USE OF GEOPHYSICAL LOGS TO ESTIMATE THE QUALITY OF GROUND WATER AND THE PERMEABILITY OF AQUIFERS

By J.D. Hudson

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch	25.40	millimeter
foot	0.3048	meter
mile	1.609	kilometer
gallon per day	3.785	liter per day
gallon per day per foot	0.2070	liter per second per meter
gallon per day per foot squared	0.04075	meter per day

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by the equation:

$$^{\circ}F = 9/5\ (^{\circ}C) + 32$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Symbols and Terms

Rw = resistivity of the interstitial water (ohm-meters)

Ro = resistivity of formation 100 percent saturated with water

Rc = resistivity correction for clay in the formation matrix

Ro_s = formation resistivity equal to clay-free, saturated sand (a sum of Ro + Rc)

Ra = apparent resistivity

r = resistance in ohms

Rt = true formation resistivity

rf = equivalent resistance of the formation

E = electrical voltage

I = current (ampere)

F = formation factor

T = average tortuosity of the porous medium

T* = tortuosity as related to three-dimensional flow in a straight capillary, porous medium

$\bar{T}$* = tortuosity as related to three-dimensional flow in a capillary tube, porous medium

n = porosity (also ϕ)

Ff = field-formation resistivity factor

Mv = millivolt

EV = electron volts

Mev = million electron volts

Ohm-m = ohm-meter, a unit of resistivity or specific resistance

µS/cm = microsiemens per centimeter at 25 degrees Celsius

Fp = permeability factor

LNR = long-normal resistivity (ohm-meter^2/meter)

SNR = short-normal resistivity (ohm-meter^2/meter)

NR = neutron-count rate

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ABSTRACT

The relation of formation factor to resistivity of formation water and intergranular permeability has often been investigated, and the general consensus is that this relation is closest when established in a clean-sand aquifer in which water quality does not vary substantially. When these restrictions are applied, the following standard equation is a useful tool in estimating the resistance of the formation water: $F = Ro/Rw$, where F is the formation factor, which is a function of the effective porosity; Ro is the resistivity of a formation that is 100 percent saturated with interstitial water; and Rw is the resistivity of the water in the saturated zone. However, arenaceous aquifers can have electrical resistivities that are not directly related to resistivity of water or porosity. Surface conductivity and ion exchange are significant factors when the sediments are clay bearing. The solid constituents are a major component of the parameters needed to solve the equation for formation-water resistivity and estimates of aquifer permeability. A correction process needs to be applied to adjust the variables, Ro and F, to the equivalent of clean sand. This report presents an empirical method of using the neutron log and the electrical-resistivity values from long- and short-normal resistivity logs to correct for fine-grained material and the subsequent effects of low impedance to electrical flow that are not related to the resistance of formation water.

INTRODUCTION

The evaluation of ground-water systems by use of geophysical logs begins with a thorough knowledge of the environmental factors that cause geophysical-log responses. This evaluation also requires an understanding of the relation among geophysical-log responses and rock properties, models, experimentally derived equations, and the principles that govern the responses of logging devices.

Established "oil-field" geophysical-log interpretation methods have been applied to the analysis of freshwater aquifers and indicate that interpretations depend on reliable empirical data. The geologist, log analyst, or reservoir engineer needs to be thoroughly familiar with the variables and assumptions applied to the quantitative or qualitative analysis of geophysical logs and to the determination of the interrelation among lithologic properties. All formation evaluations, through the use of geophysical logs, rely on some assumptions, and the finished interpretation is no better than the assumptions and data on which it is based. The limited success of applying oil-field geophysical-log analysis and interpretation methods to freshwater aquifers is, in part, a result of the use of assumptions and principles that do not apply to the analysis of freshwater aquifers.

Geophysical-logging equipment developed primarily for shallow-hole logging, such as for water wells and mineral exploration, has become readily available, more reliable, and can be calibrated to the same standards as those developed for oil-well logging. The considerably lower initial investment, relative to oil-well logging equipment, results in lower logging costs. Most shallow-hole logging equipment has digital capabilities and on-board computer software that provides cross plots and on-location log analysis. These advantages, coupled with the increase in drilling costs, have made logging of freshwater wells more cost effective. The results have been an increase in water-well logging activity and a subsequent increased demand for better interpretation principles as applied to ground-water problems. Oil-well geophysical-log interpretation principles are well established but not directly applicable to hydrologic problems, partly because of differences in the chemistry of solutions that saturate the porous media.

Purpose and Scope

This report, prepared in cooperation with the City of Albuquerque, describes methods that can be used to estimate ground-water quality and aquifer permeability through the use of geophysical logs made in freshwater wells. These methods were developed using data collected from water wells completed in basin-fill deposits in the Rio Grande Rift from near Santa Fe to the southern boundary of New Mexico (fig. 1). These data, collected over a period of about 15 years, were used to correlate geophysical-log response to known characteristics of freshwater aquifers.

A unique method of calculating formation-water resistivity from geophysical-log analysis of wells completed in unconsolidated formations was investigated, and the results of the study are described in this report. This method can be used as a guide for determining availability and quality of ground water by use of synergetic geophysical-log analysis. The unaltered use of the methods described in this report is limited to the boundaries of the study area (fig. 1); however, the methods could be applicable in other areas by adjusting the geophysical response graphs to the new lithologic environment.

During this study, a large empirical data bank was accumulated that involved numerous test-well data related to log response. Aquifer characteristics were evaluated in a number of wells penetrating unconsolidated formations, mostly in the Rio Grande Valley of New Mexico. Aquifer-test and water-sample data were collected, in some cases by using isolated sections of the test well but mostly by using a simple drawdown versus pumping rate and composite water sample. Close inspection of geophysical logs commonly indicated the most permeable sections of the drilled hole and the relative amount of permeability. Most wells completed in sand and gravel aquifers exhibit a wide range of permeability and commonly are separated by low-permeability clay, silt, and fine-grained sand sections.

For this investigation, accurate permeability data, and, therefore, the yield capabilities of the wells, were not as great a concern as the quality of water yielded by the wells. For this reason, data collection associated with the determination of the resistivity of the formation water was emphasized. However, the stratigraphic units spanned by a well may contain various sand layers containing water of significantly different quality, in which case the relative permeability of the various sand layers greatly influences the resistivity of the combined water. In these wells, the relative permeability of the aquifers is an important component in determining the suitability of the quality of mixed water for its intended use.

An overview of the basic function and theory of operation of several geophysical-logging devices is presented here. However, a more thorough knowledge of geophysical-log response would be helpful in the use of this report and the described process of aquifer analysis through geophysical-log interpretation.

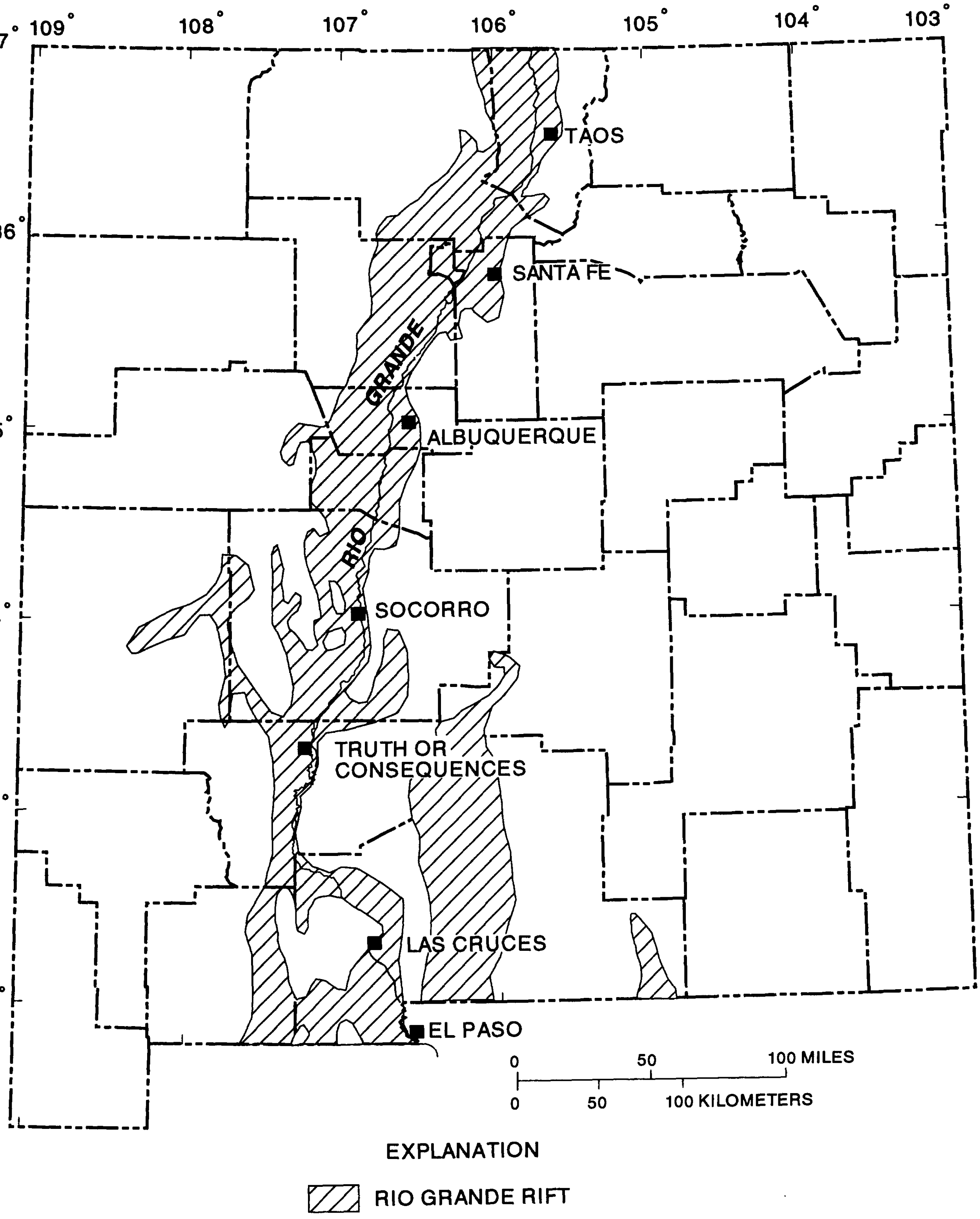


Figure 1.--Location of the Rio Grande Rift in New Mexico.

Geophysical Logs

The value of geophysical logs in evaluating physical properties of the rock matrix and contained fluids has been recognized for many years. Until recent years the costs of equipment and subsequent costs of geophysical logging have limited their use to oil and gas exploration. Several companies have recently developed small, inexpensive geophysical-logging equipment designed primarily for water-well logging. These small-diameter tools have good resolution and accurately measure electrical resistances and natural and induced radiation of geologic formations.

Geophysical logs provide a continuous analog or digital record that can be used to interpret lithology, bed thickness, potential aquifers or confining units, permeability, porosity, bulk density, hydraulic resistivity, moisture content, and specific yield. The source, movement, and chemical and physical characteristics of ground water also can be inferred.

Geophysical logs are repeatable and comparable even when made with different equipment. Repeat logs made many years after well completion and compared with previous logs might identify changes in rock matrix, water quality or temperature, gravel pack or well screen, and changes in aquifer. Repeat logging programs can assist in identifying causes of well failure and can be used as a guide for rehabilitation processes.

Log-interpretation principles are based on empirical data that are related to field exercises and laboratory experiments where the response and calibrations of the geophysical-log equipment are keyed to an environment. Because laboratory experiments cannot duplicate all the properties that influence log response in the field, basic principles established in the laboratory have to be adjusted as field data indicate. The log analyst needs to be knowledgeable of local geology, aquifer characteristics, and the mathematics of quantitative analysis to modify the basic interpretation principles. Scientific theories and equations developed in laboratory experiments can be tested through the empirical data collected in the field.

Numerous attempts have been made to equate geophysical-log response to geologic and geohydrologic characteristics of aquifers. In each case, knowledge of local lithology and hydrology and of the response of a particular logging tool to that environment has been the key factor in adjusting a theoretical equation to fit field conditions.

Although geophysical logs cannot replace adequate drill-cutting samples, drill-cutting samples are sometimes not sufficient to characterize aquifer water quality and hydraulic properties because of dynamic disturbances caused by the drilling action, lag time of the drill cuttings, and the introduction of drilling fluid into the aquifer. Conversely, the most intensive analysis of drill cuttings or cores cannot replace the value of in-place measurements of a suite of geophysical logs, but some properly taken and analyzed drill-cutting samples are essential to the interpretation of logs, especially in an unfamiliar geologic environment.

Multiple-log analysis takes advantage of the synergetic nature of many logs; the best interpretation is derived from a suite of logs and based on a thorough understanding of the equipment and principles of their operation and a thorough knowledge of local geologic and hydrologic conditions that affect log response. Basing answers and assumptions on too few data and on the first log that is run is a common mistake. Logs need to be interpreted on the basis of an assemblage of data, including a full suite of logs in the logging program; inspection of drill-cutting samples, cores, or drilling time chart; and checks against previous data sources, such as logs from the same stratigraphic unit.

Empirical knowledge of the ground-water basin can save steps in the synergetic evaluation of the log suite and can eliminate the need for some logs. For example, if the geothermal gradient is known to be normal, then the bottom-hole temperature can be closely estimated. Local knowledge of aquifer characteristics may lead to elimination of some geophysical-logging parameters not needed in the resolution of the immediate problem. Caution needs to be taken, however, in the elimination of any available data. Although some data may not be needed in the resolution of an immediate problem, future problems in the same area may require comparable log data.

Estimation of the depth to the water table is an example of the need for a synergetic evaluation of the log suite and the misleading conclusions that can be drawn as the result of too few data. Therefore, to be conclusive, most geophysical-log interpretations require two measurements that are in agreement.

In a mud-filled test hole, establishing the static water level is sometimes difficult but very important to the evaluation of the potential aquifer. The neutron log will usually show a definite shift at the ground-water table, especially in small-diameter holes; large-diameter holes or holes with deep mud invasion may cause the shift to be very subtle.

Figure 2 shows the neutron shift at the water table in a mud-filled hole. The water table is not always this obvious, but the evidence is a shift that indicates a water-content change not apparent in the lithology indicated by the gamma or long- and short-normal logs. The gamma log indicates no lithologic change at the water table, and the resistivity logs show a slight increase in resistivity, which supports the neutron evidence. The actual depth to water is at the midspan of the anomaly at 476 feet. The neutron log also shifts between 245 and 285 feet and near 335 feet, but the long- and short-normal logs show very low resistivity, which indicates clay, and, therefore, accounts for the saturated appearance.

In some cases, the water table may be masked by a clay zone at or near the static water table. Neutron logs do not distinguish between the bound water in the clay and the free water in the formation, which makes the determination of the water table very difficult.

Figure 3 shows gamma, neutron, and long- and short-normal resistivity logs in a well drilled less than 1 mile from the well referred to in figure 2. The sediments that this well penetrates are primarily clay with thin sand layers from approximately 390 feet to the total depth of the logs. If the geophysical logs were the only data available, then estimating the water table in the formation would be practically impossible. However, the water-table altitudes in other wells in this area indicate that the depth to water exceeds 450 feet. By close inspection of the long- and short-normal resistivity logs below 450 feet, the thin-bedded sand layer at 470 feet exhibiting a much higher resistivity than the sediments below 500 feet becomes apparent. The sediments are too thinly bedded to be recognized by the long-normal log, but a definite difference in the otherwise comparable sand layers is indicated in the short-normal log. Therefore, the water table is somewhere between 470 feet and 500 feet. A closer look at this 30-foot interval on the neutron log shows a subtle shift at 490 feet, which was the depth to water upon completion of the well.

In most ground-water production wells, an accurate, static water level upon well completion is not critical. Environmental evaluation test wells, however, usually have short screened sections placed at the water table, thus making an accurate water-level depth very important.

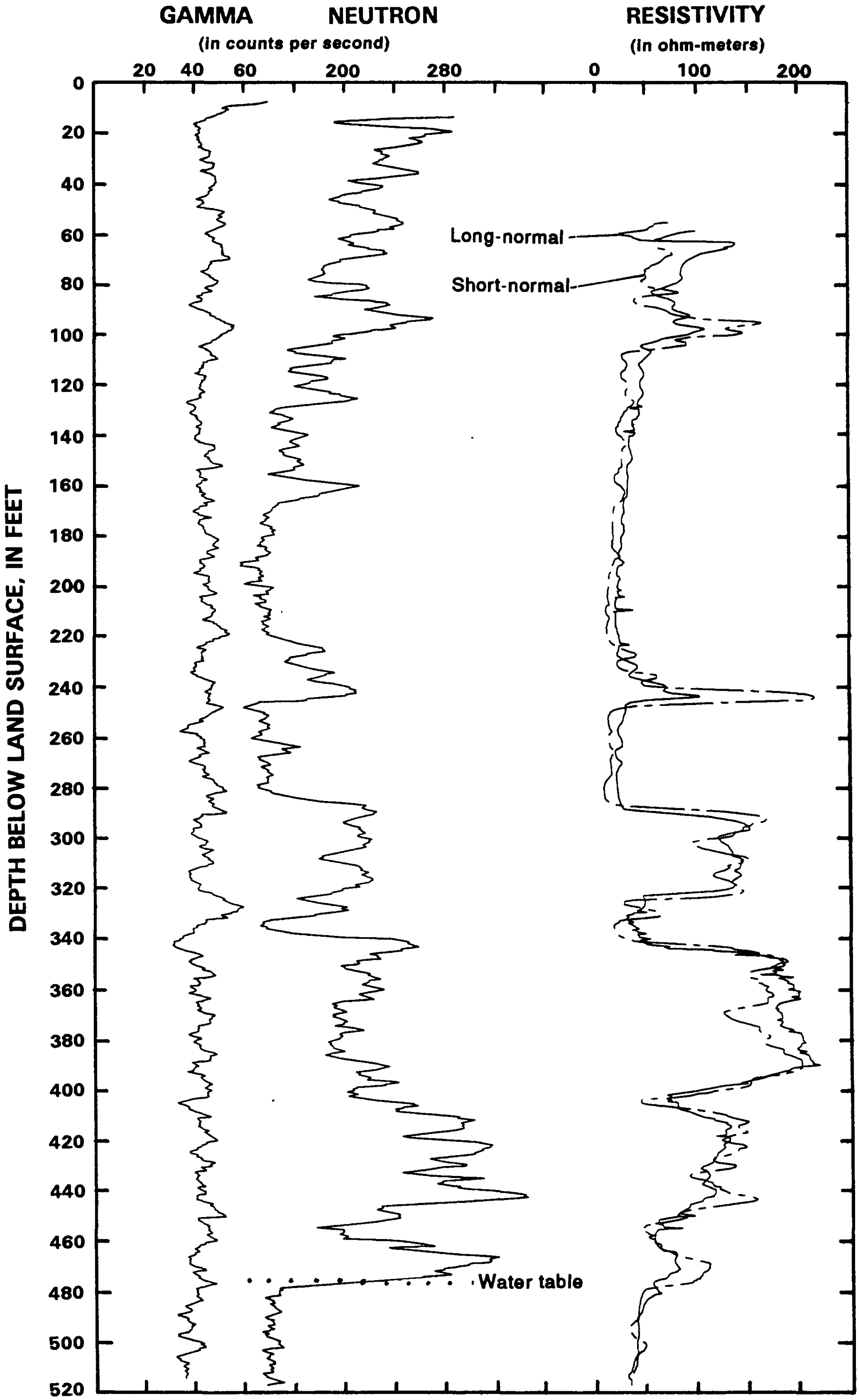


Figure 2.--Gamma, neutron, and long-short-normal resistivity logs showing neutron shift at the water table in a well near Albuquerque, New Mexico.

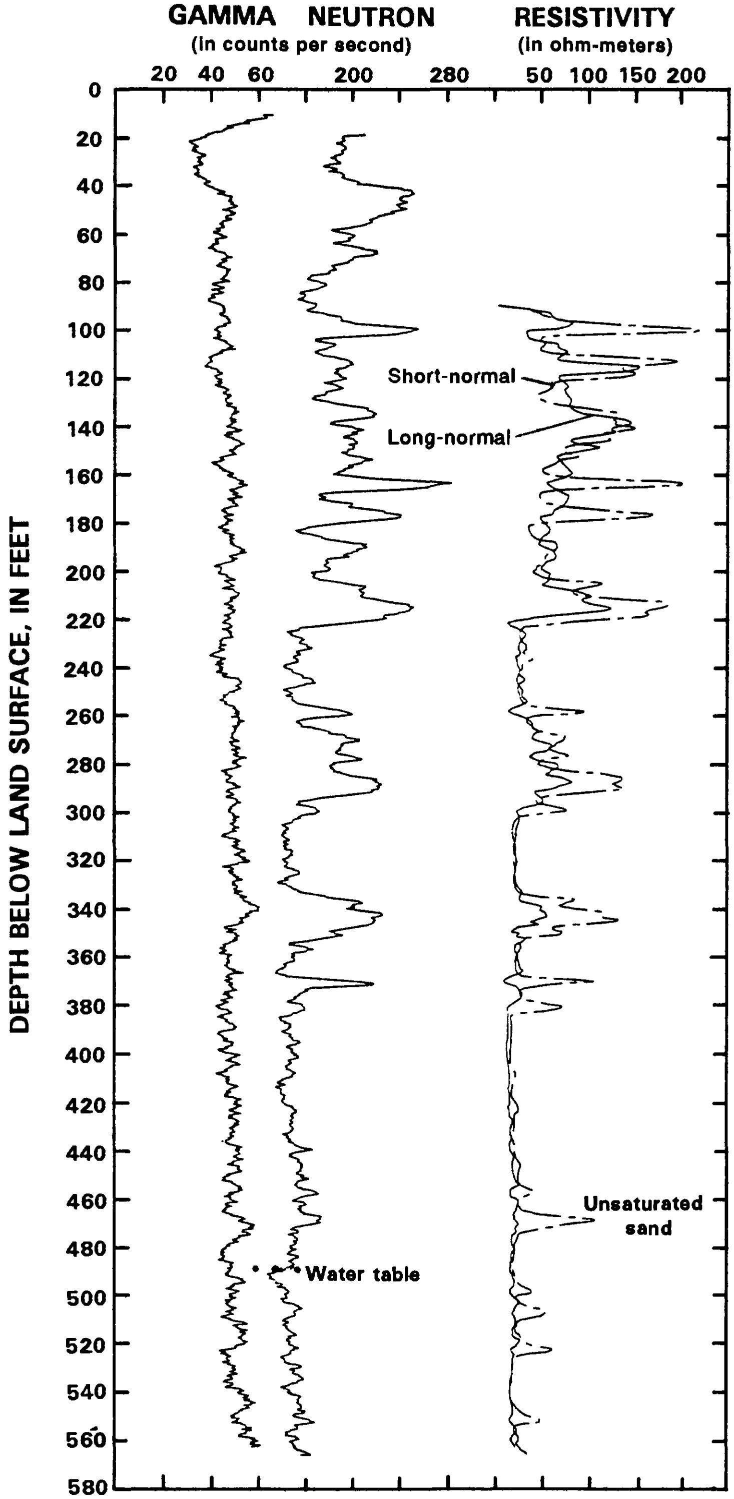


Figure 3.--Gamma, neutron, and long-short-normal resistivity logs showing a shift in the neutron log at approximately the water table in a well near Albuquerque, New Mexico.

Quality Assurance

Quality-assurance or quality-control procedures are essential for obtaining accurate geophysical logs that will meet the needs of the program. These procedures help ensure that the geophysical logs from water wells are accurate, reliable, and suitable for quantitative interpretation.

The logs required need to be determined before contacting a logging company, and the ultimate responsibility for quality logs is with the investigator who orders and accepts the logs. The investigator needs to be at the site and be qualified to recognize and assure that the best procedures are followed. The quality-assurance program requires continuous monitoring from the investigator as the logging proceeds, sometimes resulting in on-the-spot changes in the prelogging outline.

Commercial logging companies assign a project or logging engineer who is fully knowledgeable of the objectives of the quality-assurance program. A prelogging conference is needed to discuss the details of the information required. Such a conference aids in the selection of logs and decreases the probability of problems that could develop at the well site. Conference discussions need to include the purpose of logging; data to be acquired; well-construction information, including depth and diameters of the wells, restrictions, caving sections, lost circulation, and cemented or screened sections; and problems encountered during drilling, such as getting back on the bottom after drill-bit changes.

WATER-WELL GEOPHYSICAL LOGGING

The value of geophysical logs in ground-water hydrology is limited only by the lack of developed interpretation techniques, thus leaving the fundamental assumption that interpretation of logs is more art than science. To increase the value of geophysical logs in water wells, a simplified method of applying logger response to hydrologic problems is needed. In water-well logging, the most often asked questions are (1) where should the screens be set? (2) how much water will the well yield? and (3) what is the water quality? The answers to these questions are related to the permeability of the formation and the resistivity of the formation water. The use of water-well logging has frequently been limited to relative estimates of quantity and quality because of the lack of established interpretation techniques.

Reservoir evaluation that uses geophysical-log analysis in oil wells is a highly developed and well understood practice. Most attempts at ground-water applications have been extensions or variations of the theories established for oil-well log interpretation. A relation has been found in a laboratory environment, but this relation lacks merit in field use because of the much wider range of conditions often unaccounted for in laboratory experiments.

Many logging devices can assist in the solution of hydrologic problems. In this report, only two are used (neutron logs and long- and short-normal resistivity logs) for estimating formation water resistivity (Rw). This section describes the calibration method for those probes and a brief theory of their function. If this system of log analysis is applied to any other logger data, these calibration procedures need to be met or the graphs may need to be altered to fit the relative response of the other logger data. A third log (gamma) is discussed in the permeability estimates section.

Neutron Logs

Neutron logs are used mostly for delineation of porous formations and determination of porosity. These logs respond to the amount of hydrogen present in the formation. Neutrons are electrically neutral particles, each having a mass almost identical to the mass of a hydrogen atom. A cloud of neutron particles is emitted from the neutron source, penetrating the formation and colliding with nuclei of formation material and hydrogens. Because collisions with heavy nuclei do not slow the neutron down very much, it bounces off with very little loss in energy. Energy loss is greatest when the neutron strikes a nucleus of practically equal mass such as the hydrogen atom. The neutrons are slowed by hydrogen collision until they are captured, whereupon gamma radiation is emitted by the absorbing nucleus. During the slowdown process the energy level of the neutron becomes epithermal energy, equal to 0.1 to 100 electron volts (EV), and before capture the energy level is further slowed to thermal velocity, equal to 0.025 EV. Some probes measure this gamma ray energy as an indicator of hydrogen concentration.

The probe used in this study was a neutron-epithermal neutron device that has a lithium iodine crystal to detect mostly neutrons of epithermal velocity. The probe electronics further supply a window filter that screens energy not related to epithermal velocity. In this manner, fast neutrons, thermal neutrons, and gamma rays of capture are not detected. When the hydrogen concentration of the material surrounding the neutron source is large, most of the neutrons are thermalized and captured within a short distance of the source. If the hydrogen concentration is small, then the neutrons travel farther from the source before being captured. Therefore, the count rate at the detector increases for decreased hydrogen concentrations and vice versa. Clay causes errors in the log measurement of porosity because it contains bound water often equivalent to a porosity of 40 percent, but the connected porosity is very low.

Petroleum industry loggers and some water-well loggers use the American Petroleum Institute (API) calibration pits in Houston, Texas, for calibration of neutron logs. These pits contain three sets of six quarried marble and limestone blocks that represent known porosity values. The API pits are the accepted standard for neutron-log calibrations, but they are valid only for marble and limestone. Most large logging companies maintain calibration facilities of their own to calibrate to other rock types, such as dolomite and sandstone. The neutron logs used in the data collection for this report were calibrated in the limestone API pits but not corrected for other rock types.

Gamma Logs

All rocks contain some radioactive elements that emit bursts of high-energy gamma rays in the form of electromagnetic waves. Natural gamma logs can be made in open or cased, liquid- or air-filled holes, and are used primarily for identification of lithology and stratigraphic correlation. In sedimentary formations, the gamma log normally reflects the shale content of the formations because the radioactive elements tend to concentrate in clays. Nearly all natural gamma radiation encountered in the earth is emitted by the radioactive potassium isotope of atomic weight 40 and daughter products of uranium-238 and thorium-232.

Gamma radiation is detected in the gamma-probe configuration using a scintillation counter that detects pulses with amplitudes related to the energy of the impinging radiation. These pulses are amplified, shaped, and averaged over a predetermined time constant. The pulse count rate is displayed in pulses per second or pulses per minute. These are convenient units to work with because readily available pulse generators can be used to establish scales and standardize the equipment. Standardized, however, does not necessarily mean calibrated and without calibration logs cannot be compared quantitatively. Gamma probes that have different-sized crystals or different electronics may produce markedly different count rates adjacent to the same stratigraphic unit.

A problem with determining clay content using natural gamma logs is that established clay and sand gamma response values are very local and limited in areal use. Clean-sand and clay-response levels must be updated often, and are very localized because the relative amount of natural radiation fluctuates as local sedimentary conditions change during deposition of the sediments. Some sands are arkosic, containing potassium feldspar, which raises the gamma response drastically, sometimes higher than the response to adjacent clay. These feldspar-rich deposits, usually derived from a granite or gneiss origin, may cover a rather extensive area, but the relative amount of feldspar can vary from well to well within a single environment causing the relative gamma response also to vary.

Normal-Resistivity Logs

Normal-resistivity logging devices are calibrated on the surface using fixed resistors between electrodes. Figure 4 shows a schematic diagram of the system used by the U.S. Geological Survey. This diagram shows 100 ohms reference resistance placed across the electrodes. In practice, a decade box is used--so named because it has 10 position switches connected to resistors, in series, that are capable of switching resistance values from 1 ohm to more than 900,000 ohms in multiples of 10. The decade box has large clips, of the type used with battery jumper cables, that are attached to the electrodes to simulate the contact resistance and the formation resistivity. The equivalent resistance for various resistivities is calculated from the formula in Keys and MacCary (1971):

$$Ra = \frac{E}{I} 4\pi AM \qquad (1)$$

where Ra is apparent resistivity;
E is voltage, in volts;
I is current, in amperes; and
$4\pi AM$ is geometric factor for normal-resistivity devices.

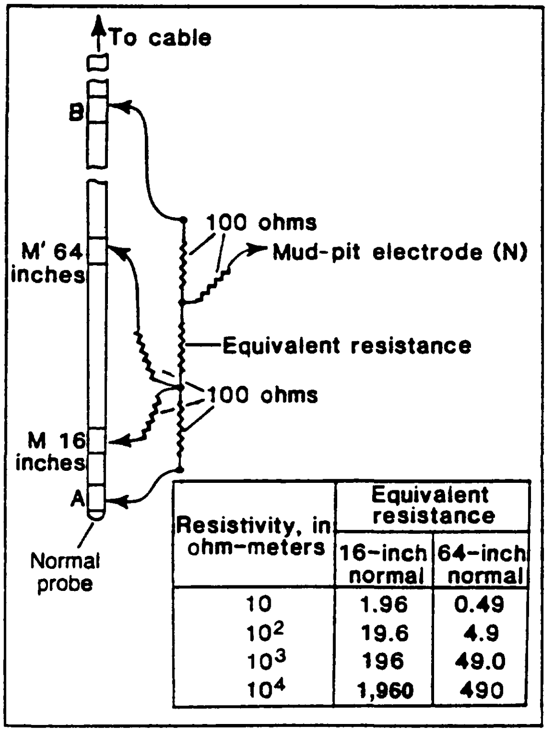
By Ohm's law the formula becomes:

$$r_f = \frac{4\pi AM}{R} \qquad (2)$$

where r_f is equivalent resistance of the formation; and
R is resistivity, in ohm-meters.

Values of r_f can be derived by substituting various values of R as shown in figure 4. A value of 1,000 ohms resistance through the decade box would simulate 196 ohms impedance to current flow from the short-normal electrodes.

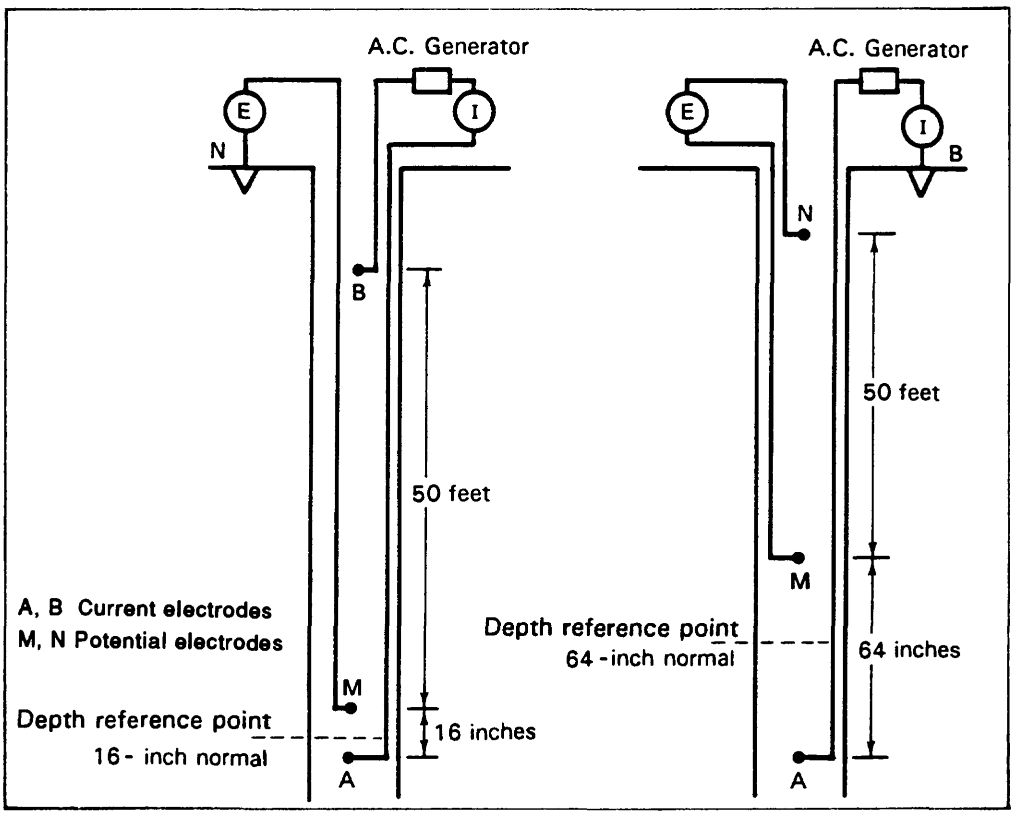
Normal-resistivity logging devices as described by Keys (1988) use a four-conductor logging cable: two conductors to carry the current to the A and B electrodes, and two conductors to carry the 16- and 64-inch potentials to the measuring circuit to be displayed or stored. Electrode A is at the bottom of a 7-foot rubber-insulated steel mandrel. Two M electrodes are located 16 inches and 64 inches above current electrode A. The M electrodes pick up the voltage changes for the 16- and 64-inch normal curves. The armored cable is insulated with a rubber sleeve for 50 feet above the mandrel where the cable-head connection serves as the remote current electrode (B) as shown in figure 4. The ground probe is placed in the mud pit and acts as potential electrode N. The arrangement of the B and N electrodes are different in the 64-inch normal illustration (fig. 5) only to demonstrate that the physical location of these electrodes is insignificant as long as they are distant from the AM electrode group.



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	1,960	490

From Keys, 1988

Figure 4.--System for calibrating normal-resistivity logging equipment.



From Keys, 1988

Figure 5.--Electrode arrangements for 16- and 64-inch normal resistivity borehole logging.

Constant current is maintained between the current electrode located at the bottom of the mandrel (A) and a remote-current electrode (B) at a distance of 50 feet or more. The voltage for the 16- and 64-inch normal resistivity is measured between a potential electrode (M) for each distance.

The principles of measuring resistivity, as described by Keys (1988), are illustrated in figure 6 where one ampere of current is passed through a cubic-meter block of material from a 10-volt battery. The constant current is passed between electrodes A and B, and a voltage drop of 1 volt is measured between potential electrodes M and N, which in the example are located 0.1 meter apart. By Ohm's law,

$$r = E/I = V/A = 1 \text{ ohm} \quad (3)$$

and

$$R = (1 \text{ ohm}) \times S/L \quad (4)$$

where r is resistance, in ohms;
E is voltage, in volts (V);
I is current, in amperes (A);
R is resistivity, in ohm-meters;
S is cross-sectional area, in square meters; and
L is length, in meters.

Therefore R is 10 ohm-meters.

The current is maintained constant so that the higher the resistivity between M and N, the greater the voltage drop.

A solid-state power supply generates a square-wave alternating current that is transmitted to the electrodes by the cable conductors. Constant current can be maintained by placing a large resistance in series with the generator and the current electrodes, so that within a frequency range the same current will flow regardless of the resistance of the material. The current produced is changed by the resistivity-scale switch on the module. As the resistivity increases, the current decreases. To maximize the log response, the optimum scale and current need to be selected. If the current is too small in less resistive material, the potential drop will be too small, resulting in lack of deflection in the log. Too much current in resistive material will cause excess voltage and saturate the recorder circuit. A resistivity scale needs to be selected that will allow maximum deflection with a minimum of overrange anomalies, then re-log the overrange anomalies at a higher resistivity scale, displaying the re-log section on the original graph as a backup scale. Re-logging overrange anomalies is not necessary if the log data are digitized. The computer can adjust the overrange anomalies to full scale or plot them on a backup scale.

A properly calibrated normal-resistivity log is a good tool for determining ground-water quality; however, certain limitations of the probe function need to be recognized and accounted for in any method of water-resistivity calculation. Most logging companies have standardized their normal-resistivity probes so that two electrode spacings are used where the short-normal AM spacing equals 16 inches and the long-normal AM spacing equals 64 inches. Constant current is applied to a current electrode (A) at the bottom of the resistivity probe. The voltage drop is measured at the two potential electrodes (M) located 16 inches and 64 inches from the current electrode. The depth-reference point is at midpoint between the current electrode and each potential electrode. These two normal-log curves typically are run at the same time and are calibrated in ohm-meters squared per cubic meter of formation (ohm-m^2/m^3) but expressed simply as ohm-meters. Normal electric logs measure the apparent resistivity of a volume of formation surrounding the logging-probe electrodes. The depth of investigation is relative to the resistivity and bed thickness, but is considered to be twice the AM spacing. The short-normal probe is considered to measure only the mud cake and the invaded zone. The long-normal probe is considered to investigate the invaded zone and the zone where native formation water is present. The normal devices give poor results in highly resistive rocks and do not function at all in very saline environments.

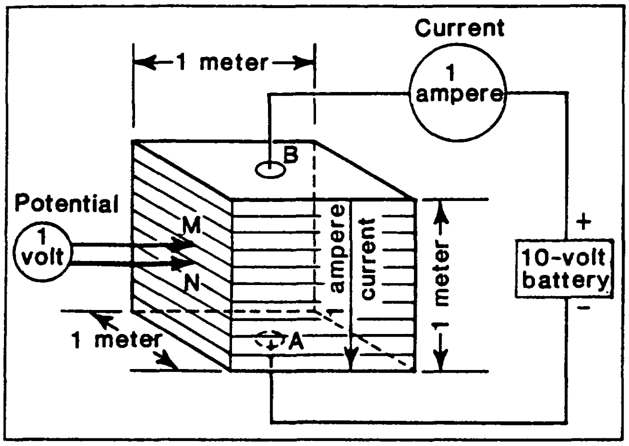
The major limitations of the long-normal resistivity log are the poor resolution in thin beds and the averaging effect in interbedded clay and sand. The bed-thickness effect, which makes the logs difficult to interpret, is a function of the electrode spacing as shown in figure 7. The theoretical-resistivity curve (solid line) and the actual log (dashed line) for a resistive bed, with a thickness six times the AM spacing (about 25 feet), are shown in the top part of the figure. As the long-short-normal electric probe moves opposite the sand bed from below, the measured resistivity gradually increases until the M electrode reaches the contact; the resistivity is then constant until the A electrode reaches the contact, when the curve shows a gradual increase in resistivity until the center of the bed is reached. The recorded apparent resistivity approaches but does not equal the true resistivity, and the bed is logged as one AM spacing thinner than the actual thickness.

When the bed is equal to or less than the AM spacing, the curve reverses as illustrated in the lower part of figure 7. The resistive sand bed actually appears to have a lower resistivity than the surrounding material, and the log does not indicate the correct bed thickness. Bed-thickness correction graphs are available in most log-interpretation manuals.

In practice, numerous parameters influence the relative response of electrical current transported through a porous medium. However, many interpretation problems encountered in oil-well logging are inconsequential or nonexistent in water-well logging. In water-well logging the drilling-fluid and formation-fluid resistivities are usually comparable, reducing the effects of invasion on the respective logs. In unconsolidated sediments, the mud-cake thickness on the borehole wall is often relative to the formation permeability. It is possible, in fact, to set up rather broad limits wherein the reading on the log may be used directly for true formation resistivity (Rt) or may be used with only a simple correction.

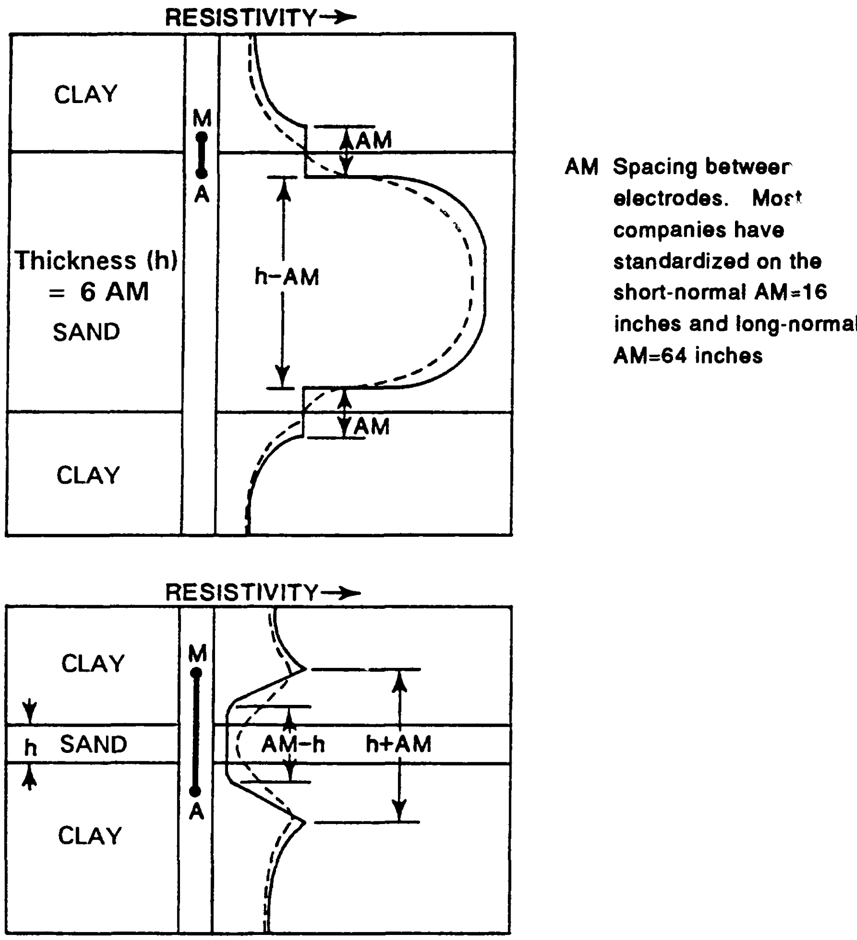
Even a very shallow invasion can cause a significant mud cake adjacent to permeable beds, causing a separation of long-normal and short-normal readings. This separation is commonly used by technicians as an indication of permeability if the drilling water and the formation water are comparable in quality. The short-normal reading may exhibit resistivity values equal to or higher than the long-normal reading when the formation water has a much lower resistivity than the drilling water and the sediments are permeable. These factors allow the invaded zone to become a significant influence on the short-normal reading but only a nominal influence on the long-normal reading (fig. 8). The long-normal reading reversed near 760 feet, exemplifying the thin-bed effect previously described.

This separation effect or anomalies that can be attributed to separate hydrologic properties of the formation are suggestive of synergetic resolution of the value needed to solve the equation for Rw. These anomalies indicate that short-normal resistivity is related to porosity as well as to resistivity of the water in the adjacent formation.



Modified from Keys, 1988

Figure 6.--Principles of measuring resistivity, in ohm-meters. Example is 10 ohm-meters.



Modified from Keys, 1988

Figure 7.--Relation between bed thickness and electrode spacing for normal probes at two thicknesses.

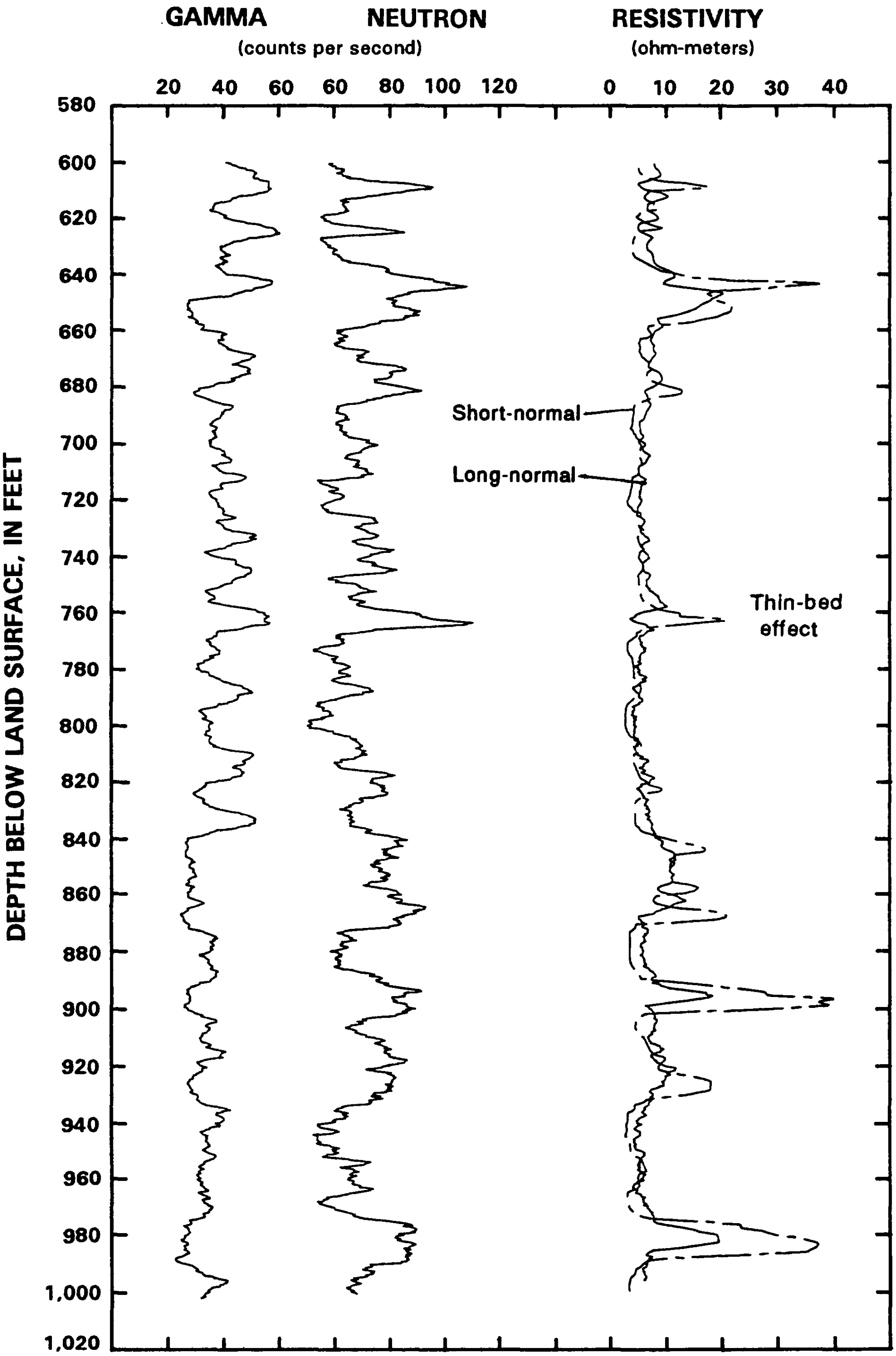


Figure 8.--Gamma, neutron, and long-short-normal resistivity logs showing example of thin-bed effect for a well near White Sands Missile Range, New Mexico.

The theory of operating water-well logging tools is identical to that of operating oil- and gas-well logging tools; thus, theoretically, the interpretation principles also follow. However, ground-water interpretation presents problems because the resistivity of saturated rocks and water saturating the rocks may be several orders of magnitude higher than those of many oil-field formation waters, and even low-yielding freshwater aquifers may have high porosity values compared to those of oil-field standards. This can result in invalidation of some of the assumptions commonly used in oil-field interpretation principles.

Numerous investigations have been conducted concerning the relation of bulk resistivity of the formation to properties of the formation, such as porosity and resistivity of the contained water. A brief discussion of some of those investigations is included in the following section.

USE OF LOGS TO ESTIMATE WATER QUALITY AND AQUIFER PERMEABILITY

Results of Previous Investigations

Estimates of formation-water quality originated from interpretation principles established in the oil-well logging industry, for which the prime objective of the log analysis is to distinguish between two dissimilar fluids and the relative quantity of each. Freshwater logging involves only one fluid, thus initial inspection implies that it is a simple matter to relate electric-log response to formation-water quality using the techniques developed by the oil-well logging industry.

Archie (1942) investigated the relation of water-saturated, clean sandstone to formation factor and found that the resistivities of the clean sandstone and the water could be related by the equation:

$$F = Ro/Rw \qquad (5)$$

where F is formation factor;
Ro is resistivity of formation 100 percent saturated with water; and
Rw is resistivity of formation water, in ohm-meters.

Further investigations by Waxman and Smits (1968) and Ransom (1977) established that porosity and permeability influence the value of the formation factor. The relation between F and the sandstone properties could be expressed more accurately when defined by the equation:

$$F = 1/\phi^m \qquad (6)$$

where F is formation factor;
ϕ is porosity; and
^{m} is a cementation exponent.

In this equation, apparent porosity is expressed as a decimal and ^{m} is an empirically derived exponent roughly related to the bulk density. In essence, this equation relates permeability to two porosity functions. The data from Archie (1942) indicate that for sandstone formations the value of ^{m} ranged from 1.3 to 2.6. For other lithologies, values of ^{m} ranged from 1.54 to 3.00 (Carrothers, 1968; Traugott, 1970). Pickett (1973) used a semilog graph plotting neutron porosity and resistivity of the water-saturated formation (Ro) to estimate the value of ^{m}. In Archie's (1942) investigation, which used data from saline-water aquifers that were drilled with saline mud, the formation factor decreased with increasing porosity.

Turcan (1962) used a field-formation resistivity factor (Ff) in shallow, clean, sand formations where a formation factor was established from empirical data and the same average formation factor was extended from well to well. This system established a field-formation factor from resolution of the equation F = Ro/Rw, where Rw is known. The long-normal resistivity is equated to Ro and corrected for temperature. Turcan labeled it field-formation resistivity factor (Ff) because it was not calculated from porosity data. Unknown Rw values were resolved by applying the field-formation factor established by data from previously logged wells in the same environment. The use of these Ff values requires that the sand remains clean and relatively constant in grain size and that Rw does not vary too widely.

Turcan (1962) applied the long-normal resistivity reading directly equal to the apparent formation resistivity (Ro), but he acknowledged that this is a valid assumption only in clean, well-sorted, water-yielding zones. A requirement for Turcan's system and the subsequent limiting factor is that sands must be free of clay and silt, which is not typical in sedimentary formations.

Alger (1966) found that the formation factor is also a function of the resistivity of the formation water in freshwater aquifers and that the formation factor decreases with increased Rw. Data from Alger (1966) also indicate that the customary relation between F and porosity, widely used in oil-well interpretation, does not apply to freshwater sediment because F varies not only with porosity but also with Rw and grain size. These data also show that both Archie (1942) and Humble Oil Company formulas, when applied to freshwater saturants, result in the formation factor being appreciably lower than those applied to petroleum industry log interpretation.

Alger (1966), using data from a study by Sarma and Rao (1963), indicated a relation between grain size and the ratio Ro/Rw in freshwater aquifers. Smaller grain sizes reduce the value of the formation factor (F), which is the reverse of that normally encountered in oil-field interpretations. Alger (1966) attributed this anomaly to surface-conductance effects, and his laboratory measurements confirmed that increased grain size causes a subsequent increase in the ratio Ro/Rw and the formation factor, when using formation waters of identical solutions. These data indicate that the standard equation F = Ro/Rw leaves considerable room for error because the influence of grain size is not taken into account in the standard oil-field interpretation equation.

Alger (1966) simply worked the data backward from known Rw to establish areal formation factors, which does not account for the wide fluctuation in effective porosity commonly found in sedimentary formations. Alger concluded that a basic relation exists between geophysical-log data and ground-water parameters and that collecting and using local empirical data result in the most reliable and accurate interpretations.

The clay content of the aquifer is a significant factor because ion exchange by clay minerals increases the conductivity of the water in the pore spaces, even though the water is very resistive after extraction from the rock (Keys and MacCary, 1971). If the saturating water is highly saline, the increase in conductivity produced by ion exchange is relatively minor, but in freshwater aquifers ion exchange from rocks may drastically alter the resistivity of the water while in close contact in the rock pores.

Keys (1988) stated that the formation factor tends to be relatively consistent for a given aquifer within a single depositional environment. This is true if the recorded resistivity is a result of clean, clay-free sands saturated with water of approximately 5 to 15 ohms. When the sediments become clayey, however, the formation factor, as a product of the Ro/Rw ratio, can fluctuate drastically, and it becomes evident that the long-normal resistivity reading is not directly equal to the resistivity of a clean, clay-free, saturated sand formation.

Guyod (1966) found that the formation factor is approximately related to effective porosity. Guyod showed how porosity and resistivity data from geophysical logs can be used to determine the salinity of the interstitial water (Rw). If all factors are equal, the higher the porosity and salinity, the lower the aquifer resistivity (Ro).

Bear (1972) reviewed the existing information concerning formation factor and concluded that formation factor is a function of effective path length and effective cross-sectional area of current flow in a nonconducting porous medium. By using three idealized models of porous medium, Bear was able to relate formation factor to porosity and tortuosity. Depending on the current flow channels, the following equations were used for these different models:

$$F = \frac{1}{n\sqrt{T^*}} \text{ or } F = \frac{1}{n\overline{T}^*} \text{ or } F = \frac{1}{n^2\sqrt{\overline{T}^*}} \qquad (7)$$

where F is formation factor;

n is porosity;

T^* is tortuosity as related to three-dimensional flow in a straight capillary, porous medium; and

$\overline{T}^*$ is tortuosity as related to three-dimensional flow in a capillary tube, porous medium.

Different flow channels, in each idealized model, account for the different symbols for tortuosity. Tortuosity in a straight capillary flow model is related to the first equation and is probably closest to a simple, unconsolidated porous medium. This value is shown as T^*, whereas capillary tube flow is related to the second equation and is shown as $\overline{T}^*$. The third equation relates tortuosity to inclined capillary.

Bear (1972, p. 115) also stated that the general formula for formation factor can be stated as: $F = C(\overline{T}^*)n^{-m}$, where $C(\overline{T}^*)$ is less than 1 and is a function of tortuosity, and ^{m} varies between 1 and 2 and is a function of the number of reductions in pore-opening sizes. Bear (1972, p. 108-109) indicated that the permeability of a porous medium depends on the porosity, tortuosity, and average conductance of the pore spaces or channels in the medium, which is related to the cross sections of the channels in the medium. From this discussion permeability can be seen to be some function of formation factor.

Worthington (1977) investigated formation factor as related to intergranular permeability to resolve the paradox that certain sediments cause the formation factor to increase with intergranular permeability, whereas other sediments cause it to decrease within the same hydrologic parameter. Worthington's data show that surface conductance and tortuosity have a significant effect on calculated values of formation factor when the matrix-conducting sands contain freshwater; conversely, the high conductivity of brine suppresses any contribution to conduction by solid constituents, even in argillaceous sands. In freshwater aquifers, the conducting properties of the solid constituents can have a pronounced influence on the values of formation factor because the electrolyte concentration is generally not sufficiently high to suppress the effects of tortuosity and surface conduction. In argillaceous sands containing freshwater, the formation factor apparently varies with electrolyte concentration and must have a correction factor to determine a value that approximates the intrinsic formation factor. Worthington's data indicate that the apparent formation factor, as related to effective porosity and intergranular permeability, is useful only as the electrolyte resistivity decreases sufficiently to suppress the contribution by the solid constituents. Worthington further stated that relating formation factor to hydrologic properties generally is not possible unless corrections for matrix conduction have been applied.

Bear (1972) found that tortuosity impeded the flow of electrical current through a porous medium. Surface conductance and tortuosity probably are directly related so it is possible that Worthington's (1977) and Bear's (1972) data are in agreement and that the effects of fine-grained material have the same influence on both measurements. Bear defined tortuosity as a function of the average path length that the current follows through the pores relative to the total length as:

$$T = \left(\frac{L}{Le}\right)^2 \qquad (8)$$

where T is average tortuosity of a porous medium;
L is total length; and
Le is average path length.

Summarizing these investigations of formation factor and calculations of Rw reveals that using an empirical method to determine formation factor is the best approach. The failure in most field applications comes from the wide range of grain sizes commonly penetrated. Previous studies have concluded that the formation factor as a function of the equation Ro/Rw = F is valid only in clean, well-sorted sands. These restrictions are seldom met in field conditions and, when not met, F is an apparent formation factor, not the intrinsic formation factor needed in Rw calculations. In clean, well-sorted sands, the apparent formation factor is a product of a two-dimensional matrix--grain size and Rw--where F increases as grain size increases and Rw decreases. When fine-grained material becomes a part of the matrix, surface conductance and tortuosity increase, porosity and Ro decrease, and the formation factor increases. Most conclusions were in agreement that the intrinsic formation factor is a function of effective porosity and is adversely affected by the elements causing noneffective porosity, such as clay. The bulk resistivity (Ro) is influenced by permeability, or lack of permeability, as related to grain size, orientation, and distribution, as well as by the resistivity of the saturant. Clay and silt-sized material introduces a resistivity value not related to resistivity of the interstitial waters, and any calculations of Rw need to account for this effective resistivity discrepancy.

The missing component in most equations appears to be a correction for clay and silt content in the matrix. A method was needed to differentiate low resistivity due to water quality from low resistivity due to clay or silt in the sand. In electric-log determination of water quality, subtle changes are often masked by the effects of porosity differences. A fine-grained or poorly sorted sand that contains highly resistive connate water may exhibit a low electrical resistivity, which is indicative of poor quality water.

Distinguishing between Electrolytic and Matrix Conduction

As pointed out by several investigators, the use of oil-field practices for estimating water quality in freshwater aquifers results in poor estimates of the resistivity of the formation water. The assumptions that apply to the oil-field saline environment do not strictly apply to freshwater aquifers. The effect of clay and other fine-grained material is significant on the effective porosity of freshwater aquifers, which influences the estimation of formation factor using equation 6. The conduction of electricity by the matrix of the porous media cannot be ignored in freshwater aquifers. In formations containing saline water and drilled with saline mud, the electrical current is conducted primarily through the pore fluid. In freshwater formations, conductive material in the matrix generally has a greater influence on the measured resistivity of the formation (Ro) than the pore fluid. Resistance to electrical current is reduced by the amount of conductive material in the matrix, such as clay, silt, and poorly sorted or fine-grained sand. Conduction of electricity by the porous media results in a measured Ro value that is not appropriate for estimation of Rw using the standard equation Rw = Ro/F.

If the Ro value could be corrected for all the conductive elements in the matrix, the corrected Ro would then equal Rw and a formation factor would not be needed. The clay portion of the matrix is the only element that directly relates to log anomalies, and this correction can be used as a first step in correcting bulk resistivity for the effects of conduction through the solid material in the matrix. Generally the matrix has other conductive values in the form of fine-grained sand and silt, causing permeability and resistivity reduction that is inferred only on log anomalies. These effects are more difficult to correct, but are an important part of bulk resistivity. Because these conductive and tortuosity effects have no direct log measurement parameters, they must be related to a base standard. The base standard was assumed to be a formation-factor value of 3.0 for clean, well-sorted sands, and any deviation from that value, after clay correction, was assumed to be related to surface conductance and tortuosity of the remaining fine-grained material. These multiple-resistivity effects have long been a problem in log analysis when relating geophysical-log data to the resistivity of formation water in freshwater aquifers.

As a result of these problems, data were collected and new approaches were developed to estimate water quality in freshwater aquifers by using geophysical logs. A method to correct the Ro value determined from the long-normal resistivity log for the effects of surface or matrix conduction was investigated first. Clay and silt-sized particles that are composed of compounds other than silica probably result in the largest amount of matrix conduction.

The neutron log was used to estimate the correction value for surface or matrix conduction, assuming that decreases in grain size result in increases in surface conduction and that clay has small grain size that results in increases in total porosity. The neutron log is the most accurate way to adjust the resistivity reading for the effects of clay. The neutron responds to hydrogen content in the matrix, treating bound water in clay as an indication of high porosity. Each variable influencing the permeability, and subsequently the resistivity, of the matrix needs to be accounted for to eventually reduce the matrix effects to nonconductive material saturated with water of Rw quality. In freshwater formations, clay has the most adverse effect on bulk resistivity (Ro). Therefore, a clay correction must be applied to Ro as a first step toward eliminating the effects of conductive material and arrival of a clay-free matrix (Ro_s).

To determine the amount of correction needed, a plot was constructed of long-normal resistivity values and known Rw at the same interval in the formation (fig. 9). Examination of this plot indicates two distinct pattern lines. The upper line represents data for formations that contain small amounts of clay, where Ro was nearly equal to Ro_s. The lower line represents data for formations that contain relatively large amounts of clay, where Ro was considerably less than Ro_s.

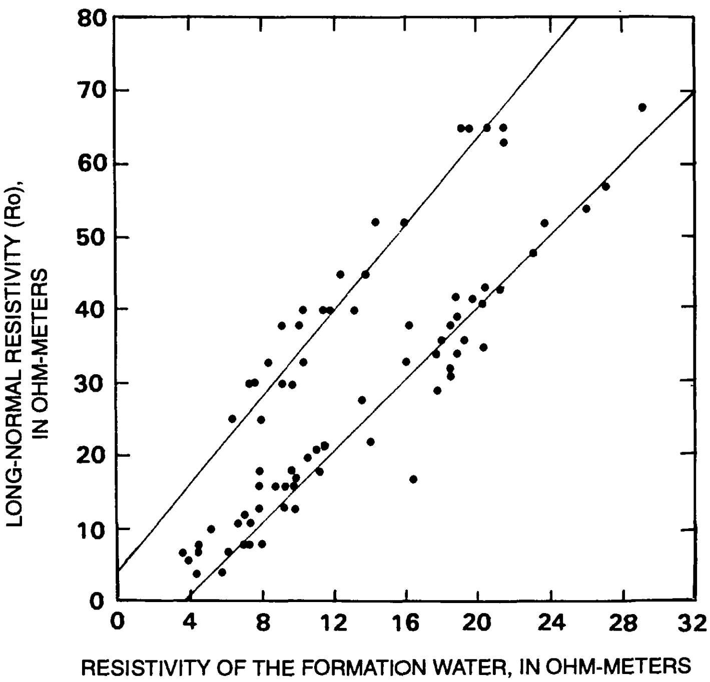


Figure 9.--Relation between long-normal resistivity and resistivity of formation water.

Determining the Formation Factor

From previous investigations and inspection of the sand line plots, clean, saturated sand apparently has a relatively constant formation factor. If sands are clean, contain no clay or silt, and are saturated with water with resistivity ranging from approximately 5 to 15 ohm-meters, a formation factor of approximately 3.0 was determined. The convergence of the lines as the Rw value decreases supports the conclusion that electrical current conducted through the pore fluid overcomes the effects of surface conduction in saline water. The data collection indicated that relatively few sampled intervals would contain enough clean sand to reach an F value of 3.0. Most intervals contained other fine-grained material that raises the F value above 3.0, and the departure from that value is related to the permeability-reducing elements in the matrix.

The departure of the lower line from the upper line on figure 9 was plotted against the neutron-log count rate to establish a clay correction graph (fig. 10). The data points for the upper line were assumed to be an average value for a clay-free matrix not completely free of conductive material. The value of the resistivity correction (Rc) that is needed to adjust Ro to the resistivity value of clay-free sand (Ro_s) can be determined from this graph as $Ro_s = Ro + Rc$. This results in a value for Ro_s that needs to be used instead of Ro in the formation-factor equation. This simple equation corrects only the resistivity of the matrix for the effects of clay.

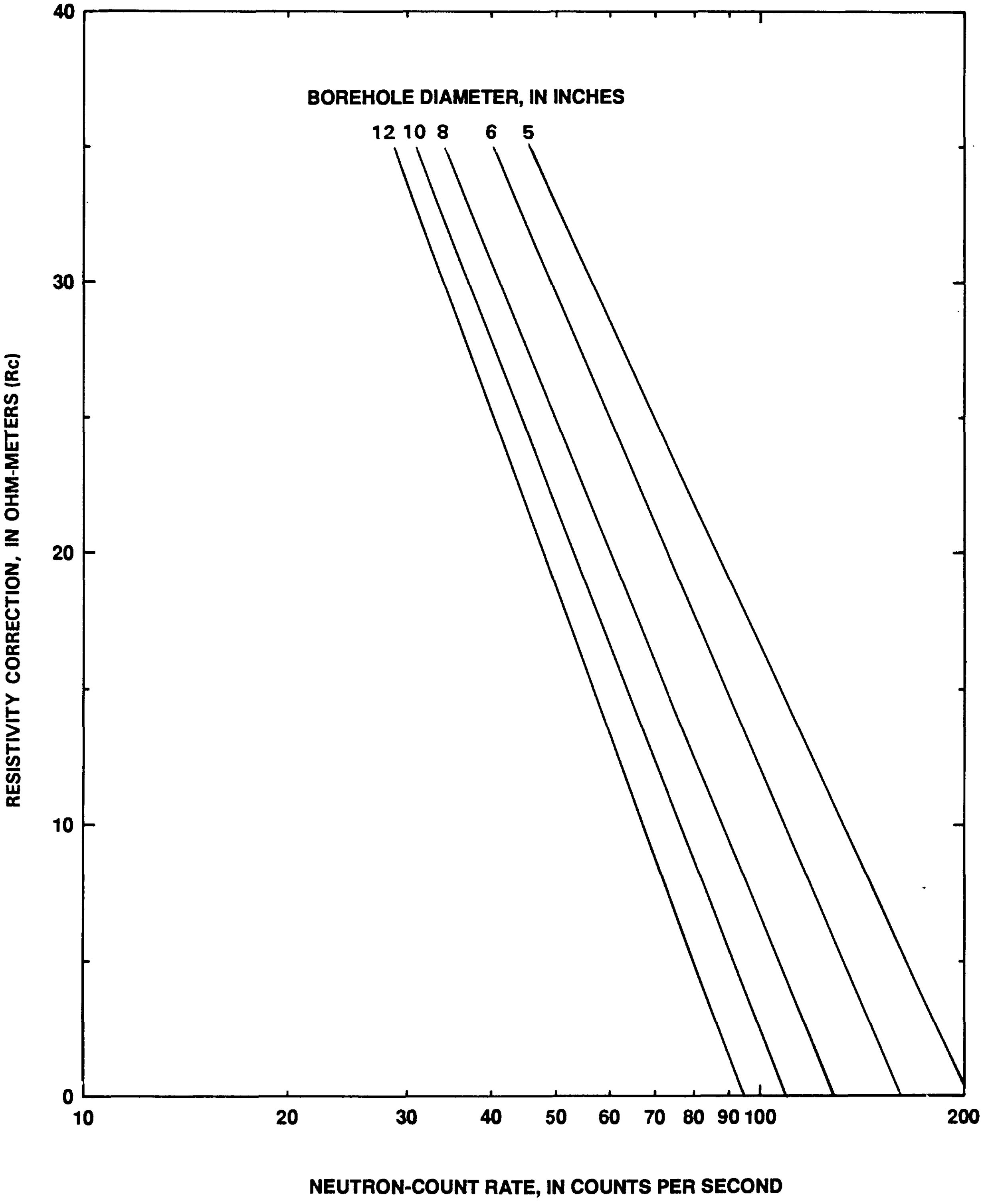


Figure 10.--Relation between resistivity correction and neutron-count rate.

The neutron-pulse count rate, rather than porosity, was used to construct the graph in figure 10 because the neutron log does not measure apparent porosity directly, but is related to porosity by calibration. Count rate is an easier, more reliable, and more accurate number to work with than porosity; however, it does limit the use of the graph to that particular probe because each probe crystal has a different response level. Figure 11 shows a plot of the apparent porosity and the neutron-count rate as calibrated in the API pits. It is a simple matter to substitute apparent porosity values, as shown in figure 11, for count-rate values used in the clay-correction graph or to compare neutron logs from other loggers that have been calibrated in the API pit, regardless of the basic unit exhibited. Most commercial loggers use a limestone porosity scale related to API units, which can usually be converted to counts per second if the conversion rate is known.

Figure 12 shows the same data points used in the plots in figure 8 after the resistivity correction (Rc) was added to the bulk resistivity (Ro). The data points in figure 12 indicate that the formation factor, as a function of the ratio Ro_s /Rw, ranges from about 3.2 for very fresh water to about 4.3 for highly conductive water.

A number of other factors influence the resistivity and the permeability that must be included in the final determination of Rw, using the equation:

$$F = \frac{Ro + Rc}{Rw} = \frac{Ro_s}{Rw} \qquad (9)$$

where F is formation factor;
Ro is bulk resistivity;
Rc is resistivity correction;
Rw is formation-water resistivity; and
Ro_s is resistivity value of clay-free sand.

The remaining factors that need to be accounted for in the matrix are, like the formation factor, related to permeability; therefore, the effects of grain size, orientation, and distribution would be accounted for in the determination of formation factor.

These permeability-influencing factors are reflected in resistivity measurements by the effects of surface conductance along the grain/aqueous interface and through the electrical path as related to tortuosity. The current path length (Le) through the formation is related to the length of the sampled formation (L), previously described in equation 8. The length that the electrical current must travel through available pore spaces to arrive at distance L is directly related to the parameters influencing permeability.

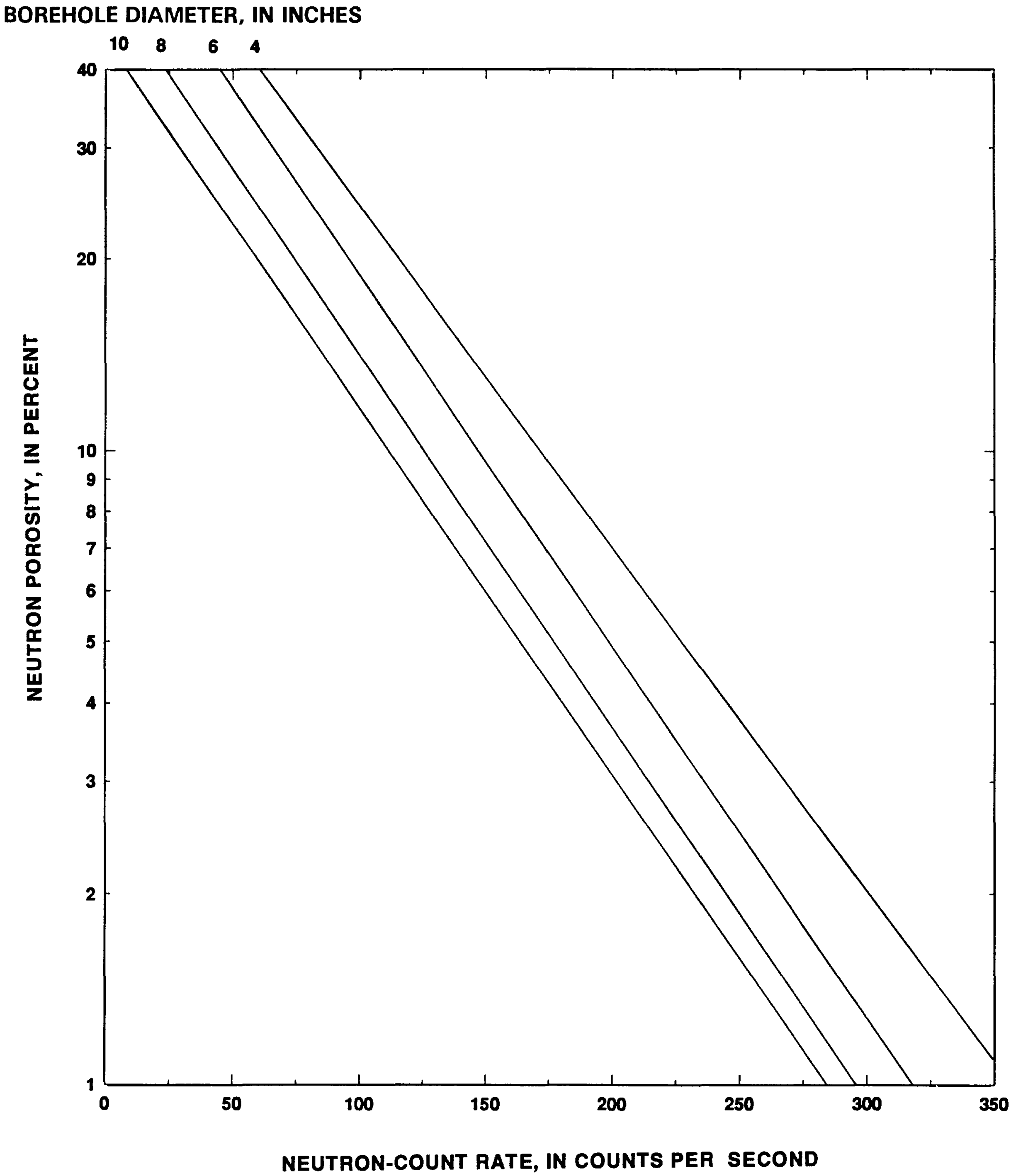


Figure 11.--Relation between neutron porosity and neutron-count rate.

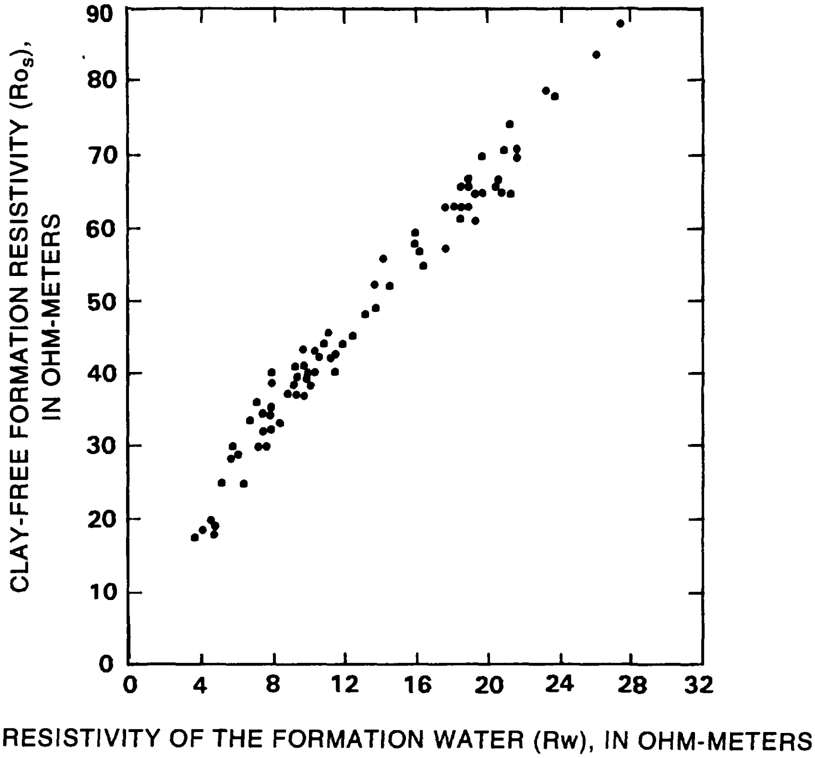


Figure 12.--Relation between clay-free formation resistivity (Ro_S) and resistivity of formation water (Rw).

The area of measurement is dependent on the AM spacing of the long- and short-normal resistivity probe. The long- and short-normal resistivity values are affected by permeability and assumed to be related to tortuosity. Permeable formations are invaded by the over-pressure drilling fluid and produce a mud cake on the borehole wall, which results in a long- and short-normal resistivity differential. These differential resistivity values are directly related to the same variables that influence permeability. In this manner, normal resistivities are used in the calculation of a formation factor that relates the parameters of permeability and makes the final adjustment to the matrix resistivity needed to calculate Rw. Formation factor is determined from figure 13 upon solution of the equation:

$$\Delta F = SNR\sqrt{LNR/SNR} \tag{10}$$

where SNR is value of the short-normal resistivity; and
LNR is value of the long-normal resistivity.

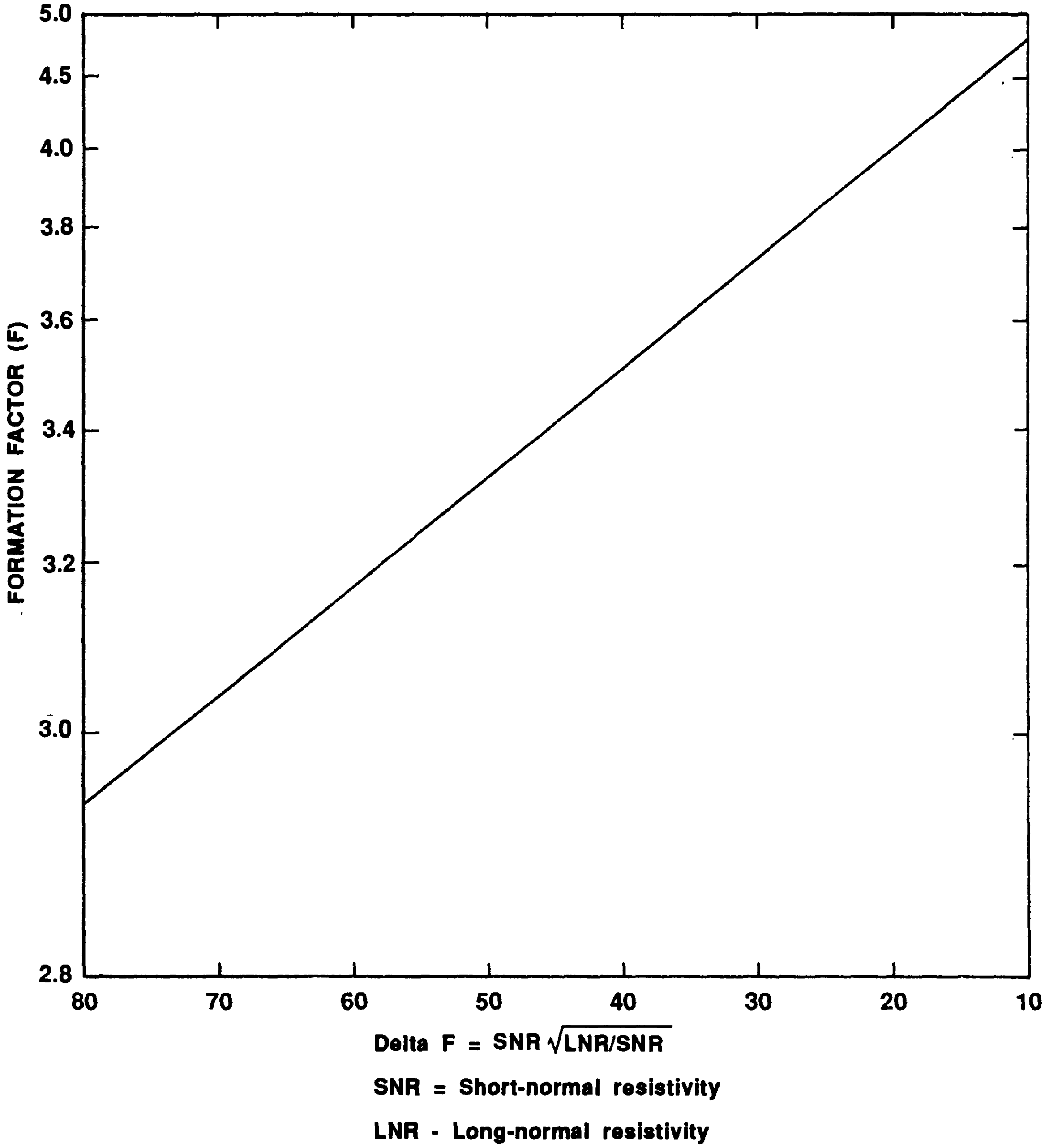


Figure 13.--Relation between formation factor (F) and delta F (ΔF).

The value of ΔF was plotted against the apparent formation factor determined by the ratio Ro_s/Rw, using clay-corrected resistivity values (Ro_s) and known resistivity of the formation water (Rw). This is based on the assumption that the formation factor in clean, well-sorted sand is approximately 3.0, and that any difference is related to tortuosity by the ΔF equation. After the matrix resistivity has been corrected for solid conductance and tortuosity of current flow by fine-grained material, surface conductance is relatively constant and requires no additional correction.

This system relates the formation factor to effective porosity using the original Archie (1942) formula $F = 1/\phi^m$ but using different parameters to establish effective porosity. From the previous discussion it can be seen that the matrix conduction is corrected for conductive elements not related to fluid conduction. These corrections are made by eliminating clay effects to arrive at a clay-free matrix (Ro_s); the remaining conductive material effect, in the matrix, is eliminated by the formation factor (F) upon solution of the ΔF equation, then $F = Ro_s/Rw$.

The formation factor increases with decreased grain size, as the original Archie (1942) equation was presented. The formation factor and ΔF are not just a product of porosity but are also related to Rw. Porosity can be unchanged but if Rw decreases, then ΔF decreases. If porosity causes an increase in the separation of long-normal and short-normal resistivities then ΔF increases and F decreases, indicating that more of the bulk resistivity is due to porosity and less to Rw. If Rw causes less separation and porosity is low then long-normal and short-normal resistivities are low and ΔF decreases.

Data Tests and Theoretical Examples

Figure 14 shows hypothetical geophysical-log data that exemplifies anomalies typical of predominately clay and various mixtures of clay and sand as a function of apparent neutron porosity. Section A of figure 14 indicates a relatively low short-normal and long-normal reading (20 ohm-meters). Although this could indicate that the low resistivity is due to clay, the neutron reading is much too high for substantial quantities of clay; therefore, the lower resistivity is only partly due to clay and partly due to conductive water in the pore spaces. If the neutron-count rate had been lower, suggesting a higher clay ratio and therefore a more substantial part of the total resistivity due to clay, the resistivity of the water would have been higher as shown in section F. The water quality represented in section F is better than that represented in section B even though the long- and short-normal resistivity values are less because a larger part of the apparent resistivity is due to clay. The apparent resistivity correction for grain size is applied only if supported by the long- and short-normal resistivity reading. Section C shows high permeability and no clay effects. The high permeability, indicated by the large difference in long- and short-normal resistivities, is responsible for the high value of Ro_s and is the reason that Rw is lower than that in section E, which has the same Ro value. Section E shows some clay, as indicated by the Rc value, which means that the water quality has to be better than that in Section C for the Ro values to be the same. As compared to Section C, the clay effect lowered the permeability, which also lowered the resistivity of the long normal and raised the resistivity of the short normal. Sections D and G show the same resistivity values but section G is much higher in clay content, which accounts for some of the resistivity. If the water quality had not been better in section G than in section D, the resistivity value would have been lower.

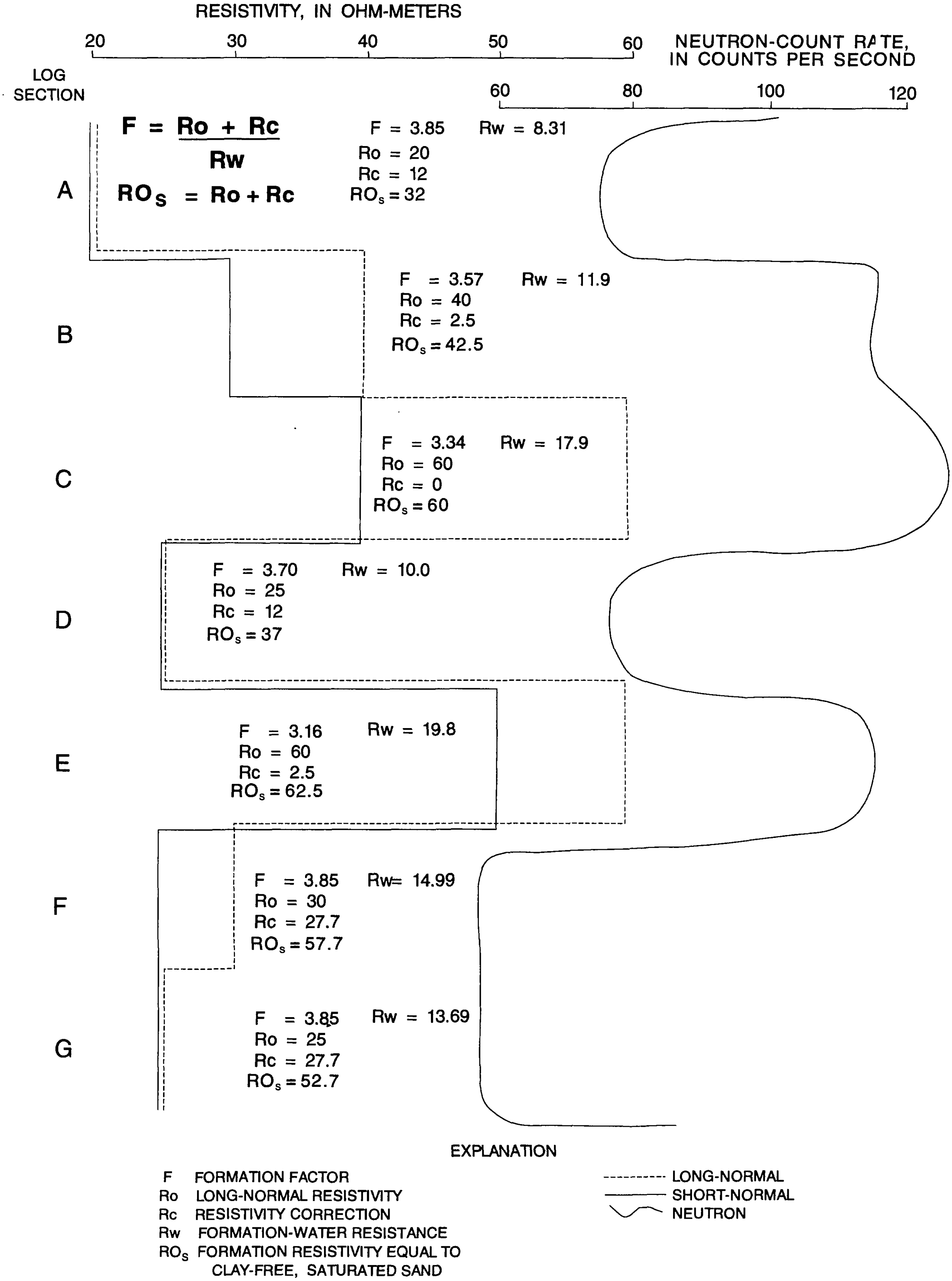


Figure 14.--Examples of hypothetical geophysical-log data representing clay units and sand aquifers, showing typical long-normal, short-normal, and neutron response.

Table 1 lists the wide range of uncorrected formation factors found in a well where the long-normal reading was applied directly equal to Ro, and the Rw value was identified from samples collected from isolated sections. Samples 7 and 9 have almost identical formation-water resistivities (Rw) and different formation factors (uncorrected) when relating Rw as a ratio of the long-normal resistivity value. This is actually a field-formation factor, or apparent formation factor, as established by Turcan (1962), but it exemplifies the influence of fine-grained material without regard to Rw. The long-normal reading (LNR) was applied directly equal to Ro, and the formation factor (uncorrected) was calculated from known Rw values using the standard equation F = Ro/Rw; the resultant apparent formation factor fluctuated widely without regard to Rw.

The formation factor (corrected) is related to the short-normal and long-normal resistivity shown in figure 13, and Ro_s is a function of LNR and a clay-correction (Rc) value determined from figure 10. By this method, Ro is adjusted equal to a clean sand containing water having a resistivity value of Rw. The formation factor (corrected) is a more stable value that is now related to a function of porosity and is not totally dependent on Rw and a resistivity value that may be depressed by clay or silt in the measurement parameter.

The short-normal reading in sample 7 is higher than the long-normal reading, indicating invasion of drilling water of a higher resistivity than the formation water. The fact that invasion occurred indicates that part of the resistivity reading is influenced by porosity as well as Rw.

Table 1.--Range of formation-factor values using uncorrected and corrected values of long-normal reading equal to the formation resistivity for a 9 7/8-inch-diameter well

[Rc = resistivity correction (neutron clay correction); Ro_s = resistivity of clean, saturated sand]

Sample number	Neutron reading (NR) (counts per second)	Short-normal resistivity (SNR) (ohm-meters)	Long-normal resistivity (LNR) (ohm-meters)	Resistivity of formation water (Rw) (ohm-meters)	Formation factor[1] (F) (uncorrected) (ohm-meters)	LNR + Rc = Ro_s (ohm-meters)	Formation factor[2] (F) (corrected) (ohm-meters)
1	115	46	71	23.0	3.22	74	3.09
2	120	45	65	19.9	3.26	65	3.26
3	130	58	65	20.6	3.15	65	3.15
4	120	32	45	12.6	3.56	45	3.56
5	100	15	32	9.6	3.94	38	3.33
6	90	15	20	6.8	4.25	29	2.94
7	80	11	7	4.1	4.90	20	1.70
8	90	10	20	6.4	4.50	29	3.12
9	120	10	20	4.4	4.5	20	4.54

[1]F = LNR/Rw
[2]$F = SNR\sqrt{LNR/SNR}$

The following models exemplify the results of various sand and clay ratios when those are the only matrix changes. Model I is a hypothetical log response to a very clayey formation and models II and III show the results of replacing some of the clay with sands identical to the original matrix sand.

Model I Typical log response and calculations in very clayey material

SNR	LNR	Rc	Ro_s	ΔF	F	Rw
29	30	30	60	29.4	3.70	16.2

Model II Response when some clay is replaced with sand identical to original matrix material

SNR	LNR	Rc	Ro_s	ΔF	F	Rw
23	38	22	60	29.5	3.70	16.2

Model III Response when more clay is replaced with sand identical to original matrix material

SNR	LNR	Rc	Ro_s	ΔF	F	Rw
21	42	18	60	29.6	3.70	16.2

The long- and short-normal resistivities in model I are almost equal, signifying that invasion is very shallow and permeability is low, which are typical of a very clayey matrix. These resistivity values can also be nearly equal due to the drilling fluid being fresher than the formation water; however, if permeability is present, allowing invasion, then the Rc value would be lower because of less clay, and the Ro_s value subsequently would be lower. The calculation of Rw would then indicate formation water of lower quality. In some instances where formation-water resistivity is considerably lower than that of the drilling fluid, the SNR value may be higher than the LNR. If the resistivity values were reversed in Model III but the clay content remained the same, then:

SNR	LNR	Rc	Ro_s	ΔF	F	Rw
38	23	22	45	29.5	3.70	12.1

Thin-bed effects can also cause reversal so care should be taken to ensure that the observed resistivity values are representative without correction.

In formations having low permeability, the short-normal and long-normal resistivities are very nearly equal and are very close to the true formation resistivity (Rt), which is the resistivity value of the complete matrix, void of invasion or mud cake. When sand becomes part of the LNR value, LNR - ΔF reflects the sand part; LNR increases because of the introduction of nonconductive sand particles, and Rc decreases because some clay is replaced by sand. If the proportion of sand is the only element changed in the matrix, Ro_s remains the same and, because Rw is not changed, ΔF remains the same. These models reflect only the effect of clay on a clean, well-sorted sand matrix. If both clay and silt had been added to the matrix, all of the values would have changed except Rw.

Table 2 shows data for four wells that were logged and then sampled by isolating intervals in the well and producing water from the screened interval until the specific conductance stabilized. Specific conductance is derived from laboratory analysis of samples collected near the end of the production period. These wells were selected because they represent a range from nearly clean sand to pure clay and from very good quality to very poor quality water. In shallow aquifers the comparison of calculated formation-water resistivities to laboratory and field specific conductance is generally good, but in deeper parts of the aquifer the variation is greater between measured and calculated values, indicating the need for a temperature correction.

A graph originally published by Alger (1966), then modified to cover a wider range of salinities and lower temperatures and specific conductance by Keys and MacCary (1971) is shown in figure 15. If the fluid temperature is known, figure 15 can be used to adjust the calculated Rw to the base standard temperature of 25 degrees Celsius. Circulated drilling fluid tends to seek a level in the borehole and invaded zones, causing a false thermal gradient and invalidating fluid-temperature logs in recently drilled holes. Bottom-hole temperature can be measured by a maximum-reading thermometer and corrected to equilibrium temperatures by methods described in Summers (1972). The equilibrium bottom-hole temperature is used with the average shallow ground-water temperature to establish a temperature-depth relation. From this relation, the temperature at any depth can be estimated.

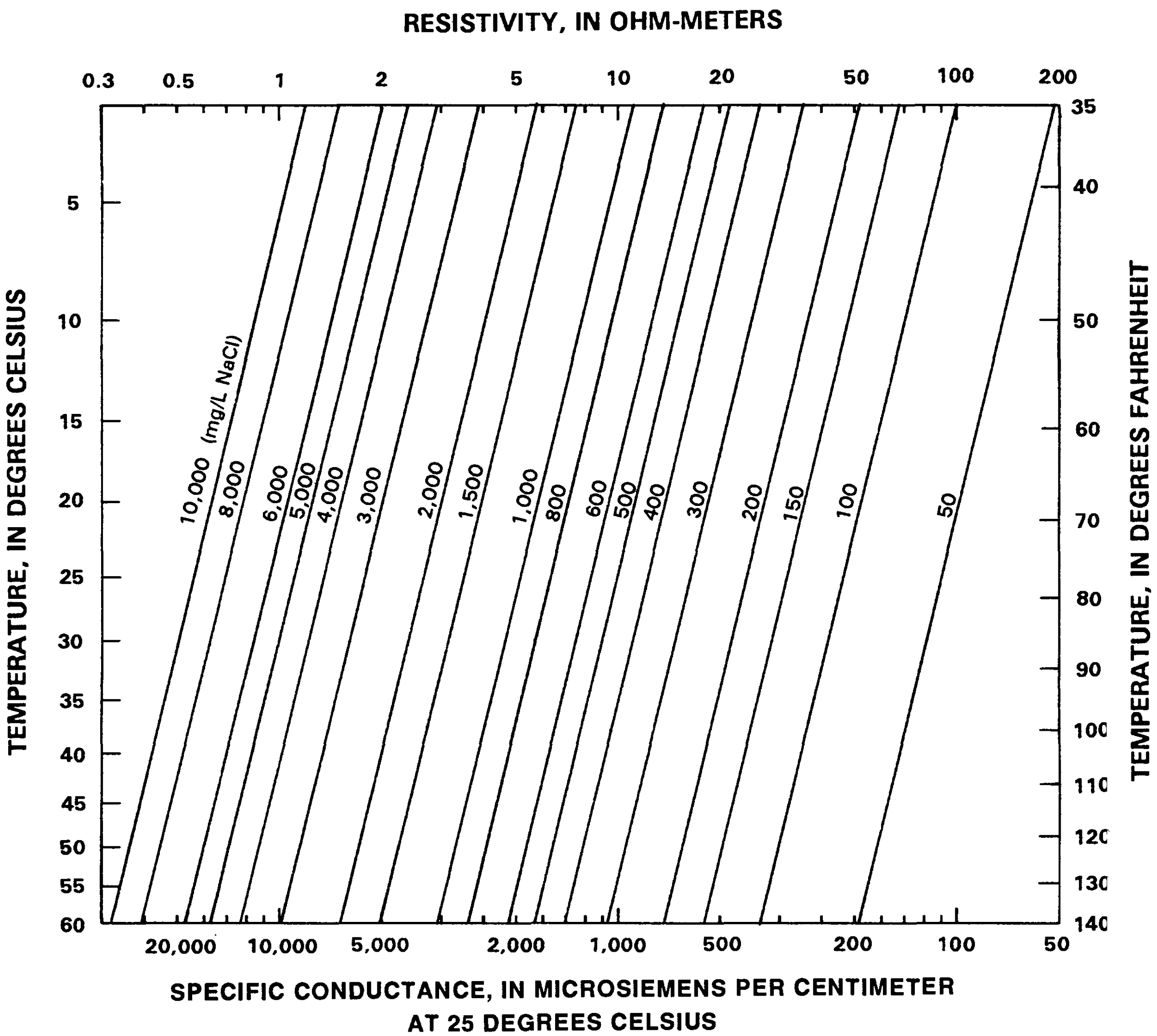
A carefully calculated formation-fluid resistivity value may be more accurate than the laboratory conductivity of the corresponding sample because an uncontaminated formation spot sample is rarely achieved by standard drill-stem tests or by blowing large volumes of air through steel pipe. Repeated temperature and conductivity logs made in new wells indicate that reaching chemical and thermal equilibrium may require as much as several months.

Neutron and short-normal and long-normal resistivity logs made in a deep, unconsolidated formation are shown in figure 16. This formation contains thick layers of relatively impermeable sandy clay that separate sand aquifers with different water quality. The logs indicate the highest permeability and also the freshest water in the section between 1,510 and 1,690 feet. The section between 1,570 and 1,590 feet was isolated and pumped long enough for the conductivity of the water to stabilize. The data for this well are listed in table 2, well 1.

Table 2.--Geophysical-log data for four wells sampled by isolating well intervals

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; SNR, short-normal resistivity; LNR, long-normal resistivity; Ro_s, a sum of LNR and resistivity correction from fig. 10; Rw, resistivity of the formation water; --, no data]

Sample interval (feet)	Specific conductance (laboratory) (μS/cm)	Specific conductance (calculated) (μS/cm)	SNR (ohm-meters)	LNR (ohm-meters)	Diameter (inches)	Neutron-count rate (counts per second)	Formation factor (fig. 12)	Ro_s	Rw (ohm-meters)
				Well 1					
458-478	829	730	26	28	10	46	3.80	52	13.68
707-712	846	901	17	21	9 7/8	45	4.10	45.5	11.09
800-820	993	932	18	20	10	46	4.10	44	10.73
1,570-1,590	584	610	30	38	10	50	3.63	59.5	16.39
1,780-1,800	2,180	1,388	8	11	9 3/4	44	5.00	36	7.20
				Well 2					
518-528	1,210	1,012	14	18	9 7/8	45	4.35	43	9.88
800-820	2,330	1,449	8	12	9 7/8	50	4.85	33.5	6.90
				Well 3					
400-410	1,250	1,298	16	16	9 7/8	58	4.35	33.5	7.70
450-460	1,210	1,269	15	16	9 7/8	55	4.40	34.7	7.88
430-440	1,210	1,269	14	18	9 7/8	60	4.35	34.3	7.88
620-630	1,400	1,366	17	13	9 7/8	54	4.40	32.2	7.32
730-740	2,050	2,145	7	8	9 7/8	60	5.25	24.5	4.66
840-850	2,150	2,227	4	4	9 7/8	52	5.45	24.5	4.49
910-920	2,220	2,242	10	7	9 7/8	60	5.22	23.3	4.46
				Well 4					
235-245	510	576	32	34	7-7/8	42	3.66	63.5	17.34
280-290	490	568	35	36	7-7/8	45	3.61	63.5	17.59
350-360	--	370	52	57	7-7/8	40	3.26	88.0	26.99
415-425	308	339	66	68	7-7/8	55	3.07	90.5	29.47
450-460	--	416	44	48	7-7/8	40	3.29	79.0	24.01
500-510	460	469	41	43	7-7/8	40	3.47	74.0	21.32
560-570	370	420	53	53	7-7/8	50	3.28	78.0	23.78
635-645	475	552	54	42	7-7/8	63	3.37	61.0	18.10



(Modified from Alger, 1966; and from Keys and MacCary, 1971)

NOTE: Sodium chloride (NaCl) concentration in milligrams per liter (mg/L)

Figure 15.--Electrically equivalent concentrations of a sodium chloride solution as a function of water temperature, specific conductance, and resistivity.

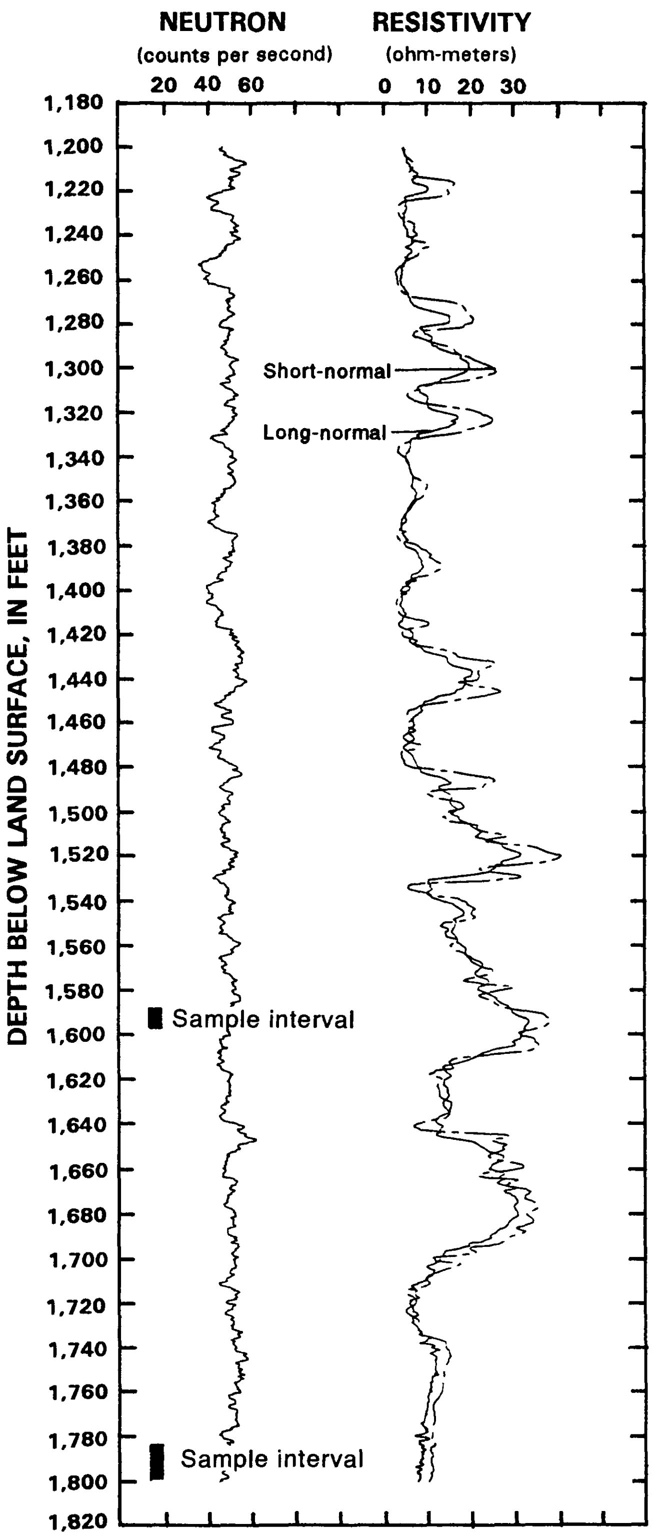


Figure 16.--Neutron, long-normal, and short-normal resistivity logs showing log examples of water-sampled intervals in a 10-inch-diameter well near Las Cruces, New Mexico.

The long-short-normal logs show a resistivity value of 30 ohm-meters for the short-normal log and 38 ohm-meters for the long-normal log in the example section between 1,570 and 1,590 feet. From solution of equation 10 $\Delta F = 33.76$ and from figure 13, the formation factor (F) is determined to be 3.63.

The neutron reading in the same section (fig. 16) is approximately 50 counts per second. When this value is entered into the graph (fig. 10), a resistivity correction (Rc) of 21.5 ohm-meters is found at the 10-inch-diameter intersection.

Then from the equation:

$$F = \frac{LNR + Rc}{Rw} \tag{11}$$

Rw can be reduced to specific conductance by:

$$\frac{10{,}000}{Rw} = \frac{10{,}000}{16.39} = 610\ \mu S/cm. \tag{12}$$

U.S. Geological Survey laboratory analysis showed that the specific conductance was 584 µS/cm.

By use of Bear's (1972) equation for relative permeability in a straight capillary flow model, the formation factor may also be calculated:

$$F = \frac{1}{n\sqrt{T}} \tag{13}$$

where F is formation factor;
n is porosity; and
T is average tortuosity of the porous medium.

Using the previous assumption that the long-normal and short-normal resistivity values are influenced by grain size and distribution and therefore related to tortuosity, the equation becomes:

$$F = \frac{1}{n\sqrt{LNR/SNR}}$$

$$F = \frac{1}{0.26\sqrt{38/30}}$$

$$F = \frac{1}{0.292}$$

$$F = 3.42$$

where LNR is long-normal resistivity; and
SNR is short-normal resistivity.

The porosity and tortuosity are defined as the path length of the current flow relative to the total length. Tortuosity can be related to the long-normal and short-normal resistivities. Using the values from the previous example, the porosity from the neutron porosity graph (fig. 11) is calculated to be 26 percent for a 10-inch-diameter well, the long-normal resistivity is 38 ohm-meters, and the short-normal resistivity is 30 ohm-meters. When the calculated formation factor is used, the clean sand resistivity (Ro_s) must be determined in the same manner as the previous example (59.5 ohm-meters). The equation then is:

$$3.42 = \frac{59.5}{Rw} \text{ and } Rw = 17.39 \tag{14}$$

and the specific conductance is 575 µS/cm.

The accuracy of the calculated method is greatly dependent on accurate porosity values from the neutron log because the formation factor (F) and clean sand resistivity (RO_s) are related to the neutron reading. Accurate neutron porosity values are often difficult to establish due to the statistical nature of the neutron signal. The cross-plot method to determine formation factor (fig. 13) uses resistivity data related to porosity and is therefore less dependent on and less influenced by the neutron count-rate determination.

The logs (fig. 16) show that the formation water becomes more saline below 1,700 feet. Because the neutron log shows very little change in the clay content, the lower resistivity is obviously due to lower Rw in the formation water. The section between 1,780 and 1,800 feet was isolated, and the laboratory analysis recorded specific conductance at 2,180 µS/cm. The electrolytic-conduction method, in contrast to the matrix-conduction method, of determining Rw begins to fail as the value of Rw approaches 5, as evidenced by the rather large conductivity discrepancy shown in the sample section.

Figure 17 shows a gamma, neutron, and electric log made in a well that penetrated formations that contain saline water. The analyzed water at 1,150 feet had a conductance of 793 µS/cm, and the conductivity of the water at 1,470 feet was 11,700 µS/cm. The freshwater/saline-water interface is 1,190 feet.

Relation between Water Quality and Permeability

Water-quality samples from multi-aquifer wells indicated that the section having the highest permeability contributes most of the water, to the producible limit of the permeable section. If that section is not overstressed during pumping, it generally is the prime contributor or even the only source of water supply. When estimating the Rw of water from a new well that penetrates several permeable sections that have variable water quality, resolving the source of the water or the most permeable sections is very important.

Flowmeter logs were made in pumped wells by lowering the flowmeter probe through tubing past the pump bowls, then starting the pump. These logs indicated that the well yielded water primarily from the highest permeability interval with little or no contribution from other known permeable sections that were lower in the well. The pumping rate was varied but the results were the same because the pump was not capable of overstressing the contributing section. The pump was lowered opposite the permeable nonproducing intervals and the flowmeter was run above the pump. The same highly permeable zone produced practically all the water, as it did in the upper pump setting.

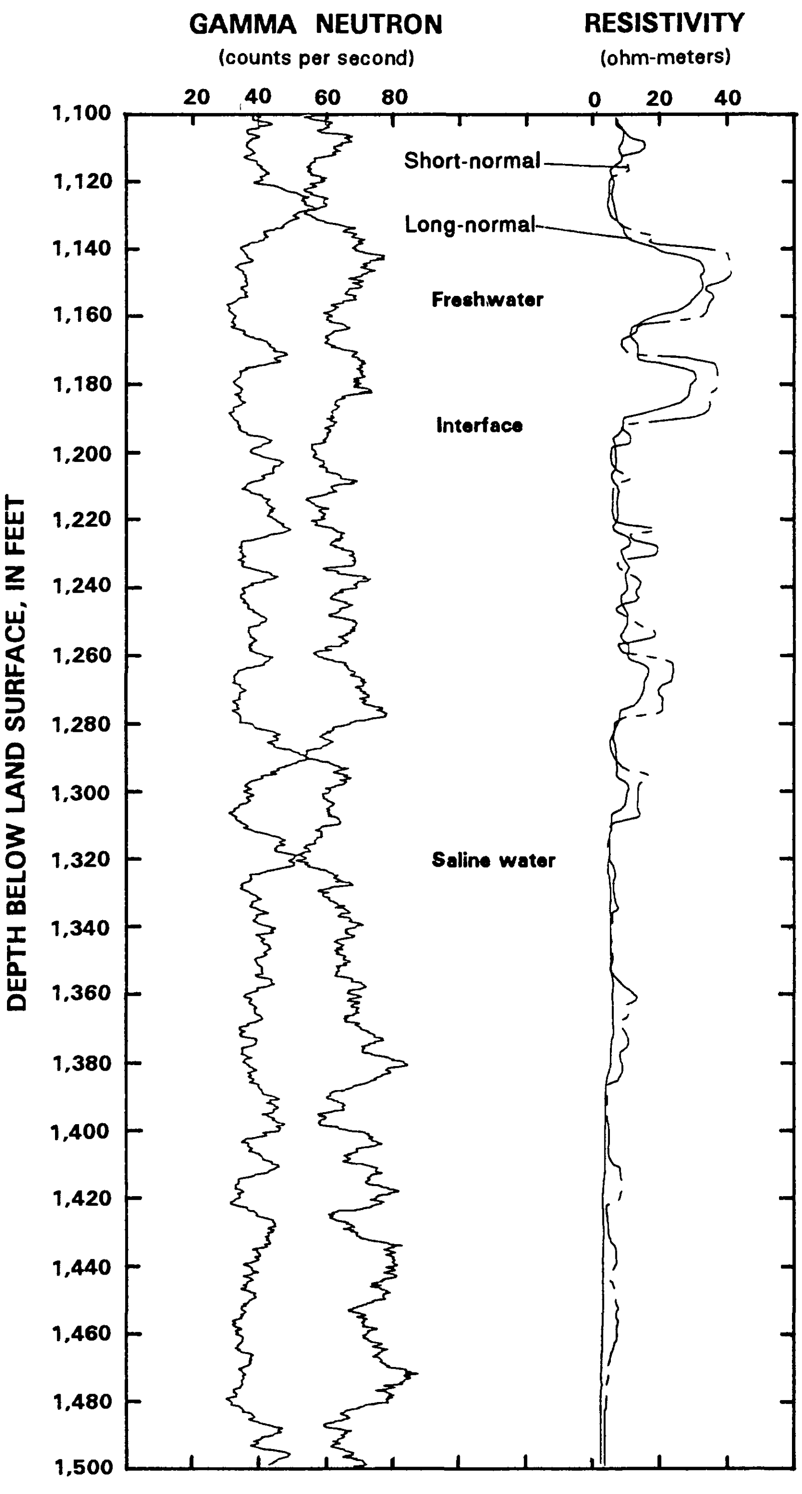


Figure 17.--Gamma, neutron, and long-short-normal resistivity logs showing freshwater/saline-water interface in a well near White Sands Missile Range, New Mexico.

Well development often does not affect the total reach of the well. A water well that has been in use for more than 10 years was pumped by isolating sections with inflatable packers, and some of the original drilling mud was recovered.

Knowledge of the well-completion program and estimated pumping rate of a new well is important in estimating the quality of the water to be pumped. The shallowest permeable zone capable of producing the pump capacity may be the only interval significantly influenced by pumping, but if the pumping rate is increased additional zones may contribute significant amounts of water and the quality of the discharged water may change. Therefore, the permeability of each major interval of the well becomes an important part of the water-quality estimate.

Permeability Estimates

Intrinsic permeability is a measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. It is, therefore, a function of only the formation properties. Apparent porosity has a general relation to permeability, but no direct relation. A fine-grained sand may have the same apparent porosity as a silty sand, but the permeability may differ greatly.

No geophysical-logging devices measure permeability directly; therefore, a permeability estimate is a hypothetical estimate and not a measurement. An extensive empirical data base is the most important tool in the development of any method for estimating permeability from geophysical logs. Bear (1972) developed purely theoretical formulas, usually using a conceptual model that leads to a relation between permeability and various matrix properties; however, the numerical coefficients need to be determined experimentally for each particular porous matrix. His report states that the formulas have the general form:

$$k = f1(s)f2(n)d^2 \qquad (15)$$

where k is permeability;
s is dimensionless parameter(s) that express(es) the effect of the shape of the grains or pores;
f1(s) are shape factors;
f2(n) is porosity factor; and
d is effective diameter of the grains.

Bear (1972) further explains d as the percentage, by weight, of the porous matrix that consists of grains smaller than the mean diameter. The product f1(s)f2(n) can be reduced to a single dimensionless coefficient, C, in the relation between k and d:

$$k = Cd^2. \qquad (16)$$

The equations used in service-company analyses are mostly empirical, specific to the rocks commonly present in oil fields, and may not be applicable to a ground-water environment, especially unconsolidated sedimentary formations.

For permeability estimates in petroleum applications, log analysis uses a two-phase system of calculating water saturation by abstracting the effective permeability from the absolute permeability to arrive at a relative permeability, which is a ratio of the effective permeability to the absolute permeability. The effective permeability depends not only on the rock itself, but also on the relative amounts of the different fluids present in the pores. The oil-well logging industry uses the terms "absolute permeability," "relative permeability," and "effective permeability" to estimate the moveability and relative quantity of the two fluids--oil and water--in the rocks. Absolute permeability is related to the pore spaces available for saturation. Because one fluid may move more readily than the other, the term "relative permeability" is important in defining the ratio of effective permeability of each fluid to the absolute permeability of the rock matrix. By contrast, permeability calculations for ground-water studies are for aquifers that are 100 percent saturated with only one fluid, removing the need for calculations of water saturation or moveability of the different fluids as a function of the viscosity and ratio of the occupied pore spaces.

Calculating effective porosity and relating it to hydraulic conductivity (K) or permeability (k) in water wells would appear to be a relatively simple matter. If all water wells were completed with 100-percent efficiency or even uniform efficiency, the empirical determination of permeability as related to log response would be easier. However, well efficiency depends on the skills of the engineers to select the proper screen, place it at the proper interval, and effectively complete and develop the well. Because of the different well-completion efficiencies, any practical exercise of relating log response to well-yield data requires a large mass of data and time-consuming data analysis. Even if a very carefully calculated permeability estimate is made at the new well site, the well may not produce to capacity. This could cause doubts as to whether the production discrepancy is because of inaccurate estimates or inefficient well completion and development. The completion and development contract usually does not allow the time needed to investigate these production questions, thus a definite answer may be impossible.

Three methods of estimating permeability and hydraulic conductivity are described in this section of the report. Each method has had limited success because of the data-collection problems already discussed.

Relation between Specific Retention and Permeability

This method establishes a permeability index that is related to specific retention. The basic assumptions are that (1) total porosity is equal to effective porosity plus specific retention; and (2) effective porosity can be related to permeability.

Oil-well service companies routinely use gamma-log data to estimate shale or clay content, which in some environments is related directly to specific retention. Silt, clay, and even poorly sorted sands will commonly cause high retention values, and the gamma response theoretically is related to the material causing these high retention values.

Data for this investigation included continuous cores (split-spoon method) from 17 wells penetrating the Santa Fe Group of Quaternary and Tertiary age near Santa Fe, New Mexico. About 100 samples were analyzed by two different laboratories that split the samples in an effort to duplicate samples. The analysis determined specific gravity, dry unit weight, total porosity, and moisture content by weight and volume.

The soil samples were saturated and weighed, then drained and weighed, "cooked" dry, and weighed again to determine the percentage of porosity and the retention value. The difference between the drained weight and the "cooked" dry weight is related to the shaliness and was plotted as percentage of clay (or specific-retention value) against gamma-count rate. From these data, a total porosity against neutron count-rate curve was constructed that agreed closely with the porosity graph shown in figure 10. Gamma response and laboratory specific-retention values showed very little correlation and the two laboratories' analyses showed very little agreement, even though the sample was meticulously split. Therefore, the retention curve, so important to the equation, is questionable. The most accurate method of estimating permeability would be a reliable curve that relates gamma response to specific-retention values, if enough data could be collected to develop that curve.

Figure 18 shows a section of gamma and single-point resistance logs made in a well near Las Cruces, New Mexico. The sand section about 70 feet below land surface has a high gamma count that is indicative of feldspar-rich sand. The gamma count opposite sand decreases with depth, as indicated by the sand near 185 and near 390 feet. This transition from high to low radiation is normal for this area, but the depth of transition is not constant from well to well. Perhaps a cross-plot method that uses gamma response and formation resistivity would result in a more reliable retention value, but gamma response alone leaves too many variables unanswered.

Relation between Effective Porosity and Permeability

The purpose of this part of the investigation was to establish a method of determining the ratio of sand and clay in areas of arkosic sand. The previous section had revealed that the gamma-count rate fluctuates widely from one sand unit to another.

This system made use of the Dresser Atlas Log Interpretation Charts (1979 edition) shaliness graph, which is computed by relating the gamma response to clean sand and pure clay. To use this graph, an empirical method of relating gamma-count rate opposite clean sands and maximum gamma-count rate opposite clay beds needs to be established for each different environment. This can typically be done by close inspection of the drill cuttings if the sand or clay beds are at least 4 feet thick. If the formation beds are too thin the measured gamma-count rate is not accurate and the drill cuttings commonly are contaminated with foreign material and are not representative. If the clean-sand and clay responses are established for an area, the sand to clay ratio can be calculated from logs using the equation:

$$IGR = \frac{Gr - Gr\ clean\ sand}{Gr\ clay - Gr\ clean\ sand} \qquad (17)$$

where IGR is gamma-ray index used for entry into the percent-sand graph;
Gr is gamma response opposite the bed of interest;
Gr clean sand is gamma response established for clean sand; and
Gr clay is gamma response established for clay.

The Dresser Atlas shaliness curve is reversed in figure 19 to show the percentage sand. This makes the calculation of effective porosity from total porosity easier using the following calculation:

$$n\ eff. = n\ total \times percent\ sand \qquad (18)$$

where n eff. is effective porosity to be calculated;
n total is total porosity indicated by the neutron porosity graph (fig. 11); and
percent sand is ratio of sand from the gamma-ray index graph (fig. 19).

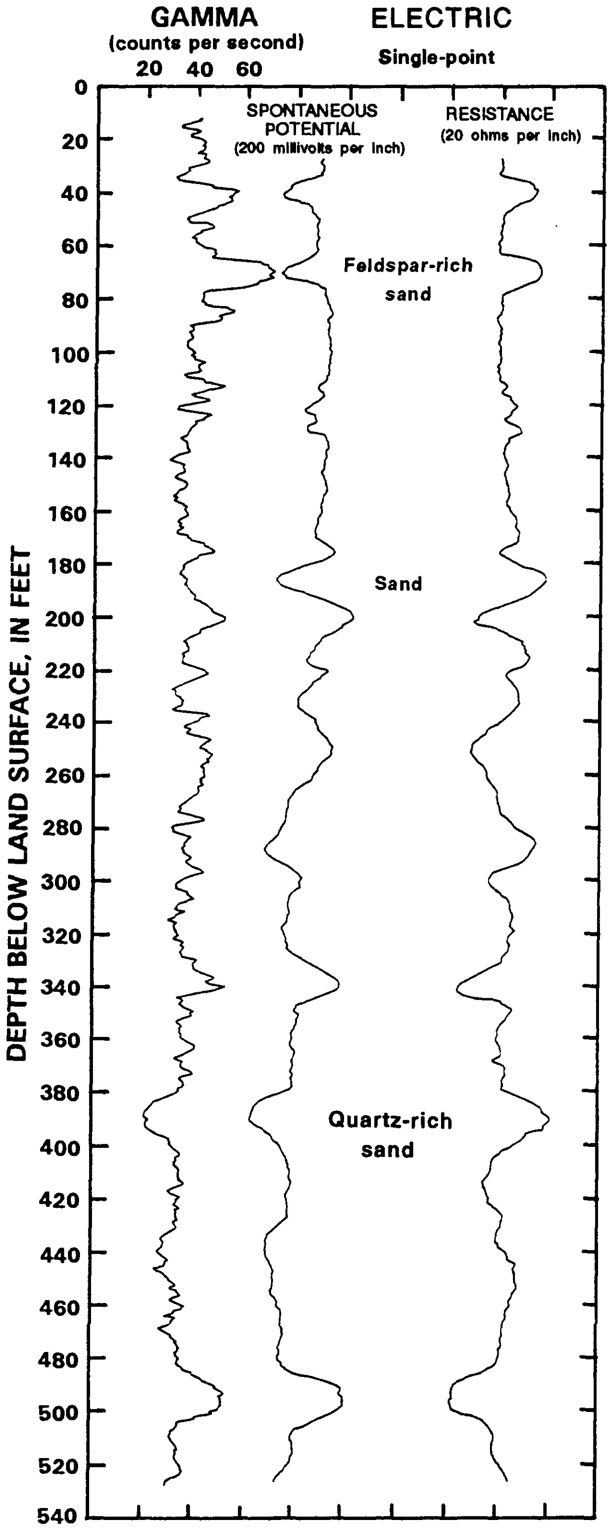


Figure 18.--Gamma and single-point resistance logs showing relative gamma response opposite feldspar-rich sand in a well near Las Cruces, New Mexico.

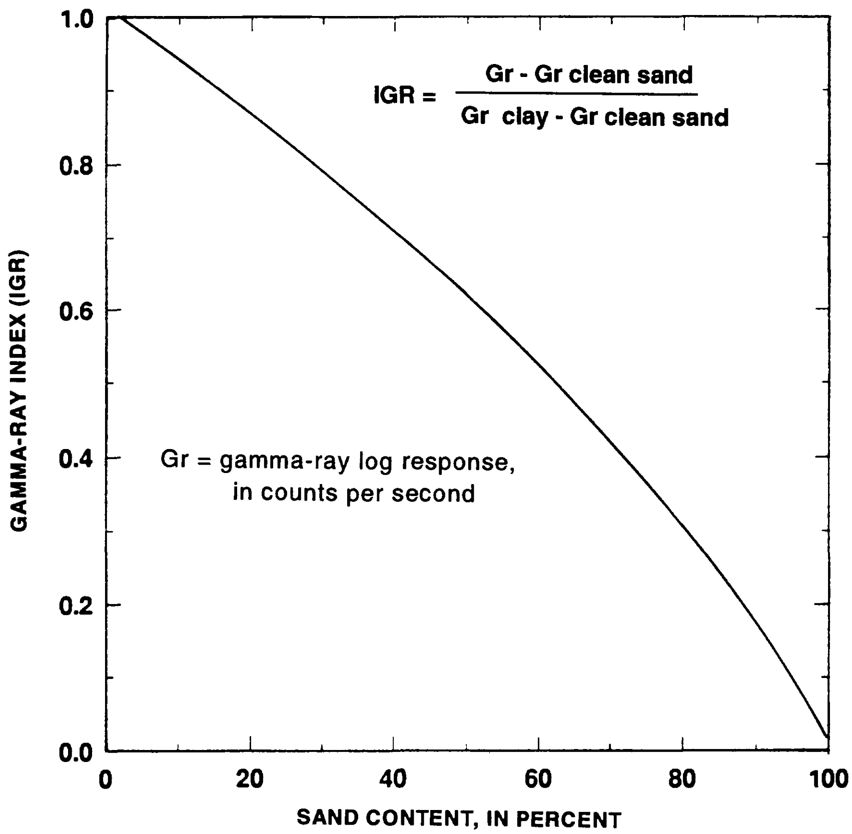


Figure 19.--Relation between gamma-ray index and sand content.

The calculated effective-porosity values were plotted against specific-capacity data determined from pumping, previously logged wells. Generally, these specific-capacity data were determined from simple step tests plotting pumping rate against drawdown, in feet below the static level. These plots resulted in a wide scatter of data points, partly because the pumping data were representative of only a part of the aquifer and the effective porosity value was an average of the whole aquifer. Figure 20 is a graph relating effective porosity to permeability.

The logic of this method is the use of apparent porosity or total porosity reduced to effective porosity by the properties that influence gamma radiation. These properties are clay, silt, and fine-grained sand, which are also the primary properties that influence effective porosity. The relative gamma response to each of these properties is proportional to the total porosity effect; that is, clay generally has a large gamma response and a large effective porosity influence, whereas fine-grained sand has a very small gamma response and smaller effective porosity influence. Therefore, if the properties that influence gamma response could be correctly identified and quantified, effective porosity could be closely calculated. The final problem of relating well-production data to effective porosity was directly related to the quantity and quality of the available data. Evaluation of the production data was difficult because of the uncertainty of well-completion and well-efficiency data. The resultant data were highly erratic, causing the limited amount of data to lack resolution.

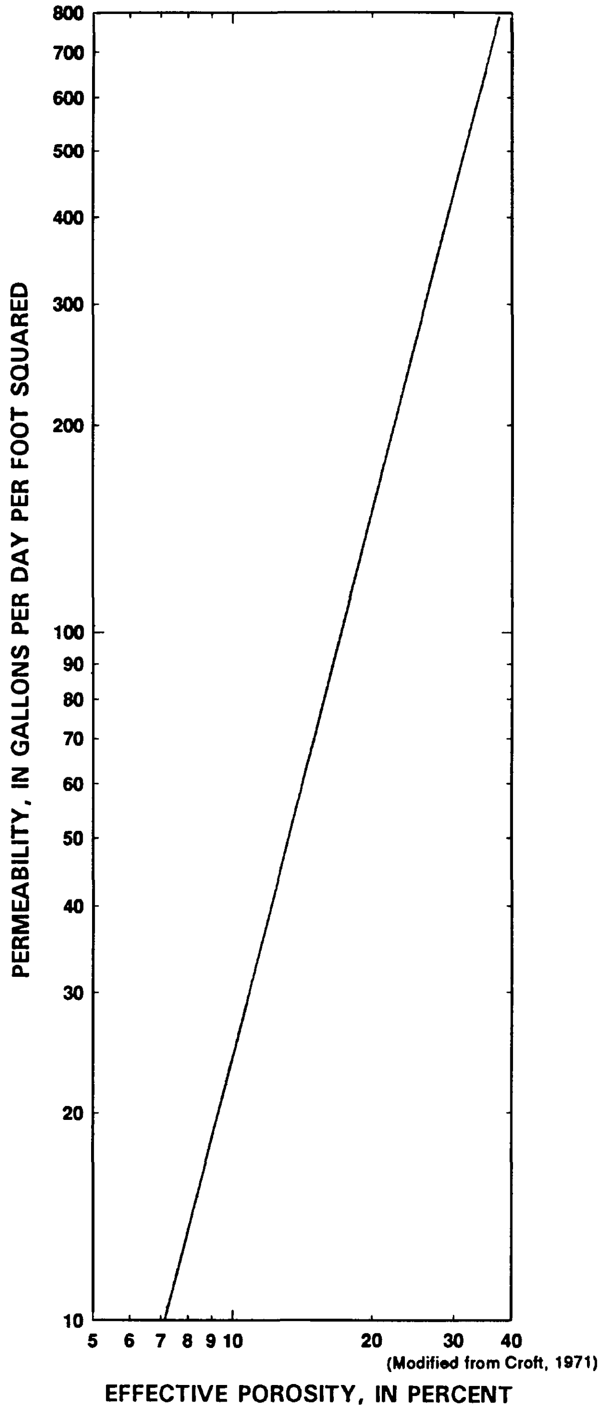


Figure 20.--Relation between permeability and effective porosity of the aquifer.

The reliability of this method is greatly dependent on the skill of the log analyst in determining clean-sand and clay sections from inspection of the drill cuttings and from geophysical-log response opposite potential aquifers. An empirical relation of electric-log response in clean sand and in clay is the most reliable method.

The neutron-count rate in the aquifer of interest can be entered into the resistivity correction graph (fig. 10). When the graph indicates zero correction, the bed can be assumed to be clean sand. The corresponding gamma-count rate can be used in the IGR equation. The use of this method reduces the error caused by feldspar-rich sand, but does not eliminate the effects. Generally, sand sections can be compared horizontally in areas of transition from radioactive sand to normal sand. Transition effects are discussed in the gamma-log section of this report. Horizontal correlation, using both the gamma log and the electric log, should be the controlling factor in extending established clean-sand count rates into unknown areas.

The gamma response for clay can be established by relating the gamma-count rate opposite intervals of very low resistivity in the long-normal and short-normal electric log, taking care that the low resistivity reading is not due to formation-water quality. Close inspection of the drill cuttings can also be very helpful. The advantage to this system is that when the gamma response against the sand to clay ratio is established for an area, permeability can be estimated with only gamma and neutron logs and can be made in new or old wells, cased or open hole. However, if the data from cased holes are used, the casing is assumed to cause a consistently reduced count rate. This is not a uniformly valid assumption because of different wall thicknesses of pipe and different well-completion methods such as gravel-packed and cemented annular space. The method should result in a relative permeability estimate that is useful and in some cases adequate. The disadvantage are the complications associated with the establishment of base gamma-count rates for sand and clay and the need for new base rates in each different environment.

Relation between Formation Factor and Permeability

In this study, feldspar-rich sand was a significant problem in the use of gamma logs as a tool for estimating permeability. The previously discussed methods of estimating permeability produced satisfactory results when extraneous effects, not related to permeability, could be identified. Those methods, using only gamma and neutron logs, have the potential for much wider application. Opportunities for data collection are more extensive because aquifer tests and geophysical logs could be made in old wells or in newly completed drill holes.

Due to the continuing problems associated with gamma logs, this investigation used Croft's (1971) method of estimating permeability from a formation factor, with some variation in establishing Rw and formation factor. The formation-factor method requires logging a newly drilled, mud-filled hole, thereby limiting data collection.

Croft (1971) used field data and a modified version of a method originally reported by Turneaure and Russell (1940), Jones and Buford (1951), and Alger (1966) to relate permeability to a formation factor established from electric logs. Croft had considerable success relating permeability and grain size to the formation factor using graphs modified from Alger's (1966) and Turneaure and Russell's (1940) data. Croft related the long-normal resistivity to the resistivity of the saturated matrix (Ro), and by projecting Rw values from nearby wells, the formation factor was calculated using equation 5 (p. 16), F = Ro/Rw.

Croft's (1971) graphs fit the limited amount of data available to this part of the investigation, and required little or no revision. The term "permeability factor" was devised, in this report, primarily to distinguish the different method of arrival from previous use of the term. Figure 21 shows Croft's graph that relates grain size to permeability factor. Figure 22 shows a graph showing the relation between permeability and permeability factor.

On the basis of a relatively limited amount of data, there appears to be general agreement between Croft's (1971) method and the effective-porosity system described previously in this report. Croft's method of estimating permeability from the formation factor is very easy and fast once Rw has been established.

To use Croft's method to estimate permeability and grain size, Rw needs to be determined by the method described in the water-quality section of this report (Use of logs to estimate water quality and aquifer permeability). The formation factor, which for clarification is labeled permeability factor (Fp), is established by the following equation:

$$Fp = \frac{Ro}{Rw} \qquad (19)$$

where Fp is value of the permeability factor;
Ro is long-normal resistivity reading in the potential aquifer; and
Rw is calculated formation-water resistivity.

The formation factor established in the water-quality section decreases as grain size increases, and is empirically related to the original Archie (1942) formula. The formation factor calculated in the permeability estimate increases as grain size increases, which agrees with the laboratory data reported by Jones and Buford (1951). This is also the order of increase of the formation factor in the water-quality section after the matrix has been equated to clean, saturated (Ro_s) sand.

The coefficient of transmissivity can be calculated by the following steps:

(1) Identify the potential aquifer sections by inspection of the geophysical logs; note the thickness of the section.

(2) Calculate the resistivity of the formation water (Rw) for each potential aquifer section; note the LNR opposite the section.

(3) Calculate the permeability factor for each section by Fp = LNR/Rw.

(4) Determine the permeability (gal/day/ft^2) from figure 21; note the value for each section.

(5) Multiply the permeability (gal/day/ft^2) by the section thickness to arrive at the transmissivity (gal/day/ft).

(6) Add the transmissivity values for all sections, including only sections adjacent to eventually screened areas.

The results will be gallons per day per foot of drawdown which can be reduced to gallons per minute per foot. The permeability factor determined in step 3 can be used in figure 21 to estimate grain size.

Not enough reliable aquifer-test data have been collected and analyzed to evaluate this method thoroughly but the results are believed to approximately estimate the producibility of wells completed in freshwater sands. A good data base could increase the reliability of the method and could eventually result in a relatively simple method. In some areas, Rw is fairly consistent and predictable so the calculation of permeability would be reduced to very few steps.

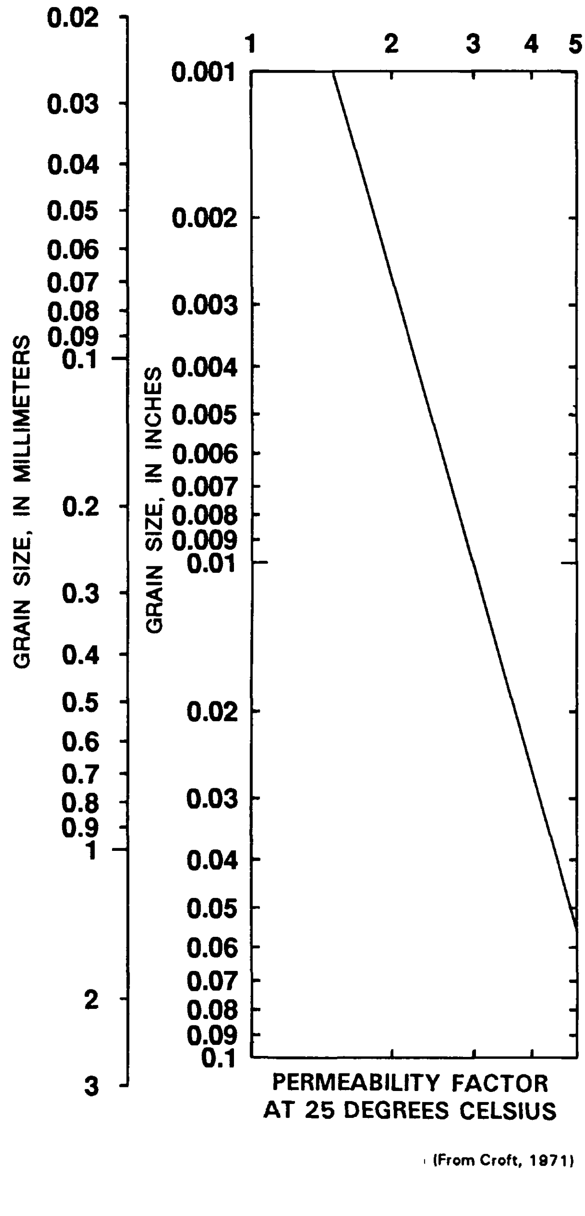


Figure 21.--Relation between grain size and permeability factor.

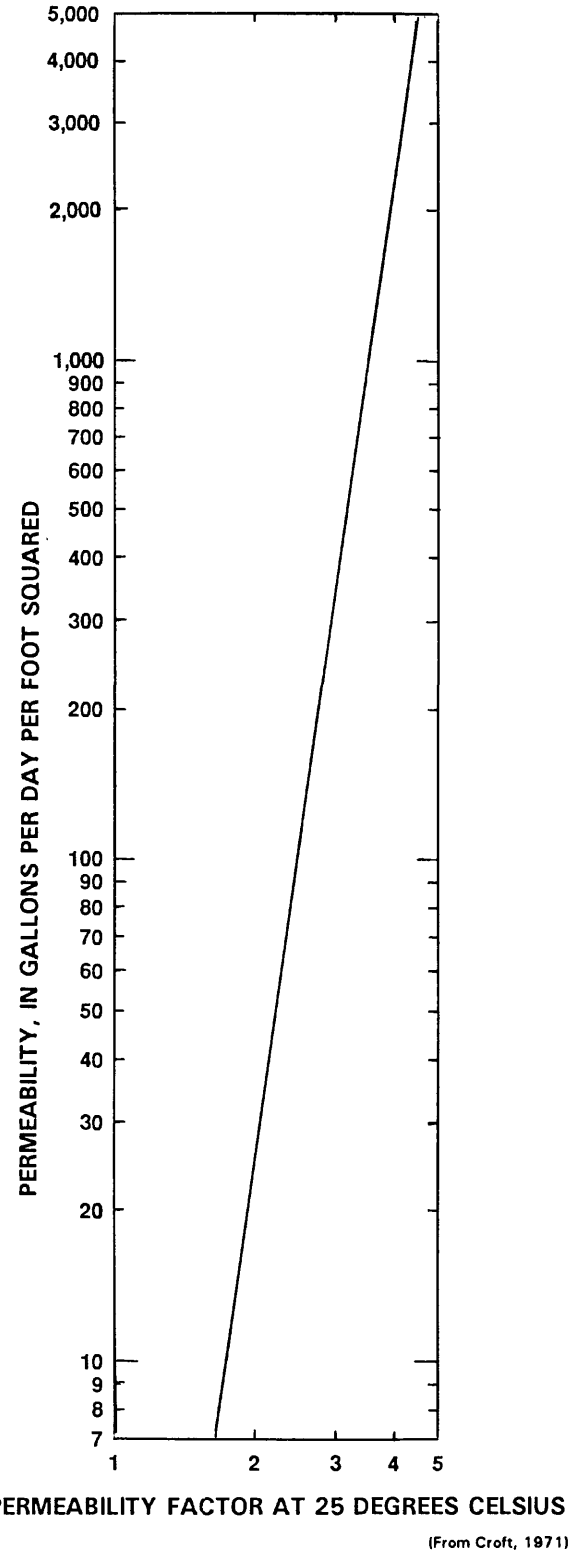


Figure 22.--Relation between permeability and permeability factor.

SUMMARY

This report presents methods that can be used to estimate the quality of ground water and the permeability of aquifers through the use of geophysical logs made in freshwater wells. These methods were developed by using data collected from water wells completed in basin-fill deposits in the Rio Grande Rift from near Santa Fe to the southern boundary of New Mexico. Data collected over a period of about 15 years were used to correlate geophysical-log response to known characteristics of freshwater aquifers. The described system of calculating formation-water quality was developed over many years by relating laboratory data to log response. This system used the theory that the apparent resistivity recorded by the electric log is suppressed by an amount partly related to the conductive matrix and partly to water quality.

The resistivity correction (Rc), determined from the neutron response, is added to the bulk resistivity (Ro) to relate the matrix to resistivity equivalent to a clay-free matrix (Ro_S). The matrix may also contain other conductive material and that resistivity influence must also be accounted for in the final calculation of Rw. These conductive materials are generally silt and fine-grained, poorly sorted sands, which reduce permeability, increase tortuosity, and increase surface conduction. Permeability and the reciprocal tortuosity are closely related to the individual and independent response of the long- and short-normal resistivities. By relating formation factor to these parameters, the electrical conduction of the matrix is corrected for the resistivity effects not related to the pore fluid. Surface-conduction effects are cancelled by inclusion of the formation-factor calculation (ΔF) and by inclusion of the clay-free matrix (Ro_S) in the final Rw calculation.

This report describes three separate but related methods of estimating permeability. The first two methods, which relate specific retention to permeability and effective porosity to permeability, respectively, have too few data to be reliable but are included because they are valid methods. Data collection was hampered by the local effects of radioactive sand. Each of these methods (especially the effective-porosity method) could be very useful in areas that have normal sands. The attractive feature of both methods is their potential for wide application and their simplicity.

The specific-retention method used gamma logs to estimate specific retention, which is then subtracted from the total porosity, reducing it to effective porosity. The effective porosity, sometimes called true porosity, is correlated to well-production data. The high radiation effects of feldspar-rich sands invalidated the gamma response in the attempt to relate the gamma response to specific-retention values. This method could have application in areas where the gamma response to clay and sand is more reliable. The conclusion is that gamma tools alone are not a suitable device for establishing specific-retention values in the area of this investigation.

The effective-porosity method assumes that effective porosity can be empirically correlated to aquifer productivity. Commercial-logging service companies routinely use the relative gamma response to calculate shaliness. Their method relates the gamma response opposite a clean sand and a pure clay to establish base-line parameters, from which the observed gamma response is used to estimate the percentage of clay (shale). For this study, the service companies' clay index graph was reversed to show the percentage of sand relative to the gamma-count rate, mostly for ease of calculating effective porosity. This method of estimating percentage of sand against gamma-count rate also was subject to errors introduced by radioactive sands. The selection and extension of clean sand and clay base values require a thorough knowledge of the log response to local formation properties. The electric log can be used as an aid in selecting clean sand sections; however, this requires a mud-filled, newly drilled hole, which limits data collection. A further limiting factor is that most well-completion and production data are reported, sometimes at a much later date than the logging. Even the most reliable data are often a misfit, sometimes completely off scale, and the cause for this misfit is very difficult to determine. Well efficiencies vary widely, especially in new wells where potential aquifers may not be fully developed.

The third method for estimating permeability uses a formation-factor/permeability relation. The formation-factor/permeability-relation graph was revised in 1971 by extending RW values from nearby wells to solve the equation $F=Ro/Rw$, where long-normal resistivity was assumed equal to Ro.

Data indicate that Rw and F vary widely within a stratigraphic unit. Because of that wide range in values, it was decided that this study would determine accurate Rw values for each formation-bed anomaly and calculate the permeability estimate individually. The calculation uses the accurate Rw value, with an Ro value directly related to the long-normal resistivity log, to arrive at a permeability factor (Fp). The permeability factor, when used with the permeability graph, gave satisfactory results in the relatively few data tests conducted.

The resolution of the graphs is not very good; because of the highly statistical nature of production data, however, this system may prove to be completely adequate and has been used with a good degree of success. This method is the best option of the three because of fewer assumptions and less personal judgment involved and its relative simplicity. Also, electrical measurements are more repeatable and reliable than radiation measurements, which are actually statistical measurements applied to a statistical data base. The formation factor calculated from the equation $\Delta F = SNR\sqrt{LNR/SNR}$ may result in a better permeability estimate because of the closely developed relation to permeability; that data, however, have not been collected or tested.

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