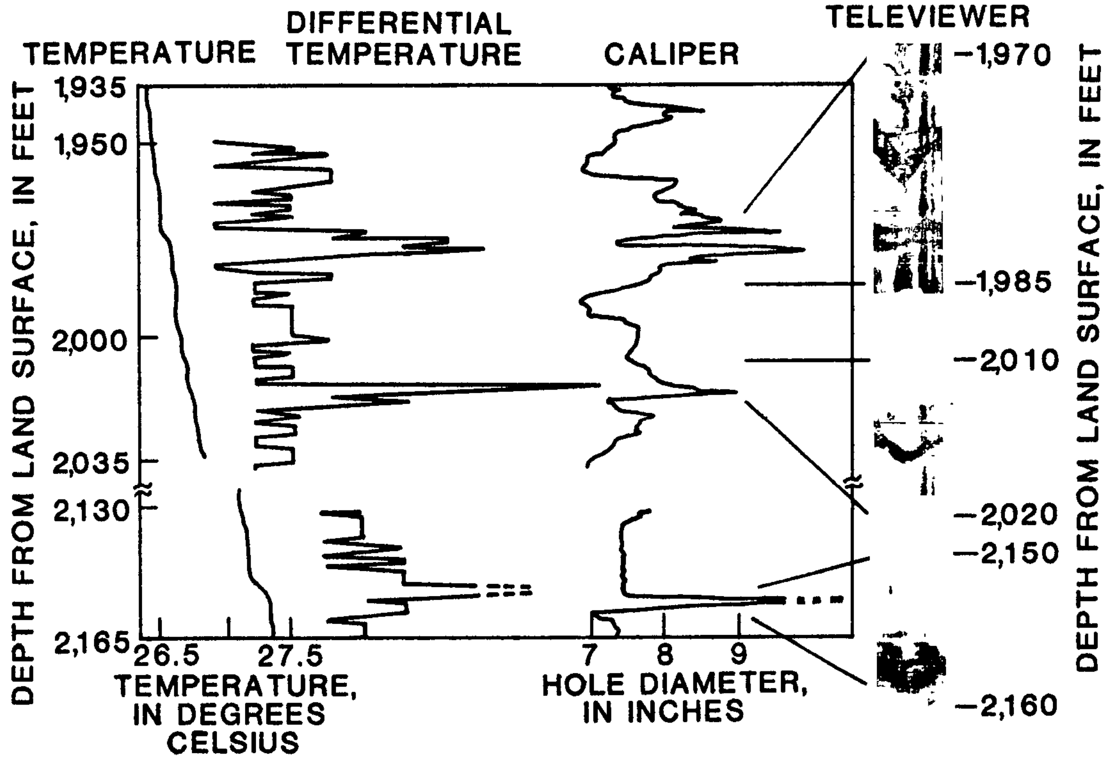

Figure 87.—Temperature, differential-temperature, caliper, and acoustic-televiewer logs of Sears test well 1 near Raleigh, N.C.

at maximum sensitivity and simultaneously produce a log without off-scale deflections is to transmit the signal to two recorder channels with a 10:1 difference in sensitivity. If the data from the probe are digitized, then the temperature logs can be replotted later at the best scale, and a differential-temperature log can be produced.

Seasonal ground-water recharge from the land surface may produce cyclic temperature fluctuations at shallow depths; vertical flow causes curvature in the geothermal gradient. Stallman (1965) suggested that measurement of temperature profiles with maximum sensitivity would permit calculation of vertical fluid movement in the unsaturated zone. Bredehoeft and Papadopulos (1965) developed one-dimensional curves for estimating vertical water movement below the water table from temperature profiles. Using this method, Sorey (1971) calculated a rate of upward water movement through semiconfining beds that was similar to rates derived from pumping tests and water budgets. From a practical standpoint, the precision of the borehole measurements was 0.01 °C; the method was restricted to ground-water velocities sufficiently fast to cause measurable curvature in a temperature log.

Temperature logs can be used to trace the movement of injected water (Keys and Brown, 1978). A few of several hundred temperature logs made during a 7-day recharge test in the High Plains of Texas are shown in figure 88. Water from a playa lake was injected into an irrigation well, and logging was used to determine the movement of the recharge water and the extent of plugging of the Ogallala aquifer. Several monitoring wells were drilled and completed with 2-in steel pipe, capped on the bottom and filled with water. The logs in figure 88 are of a monitoring well located 39 ft from the injection well. Most of the time, the water in the playa lake was warmer than the ground water and the lake-water temperature fluctuated several degrees each day. The passing of a cold front caused a marked decrease in temperature of the lake water, which was detected in the monitoring wells. The first warm water was detected in the monitoring well less than 4 hours after recharge started. The temperature logs indicate that the interval of greatest permeability was located at a depth of about 160 ft. Recharge water did not arrive at a depth of 180 ft until the third day. Diurnal temperature fluctuations and development of a recharge cone are indicated by the data in figure 88.

Diurnal-temperature cycles and traveltime of the center of thermal waves plotted in figure 89 were calculated from temperature logs made in the same monitoring well mentioned previously; however, logs

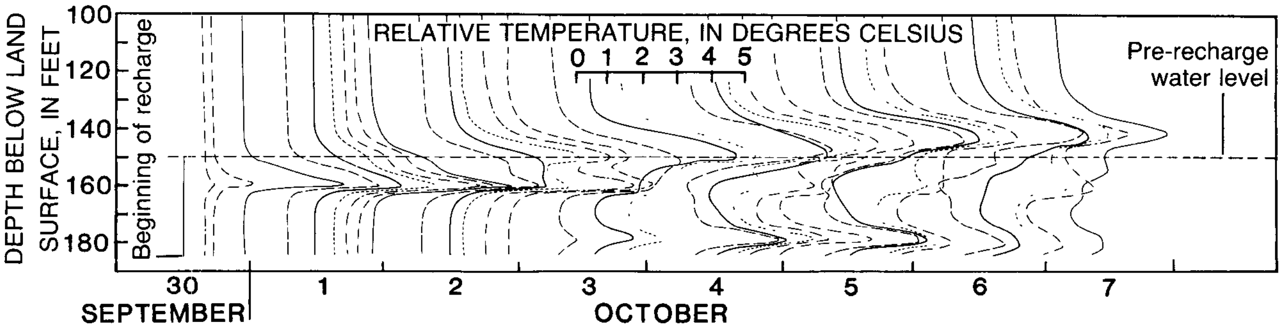

Figure 88.—Selected temperature logs made in a monitoring well located 39 feet from a recharge well, High Plains of Texas.

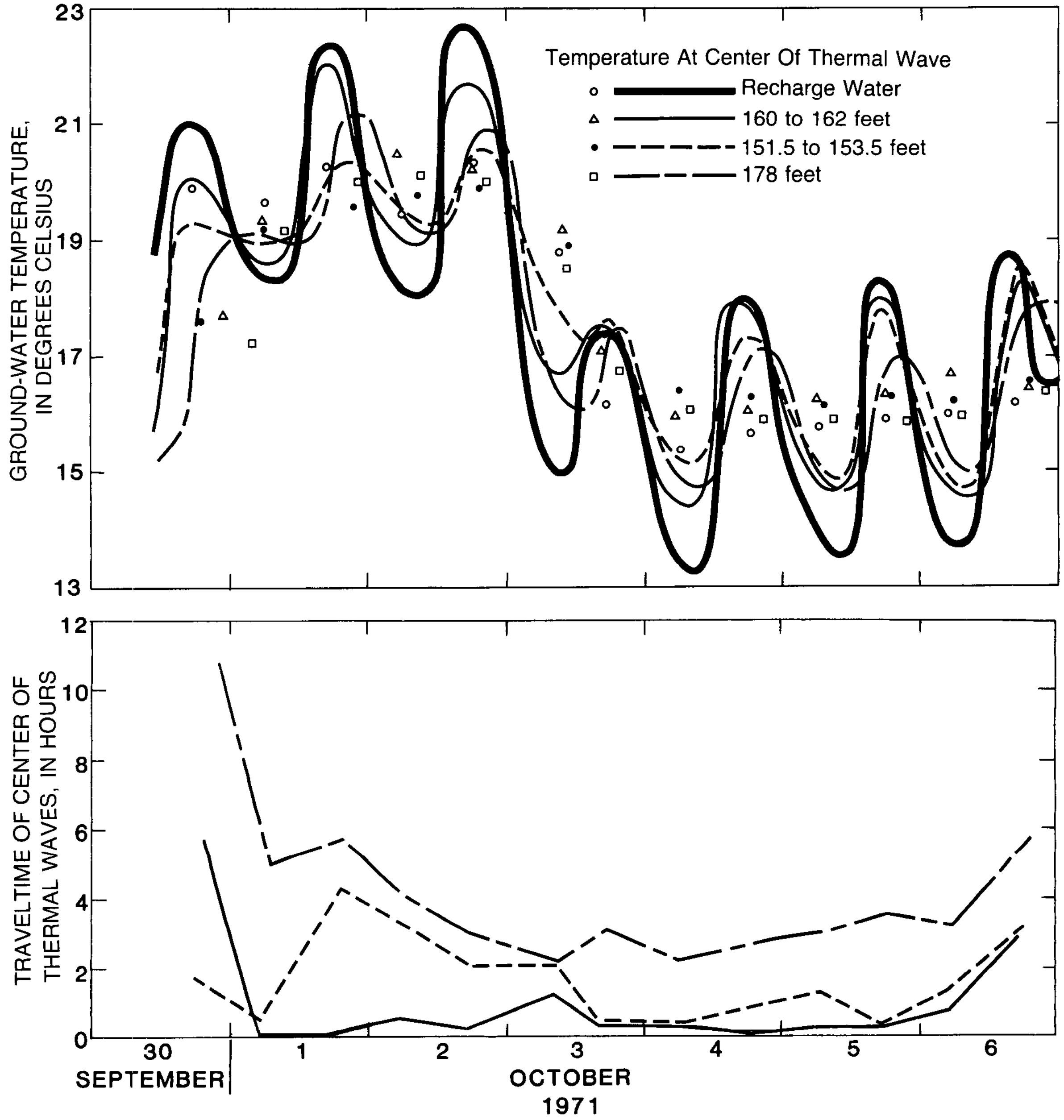

Figure 89.—Diurnal-temperature cycles and traveltimes of the center of thermal waves, based on temperature logs made in a monitoring well located 39 feet from a recharge well, High Plains of Texas.

from other monitoring wells gave similar results. The prominent solid line in the upper graph of figure 89 shows the diurnal-temperature fluctuations of the recharge water obtained from a continuous recorder on the recharge line. The other three lines represent water-temperature fluctuations at three depths in the monitoring well obtained from temperature logs. The points shown by symbols represent the temperature at the calculated center of the thermal waves. As shown by the data in the lower graph of the figure, the traveltime of the center of the thermal waves did not decrease substantially during the duration of the test, except possibly at the end. Several significant conclusions were reached as a result of this test. First, the aquifer was not plugged by recharge water containing a large concentration of suspended solids and substantial entrained air (this conclusion was confirmed by the landowner's report that well yield increased greatly over that reported before the test). Further, the temperature logs (as well as subsequent microscopic examination of core) indicated that plugging of the uniform fine-grained sand was prevented by the presence of secondary porosity.

Temperature logs can be used to trace the movement of water that has been heated in a tank by the sun and injected into the ground. In a similar fashion, temperature logs can be used to locate plumes of wastewater that result from injection into wells or seepage from ponds, if the temperature of the wastewater is sufficiently different from that of the ground water. An example of the identification of a plume of warm wastewater for a distance of more than 1.5 mi from a disposal well has been described by Jones (1961). Temperature logs made in a series of monitoring wells clearly showed the horizontal and vertical distribution of the wastewater, and the distribution was corroborated by fluid-conductivity logs.

Temperature logs can be used to determine the location of cement grout outside of casing. The casing is filled with water, and the log usually is made within 24 hours of grout injection; however, anomalous temperatures may persist for several days. A neat Portland-cement grout was determined to have a temperature of 70 °C after 4 to 8 hours and 38 °C after 8 to 12 hours, in a depth interval where normal temperatures are considerably less than 38 °C.

Temperature data from wells also are used to calculate water density, viscosity, and thermal conductivity and to develop heat-flow maps, which can be used to estimate fluid flux, particularly in geopressured aquifers.

Conductivity

Logs of fluid conductivity, which is the reciprocal of fluid resistivity, provide data related to the concentration of dissolved solids in the fluid column. Although the quality of the fluid in the column may not reflect the quality of adjacent interstitial fluids, the information can be useful when combined with other logs. The log is simple and relatively inexpensive to make, but it has not been extensively used in ground-water hydrology to date.

Principles and instrumentation

Fluid-conductivity or fluid-resistivity logs are records of the capacity of the borehole fluid that enters the probe to conduct electrical current. The probe is not affected by changes in the conductivity of adjacent fluids or solid materials because it is constructed with the electrodes inside a housing. Because the ring electrodes are installed on the inside of a steel tube that is open at both ends, water will flow through the tube as the probe moves down the well. The electrodes generally are gold or platinum, to decrease changes in contact resistance caused by chemical reactions, and they are insulated from the steel housing. Probes used on single-conductor cable have only two electrodes, which serve as both current and potential electrodes, analogous to a volt-ohm meter. A four-electrode system used on multiconductor cable provides more accurate measurements. This system consists of two current and two potential electrodes that function in the same way as those in a normal-resistivity logging system. Alternating current is used across the electrodes to decrease electrode polarization. If the probe is properly designed, the electronics in the probe will not respond to borehole temperature, and changes in the resistance of the cable will not affect the data transmitted to the land surface.

Conductivity is recorded in micromhos per centimeter, or microsiemens per centimeter, a unit equal to 10,000 divided by the resistivity in ohm-meters. Both units are used for fluid logging, and both can be converted to standard temperature by use of figure 19 or a similar chart. Specific conductance is measured at a standard temperature of 25 °C. The effect of fluid temperature on conductivity is substantial; a conductivity of 700 μmho/cm in a sodium chloride solution at a borehole temperature of 10 °C is equivalent to a specific conductance of 1,000 μmho/cm at 25 °C.

Calibration and standardization

Calibration generally is done empirically in solutions of known sodium chloride concentration because most charts are based on this salt and because conversion factors are available to correct for the presence of other ions. The salinity of the calibration solution can be calculated by adding a known quantity of salt to distilled water and converting to conductivity, or by measuring with an accurate laboratory conductivity meter. The temperature of the calibration solution is recorded while the measurement is being made; for the most accurate results, the temperature must be uniform and stable.

Onsite standardization can be done using a resistance-decade box; this method is not accurate and does not account for changes in contact resistance of the electrodes but can be used to ensure that all logs are calibrated to the same scale. A better approach is to use several fluids of known salt concentration in plastic bottles sufficiently large to allow submersion of all electrodes in the probe. A laboratory conductivity cell or a less accurate mud-resistivity kit also can be used to check the logging equipment onsite.

Extraneous effects

Disturbance of the fluid column in the borehole can make fluid-conductivity logs difficult to interpret. Disturbance of an equilibrium-salinity profile can be caused by movement of logging probes or by convective cells. Because of the possibility of disturbance by logging, the most accurate fluid-conductivity log is made during the first trip down the borehole. Because fluid-temperature logs also need to be made first, an ideal probe is capable of making simultaneous fluid-conductivity and fluid-temperature logs. Unlike temperature, chemical equilibrium between the fluid in the borehole and that in the formation can be established only by actual movement of fluid. Because of vertical flow, a fluid-conductivity log may not represent the salinity of interstitial fluids adjacent to the borehole.

Some fluid-conductivity logging systems are not designed to exclude the effect of conductivity changes outside the probe. This type of extraneous response can be detected by logging in and out of steel casing. If the log shows a sharp deflection that is not the result of a coincidental change in salinity at the bottom of the casing, equipment malfunction is indicated. Temperature drift is another common equipment problem; it is best detected in a temperature bath with fixed resistors across the electrodes so that the thermal effect on fluid conductivity is not a factor.

Interpretation and applications

When both fluid conductivity and fluid temperature are known, the equivalent sodium chloride concentration can be determined from figure 19. Water samples should be analyzed to determine the concentrations of the various ions so that corrections can be made. Fluid-conductivity logs first were used in ground-water investigations in 1930 by Livingston and Lynch (1937) of the U.S. Geological Survey. They developed equipment to locate the sources of saltwater leaking into artesian wells in Texas, a common application for these logs.

Another important use of fluid-conductivity logs is to aid in interpretation of electric logs. Spontaneous-potential, single-point-resistance, and many types of multielectrode resistivity logs are affected by the salinity of the fluid in the borehole. The substantial changes that can be produced on spontaneous-potential logs by differences in fluid conductivity are shown in figure 28. If charts are available, quantitative corrections can be made to some types of logs; if not, the reason for anomalous log response may be recognizable. Electric logs usually are made shortly after a borehole is completed; the borehole may be filled with a column of drilling mud that is rapidly changing in composition. Gravity segregation of the mud and inflowing ground water will modify the electrical conductivity of the fluid column and affect electric logs run during this period.

Regional patterns of ground-water flow and recharge areas may be recognizable from fluid-conductivity logs of the water wells in an area (Olmsted, 1962). Fluid-conductivity data can be used to map and monitor areas of saltwater encroachment. Similarly, the logs can be used to monitor plumes of contaminated ground water from waste-disposal operations. Commonly, chemical waste or leachate from solid-waste-disposal operations produces ground water having a greater than normal conductivity. Fluid-conductivity logs provide the basis for selecting depths from which to collect water samples for chemical analysis. Water samplers are available that operate on single-conductor or multiconductor cables; these samplers can be opened and closed at selected depths. Analysis of samples will provide a basis for checking the calibration of the conductivity probe and for conversion of log data to salt concentration.

Fluid-conductivity logging equipment can be used to trace the movement of ground water by injecting saltwater as a tracer. Small quantities of saltwater can be injected at selected depths, and fluid-conductivity logs can be used to measure vertical flow in a single water well, or larger quantities can be injected to trace the movement of saltwater to nearby water wells. The general technique for locating more permeable depth intervals is similar to tracing ground-water flow with temperature logs. This application of fluid-conductivity logs is discussed in more detail in the section on flow logging. The quantities of salt used must conform to applicable regulations on ground-water contamination.

Interpretation of fluid-conductivity logs is complicated by the flow regime in a water well. Unless the flow regime is understood, analysis of fluid-conductivity logs is subject to considerable error. Information on the construction of the well, flowmeter logs, and fluid-temperature logs are useful in interpreting fluid-conductivity logs. Electric logs may aid in determining if an interface between waters of different quality is spatially related to the quality of interstitial fluids. In summary, fluid-conductivity logs can be misleading unless information on the construction of the well, the flow regime, and aquifer geometry is available.

Flow

The measurement of flow within and between water wells is one of the most useful logging methods available to ground-water hydrologists. Flow measurement with logging probes can be done by mechanical methods, such as impellers, by chemical and radioactive tracer methods, and by thermal methods. Measurement of vertical flow within a single well is most common, but lateral flow through a single well or flow between wells also may be recorded by borehole-geophysical methods. Tracer methods that require sampling and analysis are not described in this manual.

Principles and instrumentation

A Price current meter was used by Meinzer (1928) to locate intervals of leakage in artesian wells in Hawaii; Fiedler (1928) used an Au deep-well current meter in the Rosewell artesian basin at about the same time. These and other methods of flow measurement in water wells prior to 1960 have been described in detail by Patten and Bennett (1962).

The most common logging probe currently (1985) being used to measure vertical fluid movement in water wells is the impeller flowmeter, which is a relatively inexpensive and reliable instrument. Most flowmeters incorporate a lightweight, three- or four-bladed impeller mounted on a shaft that rotates a magnet mounted on the same shaft. The magnet actuates a sealed microswitch so that one or more pulses are impressed on low-voltage direct current that is connected across the switch. The magnet and switch usually are located in an oil-filled housing, so a watertight seal on the shaft, which would increase friction, is not necessary. Unless these oil-filled probes are stored vertically, upside down, the oil level should be checked before each use. The impeller is protected from damage by a basket or housing, and the probe needs to be centralized with bow springs, or similar devices. Baskets and impellers of different diameters are available and are easily changed, so the maximum size for the water well being studied can be used to increase sensitivity. The pulses from the flowmeter either can be transmitted directly to the same ratemeter used for nuclear logging and integrated so the log is a record of the average rate of rotation as a function of depth, or the individual pulses can be recorded for slow rotation rates.

Continuous logs of flow rate can be made at a constant logging speed and supplemented by more accurate stationary measurements at selected depths. The main shortcoming of impeller-type flowmeters is their lack of sensitivity to slow-velocity flow. The most commonly used impeller flowmeter usually stalls at vertical velocities of 4 to 5 ft/min, although it is possible to measure velocities as slow as 2 to 3 ft/min under some conditions. Because velocities of 4 to 5 ft/min are required to start rotation, water wells can be logged at speeds greater than 5 ft/min and actual flow velocities determined by subtracting the logging speed from the recorded velocity. Addition of a packer or other flangelike device to concentrate most of the flow through the basket will improve sensitivity at slow velocities, particularly in large-diameter water wells; however, the flowmeter will need to be recalibrated after such an addition.

Tracer methods have been used in ground-water investigations for many years, but only those that use logging equipment are described here. Tracer methods are useful to determine much slower velocities than those that can be measured by impeller flowmeters; velocities as slow as a few feet per day may be detected. The most common methods use a probe to follow the vertical movement of a chemical or radioactive tracer injected at selected depths in a water well or to detect the lateral movement of water to adjacent wells. The use of salt solutions as chemical tracers has at least two limitations: they cannot be detected in water containing similar salt concentrations, and the greater specific gravity of the tracer introduces an error. Radioactive tracers can be detected at smaller concentrations than can chemical tracers, and most radioactive tracers can be detected through casing. The difficulties in obtaining the permits necessary for use of radioactive tracers has restricted their application in ground-water investigations in the United States. It is possible to create short-lived radioactive tracers from stable isotopes by activation with a neutron source.

Various salt solutions have been used as tracers within a single water well, because they are inexpensive and readily obtained, and can be detected with a fluid-conductivity probe. A tracer injector can be attached to a fluid-conductivity probe, so that multiple injections can be made and logged with the recorder on time drive, during one trip into the well. A tracer injector, which can be used with any kind of liquid tracer, consists of a positive-displacement piston-type pump that moves in either direction, with the same module used to open and close the arms on many motorized calipers. The quantity of tracer injected is a function of the time the motor is operated; the quantity can vary from a drop to 20 mL or more, depending on the capacity of the injector. The most efficient salt-injector system includes fluid-conductivity electrodes both above and below the injector, so movement in either direction can be detected. Single-detector systems should be designed so they can be located either above or below the injector, depending on the anticipated direction of flow. Injector-detector probes, like other types of flowmeters, are centralized in the borehole to measure the maximum velocity and to minimize borehole-wall effects.

Radioactive-tracer logging systems use the same injector, with either gamma probes located above and below, or double gamma detectors located in either position. Iodine-131 is the most commonly used tracer for both oil-well and water-well logging because it has an 8-day half-life, is water soluble, and is detectable at minute concentrations. A single drop of iodine-131 may produce a large anomaly on the gamma log; the amplitude will depend on the size of the detector and the degree of dilution in the borehole fluid. Numerous injections may be made with the injector full of tracer; however, like the salt-injection technique, data are collected immediately after injection as a series of point measurements with the recorder on time drive. Later, logs may be made with a gamma probe in the usual manner. Because the tracer can be detected at minute concentrations, single injections of tracer may be followed for a number of days, as described later in this section.

A thermal flowmeter, developed by Skibitzke (1955), consists of a resistance-heating element located between two thermistors in a small-diameter tube. The degree of fluid heating that occurs is inversely related to the velocity of the fluid flowing through the tube. Although Patten and Bennett (1962) reported a functional velocity range of 2 to 75 ft/min and errors in the range of 0.5 to 1 ft/min, this type of thermal flowmeter has had little use in ground-water hydrology to date.

The heat-pulse flowmeter originally was developed in England (Dudgeon and others, 1975) and evaluated for the U.S. Geological Survey by Hess (1982). The design of the heat-pulse flowmeter was modified extensively and a new probe was built by Hess for the U.S. Geological Survey (Hess, 1986). The modified version works reliably and has been used in wells to measure extremely slow velocities, as described in the section on interpretation and applications. The logging system is shown schematically in figure 90 (Hess, 1986). The wire heat grid, located between two thermistors, is heated by a short pulse of electric current, which is triggered from the land surface. The heated sheet of water is moved toward one of the thermistors by the vertical component of flow in the well. The arrival of the heat pulse is plotted on a chart recorder running on time drive, as illustrated in figure 91. A deflection of the recorder trace to the right indicates upward flow, and to the left, downward flow. The system is calibrated in flow columns of various diameters for flow in each direction because of the tendency for heated water to rise and the asymmetry of the probe to produce slightly different calibration curves in the two directions. A heat-pulse flowmeter can be used to measure vertical velocities of 0.1 ft/min or less to 20 ft/min or more, and it has advantages over both impeller flowmeters and tracer logging. An inflatable packer that can be attached to the probe and operated from the land surface has been developed. This packer concentrates all flow through the probe and, thus, improves the performance of the heat-pulse flowmeter or an impeller flowmeter.

In the past, a number of techniques for measuring horizontal flow in water wells have been tried, without much success or wide use. The techniques may not provide accurate estimates of average direction and velocity of flow in an aquifer because of the perturbations in the flow system caused by the well. A heat-pulse logging system has been developed for measuring horizontal flow (Kerfoot, 1982); the system consists of a series of paired thermistors located circumferentially around a heat emitter and is based on thermal transmission through an enclosing porous matrix of sand or glass beads. A laboratory study of the probe indicated a linear, consistent, and qualitatively predictable response (Melville and others, 1985). These tests also determined that probe response may be invalidated by channelizing near slotted casing and that complications result from permeability contrasts between the enclosing porous matrix and the aquifer.

Calibration and standardization

Calibration of flow-measuring probes is done best in laboratory facilities designed for this purpose. Subsequent calibration checks and standardization may be done in a well under the proper conditions. Personnel of the U.S. Geological Survey have designed and built a simple but functional calibration facility that is used for testing many of their flow-measuring probes. The test facility, which has been described in detail by Hess (1982), consists of clear plastic columns with inside diameters of 2, 3, 4, and 6 in connected to a

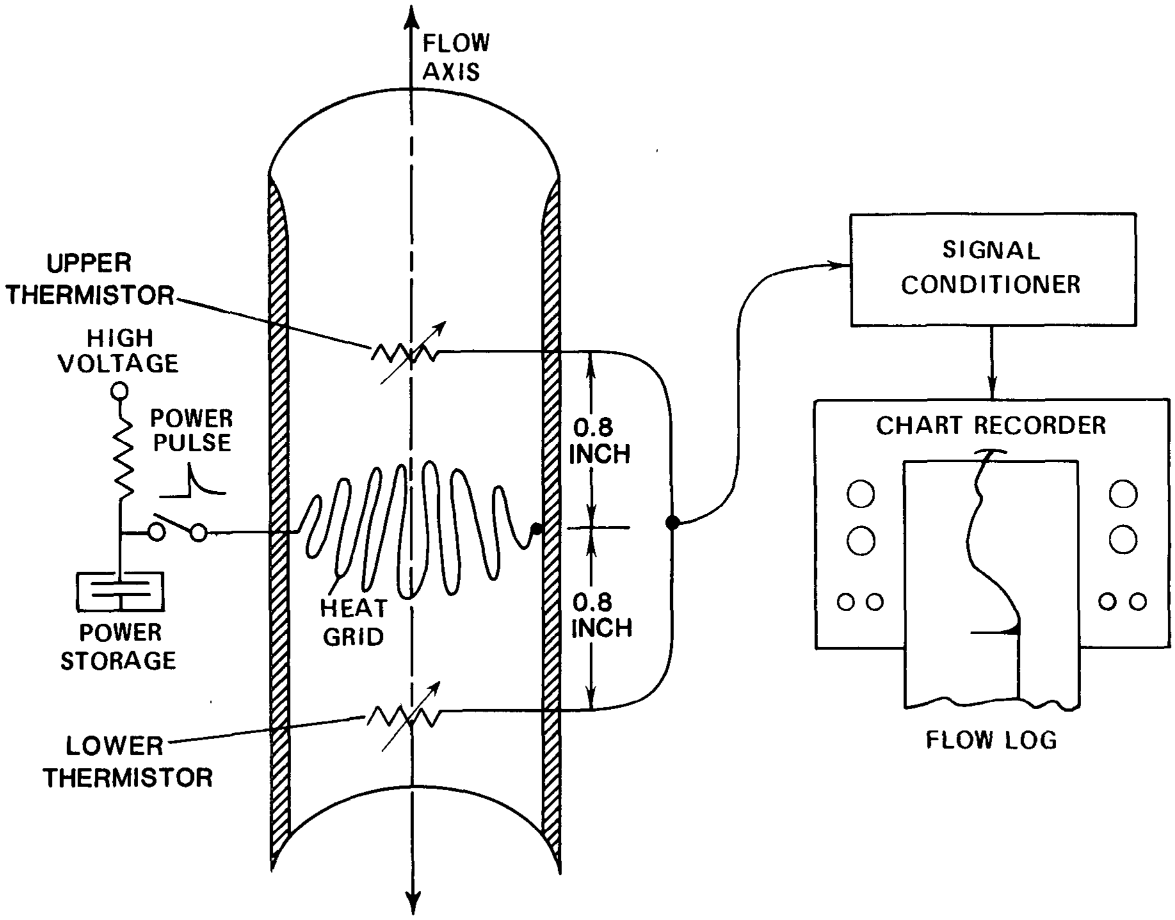

Figure 90.—Equipment for making heat-pulse flowmeter logs (modified from Hess, 1986).

pump that can circulate water in either direction at velocities of 0.07 to 50 ft/min, depending on column size, and at temperatures of 10 to 40 °C. Flowmeters should be calibrated for both upward and downward flow because their responses are not symmetrical. The clear plastic columns allow the addition of a colored tracer for visual timing and observation of convection currents; these currents are a problem if the difference between column temperature and room temperature is not minimized. Similarly, convection currents occur in wells when the borehole fluid is not in thermal equilibrium with the formation fluid.

Onsite standardization or calibration can be performed by moving the flowmeter up or down a cased part of a well at carefully controlled logging speeds. Calibration by this method is valid only at the casing diameter logged. An example of data obtained from this type of calibration in a flowing water well is shown in figure 92, in which pulses per unit time are plotted against logging speed. The different slopes of the line represent opposite directions of impeller rotation. The range of logging speeds near this intersection represents the stall zone, where the velocity is too slow to turn the impeller. Theoretically, this intersection represents the velocity at which water was flowing up the well, slightly greater than 60 ft/min. If the casing diameter is known and if the volumetric flow rate at the surface can be measured, the actual velocity can be calculated. If no flow occurs in the casing, the stall point will not necessarily be the same in both directions because of the asymmetry of the probe. If this procedure is used, logging speeds are controlled by frequent use of a stopwatch.

Tracer-injector probes or heat-pulse flowmeters are not easily calibrated or standardized onsite under static conditions; flow at the land surface at a measured rate produces one velocity that can be used as a check. Moving the probe at a carefully controlled speed may produce more errors for these systems than for the impeller-flowmeter system, because turbulence in the fluid column causes large errors at slow velocities.

Extraneous effects

Convective flow caused by vertical or horizontal thermal gradients is one of the major sources of error

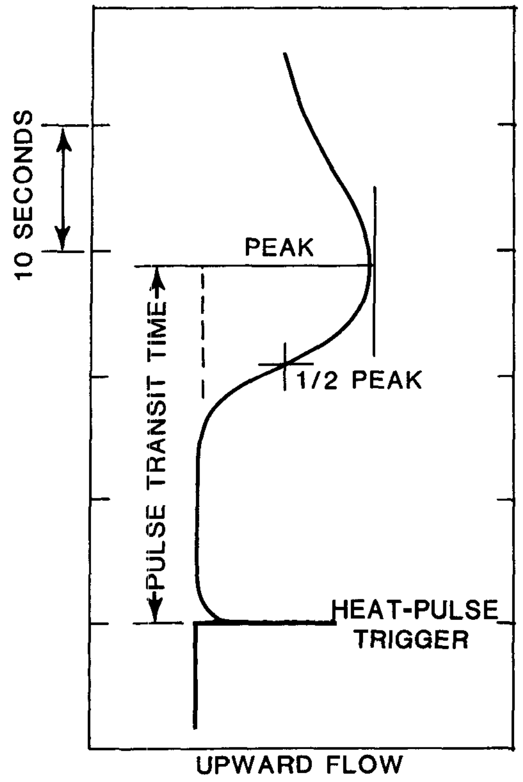

Figure 91.—Analog record of a heat pulse from a thermal flowmeter (modified from Hess, 1986).

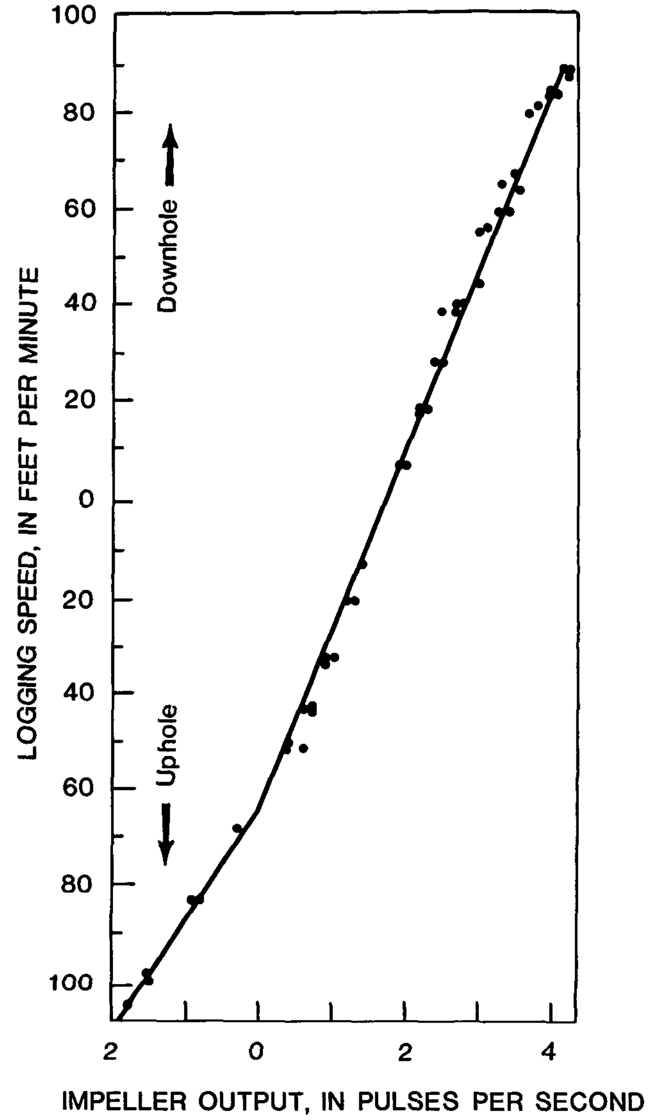

Figure 92.—Calibration data for an impeller flowmeter developed by moving the probe in a water well that was flowing.

in interpreting flowmeter and temperature logs when velocities are slow. Convective movement has not been recognized as a problem in interpreting impeller-flowmeter logs, but the advent of tracer and heat-pulse flowmeter probes capable of measuring slow velocities has created the need to study the problem. Hess (1982) has described the effects of convection on laboratory tests of the heat-pulse flowmeter. He determined that a temperature difference of 1 °C between the water in the column and the surrounding air produced a detectable, consistent flow. When the water temperature is greater than the air temperature, the flow is upward in the central part of the column and downward near the column wall. The centralized flowmeter measures an upflow when the water is warmer than the air and a downflow when the water is cooler than the air. The effect is more pronounced in the 6-in-diameter column, which agrees with equation 12 in the section on extraneous effects on temperature logs and indicates greater convective movement in larger diameter wells. This laboratory study explains anomalous results that have been obtained with tracer-injector probes in large-diameter wells.

Most older flowmeters are not centralized, and this lack of centralization may cause several errors or anomalies on logs. Two impeller-flowmeter logs, one made moving up a cased well and one moving down, are shown in figure 93. The difference between the two logs in the perforated interval is real; the sharp excursions, which did not repeat, probably were caused by the flowmeter bouncing around in the well because it was not centralized. An additional error may occur on a log made with a probe that is free to move around in the well because maximum velocity occurs in the central part of the well and minimum velocity occurs near the wall of the hole. In a well with substantial wall rugosity, turbulence is likely to be greatest near the wall of the well.

A tracer-injector probe that is not centralized may produce anomalous results if the ejection port is

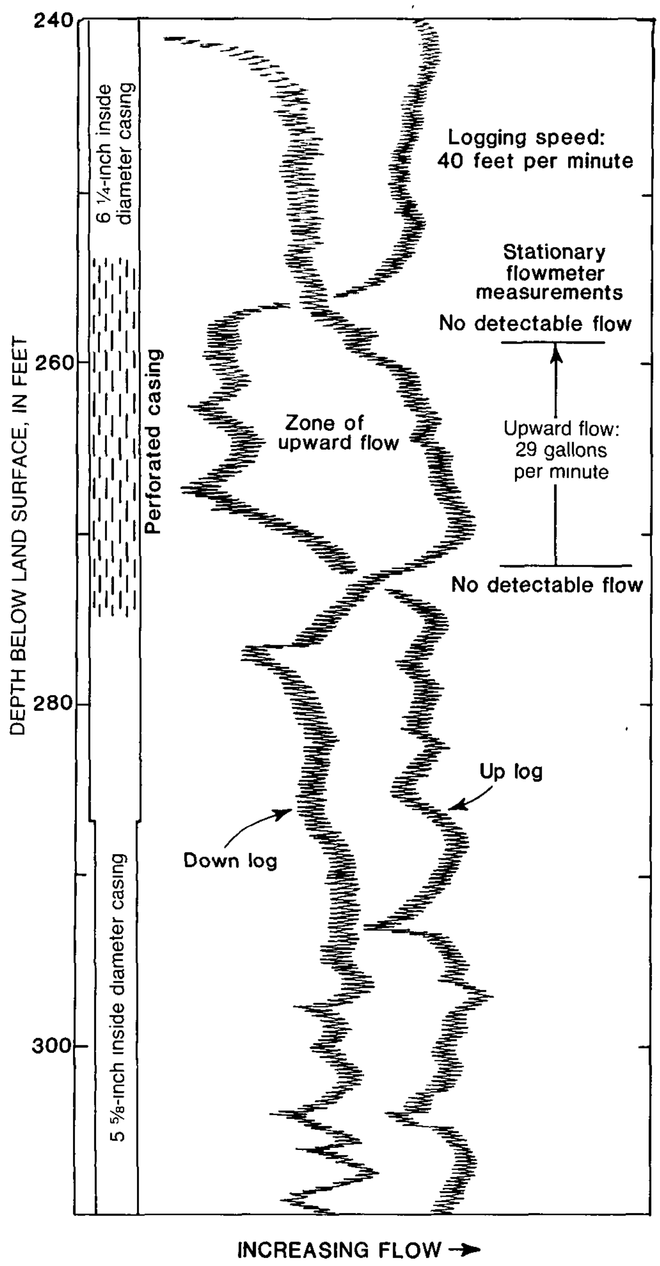

Figure 93.—Impeller-flowmeter logs made up and down a well where the casing was perforated opposite two aquifers.

against the wall of the borehole, because the tracer will not be dispersed properly. If salt tracers are used, the greater specific gravity will produce an apparent downward flow where no flow actually exists. This effect will cause the greatest errors at extremely slow velocities. Insertion of a probe to relog a well to locate the position of tracer concentrations will cause some dispersion of those concentrations. The larger a probe is with respect to well diameter, the larger the surging action and dispersion will be. An accurate caliper log is essential for correct interpretation of all types of flowmeter logs because of the effect of changes in borehole diameter on flow velocity.

Interpretation and applications

Interpretation of flowmeter logs is simple if the probe has been properly calibrated and if all the essential information on borehole diameter and construction is available. Vertical flow is common in most wells that are open to more than one aquifer. An example of an unusual situation is shown in figure 93, where the flowmeter log (spinner survey) indicates that the interval of perforated casing spanned two aquifers separated by a less permeable interval. The separation of the down log and the up log in the interval between 256 and 274 ft indicates upward flow; the down log shows an increase in apparent flow rate in the perforated interval compared with the unperforated intervals, whereas the up log shows a decrease in apparent flow rate. Stationary measurements were also taken in the cased interval, one measurement per foot; the depth interval in which average upflow was 29 gal/min was thinner when measured by stationary measurements than when measured by continuous logs. The reason for this difference is that the flowmeter stalls at a faster fluid velocity when it is stationary than when it is aided by logging at a constant speed. A more sensitive type of flowmeter probably would have indicated a thicker interval of flow. Flowmeters can be placed in a water well before temporary installation of a pump so that the permeable intervals contributing water under pumping conditions can be identified.

The heat-pulse flowmeter developed by Hess (1986) was used first in the field to identify fractures producing and accepting water in a borehole penetrating granitic rocks in the Canadian shield (Keys, 1984). A single-arm caliper log and data from the heat-pulse flowmeter are shown in figure 94. The data from the heat-pulse flowmeter were quite reproducible for 2 weeks, even though pumping and injection tests were being conducted in a borehole about 1,000 ft from the logged borehole. The flowmeter logs and acoustic-televiewer logs at this site enabled characterization of permeable fractures. In figure 94, both the upper fracture zone, at a depth of about 300 ft, and the lower zone, at a depth of about 940 ft, contain thin, discrete fractures; these thin fractures, rather than thicker, complex fractures, are transmitting most of the water. Note that slightly less than half the flow from the upper zone originates from the fracture at a depth of 308 ft; that fracture appears to be the largest on the caliper log. Similarly, the fracture that appears to be the largest in the lower zone is accepting only a small percentage of the flow. These two fracture zones were

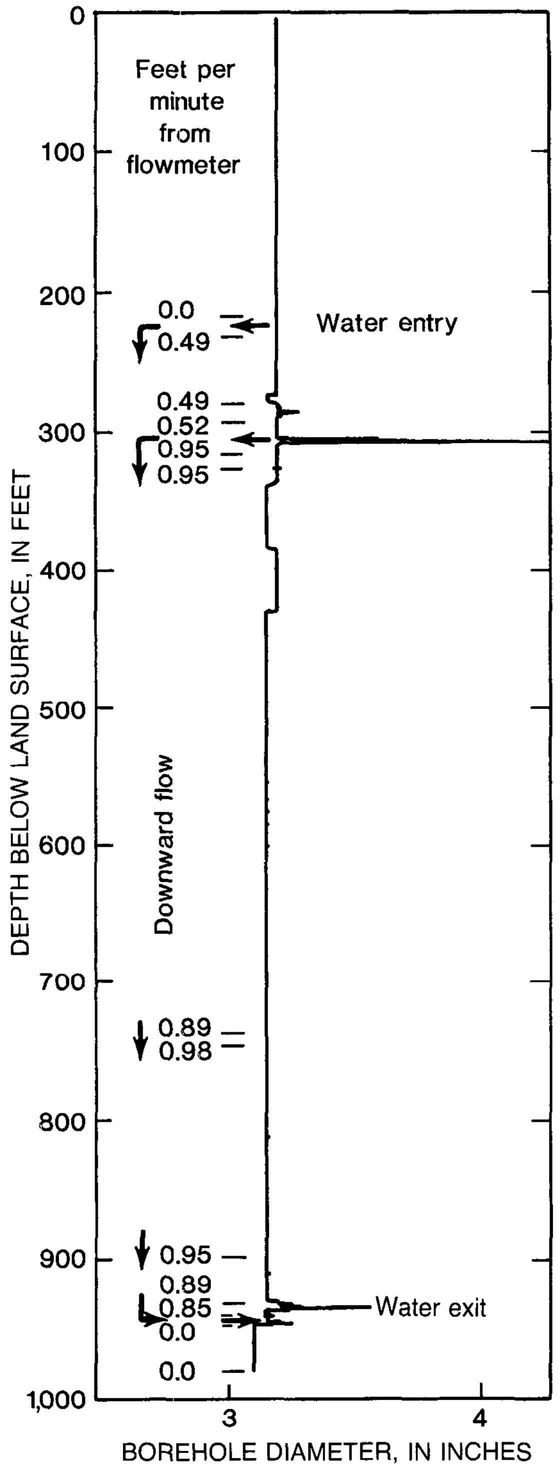

Figure 94.—Single-arm-caliper log and data from heat-pulse flowmeter showing zones of water entry and loss in a borehole penetrating granitic rocks in the Canadian Shield (modified from Keys, 1984).

intersected in other boreholes in the area and appear to constitute major aquifers.

Radioactive-tracer-injector logs can be used to locate permeable zones where flow rates are even slower than those detectable with the heat-pulse flowmeter. Tracer-injector logs are available from oil-well logging-service companies that are licensed to make the logs. State requirements with respect to water wells also must be met. Examples of radioactive-tracer-injector logs made in a U.S. Geological Survey test well completed in the Madison Limestone before and after acidizing and fracturing at a depth of 4,500 ft are shown in figure 95. The anomalies on the logs are at the lower and upper detectors in a probe, where both were located above the injector. The recorder time-drive scale is faster on the right log run after acidizing and fracturing; the much shorter traveltime for the tracer pulse indicates that the flow rate from this interval was much faster after treatment.

Both impeller flowmeter and radioactive-tracer-injector logs for Madison Limestone test well 1 are shown in figure 96. Although the logs are similar, the impeller-flowmeter log does not resolve small changes in flow rate that may be significant in rocks where secondary porosity is well developed. The radioactive-tracer-injector log not only resolves small changes, but it probably is more accurate. The flowmeter data were used in a computer analysis of other logs of this test well to identify log-response characteristics that could be used to locate intervals of secondary porosity (Keys, 1986). In this test well, both types of flowmeter logs indicate that most of the flow in the well is originating from the depth interval below about 3,030 ft. With data of this type, the transmissivity of the permeable intervals can be estimated by calculating the percentage of the total flow from each interval and multiplying these percentages by the transmissivity for the well determined from an aquifer test.

Flowmeters can be used similarly during fluid injection to locate permeable intervals, as illustrated in figure 97. Iodine-131 was injected at depths of 100, 1,200, 1,500, and 1,800 ft in a well penetrating granitic rocks near Aiken, S.C. Over a 2-week period (left graph of figure), water was injected at the land surface at a constant rate. Gamma logs of the well were made on the days indicated by dots on the curves; the depths of the tracer injection at 100 ft in the casing were used as a reference for calculating the injectivity profile on the right side of the figure. The caliper log indicates that the intervals of maximum injectivity were related to fracture zones in the granitic rocks, which have minimal primary permeability.

In the section of this manual describing temperature logs, their use for locating permeable intervals and for tracing the movement of ground water between water wells is emphasized. The relation between a plotted log of radioactive-tracer-injector data and a temperature log, which is reversed so it

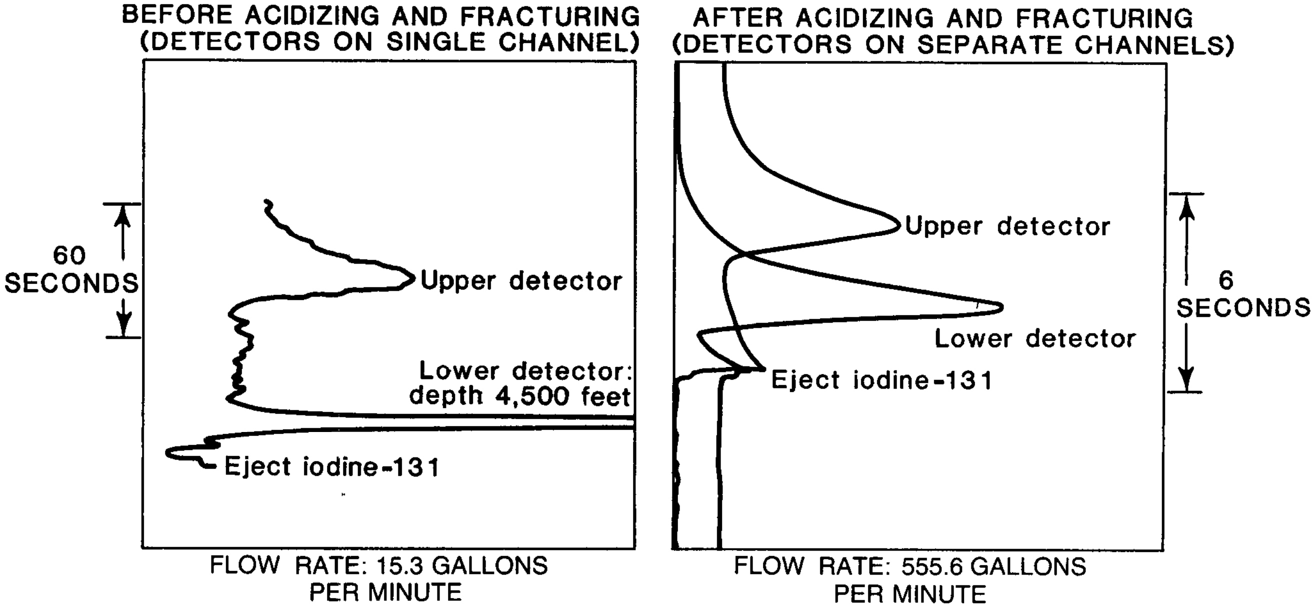

Figure 95.—Radioactive-tracer-injector logs before and after acidizing and fracturing of Madison Limestone test well 3, Montana (modified from Blankennagel and others, 1981).

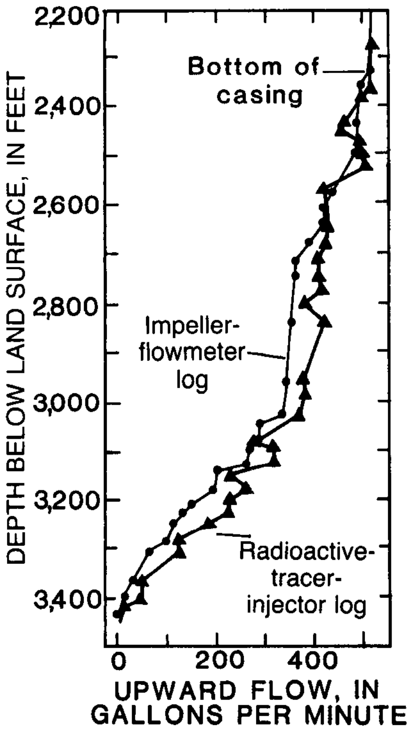

Figure 96.—Comparison of impeller-flowmeter and radioactive-tracer-injector logs, Madison Limestone test well 1, Wyoming (modified from R.K. Blankennagel, U.S. Geological Survey, written commun., 1977).

will appear similar to the radioactive-tracer-injector log, is shown in figure 98. Both logs indicate the location of permeable intervals within and just below the perforations and at a depth of 3,420 ft. However, the reversed temperature log does not correctly indicate the relative proportions of water entering the test well at these depths.

Well-Construction Logging

Logging to determine how a well is constructed is useful in planning cementing operations, installing casing and screens, hydraulic testing, and interpreting other logs. Most of the logs described in other sections of this manual can, under some conditions, provide information on well construction. They are mentioned briefly here; for more information, refer to the detailed descriptions of these logs in the appropriate sections of this manual.

Casing logging

A number of different types of logs can be used to locate cased intervals in wells. Most electric logs have a sharp deflection at the bottom of a string of steel casing, although when using a multielectrode resistivity system, the reference depth where the deflection occurs may have to be determined. Resistivity-logging systems that are operating properly record zero resistivity when all the electrodes are in the casing. Gamma-gamma logs commonly have a sharp deflection at the bottom of a steel casing and may shift at depths where a second string of steel casing is located outside the first; however, such shifts may be difficult to distinguish from changes in borehole diameter. Neutron and gamma logs also may respond to changes in steel-casing size and thickness, but the response of these logs is less predictable. Although plastic casing, which has a large hydrogen content, might cause a substantial deflection on a neutron log, plastic casing usually is not detectable below the water level. High-resolution caliper logs are excellent for locating the bottom of the inside string of casing and for locating threaded couplings. If small arms are used, they also may provide data on corrosion of steel casing and on the location of screens and perforations; however, care must be taken that the arms do not get caught in screens or perforations.

The acoustic televiewer is probably the highest resolution logging system for obtaining information on steel and plastic casing and screens, but it may be too expensive for some operations. The ATV should be operated using the mark switch, rather than the magnetometer, in steel casing to avoid distortion of the log caused by random triggering. ATV logs can provide clear images and accurate locations of screens, perforations, couplings, and damaged casing. Features as small as 1/32 in can be resolved under ideal conditions. Borehole television can provide some of the same data, but it cannot be operated on standard logging cable, and the water in the borehole must be clear to allow light transmission.

A casing-collar locator (CCL) is a useful and relatively inexpensive probe that can be operated on any logger. The simplest CCL probe contains a permanent magnet wrapped with a coil of wire. Changes in the magnetic properties of material cutting the magnetic lines of flux cause a small direct current to flow, which can be used to operate a recorder channel. The standard mode of operation is to record event marks along the margin of other logs to represent the location of collars in the steel casing. The event marker is adjusted so that it is triggered when the direct-current voltage exceeds a certain level. An event marker record (left) and two continuous CCL logs of the signal (right) are shown in figure 99. The CCL logs can be interpreted in terms of the location of perforations and screens, as shown in the figure. Changes in logging speed, direction, and the position of the probe in the borehole may change the log and complicate interpretation.

Corroded steel casing sometimes can be located by a high-resolution caliper log; spontaneous-potential logs have been used to locate depth intervals where active corrosion is taking place (Kendall, 1965). Commercial logging services are available for detecting corroded steel casing. An electromagnetic casing-inspection log measures changes in the mass of metal between two

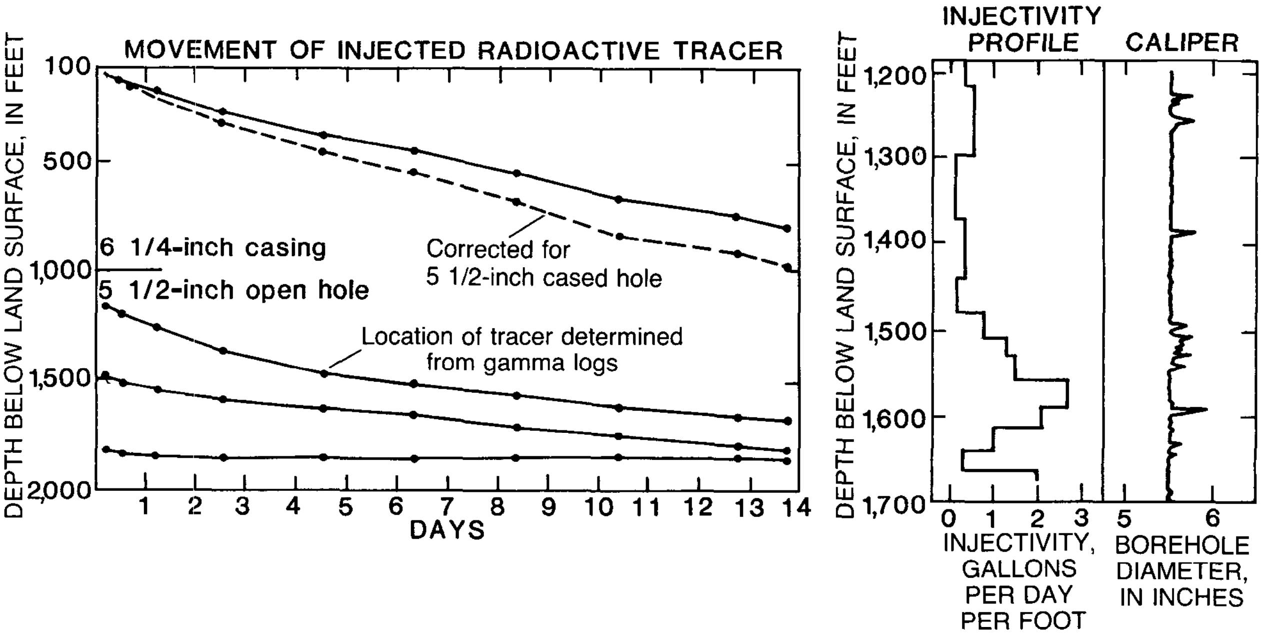

Figure 97.—Downward movement of four slugs of iodine-131 injected in a borehole penetrating granitic rocks near Aiken, S.C. The resulting injectivity profile plotted from periodic gamma logs shows water loss at fractures indicated by the caliper log.

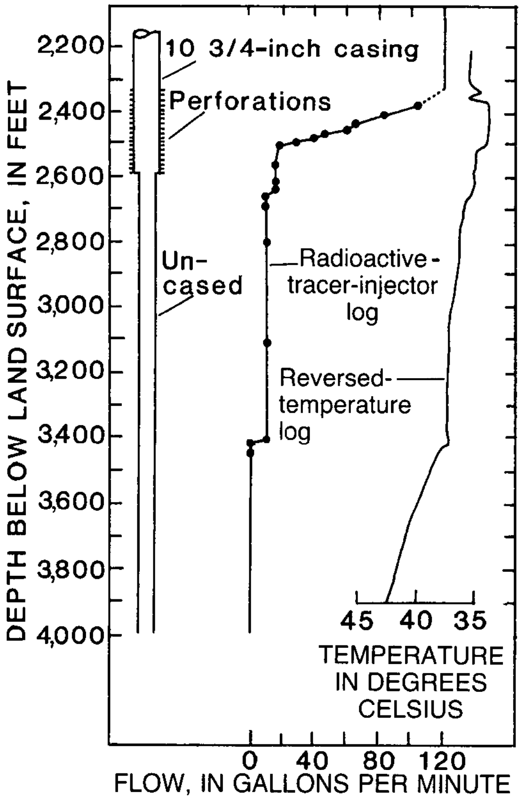

Figure 98.—Radioactive-tracer-injector and reversed-temperature logs made during pumping of test well USW H-5, Yucca Mountain, Nev. (modified from R.K. Blankennagel, U.S. Geological Survey, written commun., 1983).

coils; loss of mass may be due to corrosion (Edwards and Stroud, 1963). A casing-analysis survey is made with a centralized probe that contains several coils (Bradshaw, 1976). This survey is reported to provide information on the thickness of steel casing penetrated by corrosion, whether the damage is internal or external, and whether the damage is isolated or circumferential. An electromagnetic-thickness survey measures the average casing thickness for an interval of about 2 ft and can be used to monitor changes in thickness over time. Casing-inspection logging methods have been summarized by Nielsen and Aller (1984).

Cement and gravel-pack logging

Cement and gravel pack in the annular space outside of casing can be located with several logs, but the results may be ambiguous. A caliper log made before the casing is installed is needed to plan cementing or installation of gravel pack. Caliper logs also are useful in interpreting logs made for the purpose of locating annular material, because they indicate the thickness that would be present if the space were filled.

Temperature logs can be used to locate cement grout while it is still warm from chemical reactions during curing. Under the proper conditions, cement-bond logs can be used to locate cement after it has cured and may provide information on the quality of the bond between casing and cement and between cement and rock (see discussion of cement-bond logs in the section on acoustic-wave-form logging). An uncompensated, short-spaced gamma-gamma log can indicate the location of cured cement or gravel pack if it was made after installation of the casing and prior to filling of the annular space. The difference between logs made before and after filling the annular space may show the filled interval clearly. A gamma-gamma log run before a hole is cemented may resemble the reversed caliper log made prior to installation of the casing. The location of gravel pack occasionally is indicated by a shift on gamma logs if the gravel is either more or less radioactive than the adjacent rocks. The difference in radioactivity must be substantial, and the volume of annular material sufficient, to produce a recognizable difference between logs made before and after installation of the gravel.

Borehole-deviation logging

Deviation of boreholes and wells from the vertical is common; borehole deviation affects proper completion of the well for its intended use, and may prevent testing and logging. Casing and pumps may be impossible to install in a well that is markedly deviated; centralized logging probes may not function properly in such a well. The deviation rarely is consistent; both the angle from the vertical and the direction of deviation may change many times along the borehole. Even adjacent augered boreholes less than 100 ft deep have been known to deviate enough that transmittance logs between the boreholes are adversely affected. Information on borehole deviation is needed to calculate the true vertical depth to features of interest and to correct the strike and dip of fractures or bedding obtained from logs, such as the acoustic televiewer. The techniques and computer programs for making these corrections have been described by Kierstein (1984).

Most continuous logs of borehole deviation are made by commercial firms that specialize in this technique. Borehole-deviation data usually are not recorded by standard logging equipment, except modern dipmeters, which rarely are included on water-well loggers. A dipmeter log usually includes, in the left track, a continuous record of the azimuth (magnetic north) and the magnitude of deviation. Some borehole-deviation logging services provide a printout of azimuth and deviation at predetermined depth intervals, and sev-

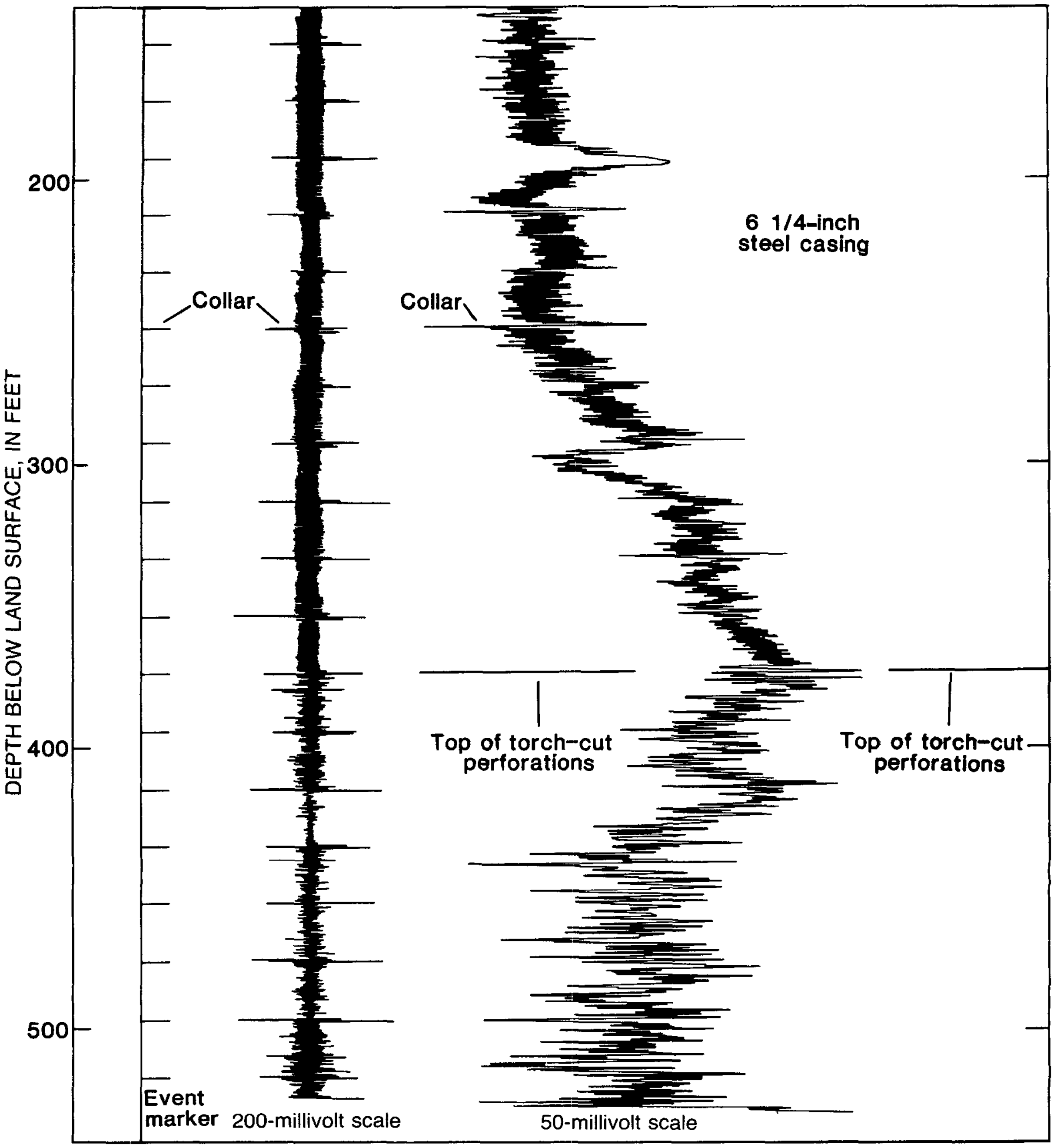

Figure 99.—Casing-collar-locator logs recorded by an event marker and analog recorder at two different gain settings.

eral methods can be used to mathematically describe the path of the deviated borehole from these measurements (Craig and Randall, 1976). Methods for calculating the path of the borehole between measuring stations are as follows: minimum curvature, radius of curvature, and tangential. The least expensive methods for obtaining borehole-deviation information use single-shot probes that provide one measurement of the deviation angle and azimuth at a predetermined depth. These probes must be brought to the land surface and reset after each measurement.

Test 5.—FLUID AND WELL-CONSTRUCTION LOGGING

1. Temperature logs can be used to
   a. Locate curing cement behind casing.
   b. Locate zones of fluid entry or loss.
   c. Measure permeability.
   d. Trace fluid movement between boreholes.

2. Differential-temperature logs
    a. Are made by different probes than temperature logs.
    b. Can be derived from temperature logs using a computer.
    c. Aid in detecting intervals of fluid movement.
    d. Are more accurate than temperature logs.
3. Reestablishing the equilibrium-geothermal profile
    a. May take only a few hours in a small-diameter cased well.
    b. May take many months under some conditions.
    c. Will never take place if vertical flow is present.
    d. Is related to volume of drilling fluid circulated and loss and temperature of drilling fluid.
4. Impeller flowmeters are superior to other flow-measuring probes because they
    a. Are simple and inexpensive.
    b. Operate from the minimum to the maximum flow rates.
    c. Need not be centered in the borehole.
    d. Operate on single-conductor or multiconductor cable.
5. Fluid conductivity
    a. Is measured directly by most logging equipment.
    b. Usually needs to be calculated from fluid-resistivity logs.
    c. Is a measure of interstitial fluids.
    d. Should be one of the first logs run.
6. A heat-pulse flowmeter log is similar to a radioactive-tracer-injector log because
    a. Upward and downward flow are clearly distinguished.
    b. Extremely slow velocities are measurable.
    c. Four detectors are used.
    d. Most measurements are made while the probes are stationary.
7. A radioactive-tracer injector
    a. Is one of the best probes for measuring extremely slow velocity flow in boreholes.
    b. Can sometimes be used to detect flow behind casing.
    c. Is limited in application because of licensing requirements.
    d. Can be used to measure water flow between boreholes.
8. Borehole-deviation logs
    a. Are used for correcting strike and dip of fractures and beds logged in a borehole.
    b. Are used because they are inexpensive and readily available.
    c. Are seldom needed because most deep boreholes are vertical.
    d. Provide information on location, direction, and angle of deviation.
9. Casing-collar-locator logs can
    a. Indicate intervals of corroded steel casing.
    b. Provide information on casing diameter.
    c. Locate collars and perforations.
    d. Be made inexpensively using almost any logger.
10. Borehole-construction information
    a. Can be obtained by several different logging techniques.
    b. Is needed for correct interpretation of most logs.
    c. Is essential for interpretation of flowmeter and temperature logs.
    d. Can be obtained reliably from drilling reports.

Summary—A Case History

The application of borehole geophysics to the solution of ground-water problems cannot be summarized in a few pages; however, a case history of a test well drilled for a regional aquifer study can illustrate application of some of the techniques described in detail in this manual. The case is based on Madison Limestone test well 1, which was drilled by the U.S. Geological Survey in the northeast corner of Wyoming. The test well was part of a USGS regional study of the quantity and quality of water that can be produced from the Madison Limestone of Mississippian age and adjacent rocks in parts of Montana, Nebraska, North Dakota, South Dakota, and Wyoming. A suite of geophysical logs of Madison Limestone test well 1 was made by a commercial service company and by the USGS. The types of logs made in this test well, and in two other test wells drilled during this project, were selected for their potential use in providing diagnostic information on the aquifers and the quality of their contained water, and for correlation with logs of numerous oil test wells in the area. Quality control of the logs was the responsibility of experienced USGS personnel who were present throughout the drilling, testing, and logging. Core analyses and hydraulic packer-test data also are available for Madison Limestone test well 1 for comparison with logs (Blankennagel and others, 1977). The logs and other data from this test well were analyzed in detail by use of a microcomputer (Keys, 1986); most of the illustrations in this manual pertaining to Madison test well 1 resulted from that study.

Considerable geologic and other hydrologic data were gathered during the regional study of the Madison Limestone and adjacent rocks, which has been described in a series of U.S. Geological Survey Professional Papers. Many of the data and conclusions in these papers were derived from geophysical logs of the three test wells drilled during the study, as well as from logs of hundreds of oil test wells that were purchased from commercial companies that sell logs to the public. The stratigraphy and sedimentary facies of the Madison Limestone and adjacent rocks in parts of Montana, Nebraska, North Dakota, South Dakota, and Wyoming are described in Peterson (1984). Correlation of paleostructure and sediment deposition for the same rocks and area are described in Brown and others (1984). The relation of porosity and permeability to petrology of the Madison Limestone in cores from the three test wells is described in Thayer (1983). Geohydrology of the Madison Limestone and associated aquifers is explained in Downey (1984). Apparent water resistivity, water temperature, and porosity of these rocks as determined from geophysical logs are described and mapped in MacCary (1984). Potentially favorable areas for development of large-yield wells in the Ordovician Red River Formation and Madison Limestone in parts of Montana, North Dakota, South Dakota, and Wyoming are shown on maps in MacCary and others (1983).

Identification of lithologic units and their correlation throughout the area studied was based mostly on geophysical logs; neutron and gamma logs were among the most useful for this purpose. Identification of lithology and stratigraphic correlation is one the most useful applications of geophysical logs because it permits lateral extrapolation of the results of log analysis and tests. An example of the correlations of some lithologic units between Madison Limestone test well 1 and oil test well MC-3, which was drilled in Montana about 12 mi northeast of test well 1, is shown in figure 100; the correlations are based on neutron and gamma logs. Use of a microcomputer permitted the vertical and horizontal scales of the digitized logs from the test well to be matched with the scales of the logs from the oil well. The neutron log for Madison Limestone test well 1 has been smoothed in the computer, which accounts for part of the different appearance compared with the log of MC-3, which has been photographically reduced. The correlations shown in figure 100 are typical for deep test wells penetrating hard rocks; similar correlations can be made to other test wells even more distant from Madison Limestone test well 1. Thus, log-analysis techniques developed to identify the most productive intervals of the aquifer, which are summarized below, may be extended to other test wells and boreholes that penetrate the same sequence of rocks.

The lithology of the rocks penetrated by Madison Limestone test well 1 is best defined by the gamma, neutron, and resistivity logs shown in figures 25 and 44. The maximum radioactivity on the gamma log is recorded in shale beds, and the minimum radioactivity is recorded in clean limestone; dolomite is slightly more radioactive than limestone (fig. 44). The neutron and resistivity logs help distinguish limestone and dolomite. The more resistive intervals also have a smaller porosity and are mostly limestone, rather than dolomite.

Impeller-flowmeter and radioactive-tracer-injector logs, shown in figure 96, indicate that more than 350 gal/min of the total of more than 500 gal/min flowing at the land surface was produced from the depth interval below 3,000 ft. Almost 100 gal/min was produced from the large solution opening at a depth of 2,550 ft, which is clearly shown on the caliper log in figure 85. The flow from this opening is also indicated by the anomaly on the differential-temperature log in figure 85.

Although the producing intervals were indicated by flowmeter and temperature logs made when Madison Limestone test well 1 was flowing at the land surface, other logs may be used to identify permeable intervals when a well completed in similar lithologic units is not flowing. The caliper logs indicate not only large solution openings, as in figure 85, but also small solution openings that are close together, identified by small-scale roughness on the logs. Small deflections on caliper logs made using a caliper probe with four independent arms are shown in figure 84. These deflections, which also appear on repeat logs, are caused by numerous small solution openings. Such openings apparently transmit most of the water in this aquifer. The acoustic-televiewer logs in figure 79 clearly show the nature and distribution of these solution openings.

Computer cross plots offer another method for identifying intervals of secondary porosity in the rocks penetrated by Madison Limestone test well 1. A plot of total porosity versus horizontal permeability measured on core samples (fig. 16) has a considerable scatter of points. It seems likely that permeability is more closely related to secondary, rather than total, porosity in these rocks. A cross plot of transit time from an acoustic-velocity log versus apparent limestone porosity from a neutron log is shown in figure 11. The lithology lines in this figure were derived from a manual provided by the logging company. The data points indicate the presence of two major rock types, limestone and dolomite. A substantial number of points plot below the dolomite curve, where the neutron log indicates a much greater apparent poros-

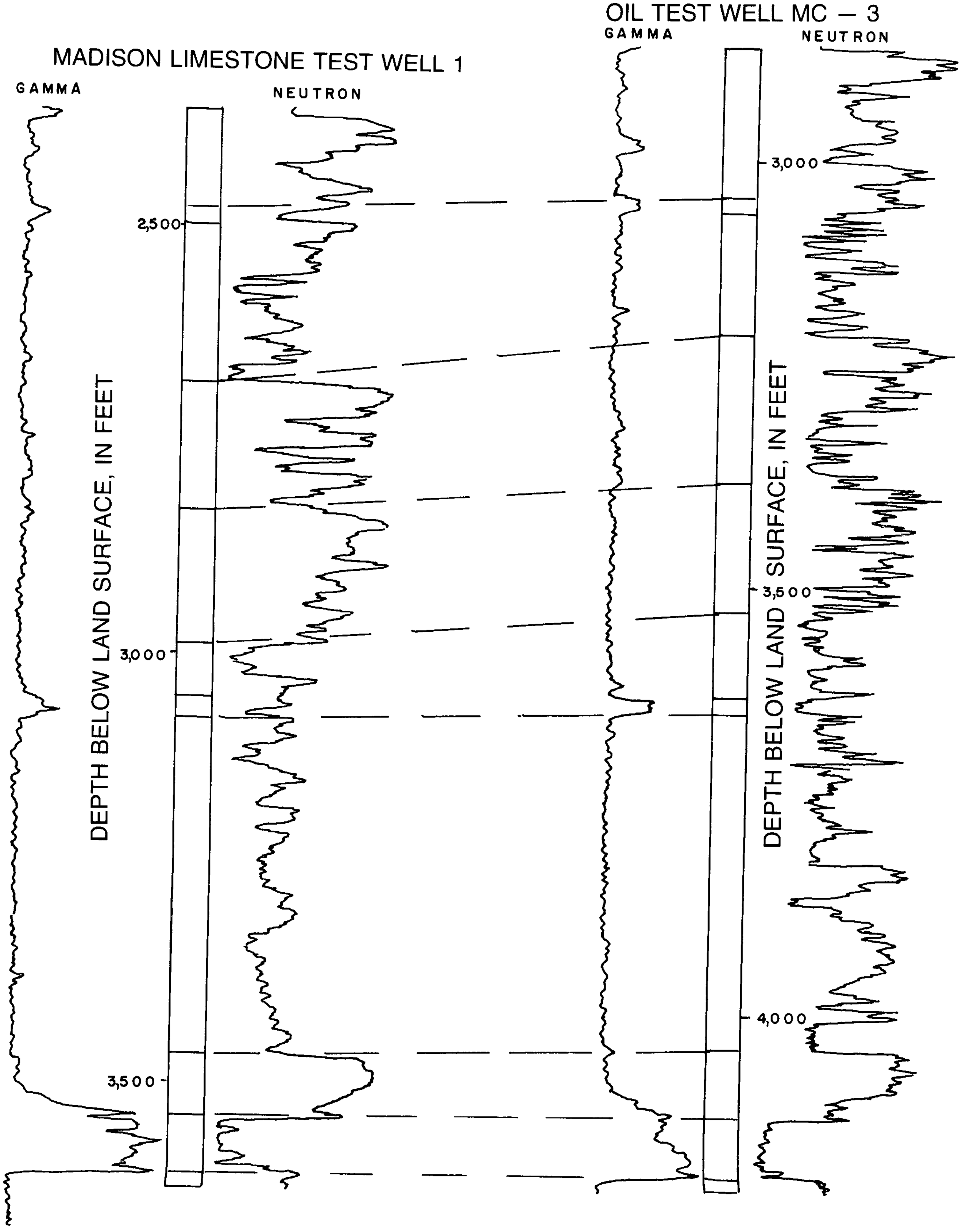

Figure 100.—Correlation of lithologic units between Madison Limestone test well 1 and oil test well MC-3 based on gamma and neutron logs, Wyoming.

ity than does the acoustic-velocity log. Average porosity derived from the neutron log, as shown in figures 25 and 26, is somewhat larger than that derived from core analyses, but not as much as the difference indicated by the acoustic-velocity data shown in figure 11. Porosity values determined from analyses of core may tend to be somewhat smaller than those indicated on logs because of the tendency for core containing numerous or large solution openings to be broken, lost, or not selected for laboratory analysis. One reason for the short transit times (smaller values of porosity) on the acoustic-velocity log in figure 11 could be the lack of response of this log to secondary porosity, such as solution openings. In contrast, the neutron log responds to all water-filled openings regardless of their size or shape. Most of the points below the dolomite line in figure 11 are from the depth interval that produced 350 gal/min based on the flowmeter logs. Thus, the difference between the porosity indicated by neutron and acoustic-velocity logs may enable identification of permeable intervals in these rocks.

Water quality could have been determined from logs of Madison Limestone test well 1 but was not necessary because water samples were available. The apparent water resistivity in the Madison Limestone and associated rocks in the project area was determined from geophysical logs by MacCary (1984), using the equations of Archie (1942) that relate formation factor, resistivity of interstitial water and water-saturated rock, and porosity.

Borehole geophysics can provide useful data on the location and character of aquifers and the quality of ground water. To optimize results from borehole geophysical techniques, the logging program must be properly planned, the quality of the logs must be assured, and the logs must be analyzed with an understanding of the basic principles of each technique and the relations between logs and the rock matrix and its contained fluids, and the construction of the well.

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ANSWERS TO TEST QUESTIONS

Test 1.—Principles, Equipment and Log-Analysis Techniques

1. b, c, d.
2. b, c.
3. b, c.
4. none.
5. b, d.
6. a, b, c, d.
7. c, d.
8. a, b, d.
9. a, b, c, d.
10. c.
11. a, b, c, d.
12. a, b, c.

Test 2.—Electric Logging

1. none.
2. c.
3. a, c.
4. a, d.
5. a, b, d.
6. a, b, c, d.
7. c.
8. c.
9. a, b, c.
10. a, b, c.
11. b, c.

Test 3.—Nuclear Logging

1. a, c.
2. a, c, d.
3. b, d.
4. a, b, c.
5. b, c, d.
6. a, b, d.
7. a, c, d.
8. a, b, c, d.
9. a.
10. b, c, d.
11. a, b, c, d.
12. d.

Test 4.—Acoustic and Caliper Logging

1. a, b, c.
2. a, d.
3. a, b, c, d.
4. a, b, c, d.
5. b, d.
6. b, c.
7. a, c.
8. b, c, d.
9. a, b, c, d.
10. b, c, d.
11. c, d.

Test 5.—Fluid and Well-Construction Logging

1. a, b, d.
2. b, c.
3. b, c, d.
4. a, d.
5. b, d.
6. a, b, d.
7. a, b, c, d.
8. a, d.
9. a, c, d.
10. a, b, c.