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U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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

Test 1.—PRINCIPLES, EQUIPMENT, AND LOG-ANALYSIS TECHNIQUES

1. Geophysical well logging reduces project costs because it
   a. Eliminates the need for coring.
   b. Provides more information from each borehole.
   c. Enables lateral and vertical extrapolation of test results.
   d. Aids in the selection of depth intervals for hydraulic testing.
2. The intrinsic accuracy of geophysical logs is usually limited by
   a. Inadequate electronic circuits.
   b. Borehole effects.
   c. Operator error.
   d. The fluid in the borehole.
3. Some geophysical logs can indicate permeability because
   a. Porosity and permeability are always related.
   b. Clay content can be related to permeability.
   c. Water flow measured in a well is an index of permeability.
   d. Computer analysis of several logs provides accurate values of permeability.
4. Which of the following geophysical logs measure(s) porosity directly?
   a. Neutron.
   b. Acoustic velocity.
   c. Gamma-gamma.
   d. Resistivity.
5. The formation-resistivity factor (F) is equal to
   a. Porosity (ϕ).
   b. $1/\phi^2$.
   c. Water resistivity (Rw).
   d. Saturated-rock resistivity divided by water resistivity (Ro/Rw) .
6. Synergistic analysis of geophysical logs is beneficial because it
   a. Helps in identifying errors in individual logs.
   b. Can improve the accuracy of data on porosity from logs.
   c. Can provide more diagnostic identification of lithology.
   d. Might decrease the number of logs needed.
7. Computer analysis of geophysical logs
   a. Eliminates the need to understand the logs.
   b. Decreases project costs.
   c. Can correct some operator errors.
   d. Is the best means to collate data from a large suite of logs.
8. The volume of investigation of a logging probe
   a. Usually is related to the source-detector spacing.
   b. Limits the resolution of thin beds.
   c. Includes all material 5 ft from the borehole.
   d. Varies with rock type.
9. Quality control of geophysical logs is the responsibility of the
   a. Equipment operator.
   b. Company providing the equipment.
   c. U.S. Geological Survey observer at the site.
   d. Project chief who planned the operation.
10. Standardization (field calibration) of geophysical logs should be done
    a. Only when a problem is identified.
    b. Daily.
    c. Before and after every log.
    d. Whenever the operator has time.
11. The difference between a portable or suitcase logger and a large oil-well-logging truck is
    a. Related mostly to depth capability and the availability of a suite of probes rather than to log response.
    b. Basically the number of cable conductors and recording capability.
    c. The size (diameter) of the borehole that can be logged.
    d. The cost.
12. Digital recording of geophysical logs at the well site is desirable because it
    a. Is more accurate than digitizing the analog record.
    b. Is less expensive than digitizing later (assuming digital recording equipment is available).
    c. May permit correction of analog errors.
    d. Can be done faster than analog recording.

Electric Logging

The term "electric logging" sometimes is used to encompass all types of geophysical logs. In this report, electric logging refers only to logs that measure potential differences due to the flow of electric current in and adjacent to a well. Logical subdivisions of electric logging are spontaneous-potential and resistivity logging, although the latter can include a variety of techniques for measuring rock resistivity. Many types of resistivity logs that have been used in the petroleum industry but very little in ground-water hydrology are discussed briefly here.

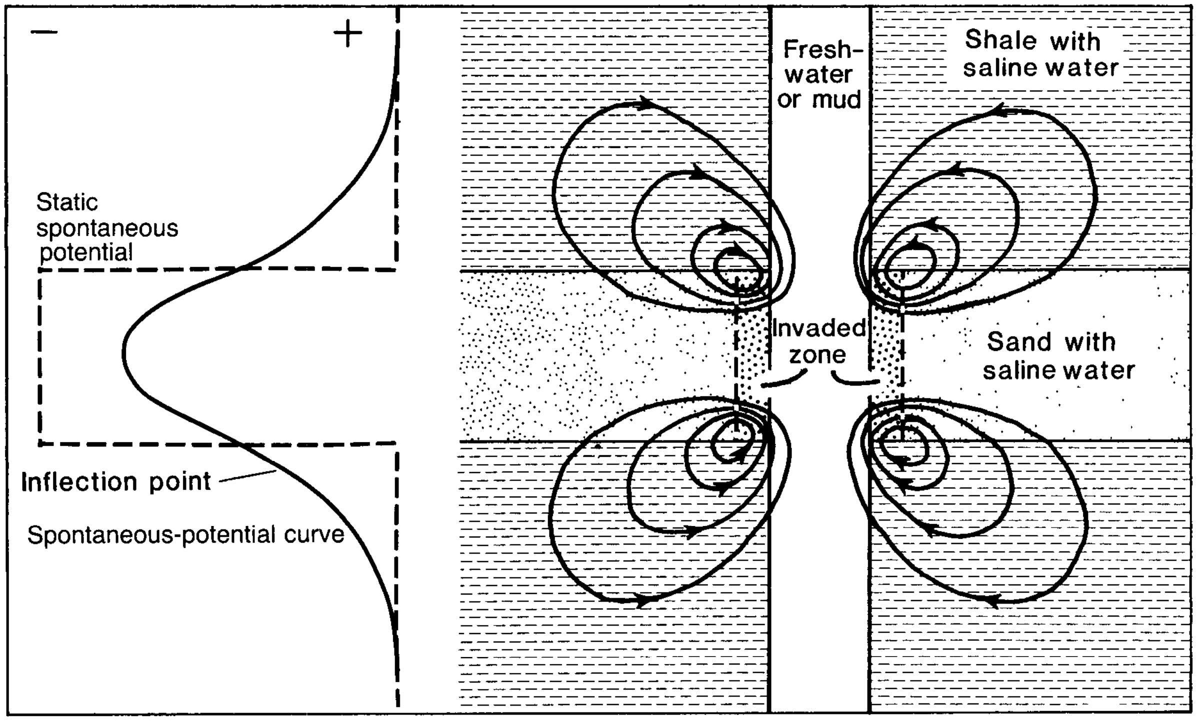


Figure 27.—Flow of current at typical bed contacts and the resulting spontaneous-potential curve and static values (modified from Doll, 1948).

Spontaneous-potential logging

Spontaneous potential is one of the oldest logging techniques. It uses simple equipment to produce a log whose interpretation may be quite complex, particularly in freshwater aquifers. This complexity has led to misuse and misinterpretation of spontaneous-potential logs in ground-water applications. Spontaneous-potential logs are widely used in oil fields to provide information on lithology and the salinity of interstitial water, but these logs are not universally applicable in fresh-ground-water environments. See Lynch (1962) for a more detailed discussion of spontaneous potential.

Principles and instrumentation

A spontaneous-potential log (sometimes called an SP or self-potential log) is a record of potentials or voltages that develop at the contacts between shale or clay beds and a sand aquifer, where they are penetrated by a borehole. The natural flow of current and the spontaneous-potential curve or log that would be produced under various salinity conditions are shown in figure 27. Spontaneous-potential measuring equipment consists of a lead electrode in the well connected through a multivolt meter or comparatively sensitive recorder channel to a second lead electrode that is grounded at the land surface. The spontaneous-potential electrode usually is incorporated in a probe that makes other types of logs simultaneously. When the electrode is pulled through a rock-water system such as that shown in figure 27, small changes in potential, usually in the millivolt range, are recorded as the spontaneous-potential curve shown on the left. The static spontaneous-potential value is rarely the same as the recorded spontaneous-potential value, except in thick conductive units, where resistance is minimal. In thin units, the recorded value may be much less than the static value because the total resistance along the flow path (shown in fig. 27) is the sum of the resistances of the borehole fluid, mud cake, invaded zone, aquifer, and shale. Spontaneous potential is a function of the chemical activities of fluids in the borehole and adjacent rocks, the temperature, and the type and quantity of clay present; it is not directly related to porosity and permeability.

The chief sources of spontaneous potential in a borehole are electrochemical and electrokinetic or streaming potentials. Oxidation-reduction potentials may constitute another source. Electrochemical effects probably are the most significant contributor; they can be subdivided into membrane and liquid-junction potentials. Both these effects result from the migration of ions from concentrated to more dilute solutions, and they are mostly affected by clay, which decreases negative (anion) mobility. Membrane potentials are developed when ions migrate from formation water (water in the aquifer) to adjacent shale to fluid in the borehole—a three-component system. Liquid-junction potentials are those developed between the mud filtrate in the invaded zone and the formation water. When the fluid column in the borehole is fresher than the formation water, current flow and the spontaneous-potential log are as illustrated in figure 27; when the fluid column in the borehole is more saline than the formation water, current flow and the log will be reversed.

Electrokinetic or streaming potentials usually are less important than electrochemical effects, but they can change the magnitude and direction of the spontaneous-potential log under some circumstances. Streaming potentials are caused by the movement of an electrolyte through permeable media. Thus, the movement of ions across the mud cake caused by the pressure differential between the fluid column and interstitial fluids can produce a streaming potential. In water wells, streaming potential may be substantial at depth intervals where water is moving in or out of the hole. These permeable intervals commonly are indicated by rapid oscillations in an otherwise smooth curve.

Calibration and standardization

Spontaneous-potential logs are recorded in millivolts per inch of chart paper or full scale on the recorder; the span used should be clearly stated in the log heading. Span or sensitivity switches on electric-logging modules usually provide a few fixed scales from 10 to several hundred millivolts per inch, but a continuously variable potentiometer may allow selection of almost any scale. Positioning can be adjusted independently; frequent repositioning is required for many water wells. An accurate millivolt source of any type may be connected across the spontaneous-potential electrodes to provide for calibration or standardization at the well. These sources, which contain a battery and selectable resistors, are available specifically for calibrating analog recorders, or may be fabricated easily. Pen response, in millivolts per inch, should be recorded directly on the log. The accuracy of some of these calibrators may be no better than +10 percent; however, this level of accuracy is adequate for most applications.

Volume of investigation

The volume of investigation of a spontaneous-potential probe is variable, because it depends on the resistivity and cross-sectional area of the beds intersected by the borehole. A greater cross-sectional area of resistive rock is required to carry a given amount of current than that required in conductive rock. Thus, the current will travel farther from the borehole in electrically conductive shale adjacent to resistive beds to find sufficient cross section to move through the more resistive material. For this reason, the volume of investigation varies as a function of resistivity and bed thickness.

Extraneous effects

Spontaneous-potential logs are more affected by stray electrical currents and equipment problems than most other types of logs. These extraneous effects produce both noise and anomalous deflections on the logs. The steel armor on the logging cable may become magnetized and produce periodic oscillations on the logs. The steel armor is electrochemically active when immersed in an electrolyte such as drilling fluid. Variations in this battery effect while the cable is moving may impress noise on a spontaneous-potential log. Wrapping the cable with insulating tape for some distance above the electrode may alleviate this problem. Stray currents, even from distant lightning strikes and magnetic storms, can render a spontaneous-potential log useless. Electrical currents related to the corrosion of buried pipelines or well casings can produce anomalous potentials in the ground, as can nearby electric motors, such as pumps. Railroad tracks and power lines also can cause problems.

An increase in borehole diameter or depth of invasion decreases the magnitude of the spontaneous potential recorded. Obviously, changes in depth of invasion over time will cause changes in periodic spontaneous-potential logs. Because spontaneous potential is largely a function of the relation between the salinity of the borehole fluid and of the formation water, any change in either will cause the log to change as well. This factor is important to interpretation and applications, and is discussed in detail in the following section. Streaming potential produced by water moving in the well is considered an extraneous factor when attempting quantitative interpretation of spontaneous-potential logs, but it also can provide important hydrologic information.

Interpretation and applications

Spontaneous-potential logs have been used widely in the petroleum industry to determine lithology, bed thickness, and the salinity of formation water. Although it is one of the oldest types of logs, it is still standard in most logging operations and is included in the left track of most electric logs. The chief limitation of spontaneous-potential logs in ground-water studies is the considerable range of salinity differences between borehole fluid and formation fluid in freshwater environments. Water wells commonly are logged

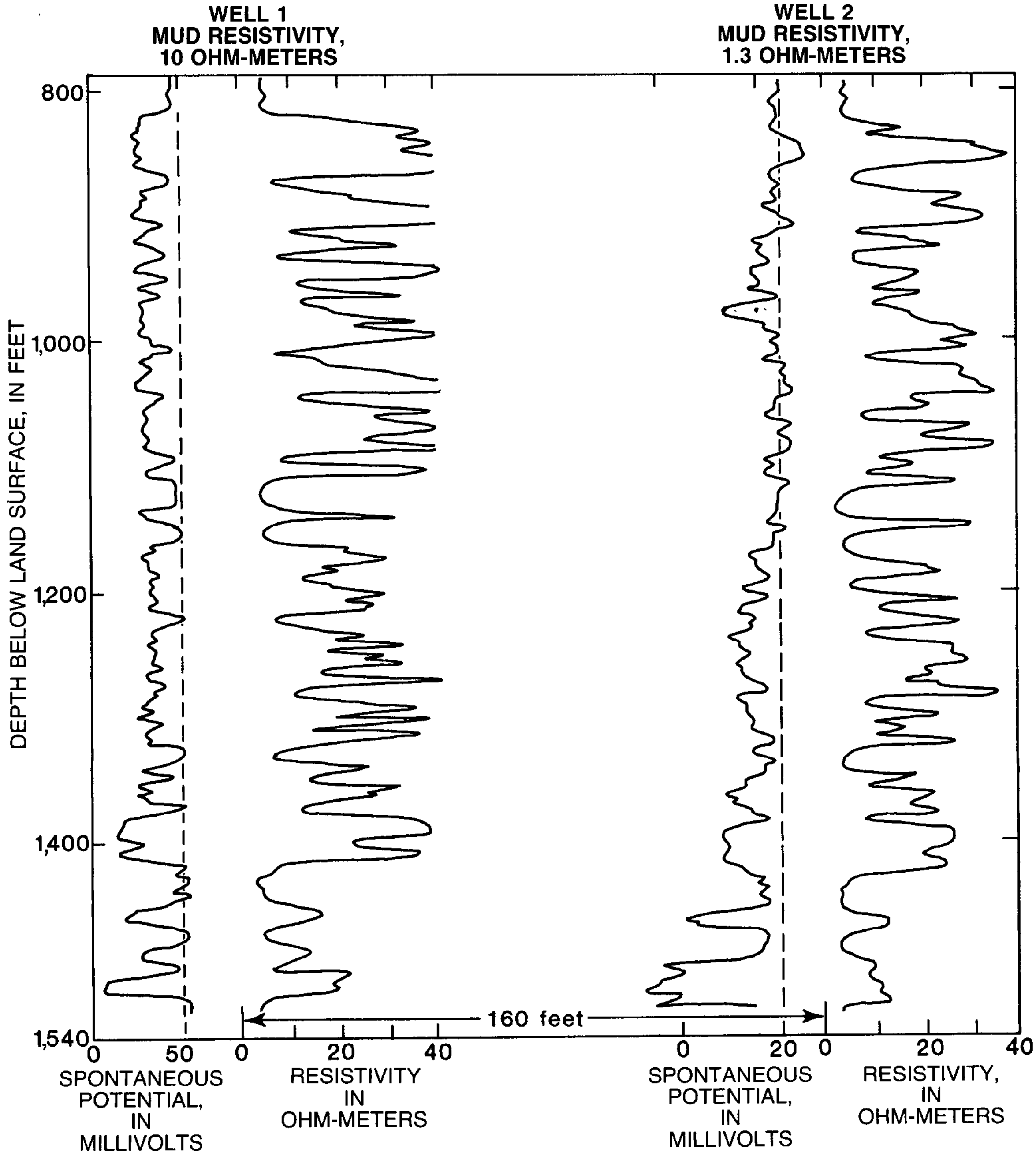


Figure 28.—Changes in spontaneous-potential and resistivity logs caused by differences in mud salinity in two closely spaced wells, Houston, Tex. (Guyod, 1966).

after drilling mud has been totally or partly replaced by formation fluids; vertical circulation is common in water wells. As shown in figure 27, if the borehole fluid is fresher than the native interstitial water, a negative spontaneous potential occurs opposite sand beds; *this is the so-called standard response typical of* oil wells. If the salinities are reversed, the spontaneous-potential response also is reversed, producing a positive spontaneous potential opposite sand beds. Thus, the range of response possibilities is very large and includes zero spontaneous potential (straight line), when the salinity of the borehole and interstitial fluids are the same.

Differences in spontaneous-potential and resistivity logs between two wells located 160 ft apart near Houston, Tex. (Guyod, 1966), are illustrated in figure 28. The differences result from differences in the resistivity of the drilling mud—10 ohm-m in well 1 and

1.3 ohm-m in well 2. Note that not only are the amplitudes of the spontaneous potential different, but the logs for the shallow part of the wells are very dissimilar. Salinity differences probably are greater in the shallow part of well 2. The amplitudes of the resistivity logs also are different, but stratigraphic units still can be correlated between the wells using these logs.

On spontaneous-potential logs, lithologic contacts are located at the point of curve inflection, where current density is at a maximum (fig. 27). When the response is typical, a line can be drawn through the positive spontaneous-potential values recorded in shale beds, and a parallel line can be drawn through negative values, which represent intervals of sand containing little clay. If the salinity and composition of the borehole and the interstitial fluids are constant throughout the logged interval, the shale and sand lines will be vertical; however, this is not common in water wells (Guyod, 1966). Where the individual beds are thick enough, these lines can be used to calculate sand/shale ratios or to calculate the net thickness of each unit. The shale fraction is proportional to the relative spontaneous-potential deflection between the sand and shale beds.

A typical response of a spontaneous-potential log in a shallow water well where the drilling mud is fresher than the formation water is shown in figure 29. The maximum positive spontaneous-potential deflections represent intervals of fine-grained material, mostly clay and silt; the maximum negative spontaneous-potential deflections represent coarser sediments. The gradational change from silty clay to fine sand at the bottom of the well is shown by a gradual change on the spontaneous-potential log. The similarity in the character of a spontaneous-potential log and a gamma log under these salinity conditions also is shown in figure 29. Under these conditions, the two types of logs can be used interchangeably for stratigraphic correlation between wells for which either the gamma or the spontaneous-potential log is not available. The similarity between spontaneous-potential and gamma logs can be used to identify wells where salinity relationships are similar to those shown in figures 27 and 29.

Spontaneous-potential logs have been used widely for determining formation-water resistivity (*Rw*) in oil wells, but this application is limited in fresh-ground-water systems. In a sodium chloride type of saline water, the following relation is used to calculate *Rw*:

$$SP=-K' \log (Rm/Rw) \qquad (2)$$

where

SP=log deflection, in millivolts;
$K'=60+0.133T'$;
T'=borehole temperature, in degrees Fahrenheit;
Rm (or Rmf)=resistivity of borehole fluid, in ohm-meters; and
Rw=formation-water resistivity, in ohm-meters.

The spontaneous-potential deflection is read from a log at a thick sand bed; *Rm* is measured with a mud-cell or fluid-conductivity log. If the borehole is filled with mud, then water must be filtered out and *Rmf*, the resistivity of the mud filtrate, is used in the equation. Temperature can be obtained from a log, but it also can be estimated, particularly if bottom-hole temperature is known. The calculated resistivity can be converted to concentration of sodium chloride using figure 19.

The unreliability of determining the resistivity of fresh formation water using the spontaneous-potential equation has been discussed by Patten and Bennett (1962) and Guyod (1966). Several conditions must be met if the equation is to be used for ground-water investigations in which the water contains less than 10,000 mg/L of dissolved solids:

1. Both the borehole fluids and the formation water must be sodium chloride solutions.
2. The borehole fluid must be quite fresh, with a much greater resistivity than the combined resistivity of the sand and shale; this requirement usually means that the formation or interstitial water must be quite saline.
3. The shale must be ideal ion-selective membranes, and the sand must be relatively free of clay. No contribution can be made to the spontaneous potential from such sources as streaming potential.

These conditions are not satisfied in most fresh-water wells. Nevertheless, water quality in some ground-water systems has been calculated using the spontaneous potential equation. Vonhof (1966) stated that a "...workable empirical relationship exists between the spontaneous-potential deflection on the electric log and the water quality in glacial aquifers." His study was made in test wells in Saskatchewan, Canada, where the chemical compositions of the drilling and formation fluids were similar and the drilling fluid was much more resistive than the water in the aquifers. Dissolved solids in the formation water ranged from 1,191 to 3,700 mg/L. Alger (1966) described the use of the spontaneous potential equation to determine the resistivity of fresh water, but he had to convert all anions and cations in the water to an equivalent sodium chloride concentration. He assumed that chemical composition would be relatively constant within one ground-water system; he started with a well for which he already had chemical analyses of water samples and a spontaneous-potential

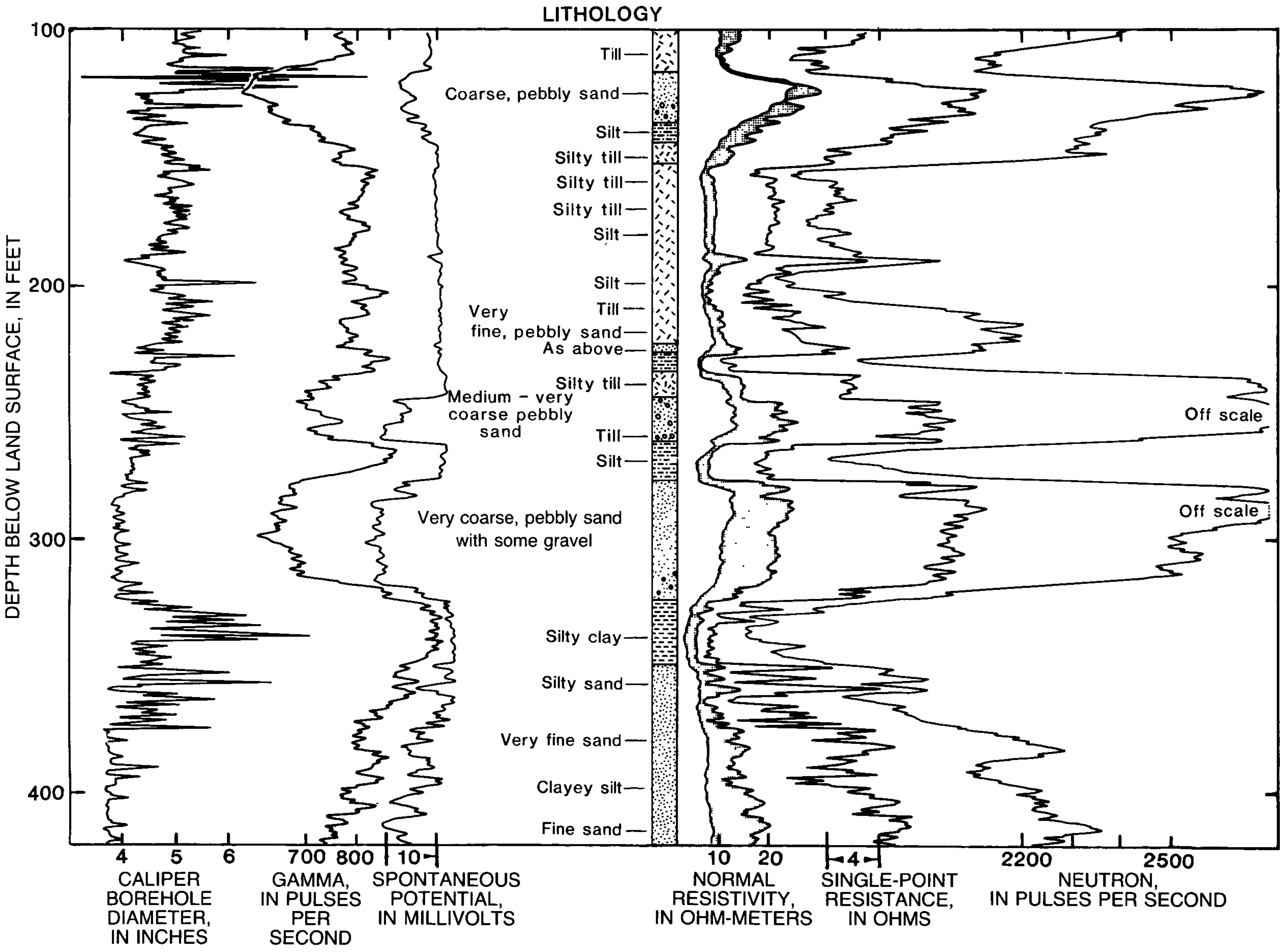


Figure 29.—Caliper, gamma, spontaneous-potential, normal-resistivity, single-point-resistance, and neutron logs compared with lithology, Kipling, Saskatchewan, Canada (Dyck and others, 1972).

log. These data were extrapolated to other wells in the area on the basis of spontaneous-potential logs. The method probably is not appropriate for determining the quality of water containing less than 10,000 mg/L dissolved solids, unless many other data are available to support the results.

Single-point-resistance logging

The single-point-resistance log has been one of the most widely used in ground-water hydrology in the past; it is still useful, in spite of increased application of more sophisticated techniques. Single-point-resistance logs cannot be used for quantitative interpretation, but they are excellent for lithologic information. The equipment for making single-point-resistance logs is available on most small water-well loggers, but it is almost never available on the larger units used for oil-well logging.

Principles and instrumentation

Ohm's law provides the basic principle for all logging devices that measure resistance, resistivity, or conductivity. The law states that the rate of current flow through a conductor is proportional to the potential or voltage difference causing that flow, and is inversely proportional to the resistance of the medium. Ohm's law is the electric analog of Darcy's law for hydraulic flow. Ohm's law can be expressed as

$$r=E/I \qquad (3)$$

where

r =resistance, in ohms;
E=potential, in volts; and
I =current, in amperes.

The resistance of any medium depends not only on its composition, but also on the cross-sectional area and length of the path through that medium. Single-point-resistance systems measure the resistance, in ohms, between an electrode in the well and an electrode at the land surface or between two electrodes in the well. Because no provision exists for determining the length or cross-sectional area of the travel path of the current, the measurement is not an intrinsic characteristic of the material between the electrodes. Therefore, single-point-resistance logs cannot be related quantitatively to porosity or to the salinity of water in those pore spaces, even though these two parameters do control the flow of electric current. Although some conductive minerals are present and surface conduction on clay can contribute to current flow in most rocks, effective porosity and fluid salinity have a much greater effect on resistance or resistivity than does mineralogy.

A schematic diagram of the system used to make spontaneous-potential and conventional single-point-resistance logs is shown in figure 30. The two curves can be recorded simultaneously if a two-channel recorder is available. The same ground and down-hole lead electrodes (A and B) are used for both logs. Each electrode serves as a current and as a potential-sensing electrode for single-point-resistance logs. The single-point-resistance equipment on the right side of the figure actually measures potential in volts or millivolts, but this can be converted to resistance by use of Ohm's law, because a constant current is maintained in the system. To obtain the best possible single-point-resistance logs, the lead electrode in the well must have a relatively large diameter with respect to the hole diameter, because the radius of investigation is a function of electrode diameter. A schematic diagram of the system used to make differential single-point-resistance logs is given in figure 31. In this system, the current flows around an insulated section from the lead electrode to the probe shell. The insulated section usually is less than 1 in thick. The differential system provides much higher resolution logs than does the conventional system.

In both single-point-resistance systems, a constant alternating current is supplied by a generator, so that resistance is inversely proportional to the potential, read in millivolts. Single-point logging systems function much like a volt-ohm meter in the ohms position. In a volt-ohm meter, the unknown resistance is connected in series with a meter and a battery. In the case of the volt-ohm meter, the battery voltage, rather than the current, is constant, so that when resistance is small, a large current deflects the meter (or a recorder); when resistance is large, the current is small. For both a volt-ohm meter and a single-point-resistance system, the response is nonlinear. A 10-ohm change is a much greater percentage of full-scale deflection at small values of resistance than at large values of resistance, and this has the advantage of decreasing off-scale deflections on the log.

Calibration and standardization

Scales on a single-point-resistance log are calibrated in ohms per inch of span on the recorder. Common scales are 20, 50, 100, 200, and 500 ohms/in; some loggers offer continuous adjustment of span. Scales are not calibrated in ohm-meters, because the log does not measure these units. Both calibration and field standardization can be done using fixed resistors or a resistance-decade box between electrodes A and B. The spontaneous-potential-calibration box provided with some loggers can be used by turning off the battery and switching between the various resistances, which can be determined with a volt-ohm meter.

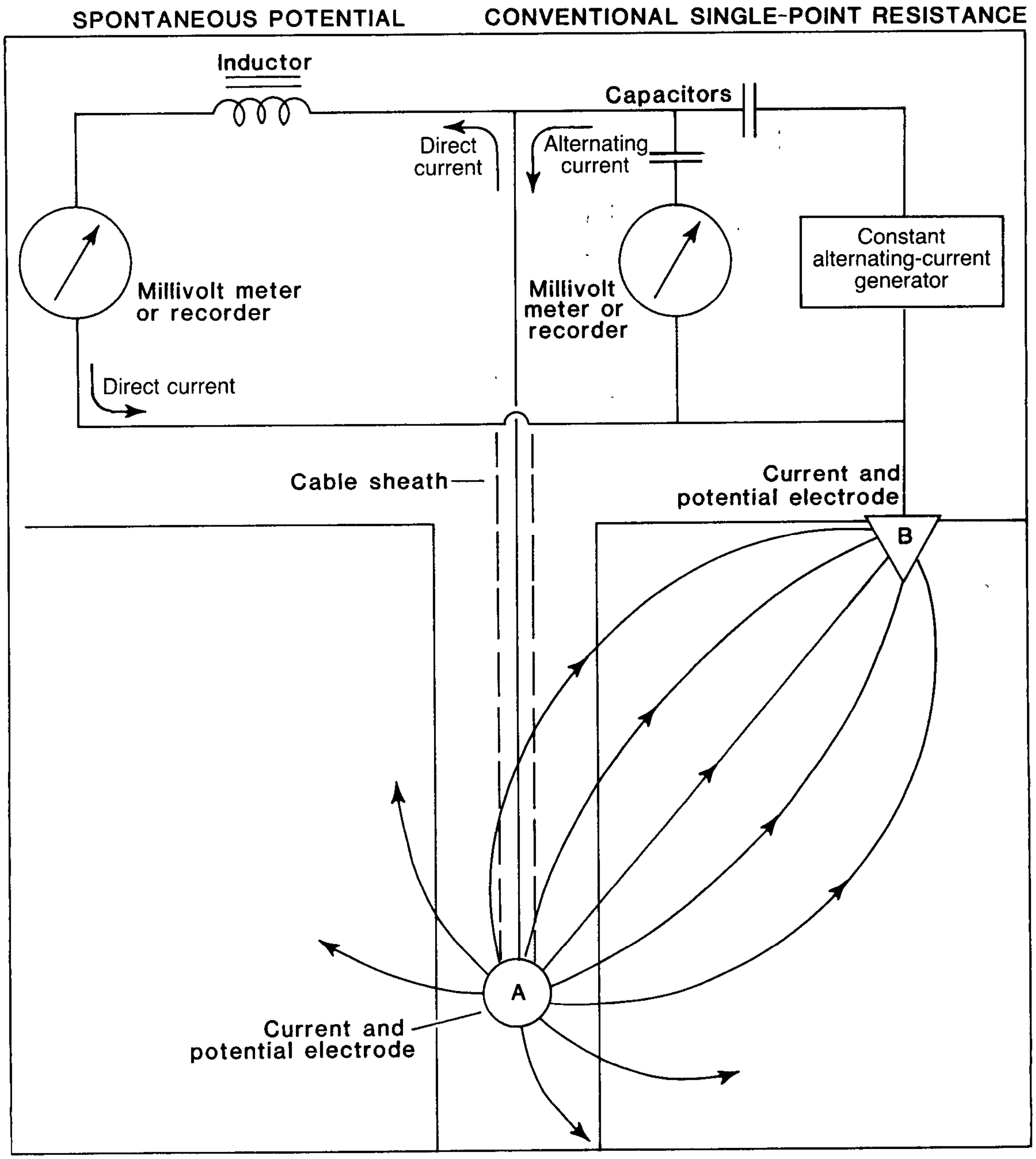


Figure 30.—System used to make spontaneous-potential and conventional single-point-resistance logs.

Volume of investigation

The volume of investigation of a single-point-resistance probe is small, about 5 to 10 times the electrode diameter. Larger electrodes will produce more signal from the rocks and less from the borehole. When a borehole in resistive rocks is filled with saline fluid, most of the current will flow in the borehole. Under these conditions, thin resistive units will be difficult to identify on the log.

Extraneous effects

Single-point-resistance logs are affected by many of the same external and equipment phenomena that produce noise on spontaneous-potential logs. Dirty or worn slip rings or brushes will produce sharp deflections of consistent amplitude and frequency that usually can be related to revolutions of the winch. A common problem is a fixed-frequency sinusoidal fluctuation of the pen, even when the probe is not moving

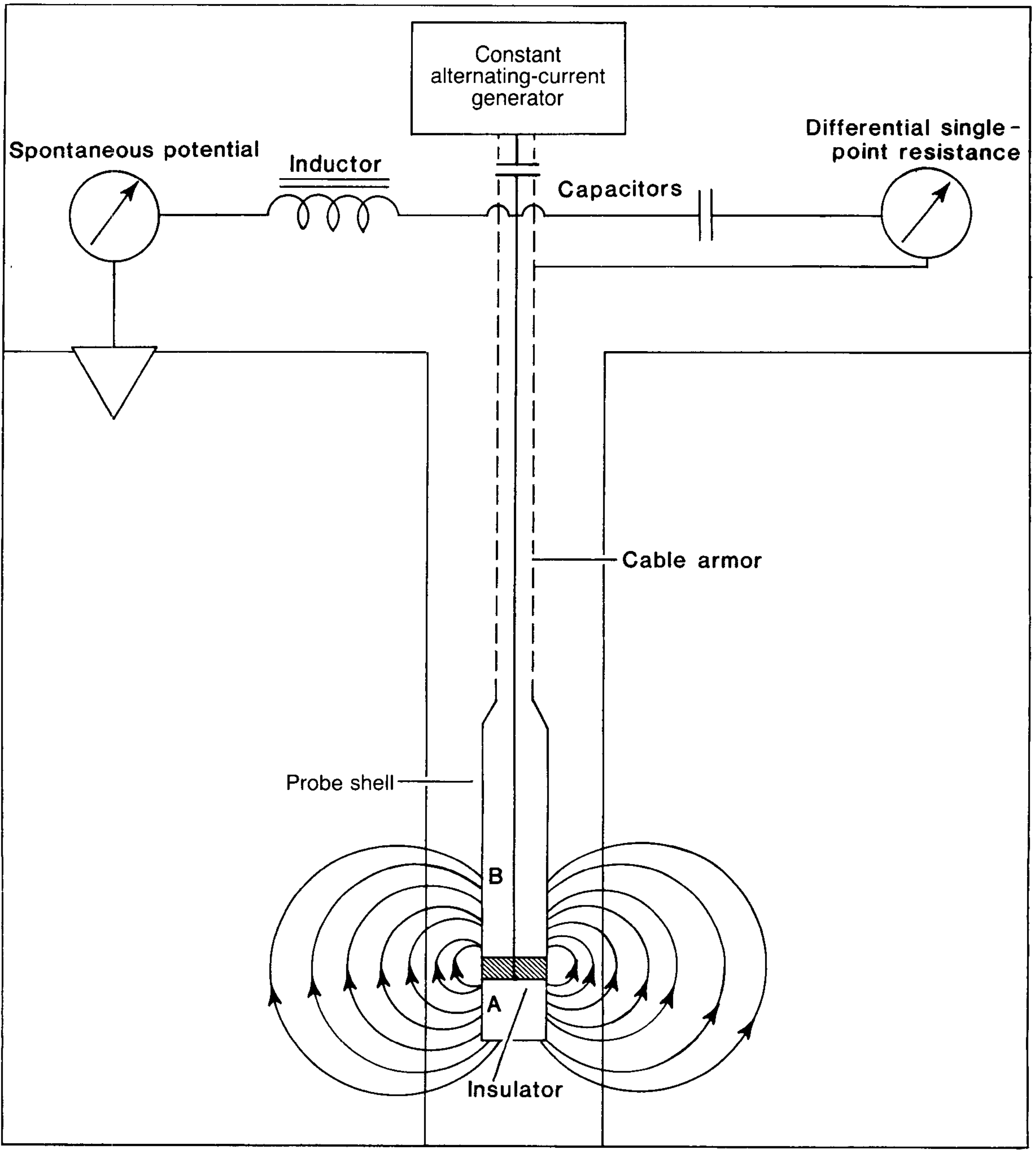


Figure 31.—System used to make spontaneous-potential and differential single-point-resistance logs.

in the well. This fluctuation usually is caused by the alternating current that is supplied to the electrode superimposed on the 60-cycle alternating current that is present in the ground from nearby power lines or other sources. Some loggers have a provision for adjusting the frequency of the power to the electrode, or the frequency of the generator, while observing the pen with the electrode stationary in the well. Differential single-point-resistance logs may be affected by changes in the logging truck ground carried through the tires and surface materials. Although the resistance of such a ground is large, a significant proportion of the current may follow this path if the rocks being logged have substantial resistivity. Most of the sheaves used for logging with single-conductor cable are insulated from the ground, even though they usually are mounted on the casing. If the cable armor intermittently touches the casing, fluctuations in log response may be noted. Grounding problems sometimes can be solved by adding a ground at the logging truck or at the casing-mounted sheave.

Single-point-resistance logs are greatly affected by changes in borehole diameter, partly because of the relatively small volume of investigation. Increases in borehole diameter add to the cross section of the current path through the more conductive borehole fluid; thus, larger diameter decreases apparent resistance. As discussed later, this aberration can be used to locate fractures.

Interpretation and applications

Single-point-resistance logs are useful for obtaining information about lithology; their interpretation is straightforward, with the exception of the extraneous effects described previously. Single-point-resistance logs have a significant advantage over multielectrode logs because they do not exhibit reversals as a result of bed-thickness effects; they deflect in the proper direction in response to the resistivity of materials adjacent to the electrode, regardless of bed thickness, and thus have very good vertical resolution.

The typical response of a single-point-resistance log to various types of lithology and to changing borehole diameter and the difference between single-point-resistance and long-normal-resistivity logs are shown in figure 32. The logs in figure 32, which is an enlargement of part of figure 7, are hypothetical because no logs could be found that illustrate all the different lithologies and hole conditions demonstrated. The purpose of the figure is to show relative log response, so scales are not included. In addition, the hypothetical log response shown cannot be used to predict response in similar rock types because lithology and relative salinity of formation and borehole fluids are so variable. In figure 32, the well is considered to be filled with saline water from below the freshwater-saline water interface that exists in the rocks. In this figure, solution openings and fractures are indicated by hole enlargements on the caliper log and by sharp, small-resistance anomalies on the single-point-resistance log. Thin beds of greater resistance, such as the limestone and gypsum beds in the upper part of the figure, are indicated correctly on the single-point-resistance log but are reversed on the long-normal-resistivity log. The single-point-resistance log shifts at the depth where drilled diameter changes from 8 to 6 in, but the long-normal-resistivity curve does not.

A single-point-resistance log is included in figure 29 as part of a suite of logs of a sedimentary sequence. Note that the scale for the single-point-resistance log, in ohms, numerically is different from the scale for the normal-resistivity logs, in ohm-meters. The differential single-point-resistance log has much higher resolution than the normal logs, and detects thin beds also detected by the caliper log. In some rock types, single-point-resistance and normal-resistivity logs also may be similar to neutron logs (fig. 29). This similarity can be used to correlate lithology between holes for which one type of log is not available; however, it should be used with caution. Different types of logs that are based on entirely different measuring principles probably will not respond similarly to a variety of rock types and hole conditions. For example, in coal or gypsum beds, neutron response will be the opposite of single-point-resistance response; the difference can be used to identify these rock types.

The responses of differential and conventional single-point-resistance logs to fractures are illustrated in figure 33. At least one of the logging systems was not properly calibrated, because the scales differ by an order of magnitude. Borehole enlargements shown on the caliper log are caused almost entirely by fractures in the crystalline rocks penetrated by this borehole. The differential single-point-resistance log defines the fractures with much more resolution than does the conventional system. Note that some relation exists between the hole diameter shown by the caliper deflection and the amplitude of the negative deflections on the differential log. In most cases, differential single-point-resistance logs will define narrow or partly closed fractures and solution openings better than caliper logs, if the rock has uniform resistivity. Single-point-resistance logs may help distinguish between a steeply dipping fracture, which may be shown on a caliper log as three anomalies, as in figure 8, and several low-angle fractures. Steeply dipping fractures are not usually detected by single-point-resistance logs because the lower resistivity is spread over a large depth interval.

Normal-resistivity logging

Among the various multielectrode resistivity-logging techniques, normal resistivity is probably the most widely used in ground-water hydrology, even though the long-normal-resistivity log has become nearly obsolete in the oil industry. Normal-resistivity logs can be interpreted quantitatively when they are properly calibrated in ohm-meters. The logs actually measure apparent resistivity, which may need to be corrected for bed thickness, borehole diameter, mudcake thickness, and fluid invasion to determine true resistivity. The capability to make normal logs is available on most water-well logging equipment that has multiconductor cable; however, long- and short-normal-resistivity logs may not be available on some equipment used for logging oil wells.

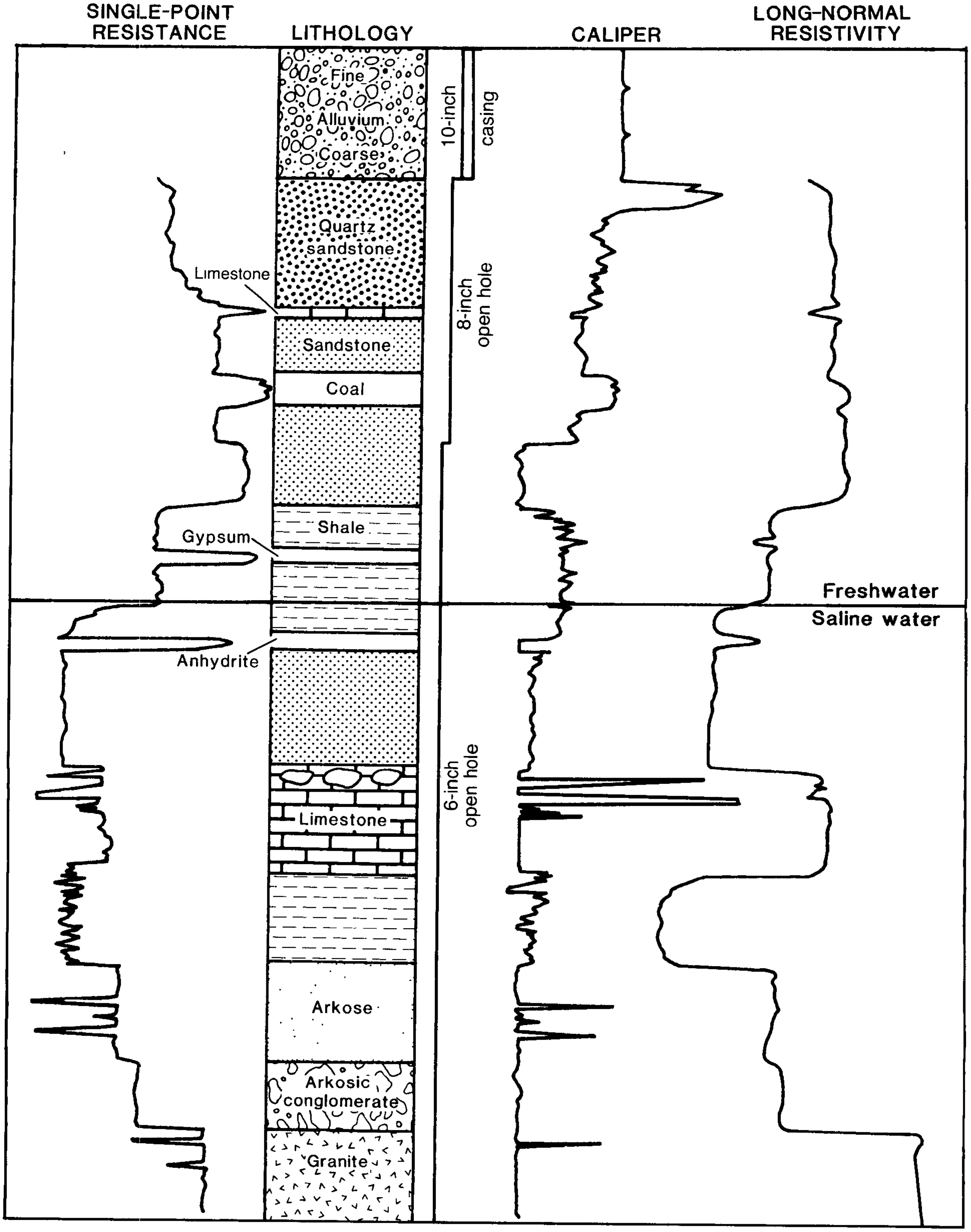


Figure 32.—Typical responses of single-point-resistance, caliper, and long-normal-resistivity logs to a sequence of sedimentary rocks.

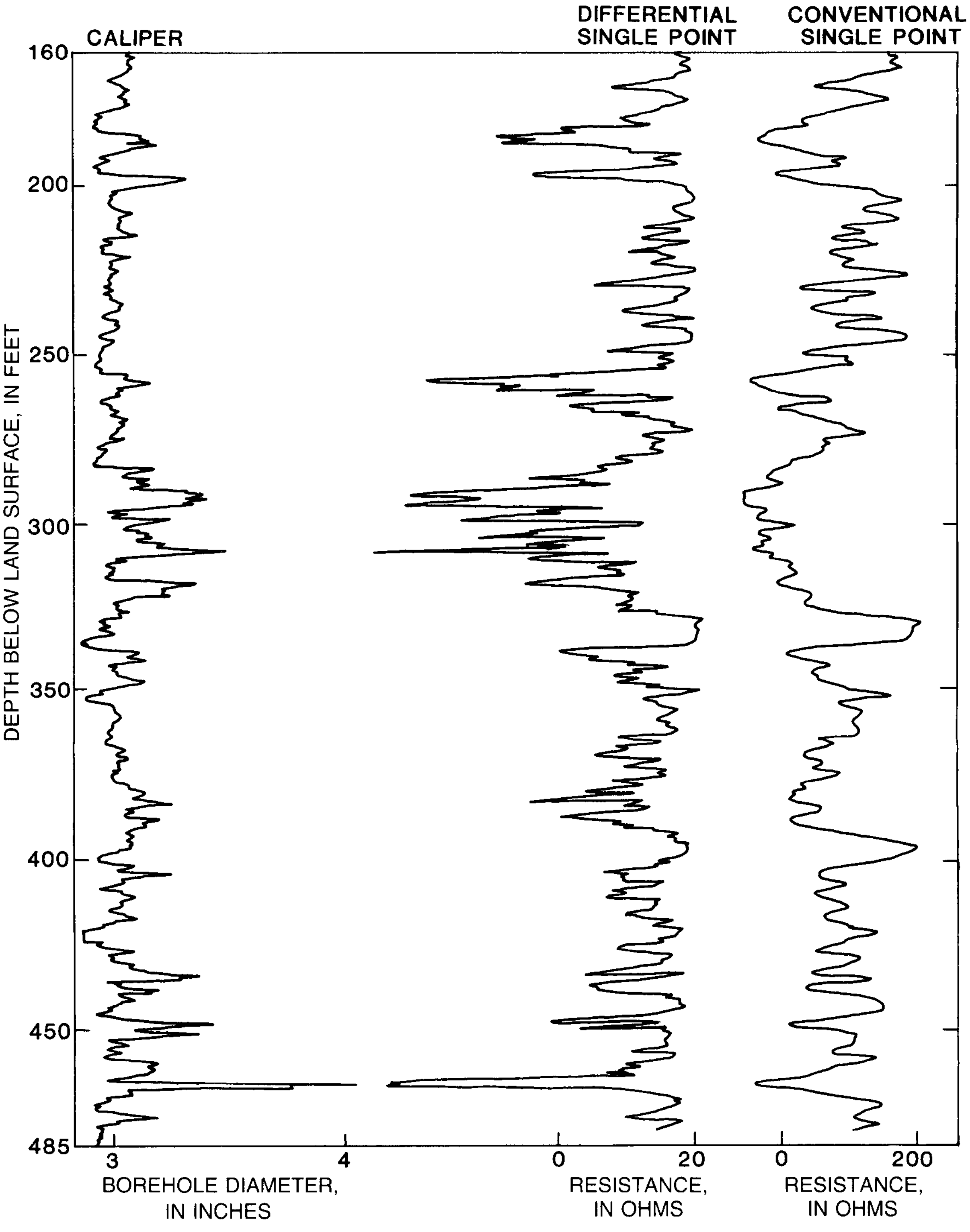


Figure 33.—Caliper and differential and conventional single-point-resistance logs in a well penetrating fractured crystalline rocks.

Principles and instrumentation

By definition, resistivity includes the dimensions of the material being measured; therefore, it is an intrinsic property of that material. The difference between resistance and resistivity is analogous to the difference between weight, in grams, and density, in grams per cubic centimeter. Resistivity is defined by the formula

$$R = r \times S/L \qquad (4)$$

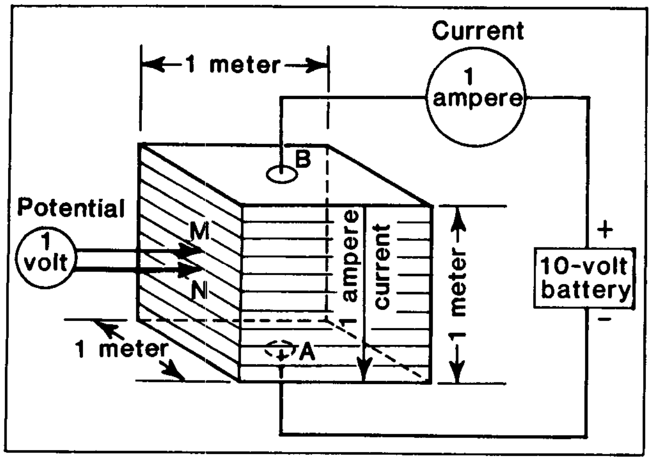


Figure 34.—Principles of measuring resistivity, in ohm-meters. Example is 10 ohm-meters.

where

R=resistivity, in ohm-meters;

r =resistance, in ohms;

S =cross-sectional area normal to the flow of current, in square meters; and

L =length, in meters.

The principles of measuring resistivity are illustrated in figure 34. In this example, 1 A of current from a 10-V battery is passed through a 1-m^3 block of material, producing a decrease in potential of 10 V. The current is passed between electrodes A and B, and a voltage drop of 1 V is measured between potential electrodes M and N, which are 0.1 m apart. By Ohm's law, the resistance is $r=E/I=1$ V/1 A=1 ohm and the resistivity is $R=r\times S/L=1$ ohm×1 m^2/0.1 m=10 ohm-m. The current is constant, so the higher the resistivity between M and N, the greater the voltage drop. Alternating current is used to avoid polarization of the electrodes that would be caused by the use of direct current.

In logging equipment, electronic circuits, rather than a battery, are used to maintain a constant current, and the electrodes are arranged differently than for measuring a sample. For normal-resistivity logging, electrodes A and M are located in the well relatively close together, and electrodes B and N are distant from electrodes A and M and from each other. The electrode spacing, from which the normal curves derive their names, is the distance between electrodes A and M, and the depth reference is at the midpoint of this distance. The most common spacings are 16 and 64 in; however, some loggers have other spacings available, such as 4, 8, 16, and 32 in. The distance to the B electrode, which usually is on the cable, is about 50 ft; it is separated from the A and M electrodes by an insulated section of cable. The N electrode usually is located at the land surface, but in some equipment the locations of the B and N electrodes are reversed.

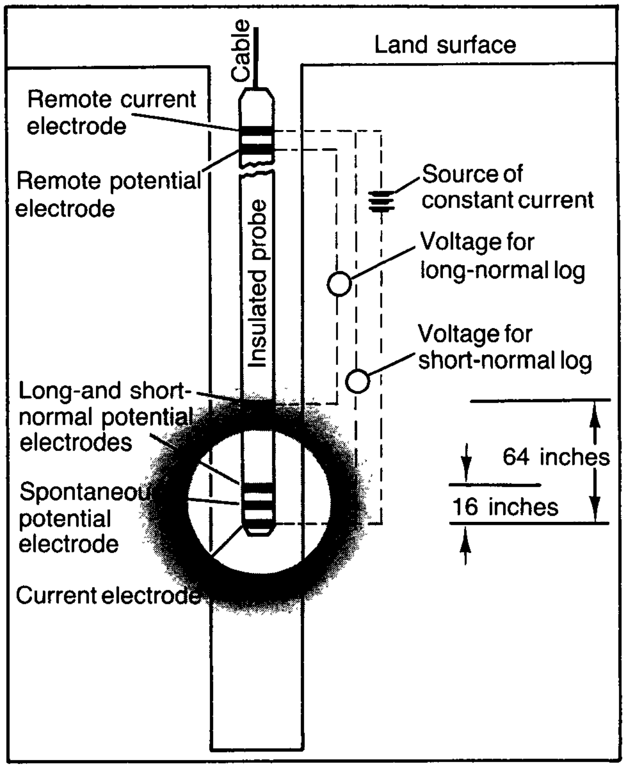
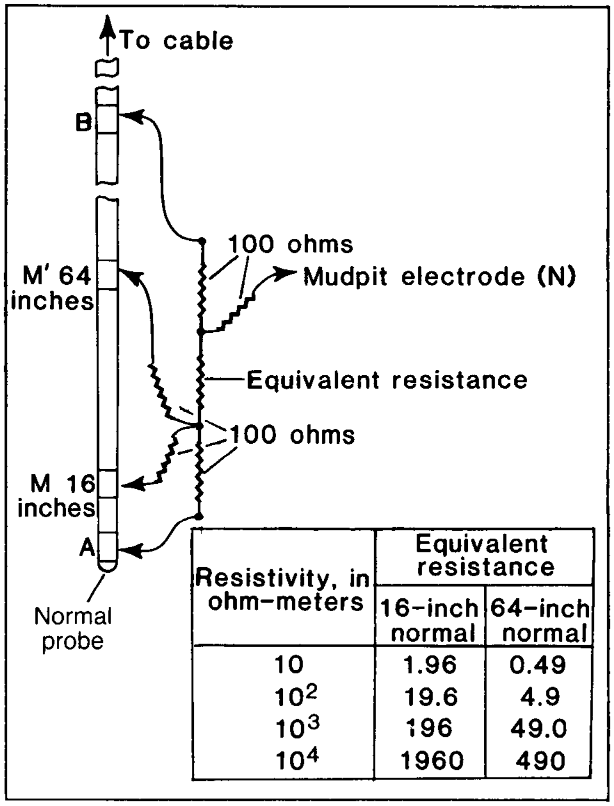


Figure 35.—System for making 16- and 64-inch normal-resistivity logs. Shaded areas indicate relative sizes of volumes of investigation.

A simplification of a normal-resistivity logging system, without the letters identifying the electrodes, is shown in figure 35. Constant current is maintained between a current electrode at the bottom of the probe and a remote-current electrode at a distance of 50 ft or more. The voltages for the long-normal (64 in) and short-normal (16 in) logs are measured between a potential electrode for each, located on the probe, and a remote potential electrode. In an actual logging system, the remote-current and potential electrodes are distant from each other. An insulating section of cable (bridle) is used to ensure that the lower portion of the logging cable does not act as the return current electrode. The spontaneous-potential electrode is located between the short-normal potential and current electrodes. The relative difference between the volumes of material investigated by the two normal systems also is illustrated in figure 35. The volume for the long-normal system is shaded dark; the volume for the short-normal system is lighter and smaller. Because the depth-reference points for the long- and short-normal systems are different when logging up the hole, the long-normal log will show a change in resistivity before the short-normal log. The long-normal reference is 2 ft above the short-normal reference, but this can be corrected by adjusting the pens on the recorder. Usually, spontaneous potential is recorded in the left-recorder track and the resistivity curves, distinguished by different pen colors or patterned traces, are recorded in the right-recorder track. Because the resistivity of rocks penetrated by a borehole may vary considerably, backup scales are useful so information is not lost. Decreasing sensitivity so all data will be on scale can result in the loss of small changes that may be significant. Onsite digitizing of the data can solve some of these problems.

From a practical standpoint, a cable must have at least four conductors to make two normal-resistivity logs simultaneously along with a spontaneous-potential log. In the past, most water-well logging has been done with single-conductor cable; however, four-conductor cable has become more widely used, largely because of the need to make quantitative resistivity logs. Equipment has been designed and tested by the U.S. Geological Survey to make normal logs on single-conductor cable, but the procedure has proved to be expensive, complex, and relatively unreliable. Selecting the optimum current for a considerable range of resistivity also was difficult with this equipment. Recent advances in electronics may increase the feasibility of making multielectrode logs using single-conductor cable.

Older normal-resistivity logging systems use a mechanical commutator to generate the square-wave alternating current transmitted to the potential electrodes. Newer equipment uses a solid-state generator, which probably is a more reliable approach. Regardless of which type is used, a provision for changing the output frequency is necessary. Constant current can be maintained by placing a large resistance in series with the generator and the current electrodes, so that, within a range, the same current will flow regardless of the resistance of the rocks. The current produced is changed by the resistivity-scale switch on the module. As resistivity increases, current decreases. To maximize log response, the optimum scale and current must be selected. If the current is too small in less resistive rocks, the potential drop will be too small and the log will lack character. If the current is too great in more resistive rocks, excess voltage will saturate the recorder circuits.



Resistivity, in ohm-meters	Equivalent resistance	
	16-inch normal	64-inch normal
10	1.96	0.49
10^2	19.6	4.9
10^3	196	49.0
10^4	1960	490

Figure 36.—System for calibrating normal-resistivity equipment.

Calibration and standardization

Normal-resistivity logging systems can be calibrated at the land surface by placing fixed resistors between the electrodes. A schematic diagram of a system used by the U.S. Geological Survey is shown in figure 36. The formula for calculating the apparent resistivity (*Ra*) of an infinite medium, in ohm-meters, incorporates a geometric factor with Ohm's law:

$$Ra=E/I\times 4AM \tag{5}$$

where *AM* (that is, the distance between the A and M electrodes) is in meters. Because $E/I=r$, the formula can be rewritten as

$$r_f=Ra/4AM \tag{6}$$

where r_f=equivalent resistance of the formation. This formula can be used to calculate the resistance values to be substituted in the calibration network shown in figure 36. The value for the geometric factor 4*AM* is 5.11 for the 16-in normal probe. Using this value in equation 6 yields the values for the equivalent resistance for the 16-in normal probe shown in figure 36. Contact resistance between the electrodes and fluid is simulated by 100-ohm resistors in the calibrator shown. This resistance may not be large enough in very resistive rocks saturated with freshwater, where contact resistance may be several thousand ohms.

A small board can be made with 100-ohm resistors and terminals to allow substitution of other resistors to simulate other values of r_f. Large clips of the type used to connect to auto batteries can be used to make electrical contact with the logging electrodes. This resistor system is sufficiently compact to be carried with any logger for onsite calibration. At the well, only one or two values of resistivity may need to be checked within the range of interest. As with logging, the proper scales must be selected for the resistor values used. For example, 10 ohm-m would not be calibrated on the 1,000-ohm-m scale. A check for zero resistivity can be done in a well with steel casing. For this purpose, the entire electrode assembly must be in the water and within the cased interval. All calibration or onsite-standardization values will be recorded directly on the log in the appropriate channel, along with information on equipment settings. If onsite digitizing equipment is in use, these data also should be on the digital record.

Volume of investigation

The volume of investigation of normal-resistivity probes is considered to be a sphere, with a diameter approximately twice the AM spacing. As an extreme example, ultra-long-spaced electric logs use AM spacings as long as 1,000 ft to investigate anomalies more than 100 ft away from the borehole. This volume contributes most of the measured signal, but it does not have distinct limits. The volume changes as a function of resistivity and bed thickness, so size and shape of the sphere change as the well is logged. Although the depth of fluid invasion is a factor, short-normal (16 in or less) probes are considered to investigate only the invaded zone, and long-normal (64 in) probes are considered to investigate both the invaded zone and the zone where native formation water is present. These phenomena are illustrated in figure 29. In this figure, the area between a 32-in curve on the left and 4-in curve on the right is shaded. The longer spaced curve indicates less resistivity farther from the borehole than in the invaded zone near the borehole; this suggests that the formation water is relatively saline with respect to the borehole fluid.

Extraneous effects

Long-normal-resistivity logs are affected by some of the same instrumentation problems as single-point-resistance logs; these problems usually appear as noise or periodic oscillations on the logs. Interference from 60-cycle alternating current from local sources usually can be eliminated by changing the alternating-current frequency of the generator on the logging truck. It may not always be possible to eliminate random noise originating from external sources; changing the equipment ground usually will help.

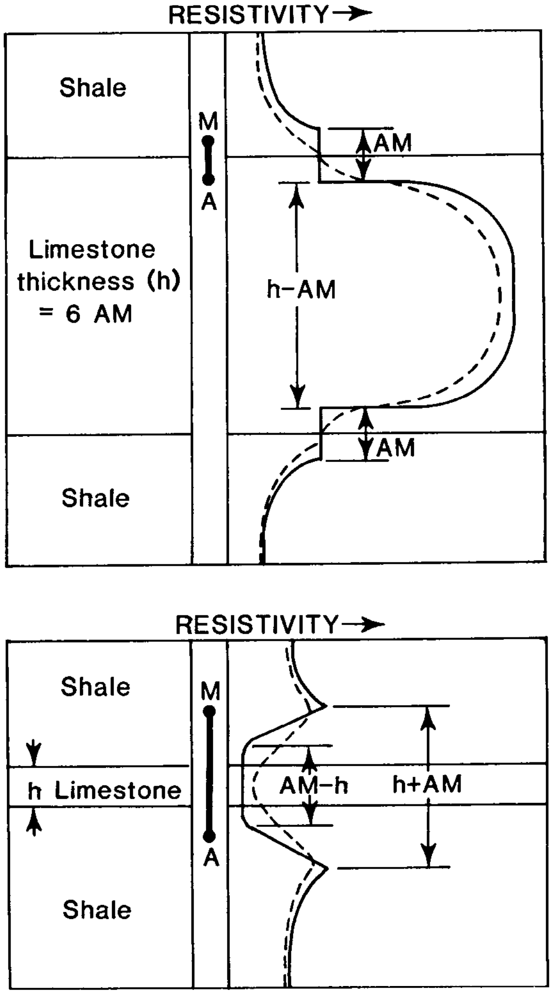


Figure 37.—Relation of bed thickness to electrode spacing for normal probes at two bed thicknesses (modified from Lynch, 1962). (Solid line is theoretical-resistivity curve, and dashed line is actual log.)

Long-normal response is affected markedly by bed thickness; this problem can make the logs quite difficult to interpret. The bed-thickness effect is a function of electrode spacing, as illustrated in figure 37. The theoretical-resistivity curve (solid line) and the actual log (dashed line) for a resistive bed six times as thick as the AM spacing is shown in the upper part of the figure. The resistivity of the limestone is assumed to be six times that of the shale, which is of infinite thickness. As the electric-logging probe moves opposite the bed from below, measured resistivity increases gradually until the M electrode reaches the bottom contact of the limestone. Resistivity remains constant until the A electrode reaches this contact, when the curve shows a gradual increase in apparent resistivity (*Ra*) until the center of the bed is reached. The upper half of the curve is a mirror image of the lower half. With a bed thickness six times AM, the recorded apparent resistivity approaches, but does not equal, the true resistivity (*Rt*); the bed is logged as being one AM spacing thinner than it actually is. The actual logged curve is a rounded version of the theoretical curve, in part because of the effects of the borehole.

The log response when the bed thickness is equal to or less than the AM spacing is illustrated in the lower part of figure 37. The curve reverses, and the resistive limestone actually appears to have a smaller resistivity than the surrounding material. The log does not indicate the correct bed thickness, and anomalies indicating a resistivity that is too large occur both above and below the limestone. Therefore, although increasing the AM spacing to achieve a greater volume of investigation would ordinarily be considered desirable, bed-thickness effects would diminish the usefulness of the logs.

The accuracy of measurement of rocks having a resistivity greater than several thousand ohm-meters is questionable for most logging systems. Most sedimentary rocks have a smaller resistivity; however, the resistivity of igneous and metamorphic rocks may exceed 10,000 ohm-m, and values on logs made in these rocks may be considerably in error.

Interpretation and applications

The most important application of normal-resistivity logs in ground-water hydrology is for determining water quality, as explained in the section on fluid conductivity. Normal-resistivity logs measure apparent resistivity; if true resistivity is to be calculated from these logs, a number of factors must be considered (Lynch, 1962). Although not all these factors are significant under all conditions, corrections must be applied for each under some conditions. The factors include resistivity of the invaded zone (*Ri*), diameter of the invaded zone (*Di*), mud resistivity (*Rm*), borehole diameter (*d*), bed thickness (*h*), resistivity of adjacent beds, and AM spacing. Temperature corrections must be applied to any measurement of resistivity. Apparent resistivity from logs may be equal to, greater than, or less than true resistivity, depending on the specific factors. Departure curves have been developed to correct normal-resistivity logs for these effects. Such curves were included in older books of log-interpretation charts provided by commercial logging-service companies, but they are omitted from recent editions because of infrequent use of all but the 16-in normal-resistivity log. Simplified versions of some of the departure curves are included in Lynch (1962) and Pirson (1963). Guyod and Pranglin (1959) have published a set of charts for determining true resistivity and the resistivity and diameter of the invaded zone based on an electric log consisting of 16- and 64-in normal-resistivity logs and an 18-ft 8-in lateral-resistivity log. These charts were derived from an analog-computer study and include a variety of conditions encountered in oil exploration. A summary of these techniques has been compiled and published by the Society of Professional Log Analysts (1979).

Resistivity-porosity cross plots, also called Hingle plots, provide a graphical method of estimating water quality from resistivity logs and logs that can be converted to porosity. Hilchie (1982) published an explanation of this technique and included the necessary graph paper for different cementation factors. When corrected log data are plotted on the appropriate paper, the intercept at 100-percent porosity approximates *Rw*. The technique is valid only for water-saturated sediments relatively free of clay, and the cementation factors must be consistent for the depth intervals on a single plot.

Turcan (1966) used a practical field method to estimate ground-water quality in Louisiana from resistivity logs. The method is based on establishing field-formation factors for aquifers within a limited area, using electric logs and water analyses. After a consistent field-formation factor is established, the long-normal log or any other resistivity log that provides a reasonably correct *Rt* can be used to calculate *Rw* from the relation $F=Ro/Rw$. Under these conditions, *Ro*, the resistivity of a rock 100 percent saturated with water, is assumed to approximate *Rt* after the appropriate corrections have been made. The specific conductance of water samples, in microsiemens per centimeter at 25 °C, can be converted to resistivity, in ohm-meters, by the following:

$$Rw=10{,}000/\text{specific conductance} \qquad (7)$$

Resistivity values from logs can be converted to standard temperature using figure 19, and the factors listed in the section on fluid conductivity can be used to convert water analyses to electrically equivalent sodium chloride concentrations. If enough data are available, specific conductance can be related empirically to dissolved-solids concentrations, as in figure 18.

The relation between resistivity as determined from normal-resistivity logs and concentration of dissolved solids in ground water is valid only if the porosity and clay content are relatively uniform and *Ra* from the logs approximates *Rt*. Only in sediments having uniformly distributed intergranular pore spaces is bulk resistivity proportional to *Rw*. This relation applies to some limestone and dolomite, but the method does not apply to rocks having randomly distributed solution openings or fractures. Because the flow of electrical current is related to tortuosity, two rocks having the same average porosity will have different resistivities if one has uniformly distributed intergranular porosity and the other has randomly distributed vugs.

Additional factors that may cause errors in determining water quality from resistivity logs because of their effect on the measured or apparent formation factor are shape, packing, uniformity, and mean size of the particles; pore-water resistivity; matrix resistivity; ion exchange; and surface conduction (Biella and others, 1983).

The normal-resistivity logs in figure 29 were used to calculate the quality of the water in the aquifers at the Kipling well site in Saskatchewan, Canada. The left trace of the two normal-resistivity logs shown is the 32-in normal, which was used to calculate *Rw* for three of the shallower aquifers intersected. The 32-in normal was selected because many of the beds in this area are too thin for longer spacing. Wyllie (1963) described a method for estimating the formation-resistivity factor (*F*) from the ratio *Ri*/*Rm*, where *Ri* is the resistivity of the invaded zone from a short-normal log such as the 4-in log and *Rm* is the measured resistivity of the drilling mud. On the basis of the 4-in curve, *F* was estimated to be 2.5 for the upper aquifer and 1.8 for the lower two aquifers. The true resistivity values for the three aquifers obtained from departure curves for the 32-in normal log are 30, 20, and 17 ohm-m at depths of 130, 250, and 300 ft, respectively. A formation factor of 3.2 provided good agreement with water quality calculated from spontaneous-potential logs and from laboratory analyses. Using an *F* of 3.2, *Rw* for the three aquifers was calculated to be 9.4, 6.2, and 5.3 ohm-m at 4 °C. The offset of the two normal curves substantiated the fact that the water in the aquifers was more saline than the drilling mud, which had a resistivity of 13 ohm-m. Although normal-resistivity logs can be used to determine lithology and locate contacts, this application is subject to considerable error because of the bed-thickness effects previously described.

Focused-resistivity logging

Focused-resistivity systems were designed to measure the resistivity of thin beds or resistive rocks in wells containing conductive fluids. A number of different types of focused-resistivity systems are used commercially; the names "guard" or "laterolog" are applied to two of these. Focused-resistivity logs can provide high resolution and great penetration under conditions where other resistivity systems may fail.

Principles and instrumentation

Focused-resistivity probes use guard electrodes above and below the combined current and potential electrode (M) to force the current to flow out into the rocks surrounding the well. The guard electrodes are electrically connected together, and a current is applied to them. This current is automatically adjusted so that the potential between M and the guard electrodes is always zero. The resulting balanced potential forces the current from M to flow outward in a relatively thin sheet. A constant current is applied to M, so that the voltage drop to the remote electrode (N) is proportional to the resistivity. The thickness of the beam of current from M is proportional to the length of the M electrode, which in most cases is between 3 and 12 in. The radius of investigation is considered to be about three times the length of one guard, so a 6-ft guard should be able to investigate material as far as 18 ft from the borehole.

With conventional guard systems, a spontaneous-potential measurement cannot be made within 25 ft of the upper guard; thus, the bottom of the hole cannot be measured. Another variety of a focused probe, the laterolog, overcomes this problem. The laterolog uses four M electrodes to focus the current in a sheet about 32 in thick. The depth of investigation is about the same as that for a 6-ft guard, but the resolution is not as good because the current beam is thicker. With this system, spontaneous potential can be measured at the potential electrodes. A number of different laterolog systems having different characteristics are available, so specific information must be obtained from the company supplying the equipment.

The difference between the current distribution around a normal electrode system and a lateral system, with the electrode array located opposite a resistive rock such as limestone, is shown in figure 38. The sheetlike current pattern of the focused probes increases the resolution and decreases the effect of adjacent beds in comparison with the normal probes.

Microfocused devices include all the focusing and measuring electrodes on a small pad; they have a depth of investigation of only a few inches.

Calibration and standardization

Because the geometric factor, which is related to the volume investigated, is difficult to calculate for focused probes, calibration usually is done in a test well or pit for which resistivity values are known. When this is done, the voltage recorded can be calibrated directly in terms of resistivity. Zero resistivity can be checked when the entire electrode assembly is within a steel-cased interval of a well that is filled with water. Resistivity values measured in shale with a focused system should be checked by comparing them with values obtained from other types of resistivity logs. The current supplied to the guard electrodes

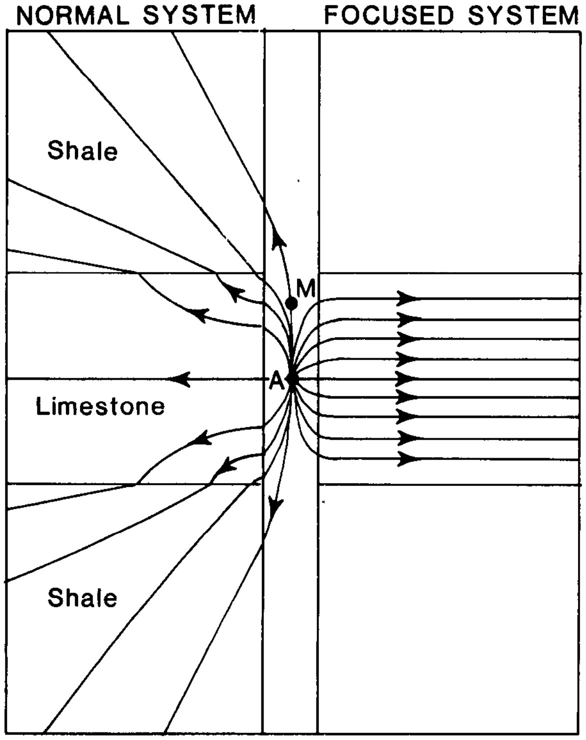


Figure 38.—Current distribution around a normal-electrode system and a focused-electrode system (laterolog).

should be continuously recorded on the log; if the record is not relatively straight, the log may be erroneous (Lynch, 1962).

Volume of investigation

The volume of material investigated by a focused system is a function of the length of the guard and current electrodes. For a guard system, the radius of investigation is about three times the length of the guard electrodes. For a laterolog 7 (7 being the number of electrodes), the current beam, which is a constant 32 in thick for some distance, starts to diverge about 10 ft from the borehole; most of the signal is from material inside this distance. For a laterolog 8, about 90 percent of the signal is derived from material within less than 4 ft of the borehole.

Extraneous effects

In general, focused-resistivity systems require less correction for extraneous effects than do normal-resistivity systems. Correction for bed thickness (*h*) is required only if *h* is less than the length of M, which is 6 in on some common probes. Resistivity values on guard logs will nearly equal *Rt*, and corrections usually will not be required if $Rm/Rw<5$, $Rt/Rm>50$, and invasion is shallow. If these conditions are not met, correction charts and empirical equations can be used to calculate *Rt* (Pirson, 1963). Borehole-diameter effects tend to be relatively small. For example, a laterolog 8 will provide values within 10 percent of *Rt* for borehole diameters ranging from 6 to 12 in (Lynch, 1962). Currents in the ground from other sources can produce errors on focused logs. If the monitoring current is not properly balanced, substantial errors may be produced on the logs.

Interpretation and applications

Focused-resistivity logs are very useful for providing accurate resistivity values in thin and resistive rocks when conductivity of the borehole fluid is relatively great. Various types of guard systems provide excellent resolution of thin beds and require no correction for bed thickness under these conditions. Focused systems provide quantitative information under favorable geometry and salinity conditions, whereas normal-resistivity systems require considerable correction. The application of these logging systems in ground-water hydrology has been limited because the equipment is not available on most water-well loggers. The equipment is available on many loggers used in oil fields, and correction charts are included in manuals provided by commercial logging-service companies.

Lateral-resistivity logging

Lateral-resistivity logs are made with four electrodes, as are normal-resistivity logs, but the electrodes are in a different configuration. The potential electrodes, M and N, are located 32 in apart; in the most commonly used probe, the current electrode, A, is located 18 ft 8 in above the center (O) of the MN spacing. The distance AO has varied over the years from 4 ft 8 in to the present standard of 18 ft 8 in, although the shorter spacings still are used for special purposes. The midpoint (O) is the reference for depth measurements on lateral-resistivity logs.

Lateral-resistivity logs are designed to measure resistivity beyond the invaded zone by use of long spacing. They have several limitations that have restricted their use in water wells. Best results are obtained when bed thickness is greater than twice AO, or more than 40 ft for the standard spacing. Marginal results are obtained in saline drilling fluid and highly resistive rocks. Corrections must be made for borehole diameter and for the effects of adjacent beds (Pirson, 1963). Although correction charts are available, the logs are difficult to interpret. Anomalies are unsymmetrical about a bed, and the degree of distortion is related to bed thickness and the effect of adjacent beds. Lateral-resistivity logs have not been

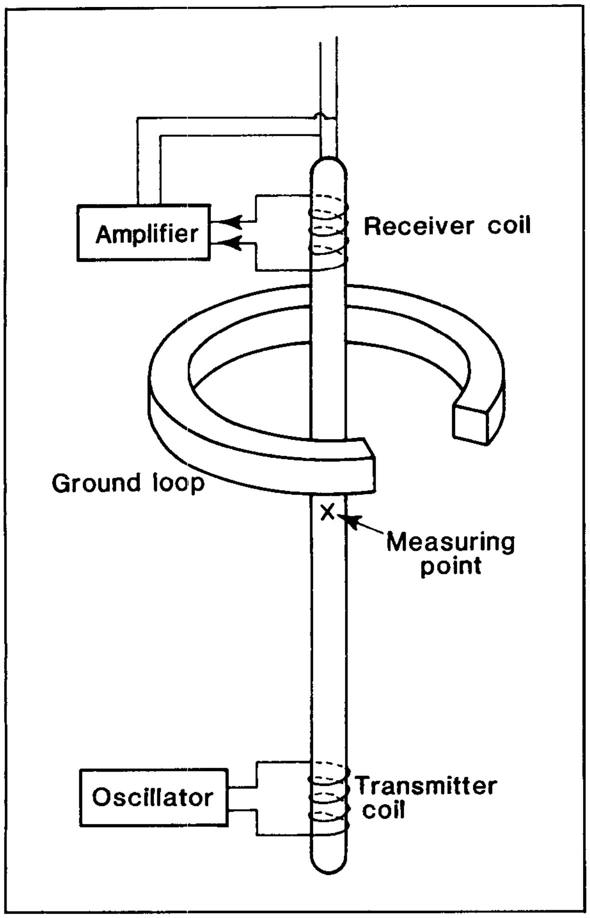


Figure 39.—System for making induction logs.

used widely in ground-water hydrology, but the equipment is still available through oil-well logging-service companies.

Induction logging

Induction-logging systems originally were designed to solve the problem of measuring resistivity in oil-based drilling mud, where no conductive medium is present between the probe and the formation. A basic induction-logging system is illustrated in figure 39. A simple version of an induction probe contains two coils, one for transmitting an alternating current into the surrounding rocks and the other for receiving the returning signal. The transmitted alternating current, at about 20,000 cycles per second (20 kHz), induces the flow of eddy currents (a ground loop) in conductive rocks penetrated by the borehole. These eddy currents set up secondary magnetic fields that induce a voltage in the receiving coil. That signal is amplified and converted to direct current before being transmitted up the cable. The magnitude of the received current is proportional to the electrical conductivity of the rocks. Induction logs measure electrical conductivity, which is the reciprocal of resistivity. Additional coils usually are included to focus the current in a manner similar to that used in the guard type of focused-resistivity systems.

Induction-logging systems provide resistivity measurements regardless of whether the well contains oil-based mud or is filled with air or fresh mud. The measurement of electrical conductivity usually is inverted to provide curves of both resistivity and electrical conductivity. The unit of measurement for conductivity is the mho-meter; however, induction logs are calibrated in millimho-meters. Calibration is checked by suspending the probe in air, where humidity is minimal, in order to obtain zero electrical conductivity. A copper hoop is suspended around the probe while it is in the air to simulate known resistivity values. It is also possible to suspend the probe in a lake or other body of water that is large enough to be infinite with respect to probe response. The electrical conductivity of the water can be measured with a conductivity cell.

The volume of investigation of an induction probe is a function of coil spacing, which varies among the probes provided by different service companies. For most probes, the diameter of material investigated is 40 to 60 in. For some probes, the signal produced by material closer than 30 in is small, and borehole diameter and properties of the invaded zone have little effect on measured resistivities. Although induction probes are not greatly affected by changes in borehole diameter, they are affected by eccentricity, so they usually are centralized. Vertical resolution of the logs is good for beds that are more than 6 ft thick.

The application of induction logs in ground-water hydrology is limited because the probe is most responsive to small changes in resistivity when background resistivity is minimal. The dual induction log configuration where the probe measures resistivity uses two different volumes of investigation is one of the most common electric logs used in the petroleum exploration industry. The ratio of Rm to Rw usually determines the applicability of induction probes. If the value of Rw exceeds 5 times Rm, which is common in wells containing freshwater, resistivity values on an induction log depart substantially from Rt.

Microresistivity logging

A large number of microresistivity probes is available, but all have short electrode spacing, and thus a shallow depth of investigation. They are of two general types: nonfocused and focused. Both types incorporate pads or some kind of contact electrodes to decrease the effect of the borehole fluid.

Nonfocused probes are designed mainly to determine the presence or absence of mud cake, but they also can provide high-resolution lithologic detail. Names for these logs include microlog, minilog, contact log, and micro-survey log. A microlateral and a micronormal configuration may be mounted on one rubber-covered pad, with dime-sized electrodes spaced from 1+ to 2 in apart. In this example, the microlateral would measure material only 1+ in from the pad; the micronormal would measure material somewhat farther away. Lateral electrodes respond mostly to the mud cake, and normal electrodes to the material just beyond the mud cake. In shale, where mud cake would be absent, the two will record the same resistivity. A uniform mud cake, such as might be present on sand, would be indicated by a greater resistivity on a micronormal log. In general, nonfocused-microresistivity logs are used to provide information about the mud cake and are not as effective where the borehole is rough. Most of these logs are limited to holes 6 to 16 inches in diameter, because of the pads; the substantial spring pressure on the pads exerts a strong pull on the logging cable, so a sturdy tower is needed.

Focused microresistivity probes also use small electrodes mounted on a rubber-covered pad forced to contact the wall of the borehole hydraulically or with substantial spring pressure. The electrodes are a series of concentric rings less than 1 in apart that function in a manner analogous to a laterolog system. The radius of investigation is 3 to 5 in, which provides excellent lithologic detail beyond the mud cake but probably still within the invaded zone. The chief use of these focused microresistivity probes in the petroleum industry is for determining the resistivity of the flushed zone or the invaded zone. Focused microprobes are most effective with a saline mud in the borehole. The logs produced by these probes also are called microlaterologs or minifocused logs.

Dipmeter logging

A dipmeter includes a variety of wall-contact microresistivity probes that are widely used in oil exploration to provide data on the strike and dip of bedding planes. The most advanced dipmeters include four arms with measurement pads located 90° apart, oriented with respect to magnetic north by a magnetometer in the probe. Older dipmeters used three pads, 120° apart. A modern dipmeter provides much information from a complex tool, so it is an expensive log to make. Furthermore, because of the quantity and complexity of the data, the maximum benefit is derived from computer analysis and plotting of the results. Interpretation is based on the correlation of resistivity anomalies detected by the individual pads, and the calculation of the true depth at which those anomalies occur.

A dipmeter log made with a three-arm probe displays the three resistivity curves in the right recorder track, along with a caliper log. The left track includes traces showing the azimuth of the number 1 electrode, the degree of borehole deviation from the vertical, the direction of that deviation, and the angle between electrode 1 and the direction of borehole deviation or drift. The log usually displays circular plots at the top, showing the relation between the various directions recorded and magnetic and true north. A dipmeter log made with a four-arm probe displays four resistivity curves and two caliper traces, which are recorded between opposite arms, so that the ellipticity of the hole can be determined. Most four-arm probes can be run in holes 6 to 18 inches in diameter, but a version is available that can be used in a hole 4 inches in diameter. A more detailed description of dipmeters has been provided by Bigelow (1985). The equipment needed to make and interpret dipmeter logs usually is available only from commercial oil-well service companies.

Although strike and dip can be determined from the analog record at the well, using a stereographic net, complete analysis is possible only with a computer.. A computer program can make all necessary orientation and depth corrections and can search for correlations between curves within a given search interval. The computer printout usually consists of a graphic plot and a listing of the results. The graphic plot displays the depth, true dip angle, and direction of dip by means of a symbol called a "tadpole" or an arrow. The angle and direction of the probe also are displayed. Linear polar plots and cylindrical plots of the data also are available. A printout that lists all the interpreted data points, as well as an index representing the reliability of the correlation between curves, also is provided.

A dipmeter log probably is the best source of information on the location and orientation of primary sedimentary structures over a wide variety of hole conditions. An acoustic televiewer log can provide similar information for a less variable set of conditions. The dipmeter also has been advertised widely as a fracture finder; however, it has some of the same limitations as the single-point-resistance log when used for this purpose. Computer programs used to derive fracture locations and orientations from dipmeter logs are not as successful as programs designed for distinguishing bedding. Fractures usually are more irregular, with many intersections, and may have a greater range of dip angles within a short depth interval. When the acoustic televiewer and the dipmeter have been compared in terms of providing information on the location, orientation, and character of fractures, the acoustic televiewer has been found to provide an understanding of complex fracture systems, whereas the dipmeter was not (Keys, 1979).

Test 2.—ELECTRIC LOGGING

1. A spontaneous-potential log is one of the most useful logs in water wells because
   - a. It provides an accurate measurement of resistivity under most conditions.
   - b. It usually provides detailed lithologic information.
   - c. It is not affected by the salinity of the borehole fluid.
   - d. The theoretical basis for the log is simple.
2. If the drilling mud has resistivity of 1.5 ohm-m at 25 °C and the 64-in normal log shows much lower resistivity than the 16-in normal log in a 65-ft sand bed, the water in the sand is
   - a. Potable.
   - b. Of low conductivity.
   - c. Too saline to drink.
   - d. Indeterminate.
3. A single-point-resistance probe is superior to 16- and 64-in normal-resistivity probes for distinguishing lithologic units because
   - a. It provides information about very thin beds.
   - b. Log values are more accurate.
   - c. It never reverses.
   - d. It is not affected by borehole diameter.
4. The 64-in normal-resistivity curve is more accurate than the 16-in normal-resistivity curve for determining quality of formation water because
   - a. It is less affected by borehole fluid.
   - b. Measurements are more accurate for thin beds.
   - c. It is less affected by clay content.
   - d. It measures beyond the invaded zone.
5. Focused or guard logs
   - a. Are used when the borehole mud is saline and the rock is resistive.
   - b. May have shallow or deep penetration.
   - c. Are available on most water-well loggers.
   - d. Are nonlinear at large resistivity values.
6. Selection of the type of resistivity logs to be made should be based on
   - a. Salinity of fluid in the borehole.
   - b. Thickness of beds to be resolved.
   - c. Anticipated resistivity of rocks.
   - d. Equipment available.
7. The dipmeter is an excellent logging system because it is
   - a. Inexpensive to use.
   - b. Best for location and orientation of fractures.
   - c. One of the best methods for determining strike and dip of beds.
   - d. Available on most water-well loggers.
8. Induction logging is useful because it
   - a. Is inexpensive and readily available.
   - b. Provides good results in saline mud.
   - c. Is the only way to measure resistivity in air- or oil-filled boreholes.
   - d. Works well in small-diameter boreholes.
9. Lateral logs are
   - a. Not symmetrical.
   - b. Distorted by thin beds and adjacent bed effects.
   - c. Used to measure the resistivity of the noninvaded zone in thick beds.
   - d. Widely used in ground-water hydrology.
10. The formation-resistivity factor (*F*)
    - a. Equals *Ro* obtained from resistivity logs divided by *Rw*.
    - b. Can be estimated from neutron, gamma-gamma, and acoustic-velocity logs.
    - c. May be consistent within a depositional basin.
    - d. Is widely used in carbonate-rock aquifers.
11. The presence of a thin, large-amplitude negative deflection on a single-point-resistance log in a depth interval where the 64-in normal-resistivity log indicates a uniform resistivity of 1,000 ohm-m means that
    - a. The single-point-resistance log is demonstrating a reversal.
    - b. The 64-in normal-resistivity log probably is not correct.
    - c. The anomaly on the single-point-resistance log could indicate a fracture or borehole enlargement.
    - d. An induction log would give more accurate values in these rocks.

Nuclear Logging

Nuclear logging includes all techniques that either detect the presence of unstable isotopes or create such isotopes in the vicinity of a borehole. Nuclear logs are unique because the penetrating capability of the particles and photons permits their detection through casing, and because they can be used regardless of the type of fluid in the borehole. Nuclear-logging tech-