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

Chapter E1

APPLICATION OF BOREHOLE GEOPHYSICS TO WATER-RESOURCES INVESTIGATIONS

By W. Scott Keys and L. M. MacCary

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PREFACE

The series of manuals on techniques describes procedures for planning and executing specialized work in water-resources investigations. The material is grouped under major subject headings called "Books" and further subdivided into sections and chapters. Section E of Book 2 is on subsurface geophysical methods.

Provisional drafts of chapters are distributed to field offices of the U.S. Geological Survey for their use. These drafts are subject to revision because of experience in use or because of advancement in knowledge, techniques, or equipment. After the technique described in a chapter is sufficiently developed, the chapter is published and is sold by the U.S. Geological Survey, 1200 South Eads Street, Arlington, VA 22202 (authorized agent of Superintendent of Documents, Government Printing Office).

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[Commonly used symbols in borehole geophysics]

A	Mass number.
A	Lower current electrode.
AM	Electrode spacing, normal device.
AO	Electrode spacing, lateral device.
API GR Unit	American Petroleum Institute gamma-ray unit.
API N Unit	American Petroleum Institute neutron unit.
B	Upper current electrode.
C	Capacitor.
CCL	Casing-collar locator.
cps	Counts per second.
cpm	Counts per minute.
D_b or ρ_b	Bulk density.
d_h	Borehole diameter.
d_i	Electrically equivalent diameter (lateral depth) of the invaded zone.
D_f or ρ_f	Density of fluid.
D_g or ρ_{ma}	Grain density or matrix density.
Δt	Interval transit time (of acoustic wave).
E (or emf)	Electromotive force.
E_c	Electrochemical component of the SP.
E_k	Electrokinetic component of the SP.
ES	Electrical Survey—SP, 16" normal, 64" normal and 18'8" lateral.
E_s	Shale potential.
E_u	Environmental unit of neutron deflection.
e	Symbol for the oribital electron.
ev	Electron volts.
F	Formation-resistivity factor, equals R_o/R_w.
F_f	Field-formation-resistivity factor.
fpm	Feet per minute.
G	Geometric factor.
g/cc	Grams per cubic centimeter.
gpm	Gallons per minute.
h (or e)	Bed thickness.
h_{mc}	Mud cake thickness.
Hz	Unit of frequency, one cycle per second.
HI	Hydrogen index, fresh water equals 1.
Kev	Thousand electron volts.
kHz	Kilohertz.
kΩ	Kilohms [thousand ohms].
LL	Laterolog.
λ	Wave length.
M	Potential electrode, normal device.
Mev	Million electron volts.
m	Cementation factor.
ma	Milliampere.
mc	Millicurie.
Meg-ohms	Million ohms.
mg/l	Milligrams per liter.
mv	Millivolt.
Mr/hr	Milliroentgens per hour.
μa	Microampere.
μg Ra-eq/ton	Microgram radium-equivalent per ton.
μmhos/cm	Micromhos per centimeter.
N	Resistivity reference electrode.
n	Symbol for the neutron.
n	Frequency, in hertz.
ohm-m (or Ωm)	Unit of resistivity or specific resistance.
ϕ	Porosity.
p	Symbol for the proton.
ppm	Parts per million.
PR	Point resistance.

PVC casing	Polyvinyl chloride casing.
r	Resistance.
r_f	Equivalent resistance of formation.
r_{sh}	Resistance of shale.
r_{ss}	Resistance of sandstone.
r_m	Resistance of mud.
R	Resistivity.
R	Resistor.
R_a	Apparent resistivity.
R_i	Invaded zone resistivity.
R_m	Mud resistivity.
R_{mc}	Mud cake resistivity.
R_{mf}	Mud filtrate resistivity.
R_o	Resistivity of formation 100-percent saturated with water of resistivity R_w.
R_s	Resistivity of surrounding formations.
R_{sh}	Shale resistivity.
R_t	True formation resistivity.
R_w	Formation water resistivity.
R_{xo}	Resistivity of flushed zone.
SP	Spontaneous potential.
SSP	Static spontaneous potential.
S_w	Water saturation.
τ	Tortuosity.
T	Temperature.
$T_{1/2}$	Half life.
tc	Time constant.
V	Acoustic velocity, in feet per second.
V_f	Velocity of sound in fluid, in feet per second.
V_m	Velocity of sound in matrix, in feet per second.
V_r	Velocity of signal in rock, in feet per second.
VOM	Volts and ohms test meter.
Z	Atomic number.

APPLICATION OF BOREHOLE GEOPHYSICS TO WATER-RESOURCES INVESTIGATIONS

By W. Scott Keys and L. M. MacCary

Abstract

This manual is intended to be a guide for hydrologists using borehole geophysics in ground-water studies. The emphasis is on the application and interpretation of geophysical well logs, and not on the operation of a logger. It describes in detail those logging techniques that have been utilized within the Water Resources Division of the U.S. Geological Survey, and those used in petroleum investigations that have potential application to hydrologic problems. Most of the logs described can be made by commercial logging service companies, and many can be made with small water-well loggers. The general principles of each technique and the rules of log interpretation are the same, regardless of differences in instrumentation. Geophysical well logs can be interpreted to determine the lithology, geometry, resistivity, formation factor, bulk density, porosity, permeability, moisture content, and specific yield of water-bearing rocks, and to define the source, movement, and chemical and physical characteristics of ground water. Numerous examples of logs are used to illustrate applications and interpretation in various ground-water environments. The interrelations between various types of logs are emphasized, and the following aspects are described for each of the important logging techniques: Principles and applications, instrumentation, calibration and standardization, radius of investigation, and extraneous effects.

Introduction

Background

A log is defined by Webster as "a record of sequential data***." Geophysical well logging, also called borehole geophysics, includes all techniques of lowering sensing devices in a borehole and recording some physical parameter that may be interpreted in terms of the characteristics of the rocks, the fluids contained in the rocks, and the construction of the well.

In the United States the first geophysical well logs may have been plotted in the 1890's from temperature measurements made by W. B. Hallock (1897). C. E. Van Orstrand (1918) of the U.S. Geological Survey described downhole-temperature equipment with a sensitivity of 0.01°C, which was used to make "depth temperature curves." These curves showed anomalies caused by escaping gas and flowing water, and Van Orstrand speculated that temperature curves might "afford a means of determining the relative water content of rocks in situ."

The first resistivity curves were run in 1927 in an oil field in France (Schlumberger and Schlumberger, 1929). These logs were made by manually plotting the deflections of a galvanometer that responded to the resistivity of the rocks and their contained fluids. A good example of the state of the art about 1927 is shown in the photographs in the paper by Schlumberger and Schlumberger (1929). The method was called "electrical coring" by the Schlumberger brothers, because it gave lithologic information about the rocks penetrated by wells. About 1931 Schlumberger engineers discovered the existence of a natural electric potential also related to lithology while they were measuring resistivity in Rumania (Schlumberger and others, 1934). A log of these potentials was called the "porosity log" by Schlumberger. Deflections in potential were logged on either side of a zero level, with positive potentials deflecting to the right and negative ones to the left. Within a few years logging of spontaneous potential and resistivity was in general use in oil fields worldwide, the methods being termed "electric logging." As new geophysical logging methods were discovered, they were for a time categorized under the general name of electric logging, even though the methods did not involve electrical measurements. By common agreement, logging service companies today use the term "electric log" only for those geophysical methods which measure the spontaneous electric potentials and electrical resistivities of natural rock materials penetrated by the drill.

In the years since the discoveries by the Schlumberger brothers, the following types of sensors have also been used for geophysical investigations in wells: Visual, mechanical, nuclear, acoustic, magnetic, and thermal. The first comprehensive description of "Subsurface Geophysical Methods in Ground-Water Hydrology" was written by P. H. Jones and H. E. Skibitzke in 1956, yet the sophistication and use of geophysical logging to solve problems of ground-water hydrology is still many years behind that of the petroleum industry.

Purpose and scope

The purpose of this manual is to furnish a guide to planning and implementing a program of borehole geophysics applicable to ground-water studies. The manual is not intended to provide operational instructions for borehole loggers; rather, the emphasis is on application and interpretation of geophysical well logs. It describes in detail those logging techniques that have been utilized within the Water Resources Division of the U.S. Geological Survey and those techniques used in petroleum work that have potential application to hydrologic problems. Most of the logs described in detail can be made by commercial logging service companies, and many can be made with small water-well loggers. The general principles and rules of log interpretation are the same, regardless of differences in instrumentation. Basic principles of logging instrumentation are described because they are essential background to planning a logging program and interpreting logs. Numerous examples are used to illustrate applications and interpretation of logs in various ground-water environments. Note, however, that these examples may not necessarily apply to a similar geohydrologic environment elsewhere. The interrelation among various types of logs is emphasized in this manual. Basic principles common to many types of logs are described only in the introductory sections, and the index provides cross-referencing information.

Why log?

Exploratory drill holes or wells are the only means of direct access to the subsurface. Drilling is an expensive means of access to the lithosphere, and sampling of the rocks and fluids penetrated and geophysical well logging are the only ways information can be derived from these holes. Valid well logs, correctly interpreted, can be used to reduce future drilling costs by guiding the location, proper drilling, and construction of test holes and production or disposal wells. Well logging also enables the vertical and horizontal extrapolation of data derived from drill holes.

Geophysical logs can be interpreted to determine the lithology, geometry, resistivity, formation-resistivity factor, bulk density, porosity, permeability, moisture content, and specific yield of water-bearing rocks, and to define the source, movement, and chemical and physical characteristics of water. Quantitative interpretation of logs will provide numerical values for some of the rock characteristics necessary to design analog or digital models of ground-water systems. Log data aids in the testing and economic development of ground-water supplies and of recharge and disposal systems and can be of considerable value in the design and interpretation of surface geophysical surveys. Stallman (1967) pointed out that if the following pretest information is not obtained, failure of pumping tests is invited: Hydraulic conditions along the well bore; storage characteristics of the aquifer; and depth to, and thickness of, the aquifer being tested, as well as changes in either within the area of the test. He also suggested that changes in transmissivity should be mapped. Estimates of pertinent hydraulic properties of the aquifer can be provided by borehole geophysical studies.

Geophysical well logging can provide continuous objective records with values that are consistent from well to well and from time to time, if the equipment is properly calibrated and standardized. In contrast, the widely used geologist's or driller's log of cuttings is subjective, greatly dependent upon personal skills and terminology, and is limited to the characteristics being sought. Geophysical logs can be reinterpreted in a postmortem investigation of some geologic or hydrologic factor that was not considered while the hole was being drilled. Serendipity —the gift of finding agreeable or valuable things accidentally—has resulted in the discovery of uranium, phosphate, potash, and other minerals from the interpretation of well logs. Each year many more wells are drilled for water than for petroleum. Although most of the water wells are shallow, each is a valuable sample of the geologic environment, and logs of these holes can aid in the definition and development of water supplies, sand and gravel deposits, other nonmetallic and metallic mineral deposits, petroleum, and waste storage or disposal and artificial-recharge sites and can provide the engineering data necessary for construction.

In contrast to uninterrupted geophysical logs, samples of rock or fluid almost never provide continuous data. Even if a hole is entirely cored, with 100-percent recovery, laboratory analysis of the core involves the selection of point samples. Continuous coring and subsequent analysis of enough samples to be statistically meaningful costs much more than most geophysical-logging programs. In addition, the volume of material investigated by most logging sondes may be more than 100 times as large as the volume of most core samples extracted from the hole.

Although geophysical logging should partly supplant routine sampling of every drill hole, some samples, properly taken and analyzed, are essential to the interpretation of logs in each new geologic environment. Sidewall-sampling techniques are available for poorly consolidated sediments and can be utilized after logs have been run, to provide the most representative samples (Morrison, 1969). Sidewall samples can also be taken in hard rocks by commercial logging service companies; however, they are relatively expensive. One well, adequately sampled and logged, can serve as a guide for the horizontal and vertical extrapolation of data through borehole geophysics. Furthermore, well logging provides the only means for obtaining information from existing wells for which there is no data and from wells where casing prevents sampling.

Geophysical logs can be digitized in the field or office by commercial service companies and are then amenable to computer analysis and the collation of many logs. They can be very economically stored on, and retrieved from, magnetic tape. Digitized geophysical logs of oil wells are transmitted by radio and telephone for interpretation by log analysts in response to the need for rapid answers at the well site.

Logging techniques also permit time-lapse measurements to observe changes in a dynamic system. Changes in both fluid and rock characteristics and well construction caused by pumping or injection can be determined by periodic logging. Radiation logs and, under some conditions, acoustic logs are unique in providing data on aquifers through casing. This permits logging at any time during or after the reestablishment of native fluids behind the pipe.

The graphic presentation of geophysical logs allows rapid visual interpretation and comparison at the well site. Decisions on where to set screen and on testing procedures can be made immediately, rather than after time-consuming sample study or laboratory analyses.

Limitations

The single most important factor that has limited the use of geophysical logging in ground-water hydrology is the cost in relation to the unit value of product. In 1966 oil-well logging costs in Canada averaged $0.75 per foot compared with drilling costs of about $13 per foot (Canadian Well Logging Society, 1967). This represents a drastic increase from 1952 logging costs of $0.10 per foot. During the same period, drilling costs decreased from $15 per foot. The logging cost increase is due mostly to an increase in the number of types of logs run and in the number of runs per well. Comparable figures are not available for water wells in the United States; however, it is known that logging costs are considerably lower and that the percentage of water wells logged increases rapidly with depth and cost of the well. If logging is to be widely used in ground-water hydrology, a constant effort will have to be made to keep its cost low in relation to the cost of drilling and development.

In order to improve the cost-benefit ratio of logging, interpretation must be provided along with logs. Inasmuch as few water-well drillers, hydraulic engineers, or hydrologists have the experience necessary to interpret geophysical logs, personnel training is essential. Logger operation is another facet of training that is greatly needed. Although the small loggers have become more dependable in recent years, they have also become more complex because of the addition of new tools. The trend toward complexity will continue as more sophisticated logging techniques become available. Therefore, in order to provide accurate, dependable logging, operators must be properly trained in both equipment operation and maintenance, and in log interpretation.

One fundamental problem in the application of geophysical logs is that the interpretation of many logs is more of an art than a science. The numerous environmental factors causing log response are difficult to analyze quantitatively. Even when theoretically derived equations are available, empirical data are needed to determine the unknowns in the equation; therefore, direct empirical methods may be more reliable. Empirical methods are based on the relationship of log response to samples, core, models, or experimentally derived equations. Most geophysical logs do not have a unique response—that is, a certain recorded deflection may be due to one lithology in one area and due to another lithology elsewhere. For this reason, background information and experience in each geologic environment is essential to guide log interpretation. Interpretation must also be based on sound knowledge of the theory of each logging technique.

There is no text that gives unambiguous rules for log interpretation. For example, clay does not always exhibit a higher natural-gamma intensity than adjacent sands. Furthermore, extraneous effects, such as borehole parameters, must be recognized and corrected, generally by empirical methods. These limitations have not prevented the nearly universal application of well logging to petroleum exploration; almost every well drilled for oil anywhere in the world is logged. Ground-water hydrologists and petroleum geologists are seeking the same basic information on the occurrence, character, and movement of fluids underground in order to guide subsurface fluid withdrawal or injection.

Following are steps essential to obtaining the maximum benefit from a geophysical well-logging program:

1. Plan the logging program on the basis of the data needed. (See table 1.)
2. Carry out drilling operations in a manner that produces the most uniform hole and the least disturbance of the environment.
3. Take representative formation and water samples where necessary, using logs as a guide, if possible.
4. Insist on quality logs made with calibrated and standardized equipment.
5. Logs should be interpreted collectively, on the basis of a thorough understanding of the principles and limitations of each type of logging technique, and some knowledge of the geohydrologic environment under study.

Lithologic Parameters

Most characteristics of rocks, the fluids they contain, and the borehole have an effect on the response of geophysical-logging instruments. Table 1 is a simplified tabulation of parameters that can be measured directly or interpreted from commonly available geophysical logs. The most widespread uses of logs in ground-water hydrology at the present time are to define the lithology and geometry of aquifer systems and to estimate the quality of contained water. In order to properly interpret one log or a set of geophysical logs, the basic principles governing the response of logging devices to characteristics of the rock matrix must be understood, as well as the interrelation among lithologic parameters. The lithologic parameters described in this section are those of principal interest to ground-water hydrologists, and they will be used throughout this technical manual without further definition.

Resistivity

The electrical resistivity of a rock depends on physical properties of the rock and the fluids it contains. Most sedimentary rocks are composed of particles having a very high resistance to the flow of electrical current. When these rocks are saturated, the water filling the pore spaces is relatively conductive compared with the rock particles or matrix. The resistivity of a rock, therefore, is a function of the amount of fluid contained in the pore spaces, the salinity of that fluid, and how the pore spaces are interconnected. The main factor in pore geometry is probably tortuosity, which is defined as the square of the ratio of the actual path length of the current to the length of the sample through which it flows. Resistivity is measured in ohm-meters, which is the resistance of a cube of material that is one meter on a side, and the resistance of that cube, in ohms, is numerically equal to the resistivity, in ohm-meters.

The resistivity of a rock that is 100-percent saturated with formation water is R_o, and the resistivity of the water is R_w. True resistivity, R_t, is distinguished from R_o because correction for partial saturation by hydrocarbons is necessary in petroleum exploration. Correction for partial saturation would also be necessary in hydrology if we made resistivity logs above the water table.

Table 1. — Summary of log applications

Required information on the properties of rocks, fluid, wells, or the ground-water system	Widely available logging techniques which might be utilized
Lithology and stratigraphic correlation of aquifers and associated rocks.	Electric, sonic, or caliper logs made in open holes. Nuclear logs made in open or cased holes.
Total porosity or bulk density	Calibrated sonic logs in open holes, calibrated neutron or gamma-gamma logs in open or cased holes.
Effective porosity or true resistivity	Calibrated long-normal resistivity logs.
Clay or shale content	Gamma logs.
Permeability	No direct measurement by logging. May be related to porosity, injectivity, sonic amplitude.
Secondary permeability — fractures, solution openings.	Caliper, sonic, or borehole televiewer or television logs.
Specific yield of unconfined aquifers	Calibrated neutron logs.
Grain size	Possible relation to formation factor derived from electric logs.
Location of water level or saturated zones.	Electric, temperature or fluid conductivity in open hole or inside casing. Neutron or gamma-gamma logs in open hole or outside casing.
Moisture content	Calibrated neutron logs.
Infiltration	Time-interval neutron logs under special circumstances or radioactive tracers.
Direction, velocity, and path of ground-water flow.	Single-well tracer techniques — point dilution and single-well pulse. Multiwell tracer techniques.
Dispersion, dilution, and movement of waste.	Fluid conductivity and temperature logs, gamma logs for some radioactive wastes, fluid sampler.
Source and movement of water in a well.	Injectivity profile. Flowmeter or tracer logging during pumping or injection. Temperature logs.
Chemical and physical characteristics of water, including salinity, temperature, density, and viscosity.	Calibrated fluid conductivity and temperature in the well. Neutron chloride logging outside casing. Multielectrode resistivity.
Determining construction of existing wells, diameter and position of casing, perforations, screens.	Gamma-gamma, caliper, collar, and perforation locator, borehole television.
Guide to screen setting	All logs providing data on the lithology, water-bearing characteristics, and correlation and thickness of aquifers.
Cementing	Caliper, temperature, gamma-gamma. Acoustic for cement bond.
Casing corrosion	Under some conditions caliper, or collar locator.
Casing leaks and (or) plugged screen.	Tracer and flowmeter.

Using R_o from logs and F, it is simple to calculate R_w, which is a function of the temperature and quality of water in an aquifer:

$$R_w = \frac{R_o}{F}.$$

Formation factor

The formation resistivity factor (F) is defined as the ratio of the electrical resistivity of a rock 100-percent saturated with water to the resistivity of the water with which it is saturated, $F = R_o/R_w$ (Archie, 1942). Because most rock grains have a very high resistance relative to water, the formation factor is always greater than 1. Formation factor is roughly related to effective porosity in poorly consolidated rocks as follows: $F = 0.62\phi^{-2.15}$. Guyod (1966) showed how porosity and resistivity data from logs can be used to determine the salinity of the interstitial water (fig. 1). The figure is based on average values for clay-free granular aquifers and is, therefore, approximate when applied to a particular aquifer. Thus, if all other factors are equal (fig. 1), the higher the porosity and salinity, the lower the aquifer resistivity.

Permeability

Permeability or hydraulic conductivity are the lithologic parameters most needed by the

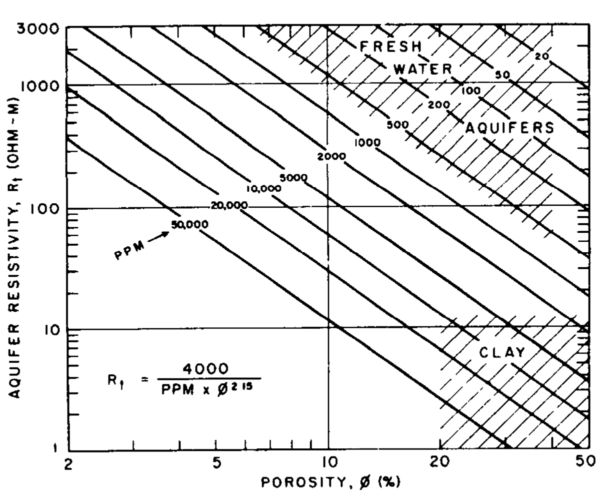

Figure 1.—Approximate resistivity of granular aquifers versus porosity for several water salinities. From Guyod (1966).

petroleum or ground-water geologist; yet, there is no log that can directly measure permeability. Intrinsic permeability is a measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. Hydraulic conductivity is the quantity of water that will flow through a unit cross-section area of rock per unit time, at a specified temperature under a unit hydraulic gradient. Permeability has been related to the response of a number of types of geophysical logs and to other parameters derived from logs. For example, an empirical relationship between natural-gamma-log intensity and permeability has been demonstrated by Rabe (1957) and Gaur and Singh (1965) for local areas. The relationship between permeability and porosity-sensitive logs, however, is generally dependent on determining the porosity and permeability of a number of samples, as an intermediate step. An example of this type of study was reported by Bredehoeft (1964), in which an empirical relation between porosity and permeability from core analyses was used to estimate permeability from acoustic and neutron logs. The relationship between permeability and formation-resistivity factor may be even more important in future work (Alger, 1966). Jones and Buford (1951) showed that both permeability and formation-resistivity factor increase with grain size. Alger used some of their data to show that the permeability of fresh-water sands increases with the formation factor, all other factors being the same, and he suggested the use of local data to establish empirical relations and guide log interpretation. Croft (1971) tested Alger's plot of permeability versus formation factor and found that permeabilities obtained from electric logs were in reasonable agreement with those obtained by other methods.

When attempting to derive permeability from logs, one must remember that permeability is not only related to porosity, but also to the grain size distribution, shape, and orientation and to the type and distribution of cementation. Another factor to be considered when attempting to relate permeability to logs is the possible error in laboratory measurements of permeability of cores. In-situ permeability measurements are needed to evaluate core permeabilities. For these reasons, empirical relationships between logs and permeability should be used only in a relatively consistent geohydrologic environment and only after the relationships have been clearly established.

Porosity

Porosity (ϕ) may be derived from gamma-gamma, neutron, acoustic-velocity and electric logs. Because porosity is related to the amount of water stored in rocks and has a local relation to permeability, it is an important hydrologic parameter. Porosity is simply defined as the ratio of the void volume of a porous medium to the total volume, and is generally expressed as a percentage. This simple definition is complicated in much of the literature on well logging by use of the word "porosity," without definition or without the modifying terms "total" or "effective." Further, total porosity and effective porosity are not easily distinguished in many rocks. Because various types of logs respond differently to the two types of porosity, an introductory discussion is necessary.

Total porosity, which will be called simply porosity in this manual, includes all the pore spaces in a material, regardless of whether they are interconnected or not. Effective porosity encompasses only the pore spaces that are interconnected and, therefore, effective in transmitting fluids. In most detrital sedimentary rocks, effective and total porosity are nearly the same; however, in volcanic rocks and in many carbonate rocks, isolated voids are common. Unconnected pore spaces filled with water do not lower the resistivity measured by an electric log, whereas connected spaces do. An additional factor to consider in interpreting porosity from logs is introduced by water held between layers in the clay minerals. Chemically bound water cannot be distinguished from free water on a neutron log. In some logging literature, the term "porosity" is used for effective porosity, and "shaliness" factors are introduced for correction of logs that respond to unconnected voids or chemically bound water. Water in the crystal structure of minerals, such as gypsum, should not be considered to be part of the total porosity. To further complicate the interpretation of porosity from geophysical logs, there are several different laboratory techniques for measuring porosity, all of which may give different results (Jenkins, R. J., 1966). Therefore, before any attempt is made to use laboratory values for calibrating log response, one must determine the kind of porosity that was measured on the samples and how it was done.

Porosity is also divided into primary porosity, or intergranular pore space, and secondary porosity. Primary porosity is characteristic of detrital rocks, related to the original size and shape of the grains and reduced by compaction and cementation. Primary porosity tends to be homogeneously distributed. Secondary pore spaces, which are formed after the rock is deposited, tend to be nonhomogeneous. Secondary porosity is caused by chemical solution, by fracturing and jointing, and by chemical alteration, such as dolomitization, and the alteration of anhydrite to gypsum. The acoustic-velocity log and some resistivity logs can provide erroneous porosities where the voids are nonhomogeneously distributed. The neutron probe tends to average the water-filled pore spaces within the volume investigated. Primary porosity is generally related to a lithologic character of the sediment, which may be interpreted from certain geophysical logs. In contrast, secondary solution openings may be distributed within a limestone, despite its lithologic differences. To locate these voids within the rock, one must rely on direct detection.

Specific yield

Specific yield is very important in groundwater studies because, when gravity drainage is complete, it is a means of comparing the various capacities of different materials to yield water. The specific yield of a rock is defined as the ratio of (1) the volume of water that the rock, after being saturated, will yield by gravity to (2) its own volume (Meinzer, 1923). Specific yield plus specific

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retention equals effective porosity. Meyer (1963) described the use of a neutron probe to determine the specific yield (or storage coefficient) of an unconfined aquifer. Johnson (1967) showed that specific yields are related to grain size distribution and porosity. In general, the highest specific yield is found in medium sand because of the more uniform size distribution, and the lowest specific yields are found in silts and clays. Specific yield can be estimated from geophysical logs.

Grain size

The importance of grain size in analyzing the hydrologic characteristics of a rock can be seen from its effect on permeability, porosity, and specific yield. No log is purported to give information that bears directly on the distribution of grain size in a sediment. However, Jones and Buford (1951) showed a fairly consistent increase in both permeability and formation-resistivity factor with an increase in grain size. Alger (1966) presented both laboratory and log data showing an increase in formation-resistivity factor with an increase in grain size.

Fluid Parameters

In addition to the lithologic parameters, a second important category of information that can be derived from well logs includes data on the character and movement of water in the borehole and the formation. Characteristics of fluids in the well bore can be measured directly, but the data on formation fluids must be inferred from logs. Logs of the conductivity and temperature of fluid in the borehole can be related to formation-fluid characteristics, provided that the well has had time to attain chemical and thermal equilibrium with the ground-water reservoir, that an adequate hydraulic connection exists between the hole and the rocks penetrated, and that the inhole flow does not disturb these conditions.

Fluid conductivity

The conductivity or resistivity (R_w) of fluid in a well bore or aquifer is one of the most useful ground-water factors that can be derived from geophysical logs. Fluid resistivity, rather than the reciprocal conductivity, is used for most oil-well logging. Figure 2 is a graph for NaCl solutions, considerably modified from one published by the Schlumberger Well Surveying Corp. (Alger, 1966). To make the chart more useful to ground-water hydrologists, it was extended to cover a wider range of salinities, as well as lower temperatures and conductivity, and Celsius temperature scales were added. If both the resistivity or conductivity of the fluid and the fluid temperature are known, then the total electrically equivalent NaCl, in milligrams per liter (mg/l), can be approximated from this graph. (At the present time all commercial logging equipment and logging literature still use Fahrenheit and parts per million.) If other ions are present, the following multiplying factors can be used for converting to electrically equivalent sodium chloride concentrations: $Ca^{+2} = 0.95$, $Mg^{+2} = 2.00$, $K^{+1} = 1.00$, $SO_4^{-2} = 0.50$, $HCO_3^{-1} = 0.27$, and $CO_3^{-2} = 1.26$ (Lynch, 1962). Thus, if the chemical nature of water in an aquifer is known from chemical analyses, and the ratios of ions are consistent, resistivity or conductivity from logs can be used to determine the approximate quantities of those ions present. For example, a solution containing 1,000 mg/l Ca^{+2} and 2,400 mg/l SO_4^{-2} would be electrically equivalent to a solution with 2,150 mg/l NaCl, calculated as follows: $1{,}000 \times 0.95 + 2{,}400 \times 0.50 =$ 2,150 mg/l equivalent NaCl solution. Thus, according to figure 2, the resistivity of the $CaSO_4$ water at 50° F (10°C) would be about 3.5 ohm-meters (2,860 μmhos/cm). Desai and Moore (1969) showed that the above conversion factors vary according to concentration, and they presented a more accurate method for dissolved solids in concentrations greater than 100,000 ppm.

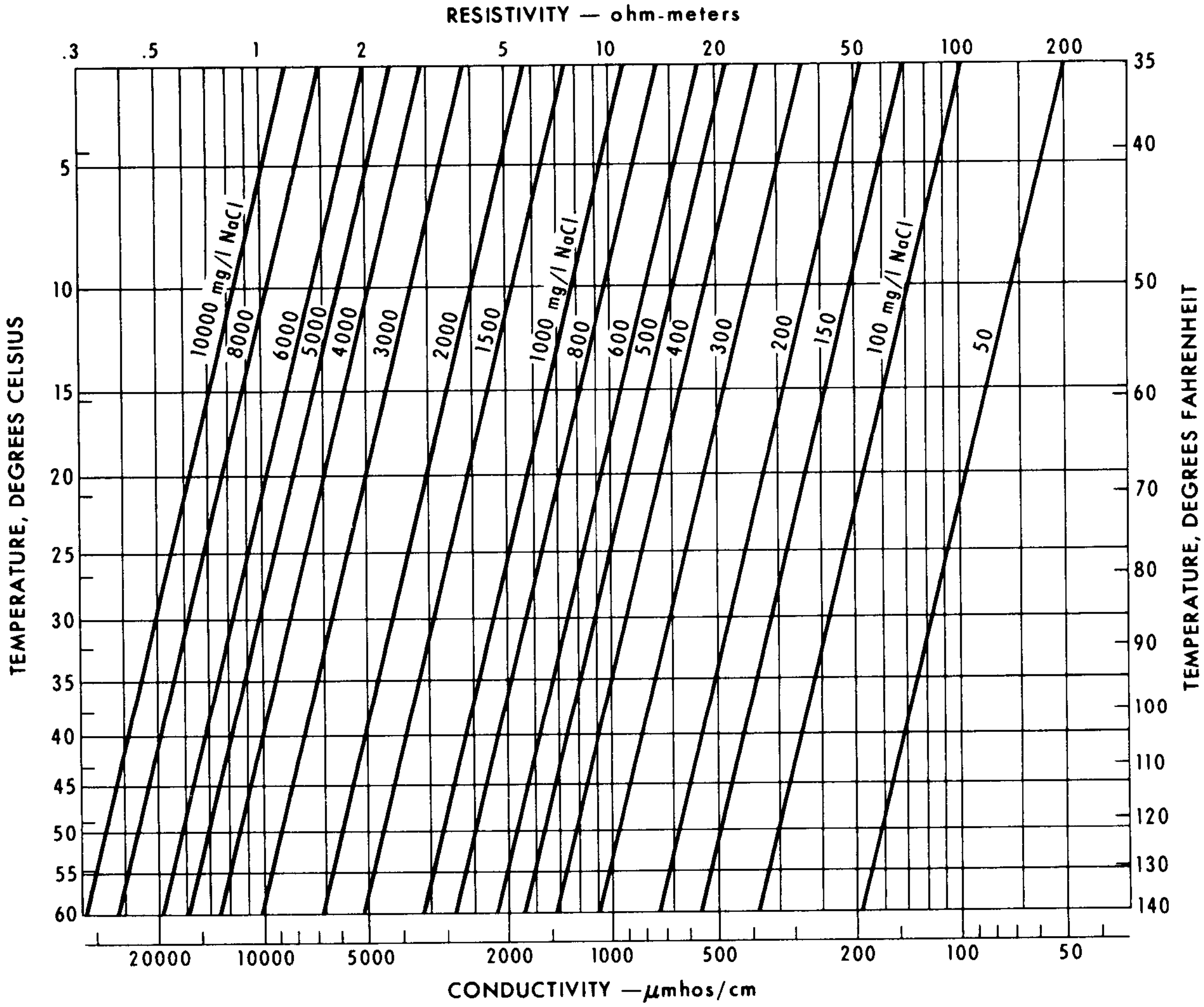

Figure 2. — Electrically equivalent concentrations of a sodium chloride solution as a function of resistivity or conductivity and temperature.

The conductivity of fluid in the hole and rock must also be known in order to correctly interpret other types of logs. The effect on resistivity logs is obvious, but it is not generally realized that high-conductivity fluids in the borehole environment can necessitate the application of a correction factor for the quantitative interpretation of both neutron and gamma-gamma logs. The effect of increased salinity is to raise the fluid density, used to calculate porosity from the gamma-gamma log. An increase in total dissolved solids also lowers the amount of hydrogen that a neutron probe measures. Therefore, a lower porosity, or moisture content, will be indicated on the log. This becomes a problem only for very concentrated solutions. Fluid-resistivity information can also be used to calculate fluid density for correction of water-level data.

The relationship of water in the hole to water in the surrounding rocks must be understood in order to properly interpret a number of geophysical logs. The chemistry of fluid in the hole is not necessarily similar to the chemistry of fluid in the rock. After a hole is drilled, cemented, or pumped, it may be as much as several months before chemical and thermal equilibrium is reached. Even in an otherwise completely stagnant column of water, convective mixing, due to temperature gradient or fluid-density differences, may occur. If the formation-resistivity factor is known and R_o can be determined from resistivity logs, R_w can be calculated and compared with values obtained from logs of fluid conductivity.

Fluid temperature

The temperature of water in a drill hole may approach the temperature in the rock without hydraulic connection between the two, provided that inhole flow is not taking place. Mud cake or casing that could prevent chemical equilibrium between the fluids in the hole and in the formation does not necessarily prevent thermal equilibrium. Temperature logs can be used to determine the position of curing cement behind casing. Temperature logs are also necessary to make correction of water viscosity, specific conductance measured by fluid-conductivity logs, and all logs sensitive to temperature changes in the hole. Water from different aquifers generally differs in temperature so that sources of water and movement in the hole may be identified from temperature logs. A new use for sensitive temperature-logging equipment is tracing of injected water, which is identified by its thermal contrast with the native fluids.

Fluid movement

The direction and velocity of fluid moving within a borehole may be measured by logging. Work with radioactive tracers at the National Reactor Testing Station in Idaho has demonstrated that stagnant water can exist in a well within just a few feet of water moving at a high velocity. If such conditions are not defined where periodic water samples are taken for monitoring ground-water contamination, stagnant water might be obtained, thus providing erroneous data. Water levels measured in wells open to a multiaquifer artesian sequence are not likely to be meaningful. For these reasons, the selection of observation wells and the depth chosen for taking water samples should always be based on information on the relationship of the fluid column to fluid in the rock sequence.

Flow in a well bore open to several aquifers or zones having different heads will cause anomalies on fluid-conductivity and temperature logs. Properly interpreted fluid-conductivity and temperature logs can be used to locate zones where water enters and (or) leaves the well bore. Flowmeter or tracer logs will also define these zones.

Moisture content

The percentage of moisture in the unsaturated zone is an important hydrologic parameter that is related to evapotranspiration and recharge, and can be derived from logging. The measurement of moisture changes by neutron logging is also one of the most accurate methods for determining the specific yield. Although neutron-logging devices are the only practical means of obtaining in-situ moisture content, other logs are invaluable aids in interpreting neutron logs. The short-spaced neutron-moisture meters (spacing between the neutron source and detector) are especially susceptible to borehole effects, and lithologic and porosity information are needed to properly interpret moisture measurements.

Log Interpretation

Log interpretation refers to all processes of obtaining qualitative or quantitative information from geophysical logs. Logs are only useful if they can be interpreted to provide new information or extend information already available.

Qualitative interpretation

In ground-water studies most well logs are used in a qualitative sense for identification of lithology, borehole conditions, and for stratigraphic correlation. To make correct qualitative interpretations of geophysical well logs, the log analyst must have a thorough understanding of the principles of each sensing technique and an understanding of the geohydrologic environment being investigated. Therefore, only the general principles of interpretation are discussed in this section, and descriptions of each logging technique must be consulted for the specific logs to be used. Because few logging systems have a unique response, log analysts must rely on background information on lithology, water quality, and hole conditions to substantiate their log interpretation. The amount of information that can be derived from logs is generally a function of the background information available, the number of different types of logs run, the number of wells logged in a geologic environment, and the experience of the log analyst. Fortunately, the novice in borehole geophysics can make simple interpretations and stratigraphic correlations.

The common technique of collecting and analyzing a few lithologic samples from each hole drilled generally does not provide adequate data to guide log interpretation. A few nonrepresentative samples of any kind can be very misleading. More information of use for quantitative log analysis is obtained either by continuous coring in one hole or by sidewall sampling after logging, or by drilling a second hole for selective coring after logging. The lithologic factors causing log response can then be extrapolated to other holes in the area on the basis of logs.

Qualitative log interpretation is more likely to be correct when several different types of logs are available. On the other hand, it is expensive and nonproductive to run every kind of log available in every well because many types of logs are only informative under certain conditions. Caliper logs are essential for determining hole-diameter effects. Two different porosity-dependent logs will often provide more information than one. For example, resistivity logs will give a different response in sands of the same porosity that are filled with water of different quality, whereas certain types of neutron logs will vary little in response to minor changes in fluid resistivity. The natural-gamma log will often indicate the sands which have the highest clay content, and, therefore, a lower effective porosity and permeability. Fluid-conductivity and temperature logs or a flowmeter log might indicate that the sand with fresher water was being contaminated with saline water moving up or down the hole from another aquifer. These are examples of the types of interpretation that can be made by rapid visual examination of logs, along with application of some knowledge of the geohydrologic environment.

Interpretation is more apt to be correct as logs of more wells in a single geohydrologic environment become available and can be related to whatever is known about the wells. Incorrect analysis of log response in one well due to some extraneous borehole effect is not likely to be repeated throughout the area. If a response does repeat consistently, then it is probably due to a lithologic characteristic. Gradual changes in log response due to changes of bed thickness or facies changes become apparent when a number of logs are available in a depositional basin.

Quantitative interpretation

The most important and, to date, little used function of water-well logs is to quantify geohydrologic parameters. Quality control of logs is most important to this aspect of borehole geophysics (Wyllie, 1963; Lynch, 1962). To be most useful quantitatively, logs should be recorded at the highest sensitivity that is consistent with a minimum of off-scale deflections; scales and other pertinent data must be recorded on each log, and the equipment must be properly calibrated and standardized. Vertical scales should be selected on the basis of the detail required. For example, if in doubt, select 10 feet per inch rather than 20 for shallow wells. Seldom is 50 feet per inch justified for shallow water wells, and when used for deep wells, a second log at 20 feet per inch is often useful. Vertical detail that is lost cannot be regained by photoenlargement. Logs should always be inspected for equipment malfunction. Repeat logging is the best way to check a questionable log. Most of the logging tools described in this manual do not directly measure the lithologic or fluid parameter that is desired. Instead, they measure a physical property from which the required parameter may be calculated or inferred, mostly by means of empirical relationships. To make quantitative analysis of logs, the equipment must first have been properly calibrated and standardized, the extraneous effects of petrophysics and fluid characteristics must be considered, and all corrections for borehole and geometric effects must be made. These factors are common to the interpretation of most types of geophysical logs and are a prerequisite to quantitative log analysis. Environmental scales displayed on well-log headings, such as g/cc (grams per cubic centimeter) or percent porosity, should never be accepted at face value, unless the equipment has been calibrated and (or) standardized. Extraneous effects, such as borehole diameter, must also be considered before these environmental scales become meaningful.

Log calibration

Calibration of logging equipment refers to the process of making sure the values on the curve scales used are correct. Too often, the scales on log headings signify nothing more than the position of the scale-selector switch. This is particularly true for the single-point resistance and gamma logs. Calibration defines the numbers on log scales, such as 0, 10, 100, and 1,000 ohm-meters. Standardization is a method for comparing these values in time. Are 0, 10, 100, and 1,000 ohm-meters still in the same place on the chart, even though they may not be correct? Calibration is generally accomplished in models that simulate inhole environmental conditions or by measuring physical properties of core samples from a logged hole.

Prior to calibration, the scale units for the log must be selected. It is preferable to label log scales with units that are actually related to a measured phenomenon, rather than to use units based on an inferred relationship to the quantity measured. Thus, it is preferable to use microseconds per foot for acoustic logs and counts per second for neutron logs, rather than to use environmental scales of porosity, in percent. Porosity scales should be superimposed on these logs only after the log response has been related to standards and has been corrected for extraneous effects. If possible, it is desirable to use units that are widely accepted in the industry, so that logs made by different companies can be compared. Inches of hole diameter for caliper logs and ohm-meters for resistivity logs are examples of units that are universal. In contrast, the following units have been used for natural-gamma logs: Counts per second or minute, milliroentgens or microroentgens per hour, micrograms of radium-equivalent per ton, inches of deflection, and API gamma-ray units. There is no accurate method of quantitatively relating gamma logs made with different equipment and with different scale units unless the response of instruments has been compared in an environmental calibrator.

Calibration of logging equipment should be done at sufficient points on each scale to establish the linearity of equipment response. Calibrators or environmental models should be considerably larger than the radius of investigation of the logging device—that is, they should be large enough so that a further increase in the radius of investigation would not alter the response of the logging system. Calibration devices must be stable, or vary only in a readily predictable way. Calibrators should be so constructed that the geometrical relationship of the logging sonde and the environment modeled can always be duplicated exactly.

Although two different sondes may have the same response in one simulated environment, they may not have the same response in all environments. For example, two neutron probes may give the same porosity values in limestone but may give different values in a shaly sandstone. Most companies that make the same general type of tool use different signal sources, detectors, and electronic circuits, which will modify tool response. For this reason, where quantitative measurements are desired, it is best to calibrate logging equipment in models that closely simulate the actual environment. A flowmeter to be used in a 4-inch hole should be calibrated in a 4-inch, not an 8-inch, pipe; and a neutron probe to be used for measuring the porosity of sand will probably not provide the correct values if it is calibrated in the American Petroleum Institute limestone pits. (See section on "Neutron Logging.") However, correction factors for borehole, fluid, or lithologic effects can be applied.

Laboratory core analyses are widely used for placing values on logs. This is generally an interpretive postmortem process that attempts to relate a parameter, which was not measured directly, to log response. When comparing laboratory data to logs, remember that cores represent point values. In contrast, some logs represent an average value of a physical parameter for a volume of material more than 100 times larger than the core sample. A large number of core samples must be taken and analyzed in order to be statistically representative of the usual nonhomogeneous geologic environment. If the core samples are representative, the next problem is relating the point values to the continuously varying geophysical log. The error introduced at this point can be most significant. If the trace of most geophysical logs sensitive to lithologic parameters is analyzed, the pen deflections between 45° and horizontal will be predominant. A small error in the vertical placement of a laboratory value on this type of log can result in a very large error in the related log value unless the vertical scale of the log is greatly amplified. The exact depth of a sample is subject to an error which may be very large in a single-coring run with high core loss, if the driller cannot determine which interval was retained. Likewise, geophysical logs are subject to footage discrepancies due to cable stretch, equipment malfunction, and human error. In addition, the measuring datum for drilling and logging may not be the same. The kelly bushing on the drill rig is commonly used as zero datum on commercial logs. To ameliorate some of these difficulties, the usual technique is to plot the laboratory data on the same depth scale as the log and then slide the plot up and down on the log until the best fit is obtained. This technique can also lead to significant errors in individual values. A recent paper by Jeffries (1966) describes the use of correlation functions to derive the best relationship between samples and logs. Figure 3 shows a neutron log and a plot of more than 200 values of porosity measured on core samples in the laboratory. Note the wide variation in core values between depths of 200 and 300 feet. If only a few of the samples in this depth interval had been analyzed and used for calibrating the neutron log, the results could have been very inaccurate. Also note how great the porosity error would be in figure 3 if the core locations were plotted in slight error vertically between depths of 360 and 420 feet.

Standardization and log accuracy

Most of the environmental calibrators or models are too large for transportation in logging vehicles; yet, it is highly desirable to run checks on the reproducibility of logs in the field. Devices used to check the response and stability of logging equipment in the field are referred to in this manual as standards. They provide a means of comparing the response of geophysical-logging equipment from time to time and from place to place. If a standard check is not recorded on a geophysical log, the accuracy of the scale shown is open to question. Because temperature drift is such a common problem in certain logging equipment, it is desirable to record standard checks both before and after logging if a high degree of accuracy is required. Some logging sondes have built-in standards that provide a reference signal which may be recorded at any time as a means of checking system drift. Other types of standards are resistance-decade boxes for conductivity or resistivity tools, plastic cylinders for neutron tools, and radioactive sources for gamma tools. At least two standard values should be available so that both positioning and scale span, or sensitivity, can be checked.

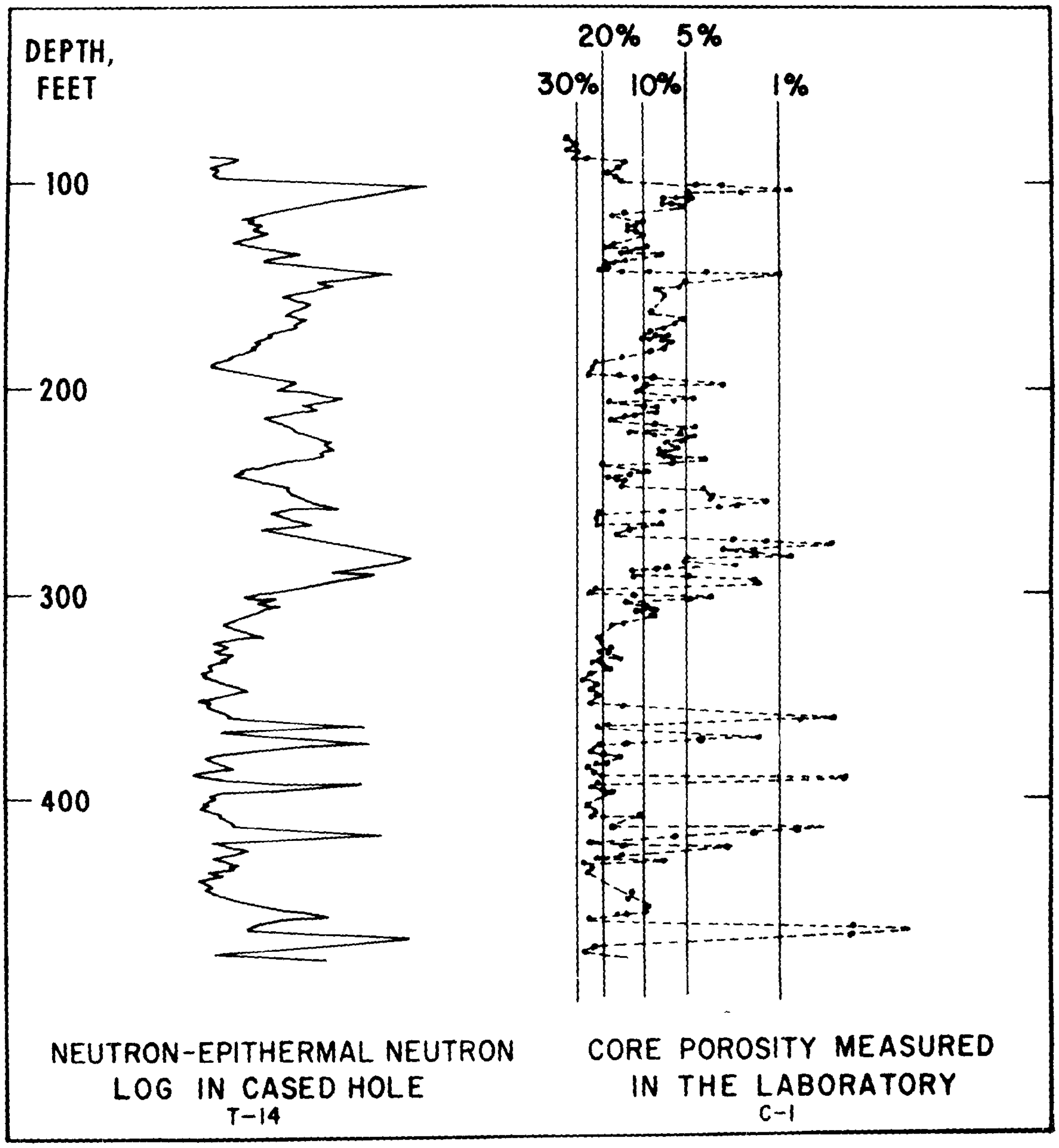

Figure 3. — Neutron log and a plot of porosity measured in the laboratory, upper Brazos River basin, Texas.

Standards may or may not display unit values that are the same as the units in which the equipment is calibrated. Most logging standards used in the field do not accurately simulate the environment being logged. Therefore, values placed on logs by the use of field standards may not be accurate guides to log interpretation. The resistance-decade box, commonly used for standardizing fluid-conductivity tools, can be related to actual fluid resistivities; however, decade-box values will not be true if the contact resistance of the electrodes in the tool changes.

If logs are to be interpreted quantitatively, calibration, standardization, and corroborating data are essential to establish the accuracy of the response values. This applies to commercial logs made with oil-well equipment, as well as to those logs made with small water-well equipment. An understanding of the principles of each logging technique used will permit an evaluation of the methods of determining log accuracy. Although most questions of log accuracy relate to the recorder deflection of the logging equipment, errors in depth or footage do occur, and, therefore, cross-checks with other logs or data on the hole should be made if depth measurements are suspect.

Composite interpretation

As a general rule, the more types of geophysical logs that are available for a single well and the more wells that are logged within a given geohydrologic environment, the greater the benefits that can be expected from logging. The synergistic character of logs is due to the fact that each type of log actually measures a different parameter, and when several are analyzed together, each will tend to support or contradict conclusions drawn from the others. Similarly, a large number of wells logged in one ground-water environment will provide a statistically meaningful sample of the environment and reduce the chance of interpretive errors.

Three nuclear logs, natural-gamma, gamma-gamma, and neutron logs will be used to illustrate the synergistic nature of logs. Figure 4 is a hypothetical diagram of nuclear-log response in saturated clastic sediments. For illustration purposes, these sediments are considered to be a mixture of water, quartz sand, and clay, in various proportions, which may change the porosity and permeability of the hypothetical aquifer as described on the outside of the triangle. The following generalities can then be made about nuclear-log response, which is shown on the inside of the triangle:

1. The natural-gamma count rate will increase with increasing clay content.
2. The neutron count rate will increase with decreasing porosity.
3. The gamma-gamma count rate will increase with increasing porosity.

A sample of this hypothetical sediment will fall somewhere within the triangle illustrated and can be characterized by relative percentages of the three components. Natural-gamma logs indicate sand-clay ratios and relative permeabilities, but do not necessarily

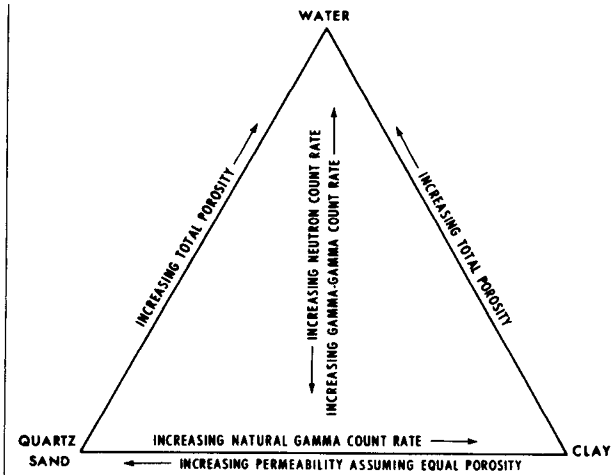

Figure 4. — Hypothetical response of nuclear logs in a mixture of quartz sand, clay, and water.

relate directly to porosity. The neutron and gamma-gamma logs are both related to porosity, even though they measure different parameters, and will therefore not respond the same to the different lithologies.

Figure 5 shows how the relationship of various logs can be utilized to determine hydrologic characteristics. These six different logs were run in a rotary-drilled test hole adjacent to a core hole on the upper Brazos River in Texas. The lithologic description on the left was derived from the cores.

The simplified response of these six logs is listed below:

Type of log	Parameters measured and direction of log deflection	Parameters inferred and direction of log deflection
Caliper	Hole diameter (increases to right).	Cementation and effect of drilling.
Gamma-gamma.	Scattered and attenuated gamma photons (radiation increases to right).	Bulk density (decreases to right) and hole diameter (increases to right).
Natural-gamma.	Natural-gamma radiation (increases to right).	Clay content (increases to right).
Spontaneous potential.	Natural electrical potentials (positive to right).	Clay or shale content.
Single-point resistance.	Electrical resistance of hole and adjacent rocks (increases to right).	Hole diameter and water salinity (decreases to right); effective porosity (increases to right).
Neutron-neutron.	Neutrons slowed and scattered by hydrogen (radiation increases to right).	Saturated porosity (decreases to right).

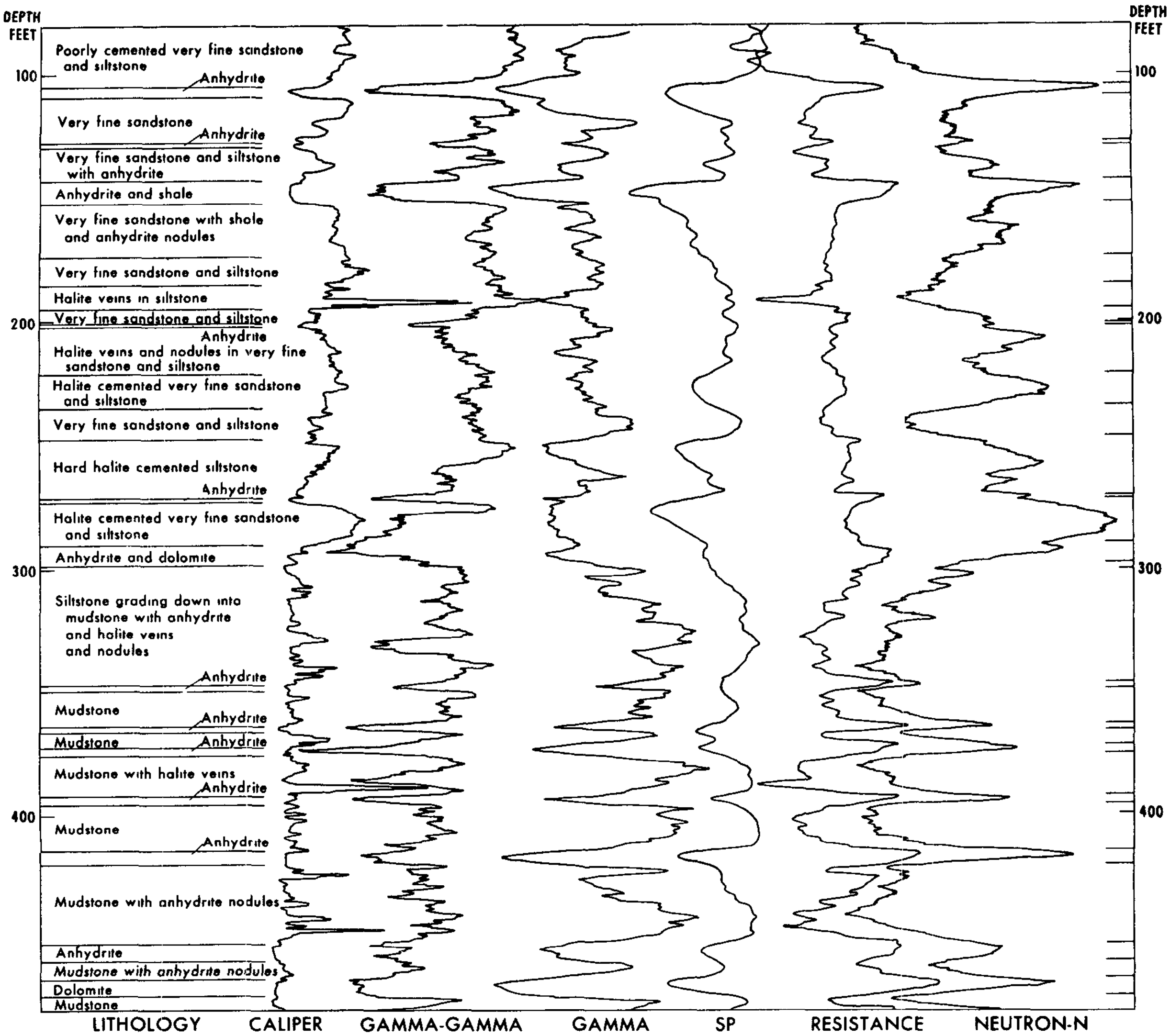

Figure 5. — The relationship of six different geophysical logs to lithology, upper Brazos River basin, Texas.

The significant increase in total porosity (deflections to the left) shown on the neutron log below a depth of 300 feet does not indicate an increase in effective porosity or permeability as might be expected. Instead the gamma log suggests that the increase in total porosity is due to an increase in clay content. (See section on "Gamma Logging.") Laboratory analyses of particle-size distribution showed a higher percentage of clay particles, in agreement with the higher gamma log response. From these logs the zone above 100 feet was selected as having the highest permeability in the well and this was borne out by packer and pumping tests. This more permeable zone shows the highest total porosity on the neutron log, the lowest resistivity on the single-point resistance log and, as indicated by the natural-gamma log, the lowest clay content. The neutron log measures total porosity in saturated rocks, which in some areas can be related to permeability. Shales and clay-bearing sedimentary rocks tend to have a high total porosity but a low permeability, and, therefore, they produce water slowly. Composite interpretation of gamma and neutron logs helps to distinguish these sediments and also identifies zones where chemically bound water may cause an error on neutron logs.

A very useful technique of composite log interpretation has been pioneered by Schlumberger Well Services (Raymer and Biggs, 1963). Figure 6 is an example of a Schlumberger plot of apparent limestone porosity from neutron-log response versus bulk density from gamma-gamma log response. The basis for this chart is the difference in response of the two types of porosity devices due to the effects of rock matrix characteristics. Neutron and gamma-gamma tools will not give the same count rate in limestone and dolomite of the same porosity. With properly calibrated gamma-gamma and neutron equipment, a plot like this may be used to determine the lithology of the rock matrix and to correct porosity for matrix effects. For example, an apparent neutron porosity ϕN of 10 percent on the abscissa and a gamma-gamma bulk density ρ_b of 2.76 on the ordinate would indicate that the rock was actually a dolomite with 6-percent porosity. If the gamma-gamma-log bulk density was 2.44 g/cc and the apparent neutron porosity was 10 percent, the rock would be interpreted as a sandstone with a porosity of 13 percent. Similar charts relating acoustic-log response to either neutron or gamma-gamma log response are

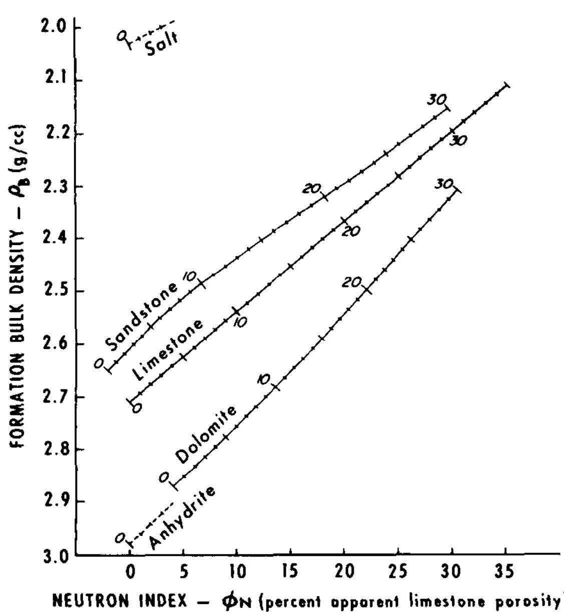

Figure 6. — Lithology and corrected porosity from composite interpretation of gamma-gamma and neutron logs.

available from commercial logging service companies.

Another example of the synergistic nature of logs is furnished by use of the Archie equation $F = R_o/R_w$, where F = formation-resistivity factor, and R_o = resistivity of a formation saturated with water of resistivity R_w (Archie, 1942). He also established that F is related to porosity and permeability, and expressed this relationship as $F = \phi^{-m}$, where m is a cementation factor that varies between 1.3 and 2.6. Both F and m tend to be consistent within a lithologic unit in a given depositional basin. The Humble Oil Co. formula $F = 0.62\phi^{-2.15}$ is widely used for sandstones (Winsauer and others, 1952). By combining either of the preceding formulas with $F = R_o/R_w$, R_o, derived from a multiple-electrode resistivity log, and ϕ, derived from a neutron, gamma-gamma, or acoustic log, would permit the calculation of R_w, a quantity which is related to the salinity of water. (See fig 2.) An empirical approach to obtain F and R_w was devised by Turcan (1966). (See section on "Normal Devices.")

Computer collation and interpretation of geophysical logs is now available from some commercial well logging companies. The programs were written for oil-field applications; however, factors useful in ground-water hydrology may also be computed from logs recorded digitally on magnetic tape. These include corrected total porosity, effective porosity, grain density, shaliness, true resistivity, and formation-fluid resistivity. Computer output may be printed numerically or plotted continuously as a graphic record, with the presentation of data preselected to fit the problem. Logs either can be digitized in the field as they are run or existing graphic geophysical logs can be digitized and recorded on magnetic tape, making them amenable to computer analysis.

Computer interpretation of geophysical logs is also used in uranium ore reserve and bulk-density calculations by the U.S. Atomic Energy Commission (Scott, 1963; Dodd and Droullard, 1966). For programing and computer time to be economically justified for ground-water applications, a large number of digitized logs must be available. One meaningful use of computers that does not require a large number of logs for justification is the use of correlation functions to fit laboratory data to geophysical logs or to correlate several different logs (Jeffries, 1966).

Geometric effects

Anomalies in logs due to variations in the size and shape of the environment that is sensed by the logging device are called geometric effects and must be considered in the interpretation of all geophysical logs.

Radius of investigation

The interpretation of many well logs depends on an understanding of the radius of investigation or volume of influence. These terms refer to the material in and around the borehole that contributes to the varying signal measured by the logging probes. For sake of simplicity, the radius of investigation is here considered to include that part of the formation contributing 90 percent of the measured signal. The radius of investigation ranges from fractions of an inch for microresistivity logging devices to many feet for focused resistivity sondes. Radius of investigation must be considered for all logging devices measuring lithologic characteristics.

If a logging sensor is visualized to be within a volume of material that is contributing to the recorded signal, the drill hole, the fluids in the hole, and the wall of the hole that has been invaded and caked with drilling materials are also within the volume investigated. Changes in any of these factors will alter log response even though the characteristics of the surrounding rocks are constant. Furthermore, sondes measuring similar parameters but having different volumes of investigation will record dissimilar logs. Therefore, several kinds of resistivity sondes having different volumes of investigation can be used to measure the thickness of the invaded zone which is related to formation permeability. Some resistivity sondes have a zone of maximum response that is some distance from the pickup electrodes. For most logging devices, however, the materials closest to the sonde contribute most of the recorded signal.

Bed-thickness effects

The concept of a volume of material being measured by a downhole sensor also serves to explain the effects of bed thickness on logs. For a thin bed, the volume being investigated may include part of the adjacent rocks, so that the logging sonde does not measure the same value that it would in a thick bed of the same lithology. (See fig. 42.) If a logging device has a volume of investigation that extends a considerable distance up and down the hole from the detector, a lithologic change will begin to affect the signal transmitted from the sensor before it actually reaches the depth at which the change occurs. The effect of the bed will also be seen on the log after the sensor has passed beyond the bed boundary. This is the characteristic of radiation-logging devices that produces a gradual change in log response even though the lithologic change may be sharp. Thus, the common technique of drawing lithologic contacts through the half-amplitude point on radiation logs can be misleading, particularly for thin beds.

A serious problem is encountered when interpreting some multiple-electrode resistivity logs in thin-bedded sediments. These logs may actually exhibit a cratering effect or reversed response in thin beds of higher resistivity rocks between layers of lower resistivity rocks. (See section on "Normal Devices.") The only resistivity curves that do not exhibit reversals are made with the single-point device. It is, therefore, one of the best tools for logging lithology in a thin-bedded sequence. However, because of its sensitivity to borehole effects, it cannot be used quantitatively for measurement of resistivity and is more correctly called a resistance log. The spontaneous-potential log is effective for determining the true position of bed boundaries because contacts are generally at the point of maximum inflection on the curve. A sensitive caliper log is also useful for locating bed boundaries; however, logs made with a feeler-type sonde must be corrected for the different measuring depths caused by major changes in hole diameter. In summary, the accurate measurement of bed thickness and the location of bed boundaries is best accomplished by using several types of logs with proper recognition of the volume of material investigated by the various logging sondes.

Borehole effects

A hole cannot be drilled without disturbing the environment to be measured. Most borehole effects are extraneous to the logging measurement desired and must, therefore, be considered in log interpretation.

Hole-diameter effects

One of the most common extraneous effects present on logs is caused by changes in the diameter of the hole. Diameter changes are divided into two types that may affect logs in different ways — changes in average hole diameter and changes in borehole rugosity. Differences in average hole diameter are generally due to changes in bit size or drilling technique, or to thick units of different lithology. Changes in average diameter that extend over a depth range of many feet do not greatly affect the signal from decentralized logging tools. In contrast, borehole rugosity, or rapid fluctuations in hole diameter, will cause erroneous values on logs from decentralized and axially symmetric logging devices. Hole diameter, measured with caliper probes, is essential for the quantitative interpretation of most logs.

Few holes drilled for ground water have smooth walls or are of constant diameter. The most irregular bores are in poorly consolidated or thin-bedded sediments, and the smoothest bores are generally in igneous rocks. In sedimentary rocks the drilling technique is a major factor in hole diameter; for example, a rapidly drilled hole generally has the smoothest bore. The longer the drilling and sampling operations are continued in a hole drilled in poorly consolidated sediments, the larger and more irregular the bore becomes. Circulating drilling mud or water for long periods also tends to affect the diameter. Drilling techniques and major changes in lithology are the common reasons for changes in average hole diameter. Thin-bedded units, fractures, and solution openings are responsible for most borehole rugosity. Correction of logs for rugosity where the tool spans thin washed-out zones generally is not possible. These zones should be eliminated from quantitative log analysis because, even with the aid of caliper logs, corrections cannot be made.

Decreases in hole diameter to less than bit size are due either to mud cake build-up or to clay squeezing into the hole. Clay squeezes will generally continue to decrease diameter until the hole is closed. Mud cake or clay squeezes will affect the response of some logging devices. Scale and mineral deposits may decrease the hole diameter or increase the casing or screen thickness in pumped wells. Any change in the nature or thickness of material between the logging sensor and the rock being measured is likely to affect the log response. Therefore, the sensitivity of each logging device to hole diameter should be considered, and where necessary, a caliper log should be made.

Casing effects

Only the nuclear logs are routinely used for logging through casing, although it is possible to use acoustic-velocity logs if the casing is bonded to the wall of the hole by cement. Casing and cement introduced between a radiation detector and the wall of the borehole change the radiation detected. Casing of consistent thickness and type introduces a constant error that will shift or suppress log response, but it generally does not change the character of the log.

Qualitative nuclear logs can even be made through two thicknesses of casing or through drill stem, but each change in size or type of pipe will cause a baseline shift on the log. Furthermore, as casing thickness increases, the signal-to-noise ratio decreases, and log character is subdued. The increase in metal thickness at casing collars or joints is easily apparent on some gamma-gamma logs, but generally is not discernible on neutron or natural-gamma logs. Also, as the radius of investigation increases, the effect of casing decreases. The short-spaced neutron-moisture tool does not provide accurate values in casing that is more than 2 inches in diameter, whereas the conventional long-spaced neutron-logging tool will make excellent logs in 10-inch casing. In general, however, better logs can be obtained in small-diameter casing. A caliper log prior to the installation of pipe is the only way to accurately measure a borehole diameter. As an alternative, radiation devices having different radii of investigation can be used to derive qualitative information on hole-diameter changes behind casing.

Drilling effects

Drilling a hole generally disturbs the fluids and pore spaces in the environment to be measured. Rotary drilling with mud probably causes the greatest disturbance in the environment near the borehole. Augering probably produces the least disturbance in the environment. Vibration caused by driving casing in cable-tool drilling may compact unconsolidated sediments and reduce the porosity and permeability. Drilling operations can also produce changes in the temperature and resistivity of fluids in the borehole and adjacent rocks, reduce the movement of fluid between the hole and the rocks, and change the porosity and permeability of the rocks.

In rotary drilling, a natural or artificial mud is circulated down the drill stem to bring the cuttings back to the surface; the mud also keeps the hole open, cools the bit, lubricates the drill stem, coats the wall of the hole to reduce fluid loss, and serves as an electrical-coupling medium necessary for many logging operations. Because the pressure of the mud column exceeds the hydrostatic pressure in the formation being penetrated by the bit, the mud filtrate invades the rock adjacent to the borehole and displaces the native fluids away from the hole. During this process, many of the particles suspended in the mud are filtered out and form a mud cake, or filter cake, on the wall of the hole. The invaded zone and mudcake may introduce unknown and, in general, undesirable factors in log interpretation.

The effects of drilling also have a positive aspect. Thickness of the filter cake and thickness of the invaded zone are sometimes related to the hydraulic properties of the aquifer system. In addition to the type of mud, the differential pressure, and the length of time an aquifer has been exposed to mud, the porosity and permeability of sediments will also determine the depth of invasion. In most oil fields, if all other factors are equal, the low-porosity sediments will generally be invaded deeper than the high-porosity sediments. The most obvious reason for this apparently anomalous relationship is that there is a greater volume to fill in high-porosity formations. Further, the permeability of the mud cake is generally lower than the permeability of the rock, so that the mud cake and the differential pressure become the factors that control the rate of filtration. In contrast, thicker invaded zones were found to occur in aquifers, rather than in confining beds in shallow, poorly consolidated sediments. A complete discussion of invasion characteristics is beyond the scope of this manual, and reference should be made to Doll (1955).

Inasmuch as both the mud cake and the zone of filtrate invasion vary in thickness, logging devices having different volumes (radii) of investigation provide a means of measuring these factors. A sensitive caliper log can provide data on mud cake build-up, and various multielectrode-resistivity devices are designed to investigate the mud cake, the invaded zone, and the native fluids. Nuclear logs provide a means of investigating the changes that occur behind casing as drilling mud and filtrate are gradually dissipated by native fluids and natural conditions are approached.

Thus, if the drilling process can alter conditions in and near a drill hole, it follows, then, that pumping and development operations can remove mud cake and invading fluids and increase the porosity near the hole. Procedures used for the development of water wells are intended to increase porosity and permeability near the hole to greater than natural undisturbed values. This is achieved in granular sediments by removing fine-grained material from between the larger grains. Logs related to porosity, such as the neutron log, can provide data on the relative effectiveness of well development and the location of developed zones. (See fig. 52.) This can be done by running logs at intervals during development. The same procedure can be used with resistivity logs to observe the return toward normal fluid conditions in and near uncased drill holes, or through some plastic well screen. (See section on "Normal Devices.")

Drilling and sampling operations should always be designed to cause the least possible disturbance in the environment if logging is to be done. Changes caused by these operations, and subsequent changes with time, must always be assessed in the interpretation of geophysical logs. For this reason, a two-hole drilling, logging, and sampling operation may provide more reliable data for the drilling dollar. This is accomplished by rapidly drilling one hole to the desired total depth and making a full suite of geophysical logs. On the basis of the geophysical logs, sample depths are selected that will provide the most representative and meaningful core and water samples. If a sidewall sampler is available, cores can be taken subsequent to logging the first hole; if not, a second hole can be drilled close to the first hole and cored at the intervals predetermined from log analysis. Another advantage to drilling a second hole is that aquifers selected from logs can be developed and tested before they become greatly affected by drilling mud.

Logging Equipment

Geophysical-logging equipment appears complex, and the variety of instruments in use is very large. Fortunately, any well logger—from the single-conductor water-well unit to the seven-conductor oil-well unit—can be divided into the same basic components. Minor differences in operating controls and how a function is performed are not fundamental to an understanding of logging. Any basic measuring system consists of a sensor, signal conditioners, and recorders or indicators. Figure 7 shows the basic components of geophysical well-logging equipment. In a well-logging system the sensor is contained in a watertight probe or sonde, which generally receives power from the surface and transmits a signal to the surface through logging cable. The cable also serves to position the probe in the hole by means of a winch. Controls on all recent loggers are used for regulating (1) logging speed and direction, (2) power to surface and downhole electronics, (3) signal conditioning, and (4) recorder response.

Chart paper or photographic film is moved through the recorder as a function of the position of the sonde in the hole. This is accomplished either by a mechanical connection between the cable sheave or by self-synchronous motors (selsyns). Vertical scales, in feet per inch, are generally selected by changing a gear ratio in the recorder. The depth indicator is preset when the probe is at the surface, and is then turned by the cable-measuring sheave.

The signal transmitted by the cable varies in response to lithologic, fluid, or borehole parameters, which change as the probe moves down or up the hole. This signal is processed by electronic equipment at the surface and, if necessary, changed to a varying direct-current voltage that moves the recorder pens or optical galvanometers horizontally. Operator adjustments necessary for all logs are made at this point. They include zero positioning, or basing, the pen on the paper and sensitivity, or scale selection, which controls the amount of pen deflection for a given change detected in the hole. Many other operator adjustments, such as time constant, pulse-height discrimination, frequency, and so forth, are made both in the tool and at the surface in some types of logging operations.

The basic logging equipment described is extremely dependable when properly built, tested, maintained, and operated. To derive the maximum amount of accurate data from logging equipment, operators must understand basic log interpretation, and log analysts must understand the principles of logging-equipment operation. The operator should be able to recognize equipment mal-

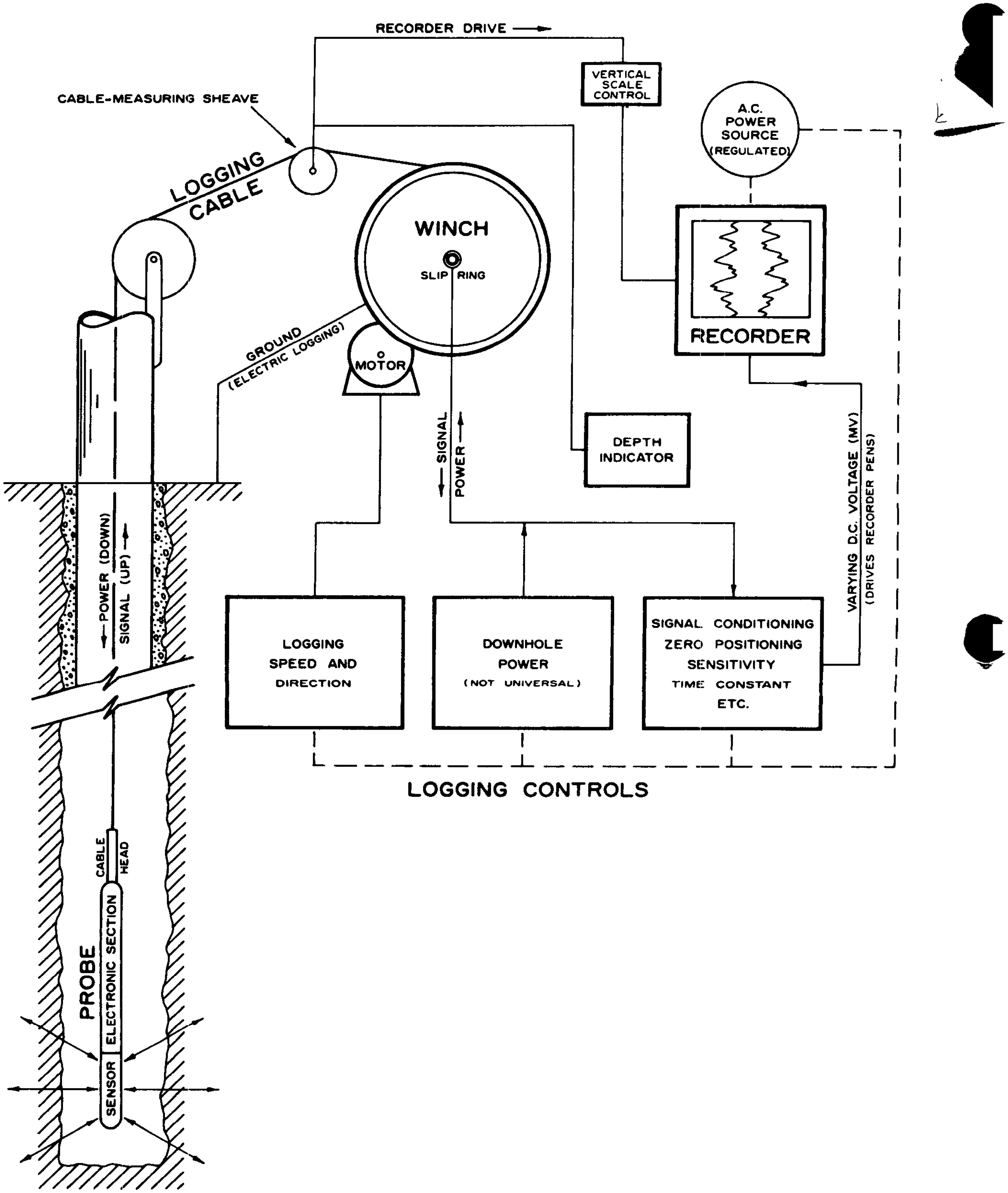

Figure 7. — Schematic block diagram of geophysical well-logging equipment.

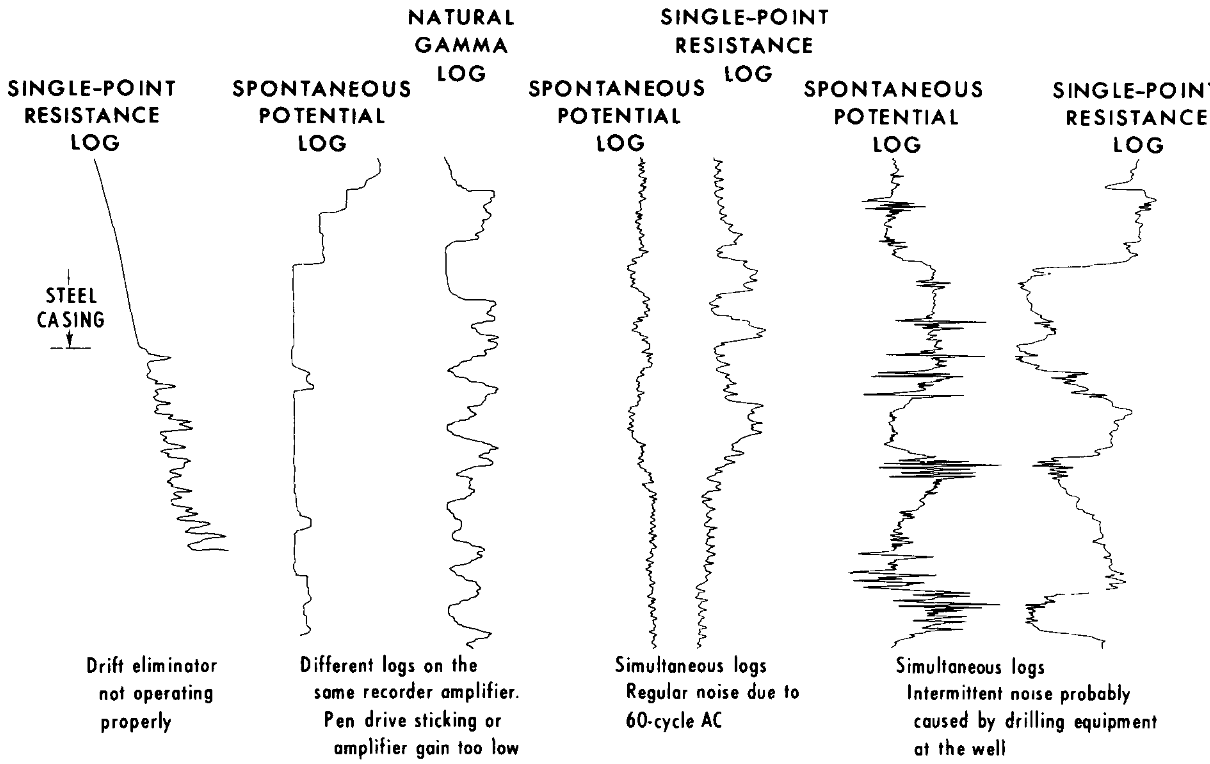

Figure 8. — Geophysical logs, showing some common equipment problems.

functions from a log in the field, where it is often possible to correct the problem and rerun a log. If the log analyst is completely familiar with logging equipment and procedures, he will not make lithologic interpretations of instrumental problems shown on the logs. Figure 8 illustrates several obvious extraneous or instrumental effects on actual logs. These and many other problems are very common on geophysical logs run with all types of equipment both in the petroleum field and in ground-water hydrology. Unrecognized equipment malfunctions and operator errors are responsible for most poor-quality logs.

Because such a wide variety of logging equipment is utilized in ground-water hydrology, the equipment used to make each type of log will not be described in detail. In this report the basic principles of each logging device and the major differences between types of sondes are discussed in the sections on instrumentation. All the sondes described will operate in the basic logging system shown in figure 7.

Spontaneous-Potential Logging

Spontaneous-potential logs are records of the natural potentials developed between the borehole fluid and the surrounding rock materials. The spontaneous potential is used chiefly for geologic correlation, determination of bed thickness, and separating nonporous from porous rocks in shale-sandstone and shale-carbonate sequences.

Because the electric log is a measure of natural potentials and resistivities, it can be run only in open (uncased) holes that are filled with a conducting fluid, such as mud or water. The chart paper commonly used for the electric log is divided into two vertical columns, called tracks. Under the

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API (American Petroleum Institute) system, the left-hand track is 2½ inches wide, with four divisions per inch and major divisions at 1¼-inch increments across the width of the track. The right-hand track is 5 inches wide, with four divisions per inch, and also has major divisions at 1¼-inch intervals across the width of the track. The footage scale is divided into 10 divisions per inch, with major divisions at ½-inch and 2½-inch intervals. The API chart paper allows for a wide choice in SP, resistivity, and footage scales. The electric log usually includes the spontaneous potential in the left-hand track and one or more resistivity curves in the right-hand track. Some of the commonly used resistivity curves are the single point, short normal, long normal, lateral devices, microlog, microfocused log, and the guard, or laterolog. Each of these devices has its application, depending on the lithology, depth of mud invasion, and other borehole conditions. Table 2 shows the applicability of various electric logging methods to the solution of typical hydrologic problems.

Principles and applications

The spontaneous-potential log is a graphic plot of the small differences in voltage, measured in millivolts, that develop at the contacts between the borehole fluid, the shale or clay, and the water in the aquifer. Two sources of potential are recognized. The first source, and least important to the magnitude of SP, is the streaming potential caused by electrokinetic phenomena. This electromotive force (emf) develops when an electrolyte moves through a permeable medium. The emf appears in the borehole at places where mud is being forced into permeable beds, although in water wells, streaming potentials may be generated in zones gaining or losing water. Streaming potentials can sometimes be detected on the SP curve by sudden oscillations or by departures from the more typical response in a particular environment. (See section on "Extraneous Effects.") A discussion of the streaming potential and its effects on SP was given by Gondouin and Scala (1958).

The second and most important source of SP arises in the electrochemical emf produced at the junction of dissimilar materials in the borehole. The junctions are between the following materials: Mud–mud filtrate, mud filtrate–formation water, formation water–shale, and shale–mud. Because the mud filtrate is derived from the mud, it generally has a similar electrochemical activity, and any emf developed across this junction will be minimal and can be disregarded. The potential developed across the junction from

Table 2. — Hydrologic applicability of electric logs

Properties to be investigated	Type of electric log								
	Single point	Short normal	Long normal	Lateral device	Wall resistivity (nonfocused)	Focused guard and laterolog	Micro-focused	Induction	SP
Lithologic correlation	×	×	......	......	......	×	......	×	×
Bed thickness	×	×	......	......	×	×	×	×	×
Formation resistivity (low R muds)	......	......	×	×	......	×	......	×	......
Formation resistivity (fresh mud)	......	......	×	×	......	......	......	×	......
Invaded zone resistivity	......	×	......	......	......	......	......	......	......
Flushed zone resistivity	......	......	......	......	×	......	×	......	......
Mud resistivity[1] (in place in hole)	......	......	......	......	×	......	......	......	......
Formation water resistivity	......	......	×	×	......	×	......	......	......

[1]Use mud kit for pit samples.

formation water to shale to mud is called the membrane potential, and the potential developed across the junction from mud filtrate to formation water is called the liquid-junction potential. The potentials arising from these junctions cause a current to flow near shale-aquifer boundaries in the mud column in the borehole. Figure 9 is a schematic diagram of the circulation of current across the various junctions and through the borehole (Doll, 1948). When the formation water is much more saline than the mud, the current follows the paths shown by the arrows, entering the mud column from the shale and moving into the sandstone. As the SP electrode moves upward through the bottom shale (fig. 9), it senses a decreasing potential because the current flows parallel to the well bore. At the bed boundary the current density is maximum, and the SP curve exhibits an inflection at this level. As the SP electrode moves toward the midpoint of the sandstone bed, the current density decreases, the curvature of the SP curve is reversed, and the SP attains its maximum negative potential at midpoint in the sand. As the SP electrode moves beyond the midpoint of the sandstone, the curve recorded is a mirror image of the lower half if the beds are uniform. The SP log, therefore, is a measure of the potential drop that occurs in the mud, and only approaches the static spontaneous potential (SSP) under favorable conditions. (See "Glossary" for definitions.) If, on the other hand, the formation water is fresh compared with the mud, the polarity of the SP curve is reversed, and the reciprocal of the log in figure 9 is produced. The SP is, therefore, more positive opposite the sands and is more negative opposite the shales. This condition occurs in hydrologic regimes where ground water contains very few dissolved solids and results in an electric log on which both the SP and the resistivity deflect in the same direction, opposite the sand and shale beds. An example of this is illustrated in figure 10. The water in the formations above 500 feet contain dissolved solids of the drilling mud lie somewhere tions below 800 feet have a dissolved-solids content of about 250 mg/l. The dissolved solids of the drilling mud lie somewhere

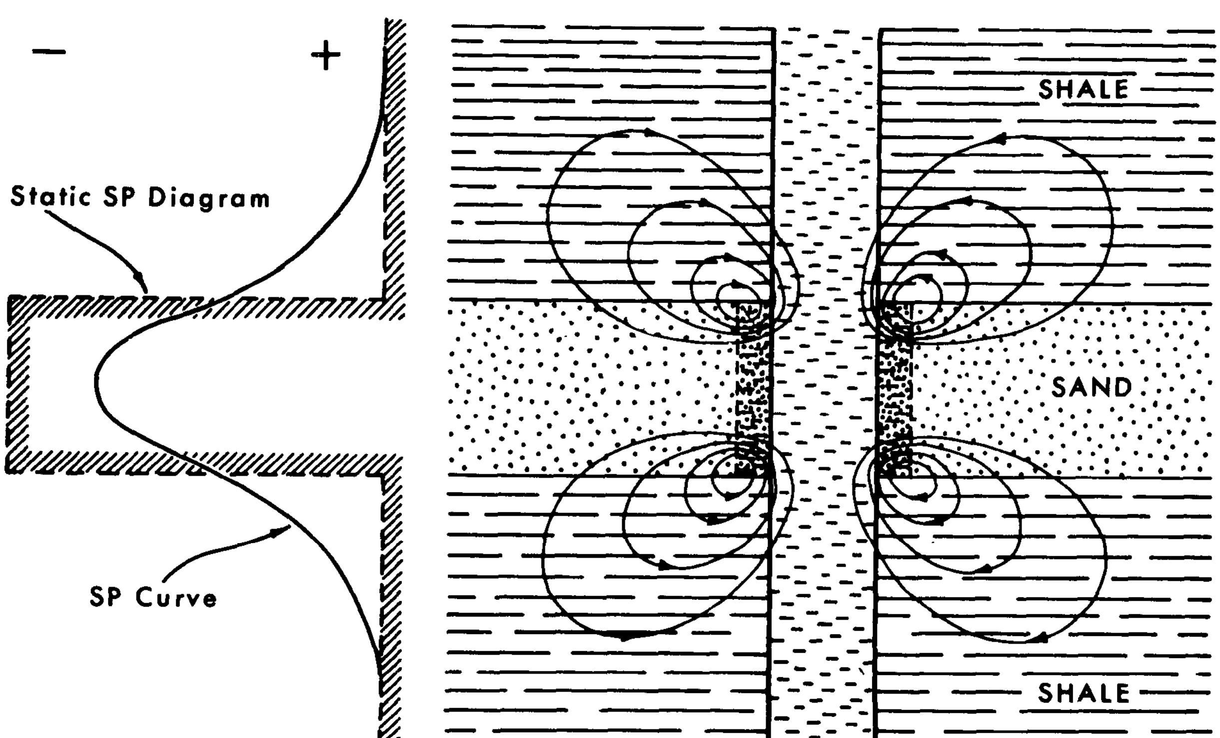

Figure 9. — Spontaneous-potential junctions and currents. From Doll (1948).

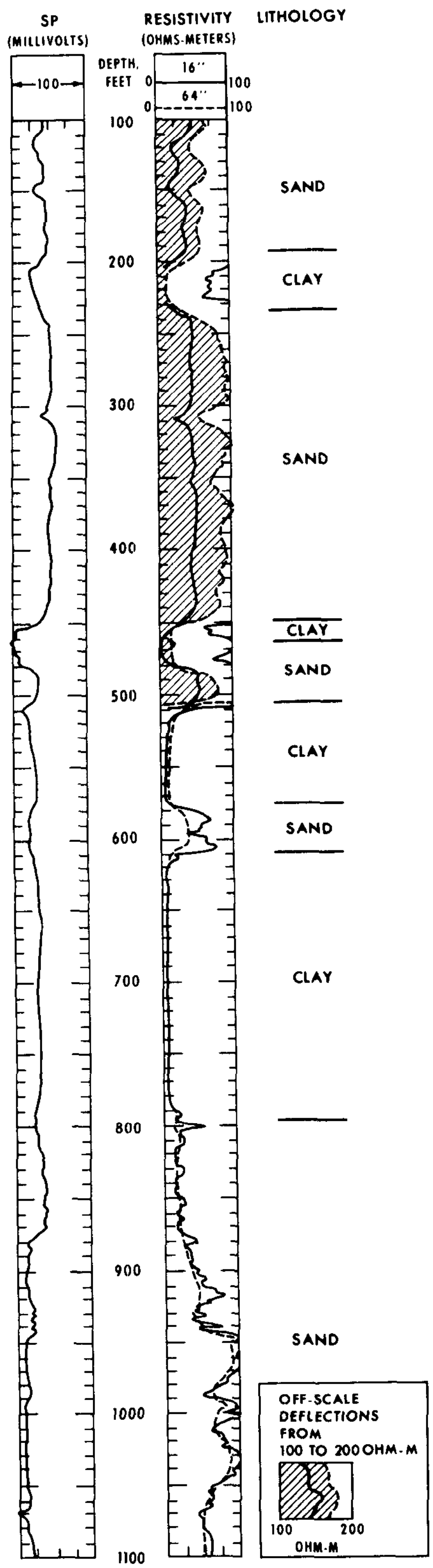

Figure 10. — Electric log of oil-test well in western Kentucky.

between these two extremes. The resistivities above 450 feet are all off-scale to the right, and lie between 100 and 200 ohm-meters.

Spontaneous-potential deflections are recorded on the left-hand track of the electric log, with deflections to the left considered as negative and those to the right as positive. In a sand-shale sequence containing formation water that is more saline than the mud, the greatest positive deflections can be expected opposite the shales, and the greatest negative deflections can be expected opposite the sands. A shale line can be constructed to fit through as many of the extreme positive deflections as possible, and a sand line through as many of the extreme negative deflections as possible. If the ionic concentration of the borehole fluid and the aquifer water are constant throughout the length of the borehole, the shale line and the sand line will generally be parallel to the vertical axis of the log. The shale line is considered to be the base line, and all potential measurements are made perpendicular to this line, using the scale of SP, in millivolts, on the log heading. When carefully applied, this method can be used to estimate sand-shale ratios and is applicable to aquifers with water of high salinity and, in some cases, to fresh-water aquifers. Unfortunately, the method fails in many water wells in sand-shale formations because the SP deflections are not necessarily negative opposite the sands. If the borehole fluid has a very low resistivity compared with the sand beds, the SP deflections opposite the sands may actually be more positive than the SP deflections opposite the shales. Accordingly, the sand-shale ratios become meaningless for formations that do not contain shale or clay beds, even though large positive SP deflections can be seen. (See Guyod, 1966, fig. 11.)

Perhaps the most significant, but often misapplied, use of the SP in ground-water hydrology is the determination of water quality from SP deflections. In petroleum exploration, where NaCl is dominant, the following equation is useful to calculate the quality of the formation water:

$$SP = -K \log \frac{R_m}{R_w},$$

where

SP = log deflection, in millivolts;
K = $60 + 0.133T$;
T = borehole temperature, in degrees Fahrenheit;
R_m = resistivity of borehole fluid, in ohm-meters; and
R_w = resistivity of formation water, in ohm-meters.

In actual practice, the SP deflection opposite a sand bed is read from the log, and the R_m is measured with a mud kit or a fluid-resistivity tool. Inserting these values in the equation determines the formation fluid, R_w, which can be related back to milligrams per liter of NaCl from salinity-resistivity charts. The equation is predicated on the following important assumptions, which may or may not hold true in water wells: (1) Both the borehole fluid and the formation water are sodium chloride solutions; (2) the shale formations are ideal ion-selective membranes, and the sand formations have no ion-sieving properties (no clayey sand or sandy clays in the zone of investigation); and (3) the borehole fluid has a much greater resistivity than the combined resistivity of the sand and the shale. In petroleum logging the sand formations are generally saturated with brines of low resistivity, and the conditions in assumption 3, above, are generally satisfied. In hydrologic logging where the sand formations are saturated with fresh water, the resistivity of the sands may be many times that of the borehole fluids, and the conditions in assumption 3, above, may no longer be valid. However, the combined resistivity of the sands and shales can be less than that of the borehole fluid if the fresh water used in the drilling fluid has a lower ionic concentration than the formation water.

The divalent ions Ca^{+2} and Mg^{+2} commonly found in fresh water have a different effect on the SP than Na^{+1}. The calcium and magnesium solutions affect the SP as though the water were saltier than its resistivity indicates. Alger (1966) described a method for finding the R_w of fresh waters by use of the equation SP = — K log (R_m/R_w). In order to correlate SP deflections with water resistivity and ionic concentration from salinity-resistivity charts, he found it necessary to convert all anions and cations in the water to an equivalent sodium chloride solution. Alger assumed that, within one ground-water regime, the relative ionic concentrations and ratios are approximately constant. The relations between SP, R_w, and total dissolved solids — once determined from a borehole having an electric log and water analyses — were extrapolated by Alger to other boreholes in the regime exclusively from the SP deflections.

In an unpublished paper by Hubert Guyod, Consultant, entitled "Fundamentals of Electrical Logging and their Application to Water Wells," presented at the Second Advanced Seminar on Borehole Geophysics, U.S. Geological Survey, Denver, Colo., December 1968, Guyod pointed out that the formula

$$SP = -K \log \frac{R_m}{R_w}$$

can be used only when the following conditions are simultaneously satisfied: (1) The formation water is very saline, (2) NaCl is the predominant salt, and (3) the mud is relatively fresh and contains no unusual additives. Guyod further stated that "the three conditions specified above are probably never met by fresh water aquifers. Therefore, it is not possible to determine, not even estimate, from the SP curve the resistivity of formation water, that is, the total dissolved solids in fresh water sands."

Patten and Bennett (1963) also emphasized the unreliability of the SP formula for determining dissolved solids. Considering the unreliability of the method, especially for dissolved solids of less than about 10,000 mg/l, the method probably should not be used in the analyses of fresh-water-bearing aquifers.

Vonhoff (1966), however, found that a "workable empirical relationship exists between the spontaneous-potential deflection on the electric log and the water quality in the glacial aquifers." His conclusions are based on a study of test wells in Saskatchewan, Canada, in which the ionic composition of the drilling fluid and formation water are similar, and the resistivity of the drilling fluid is much greater than that of the formation water. The actual dissolved solids in the test wells ranged from 1,191 to 3,700 mg/l.

Instrumentation

In its simplest form, an SP logging device consists of a movable lead electrode, which traverses the borehole on an insulated wire; a ground electrode, also made of lead; and a device for measuring potential, such as a millivolt meter. The movable electrode senses the ohmic-potential drop caused by the currents flowing into the mud column near the shale-aquifer boundaries. Because potential at the ground electrode remains constant, the potential read from the meter represents the change in potential in the mud between the shales and the permeable formations. Figure 11 shows the SP measuring circuit and, also, the electrical equivalent, as depicted by Lynch (1962). In this diagram the upper E_k represents the shale streaming potential, the lower E_k is the streaming potential developed across the sand, E_b is electrochemical potential developed at the liquid junction (mud filtrate–formation water), and E_s is the membrane or shale potential. The terms r_{sh}, r_{ss}, and r_m are the resistances of the shale, sandstone, and mud, respectively.

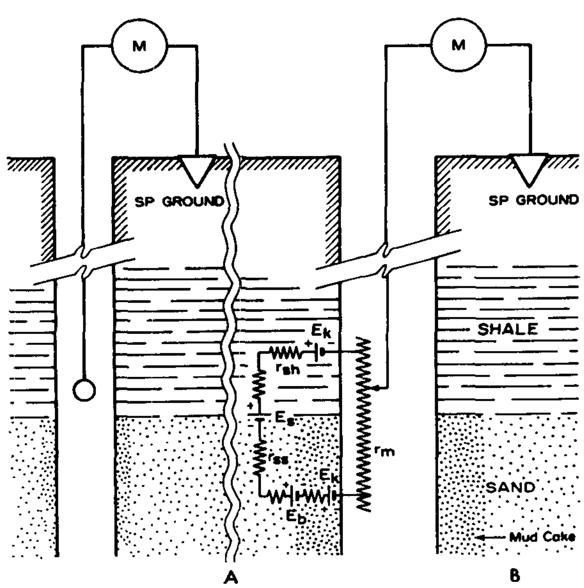

Figure 11.—Spontaneous-potential measuring circuit (A) and the electrical equivalent (B). From Lynch (1962).

Calibration and standardization

Spontaneous potential is measured in millivolts, and the millivolts per horizontal chart inch, or full scale of the chart paper (sensitivity), is shown on the log heading of the left track. The small single-conductor cable loggers used in ground-water studies commonly have SP sensitivities of 10, 25, 100, and 200 mv per inch. Some loggers are furnished with an auxiliary SP calibrator. The main purpose of the calibrator is to check logger function on all ranges of SP sensitivity. The calibrator contains a battery and resistors so as to provide a predetermined potential, in millivolts, which is applied to the SP electrodes of the logger. Each range on the calibrator should produce a 1-inch deflection of the recorder pens when the SP sensitivity control on the logger panel is set in the corresponding range. Calibrators supplied with the single-conductor loggers are not precision devices, and deflections on corresponding recorder ranges may or may not exactly equal 1 inch (or one division). Accuracies are generally on the order of ±10 percent.

Radius of investigation

The potential drop along the mud column results from currents that originate away from the borehole along formation boundaries. For example, in a lithologic section, such as that in figure 12 (Schlumberger Well Surveying Corp., 1958), the currents tend to flow from the borehole into the permeable beds until a sufficient cross-sectional area of the compact (very resistive) formation is encountered to carry the current. The current then flows across the large area of resistive formation until an impervious conductive shale bed is intersected. The currents then travel with greater density along the conductive beds until the borehole is intersected again. Therefore, the radius of investigation is highly variable. Also, the SP may not relate directly to the permeable beds because the effect of these beds spreads the SP above and below the bed boundaries, as shown by the SP curve on the left-hand side in figure 12.

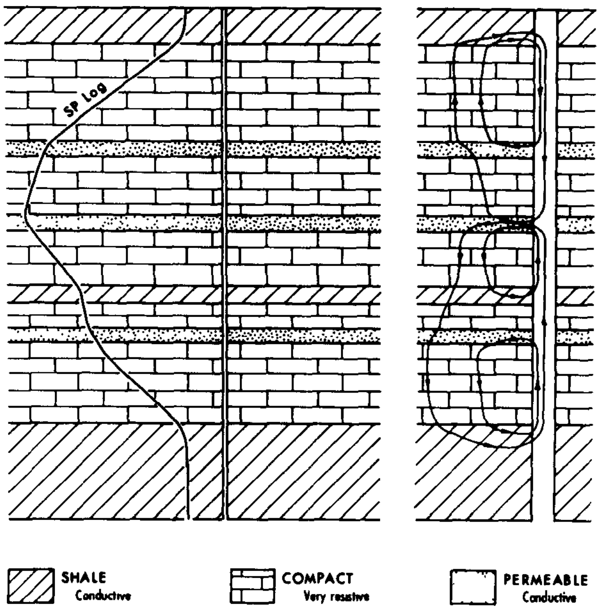

Figure 12. — Spontaneous-potential current flow in highly resistive beds. From Schlumberger Well Surveying Corp. (1958).

Extraneous effects

SP noise can be defined as any spurious or unwanted signals that are not correlated with the actual SP in the borehole. Noise and anomalous potentials are relatively common problems in SP logs. Some of the early model loggers used insulated cable with a single conductor, and the SP was relatively free from noise. With the introduction of steel-armored cable, noise became troublesome. Steel is electrochemically active, and when the cable is immersed in an electrolyte (water or drilling mud), a battery effect develops along its entire wetted length. If the cable remains motionless in the drill hole, the batteries become polarized, and their output remains constant. This small current impresses on the SP electrode a potential that merely shifts the SP curve left or right. When the cable begins to move in the hole, however, the polarization film is wiped off intermittently, and the current output from the battery effect is therefore varied. The varying potentials resulting from cable motion are thus impressed on the SP to produce noise. The source and effect of this noise is shown in figure 13 (Electro-Technical Laboratories, 1959).

Noise from the part of the armored cable near the surface in the borehole can also be coupled into the SP ground electrode. If the well is cased to considerable depth, the casing may act as a shield around the wetted upper part of the cable to effectively screen the SP ground electrode from cable noise. This type of noise is most troublesome where surface formations have high resistivities. Corrective procedures to lessen cable noise caused from battery effect are based on the electrical isolation of the SP electrode and the SP ground electrode from the cable. Wrapping the armored cable with insulating tape for 10 feet or more above the SP electrode may displace the battery effect far enough uphole to reduce the magnitude of this source of potential. Moving the SP ground electrode as far as possible from the well head may also help. Most noise-reduction procedures are largely trial-and-error processes because the source of noise generally is not evident.

Other sources of noise and anomolous SP are magnetization of armored cable, currents

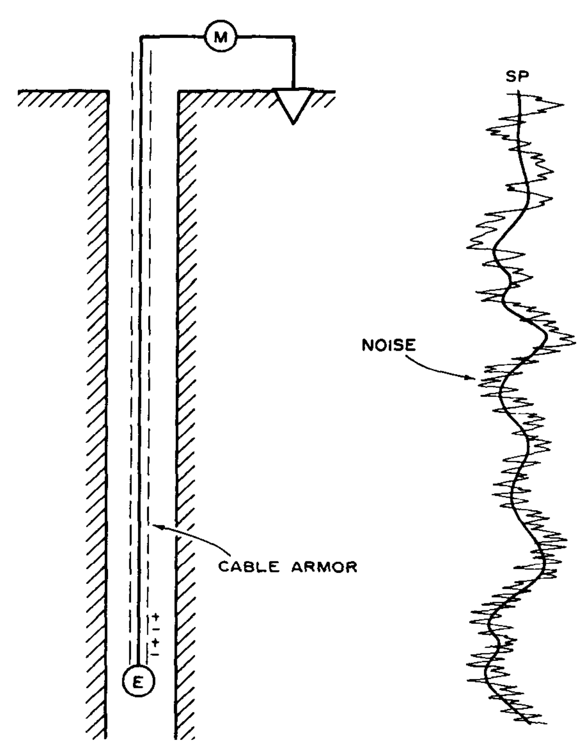

Figure 13. — Spontaneous-potential noise from electrolytic action of steel cable. From Electro-Technical Laboratories (1959).

set up by casing corrosion in the logged well or in nearby wells, magnetic storms from solar flares, flow of ground water through the well bore, and manmade effects. In this last category fall such influences as circulating ground currents near electrical switch yards and transformer stations, electrochemical action along buried pipelines, cathodic protection of buried pipelines, and potentials set up along large or long metallic objects, such as railroad tracks. If the SP ground electrode is in the mud pit, even the operation of the rig mud pumps, or generator, or the dragline cleaning of the pits may disturb the SP (fig. 8). Water moving into the hole may be located by SP noise. The oscillating SP between 700–750 feet in figure 14 is probably due to streaming potentials caused by water moving into the well bore.

Resistance Logging

One of the basic concepts of electric theory is Ohm's law, which states that the rate of current flow, I, through a conductor is proportional to the potential difference, E, causing the flow. Another parameter, resistance, r, determines the rate of flow and enters Ohm's law as a constant to proportionality, expressed as the formula

$$E = Ir,$$

where

E is in volts,
I is in amperes, and
r is in ohms.

The resistance of a conductor depends not only on the nature of the conductor, but also on the cross-sectional area and length of this conductor. Resistance-logging devices measure the resistance, in ohms, of the earth materials lying between an inhole electrode and a surface electrode, or between two inhole electrodes. Actually, a potential difference in volts or millivolts is measured between the electrodes, and this is converted to resistance by Ohm's law because a constant current is maintained. These qualitative-logging methods are known as single-point, point-resistance, or single-electrode systems to distinguish them from the two- and three-

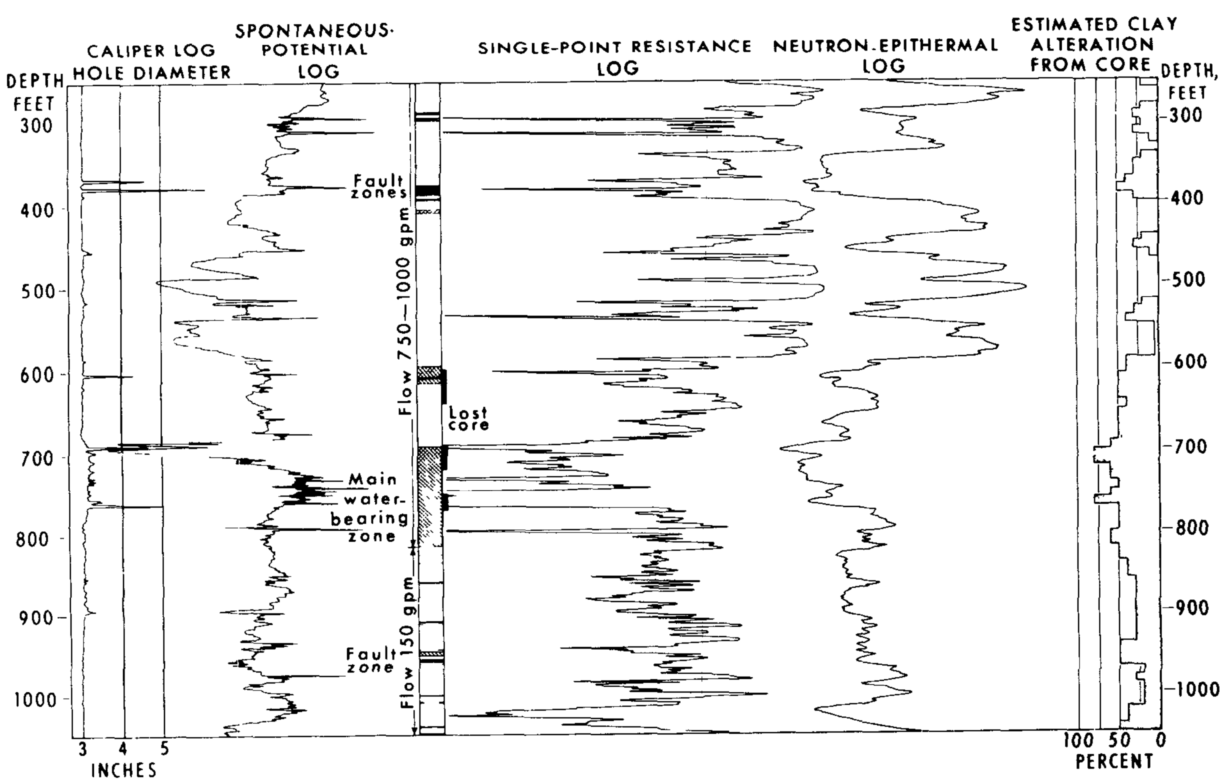

Figure 14. — Geophysical logs of granite in drill hole CX 111, Clear Creek County, Colo.

electrode systems used for quantitative measurements of resistivity. (See section on "Resistivity.") The main uses of point-resistance logs is for geologic correlation, such as determining bed boundaries and changes in lithology and identifying fractures in resistive rocks.

Principles and applications

The point-resistance log, as it is commonly called, is the simplest electric-logging system. In its simplest form, using insulated cable, a single lead electrode is lowered into the hole and the return path for the current flow is furnished by the ground electrode, which is also made of an inert metal, such as lead. This method is herein termed the "conventional" single-point system. Another single-point resistance system currently in use employs the tool shell as the return electrode for the current. This method is herein termed the "differential" single-point system.

The electrode arrangement and current flow through a homogeneous isotropic media for the conventional point-resistance system is shown in figure 15 (Guyod, 1952). The electric current from the AC generator (fig. 15) travels down the cable to electrode *A*, moves radially out through the surrounding rock, and returns to ground electrode *B*. Each current electrode, *A* and *B*, however, does double duty and functions as a current electrode and as a potential-sensing electrode. Current electrode *A* and potential electrode *A* are physically the same piece of metal, and surface-current electrode *B* and potential electrode *B* are also physically the same. Because the current and potential electrodes are coincident, the single-point device functions in a manner similar to a VOM switched to the ohms position. The unknown resistance is, in effect, connected in series with a battery and the meter movement. When the unknown resistance is relatively small, a large current flows to deflect the meter movement, but when the unknown resistance is relatively large, only a very small current flows to deflect the meter because the battery voltage remains constant. For example, the percentage of full-scale meter deflection for the 10 ohms of resistance between 10 and 20 ohms on the meter face is much larger than the percentage of deflection for the 10-ohms increment between 100 and 110 ohms on the meter face. Thus, the single-point logging system exhibits a nonlinear response that is compressed at the higher resistances.

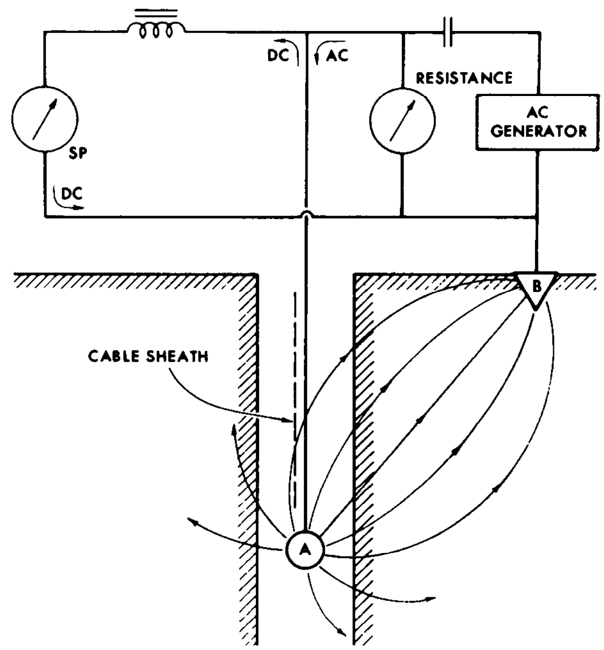

Figure 15. — Conventional simultaneous single-electrode resistance and spontaneous-potential logging system. From Guyod (1952).

With application of a constant current from the AC generator (fig. 15), the potential variations read on the meter are inversely proportional to the resistance between the *A* electrode and ground electrode *B*. Because current and potential points *A* are on the same electrode, the radius of investigation is small, from about 5 to 10 times the electrode diameter. We can assume that the resistance measured by the point resistance to consist of three resistances, in series according to an unpublished study by Hubert Guyod, Consultant (written commun., 1968): (1) The resistance of a spherical volume of borehole fluid and rock surrounding the point electrode to a radius of 10 electrode diameters, as mentioned above; (2) the resistance of a surface-electrode hemisphere, the counterpart of the borehole-electrode sphere; and (3) the resistance of the volume of rock lying between the resistance sphere in the borehole and the resistance hemisphere at the surface. Item 3 above includes such a large volume of rock that its resistance is very small, and can be regarded as a negligible constant.

Because the radius of investigation is small, the single-electrode log is strongly affected by conductivity of the borehole fluid and by changes in hole diameter. If a bed to be logged has a higher resistance than the borehole fluid, only a small amount of current will flow in the rock, and most of the current will flow in the borehole fluid. As a result, thin resistive formations do not significantly affect the flow of current and may be difficult to distinguish if the single-point method is used in salty mud or brine-filled holes. At points of hole enlargement (caving, washouts, fractures) the single electrode mainly measures the resistance of the borehole fluid, which results in a decrease in resistance on the log. Despite these apparent shortcomings, the single-electrode method is a very useful tool, inasmuch as any increase in formation resistance produces a corresponding increase in resistance on the log, and the deflections on the single-point logs are interpreted to be due to changes in lithology. Reversed log response due to the effects of thin beds and adjacent beds are common on multielectrode logs, but are not found on single-point logs. Figure 16 shows a typical response to lithology for a point-resistance device. The resistance increases next to the lignites, sands, and sandstones, as seen at letters *A*, *C*, *D*, *F*, *H* and *I*. The resistance decreases next to the shales, siltstones, and clays, as seen at letters *B*, *E*, and *G*. The single-point logs are highly desirable for geologic correlation because of their unique response to changes in lithology and the good vertical detail obtained in formations of low to moderate resistance. Increases in hole diameter appear as excursions to the left on the single-point log. In fractured rock the single-point log commonly appears as a mirror image of the caliper log.

The other type of single-point system uses a differential-resistance measurement. A diagram of the circuit of the differential-resistance system is shown in figure 17. In this circuit, current leaves electrode *A* and returns to electrode *B*, which is the shell of the tool, separated from the *A* electrode by less than 1 inch of insulation. In the differential system, the shell and the cable armor act as the return path for resistance, and the conventional ground electrode is used only for SP. Because the electrodes are so closely spaced, the current configuration is torus shaped, with the greatest current density parallel to the plane of the insulation between electrodes. Due to the focusing of the current, the differential-resistance system is very susceptible to changes in borehole diameter. In fact, the method can be used to locate fractures with greater accuracy than with a caliper log because the differential-resistance method detects nearly closed fractures not delineated by the caliper tool. Figure 18 compares the response of the conventional resistance log with that of the differential system in a borehole penetrating fractured crystalline rocks. Some of the sharp spikes on the left of the differential system at fluid-filled fractures are identified by the letters *A* through *H*. As seen in figure 18, the type of log response can be altered considerably by choosing one point resistance in preference to the other. If a smooth, more or less integrated response is preferred, the conventional point resistance should be used. If, however, a sharply deflecting log responding to minor fractures and incipient fractures is required, the differential system should be used.

Figure 18 also illustrates the qualitative nature of point-resistance logs. Both logs were run in the same borehole and, except for extreme peaks, were adjusted to give approximately the same amplitude of deflections. The log on the left shows a resistance scale of 10 ohms per unit, whereas the log on the right shows 100 ohms for the same horizontal unit. The 10 to 1 scale difference between two single-point logs of the same borehole points out the advisability of not attributing quantitative values to point-resistance measurements made in the usual way. Quantitative values can be obtained from conventional single-point loggers by using

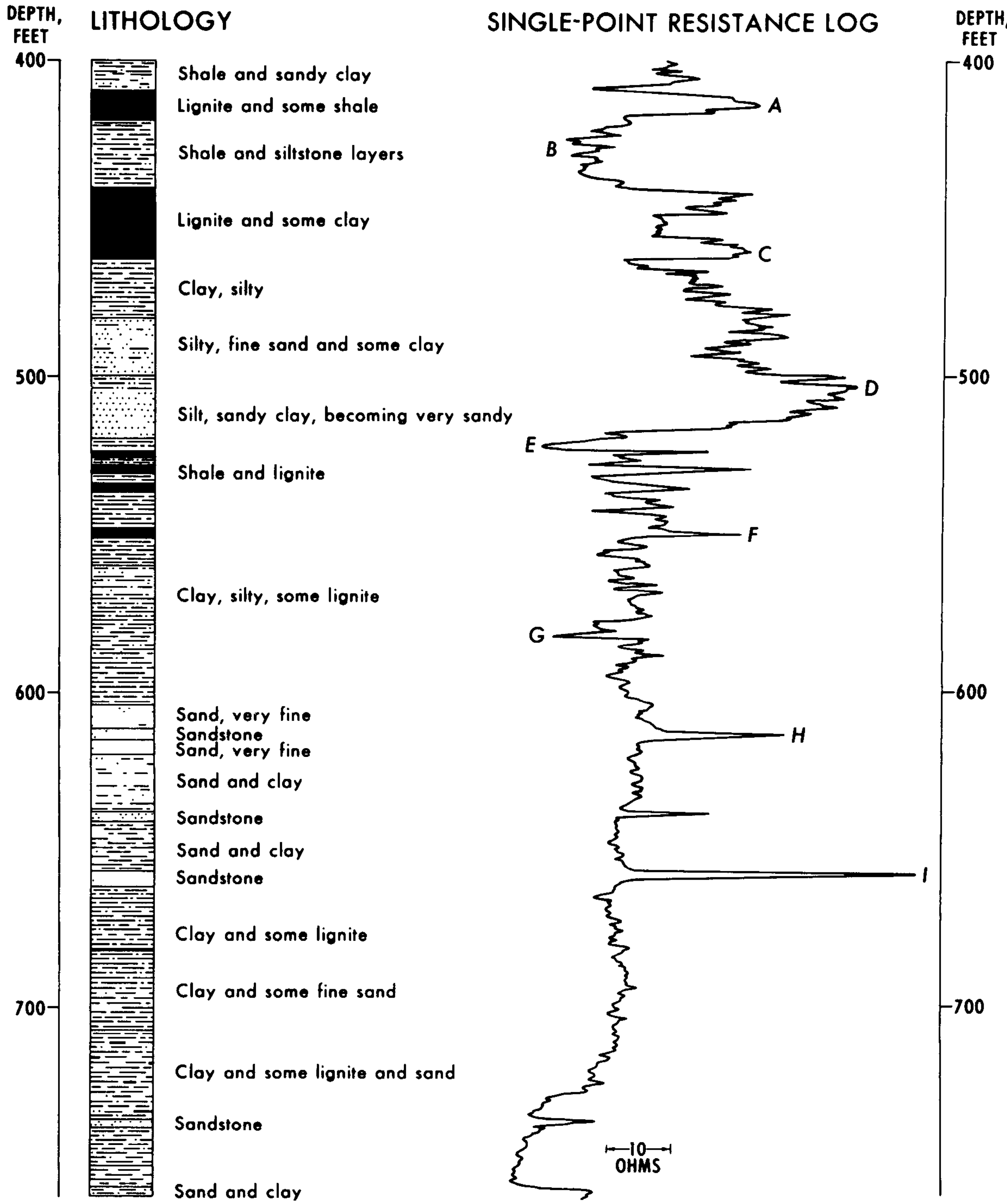

Figure 16. — Response of single-point log to lithology, test hole 3,433, Mercer County, N. Dak.

two ground electrodes, making a series of measurements from each, in turn, to the logging electrode, while the latter is held stationary in the hole, then measuring the resistance between the two ground electrodes, and placing the values in a suitable equation. The

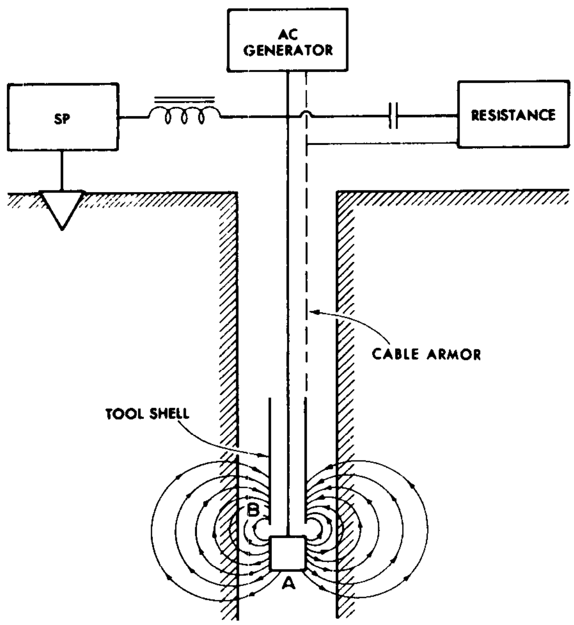

Figure 17. — Differential-resistance system, showing current distribution.

method is somewhat involved and gives values for discrete points in the hole rather than a continuous log.

To examine the response of the differential single-point resistance to borehole fractures more closely, figure 19 was prepared by plotting the caliper log on the right side and the mirror image of the point resistance on the left (compare with left side of fig. 18). Some of the fluid-filled fractures on the sensitive caliper log show up to good advantage on the reversed differential single-point log, shown by the letters *A* through *H*.

Another feature of the single-point method that works to advantage is the nonlinear scale. At low resistances the response is amplified with resulting detail, whereas at high resistances the response is flattened. In other words, a very large range in resistance can be portrayed on the log without off-scale deflections at the high-resistance end.

A comparison of a commercial laterolog and a differential single-point log made in the

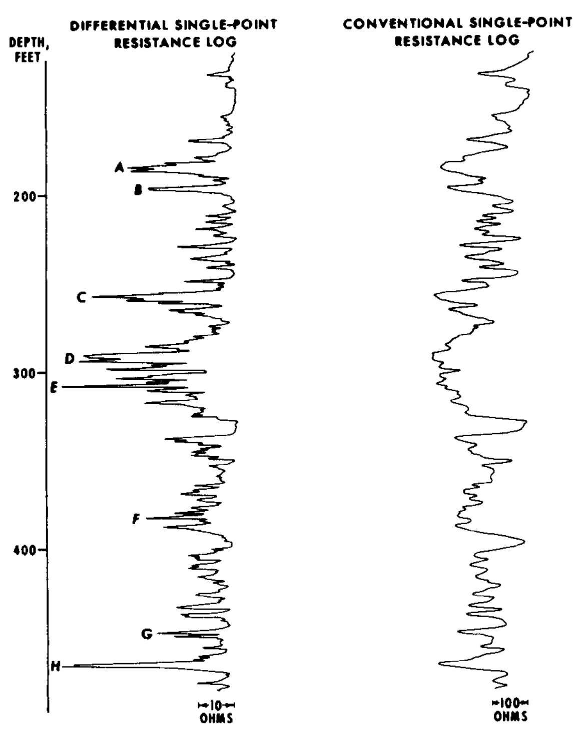

Figure 18. — Examples of differential and conventional single-point resistance logs of fractured crystalline rocks. Golden Gate Canyon well, Jefferson County, Colo.

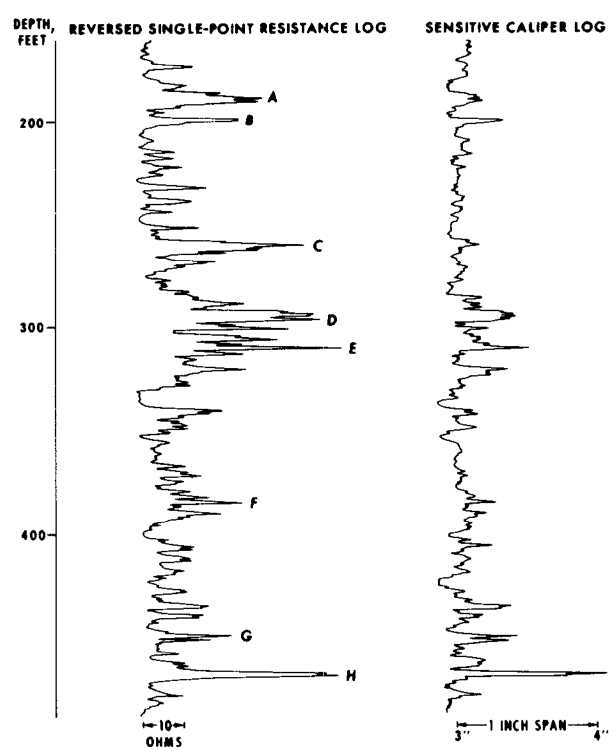

Figure 19. — Identification of fractures from caliper and differential single-point resistance logs.

same hole (fig. 20) illustrates the sensitivities of the single-point log over a wide range of resistivity, as well as hole-diameter effects, the major enlargements of which are shown by letters *A* through *D*. The somewhat focused character of the current around the differential single-point sonde produces a log response which is markedly similar to the strongly focused current in the laterolog.

Instrumentation

The equipment for single-point logging is similar to that used for the SP, and includes the sonde, logging cable, winch, uphole circuits, and recorder. Single-conductor loggers currently in use by the Water Resources Division will log SP and resistance simultaneously. This is possible because the SP is a measure of direct current, and the resistance is measured with alternating current. Typical logging circuits for measuring SP and resistance are shown in figures 15 and 17.

Calibration and standardization

The point-resistance method measures resistance in ohms and should be calibrated in ohms. The number of ohms per inch of span (sensitivity) should be indicated at the log heading on the right-hand part of the recorder chart. The single-conductor loggers commonly used in water-resources studies have resistance scales on the order of 20, 50, 100, 200, and 500 ohms per inch (or full scale on some makes of loggers). The SP calibrator furnished with conventional single-point loggers can also be used to calibrate resistance by switching off the internal battery and using the resistors to supply a predetermined resistance across the electrodes of the logger. This device allows the operator to determine that each scale is functioning, and permits calibration of the logger, in ohms per unit of chart. Erroneously, many of the older loggers had scales calibrated in ohmmeters. Each range on the calibrator should produce a 1-inch or full-scale deflection on the logger when the sensitivity control on the logger panel is set in the corresponding range.

Radius of investigation

Single-electrode systems have very little radius of investigation and actually measure the resistance of the borehole fluid as it is affected by the resistance of the surrounding volume of rock.

Extraneous effects

Single-point loggers used are susceptible to several of the same kinds of noise that affect the SP logs. Noise generated by dirty brushes or by worn slip rings on the winch can cause a periodic sharp deflection to be superimposed on the resistance curve. This type of noise can sometimes be spotted because it occurs at regular intervals, related to the winch revolutions. Another type of anomalous effect is caused by ground currents from powerlines or other electrical sources beating against the alternating current used in the resistivity electrode. The beats appear as a sine wave superimposed on the resistance curve. Some loggers have a provision to eliminate beats by adjusting the frequency of the AC current used in the resistance electrodes. Another way to minimize these beats is to adjust the frequency of the 110-volt alternator (which supplies the logger) so as to lower or raise the nominal line frequency of 60 Hz.

Another type of erratic behavior of the resistance log occurs occasionally with the differential system. The cable armor is grounded to the truck, but is isolated from the well casing by an insulated sheave. The SP ground electrode in this system is isolated from both the cable armor and the truck ground. If auto tires were perfect insulators, the circuits would remain isolated; however, tires contain a conducting medium (carbon), and mud and water add to conduction. The resistance of the earth material at the surface also affects this problem. The result is

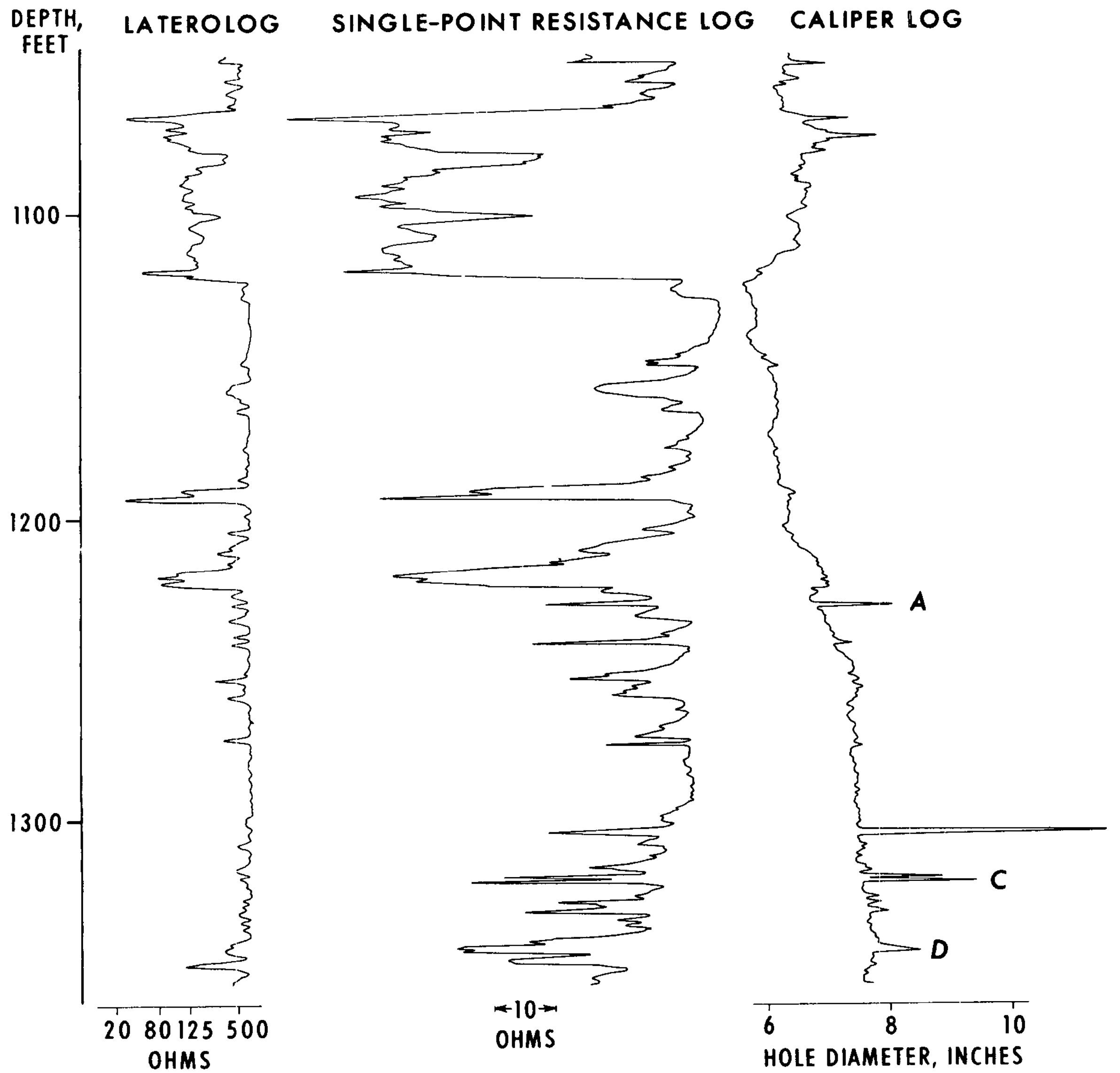

Figure 20. — Response of laterolog and differential single-point logs to changes in hole diameter. Core hole No. 2, Rio Blanco County, Colo.

a finite resistance from the truck frame to the ground. In effect, the truck ground (cable armor and resistance ground points) are connected to the earth (SP ground rod) through a large but finite resistance. Part of the current now follows this path, and upsets both resistance and SP logs. This situation generally causes difficulty in obtaining useful logs if the materials in the hole have extremely high resistance, such as in crystalline rocks saturated with fresh water.

Resistivity Logging

The linear and cross-sectional dimensions of a conductor can be included mathematically with its resistance to obtain a property that depends only on the material nature of the conductor, and not on its dimensions. This property is called resistivity, or specific resistance, and is defined by the formula:

$$R = r \times \frac{S}{L} = \text{ohms} \times \frac{\text{meters} \times \text{meters}}{\text{meters}} = \text{ohms} \times \text{meters},$$

abbreviated ohm-m or Ωm, where

R = resistivity, in ohm-meters;
r = resistance, in ohms;
S = cross section, in square meters; and
L = length, in meters.

The units of resistivity, therefore, are resistance times length, conventionally in ohm-meters. Resistivity, in ohm-meters, can also be defined as the resistance, in ohms, between opposite faces of a cube of conductor that measures one meter on each side.

Resistivity-logging devices measure the electrical resistivity of a known or assumed volume of earth materials under the direct application of an electric current or an induced electric current. Depending on the device employed, resistivity logs can be used for geologic correlation, although this is not the most important application. Resistivity devices are generally used to determine the formation resistivity, formation porosity, mud cake resistivity, invaded zone resistivity and porosity, hydrocarbon and water saturation, fluid resistivity, and formation factor.

Measuring resistivities in a borehole is similar to the technique for measuring resistivities in the laboratory or in surface-resistivity investigations. Figure 21 shows the similarity of electrode arrangement and nomenclature for resistivity measurements in both cores and boreholes. In practical well logging, however, only two or three of the electrodes actually influence the measurement, as the remaining electrodes are located remotely from the sphere of influence.

By convention, the current electrodes are designated by the letters A and B, and the potential electrodes are designated by the letters M and N (fig. 21). Two outer electrodes, A and B, supply current to the sample under study, and two inner electrodes, M and N, measure the potential drop across a known section and length of the sample (fig. 21). The current flows from electrode A of higher potential to electrode B of lower potential. Ordinarily, the potential drop, in volts or millivolts, between electrodes M and N is measured, and the current between electrodes A and B is held constant by suitable circuits. The more resistant the sample, the greater the voltage drop between electrodes M and N. Both in laboratory measurements and in actual logging, alternating current is used as the source of potential. Direct current is unsatisfactory because a DC voltage applied to the natural electrolytes in rocks would cause the migration of anions and cations and, hence, introduce polarization effects.

Except for conductive minerals like graphite, metallic sulfides like pyrite and galena, and native metals, such as silver, most minerals are good insulators when they are dry. Completely dry rocks rarely occur in boreholes, and subsurface formations have measurable resistivities due to formation water in rock pores, solution channels, and adsorbed water on clay particles. The resistivity of a rock therefore depends on the composition of the contained water, on the amount of water, and on the shape and

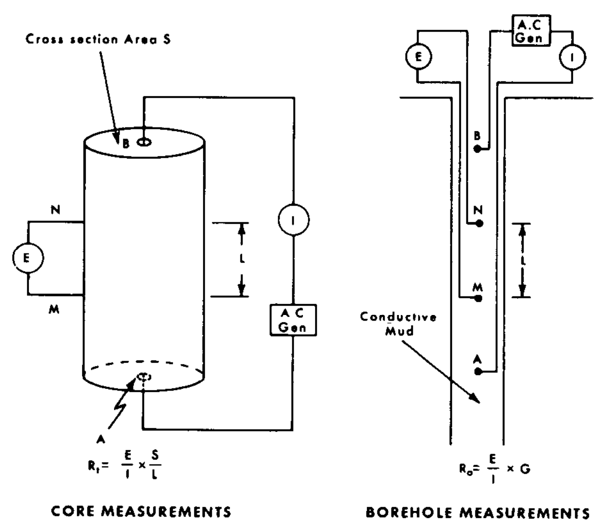

Figure 21. — Electrode arrangement for resistivity measurements in cores and in boreholes.

length of the interconnected pores. True resistivity, R_t, is given by the formula

$$R_t = \frac{E}{I} \times \frac{S}{L},$$

and is based on precise control of the current, I, through the rock sample and on the accurate measurement of the voltage drop, E, between the potential electrodes. The cross-sectional area, S, and the length, L, are measured directly on the sample. Usually, the samples are in the shape of a cylindrical core of predetermined diameter and length, thus simplifying the geometric factor S/L (fig. 21).

In the field, resistivity is generally measured in a borehole that penetrates the rocks. Although the current and potential electrodes on the sonde may occupy the same relative positions as they do in core measurements, the current flow lines are no longer confined to a cylindrical shape as they would be in the core sample; thus, the geometric factor, G, is no longer a simple ratio of area to length.

The combined effect of the new geometric factor, G, and the current-distorting properties of the mud column results in an apparent resistivity measurement, which is an average of the resistivities of the rocks surrounding the sonde. This apparent resistivity, R_a, is the value recorded by the electric logging equipment and is expressed by the formula $R_a = E/I \times G$ (fig. 21). Values for G must be calculated from the electrode arrangement and from the electrode spacing for each type of electric logging device.

In petroleum logging, the value R_t represents the actual resistivity of the formation which may contain both water and oil (or gas), and R_o represents the original resistivity of the formation where it is 100-percent saturated with water. Because hydrocarbons are electrical insulators, R_t is greater than R_o for the same formation, and empirical relations between them are used in petroleum work to determine water saturation in the oil reservoir. Generally, in hydrologic investigations, only the water-saturated zones are logged, and the value of R_o is obtained from the apparent resistivities.

Normal devices

Normal logs measure the apparent resistivity of a volume of rock surrounding the electrodes. The short normals give good vertical detail and record the apparent resistivity of the invaded zone. The long normals record the apparent resistivity beyond the invaded zone. The normals give poor results in highly resistive rocks. The tool used by commercial services also logs the lateral curve. Commercial service tools are about 8 feet long and 3⅝ inches in diameter; they weigh up to 125 pounds, and require a heavy rubber-covered bridle more than 50 feet long that carries the current and reference electrodes. Generally, a tower, an A frame, or a derrick over the hole is needed for commercial service electric logging.

Principles and applications

Multiple-electrode resistivity measurements include such curves as the short and long normal, lateral, microlog, and focused logs (guard log and laterolog). These are resistivity devices, and their curves are calibrated in ohm-meters. Table 3 cross references the generic log types with the numerous trade names applied to these logs by the commercial service companies.

The normal curves are derived from a four-electrode system, using two current electrodes, A and B, and two potential electrodes, M and N. Because only two electrodes, A and M, are effective in measuring apparent resistivity, the normals are sometimes called the two-electrode method. Spacings between electrodes A and M gave rise to the names of the various normal curves; for example, the 8-inch, 10-inch, 16-inch, 18-inch, 32-inch, 39-inch, 40-inch, 63-inch, 64-inch, and 84-inch normals. Most logging companies have standardized on the short normal, where AM = 16 inches (some use 18 in.) and the long normal, where AM = 64 inches. These two normal curves are generally run at the same time.

The electrode arrangements for normal logging are shown in figure 22. The diagram shows that electrodes A and M are relatively close together, whereas B and N are not

Table 3. — Electric log cross reference

Service Co.	Generic log type					
	Spontaneous potential	Electric log[1] (nonfocused)	Focused electric log	Wall resistivity	Microfocused	Induction log
Birdwell	Spontaneous potential.	Electrical log	Guard log	Micro Contact log.		Induction-electric log.
Dresser Atlas	do	Electrolog	Laterolog.	Minilog	Microlaterolog	Induction electrolog.
Schlumberger	do	Electrical log	do	Microlog	do	Induction electrical log.[2]
					Proximity log	Dual-induction laterolog.
Welex	do	Electric log	Guard log	Contact log	FoRXO log	Induction electrical log.

[1] Includes short normal, long normal, and lateral.
[2] Includes 5FF40 induction log, 6FF40 induction log, and short normal or laterolog.

only far from each other, but are also distant from the electrode group AM. In practice, the distance from the group AM to the B or N electrode is about 50 feet. This means that the apparent resistivity is determined primarily by the potential of the measuring electrode M. Figure 22 also shows that the physical location of electrodes B and N has no bearing on the normal curves, provided they are distant from each other and from the AM electrode group. The geometric factor, G, for the normal device is equal to $4\pi AM$, where the distance AM is in meters.

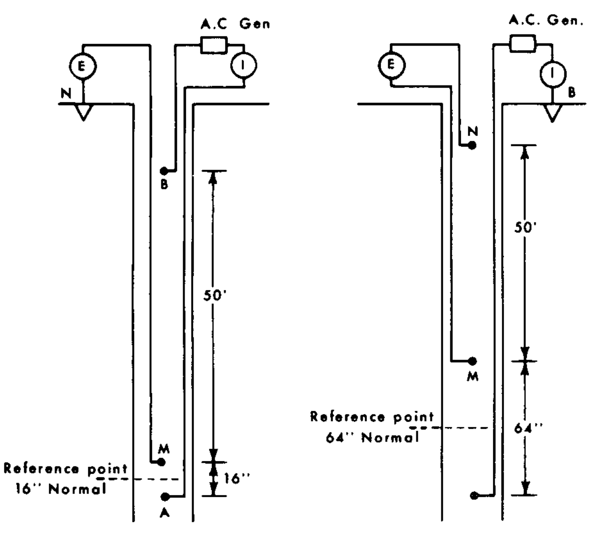

Figure 22. — Electrode arrangements for the 16- and 64-inch normals.

This value is substituted in the formula

$$R_a = \frac{E}{I} G = \frac{E}{I} 4\pi AM,$$

in order to convert the potential measured into an apparent resistivity.

A hole is generally logged from bottom to top, so that the long normal electrode, which is near the top of the sonde, is the first electrode to enter a given bed or formation. The long-normal pen deflects first; then, when the sonde has moved 2 feet (the space between reference points), the short normal begins to "see" the same bed.

Both normals are calibrated at zero on the left edge of the resistivity side of the recorder chart. To distinguish one from the other when the curves cross or run nearly the same, the long normal is shown as a dashed trace.

The spacing of the short normal (AM = 16 in.) was selected by the commercial logging companies because this spacing gives good vertical detail and measures an apparent resistivity that is related primarily to the invaded zone resistivity in petroleum logging. The long-normal curve (AM = 64 in.) was selected by commercial logging companies to investigate the average resistivity beyond the invaded zone for a radius of approximately twice the AM spacing. The short- and long-normal logs are generally used in conjunction with departure graphs or other interpretative charts (Schlumberger Well Surveying Corp., 1966), so that invaded

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zone resistivity (R_i), true formation resistivity (R_t), and depth of invasion (d_i) can be completely and accurately determined. The true resistivity of beds that appear infinitely thick to the sonde (10 ft for short normal; 25 ft for the long normal) can be determined from the normal logs by using departure diagrams. Figure 23 shows the relative radii of investigation of the point-resistance device, as well as the 16-inch and 64-inch normals in a homogeneous medium. The volume of investigation has gradational limits and depends, in part, on the resistivities of rock and mud. Therefore, the volume sampled constantly varies as the sonde traverses the borehole. Nevertheless, for the type of formations for which the normal devices are most efficient (formations of low to intermediate resistivities), the region that contributes the major part of the resistivity signal is, on the average, a sphere centered at the midpoint between *A* and *M* and having a diameter equal to about 2 times the *AM* spacing.

Using 4-inch and 16-inch normals, Water Resources Division researchers have succeeded in making valid logs in well bores lined with short lengths of plastic well screen. A test hole was drilled and logged using the 4-, 16-, 32-, and 64-inch normals. After logging, a 10-foot length of plastic well screen was placed in the hole opposite a resistive sand bed. The plastic screen has 20-foot lengths of blank plastic pipe both above and below. After screening, the hole was logged again, using the same equipment settings. When the sonde entered the plastic pipe below the screen, the pens moved rapidly to the right, showing the sudden jump to nearly infinite resistivity. With the sonde in the screened part, it was found that adjustment of the zero-suppression control on the equipment would bring the 4- and 16-inch normals back on-scale. After some experimentation, it was possible to log the screened part and obtain nearly the same normal curve as was run in the open hole. With only 10 feet of screen, only the shortest of the normals would have both the *A* and *M* electrodes within the screened part for a sufficient distance to develop a meaningful curve. With long lengths of plastic screen, the longer normals

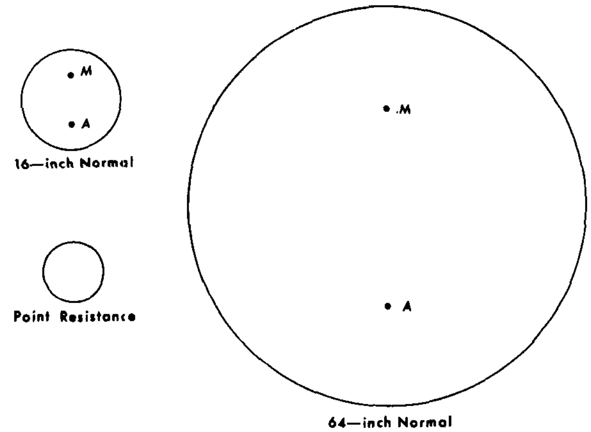


Figure 23. — Relative radii of investigation of point-resistance and normal devices.

would work satisfactorily, also. Periodic logging through plastic screen permits the measurement of changes in porosity and fluid resistivity during pumping or injection.

One important application of the normal curves is in the estimation of water quality in clastic rocks from electric logs. A relation between ionic concentration of formation water and the long-normal resistivity reading can be established empirically. Early work by Jones and Buford (1951) on laboratory samples and later work done under field conditions by Turcan (1966) have shown how the ratio can be determined for a specific ground-water environment. Once determined, the relationship can be used to approximate water quality from electric logs.

Hubert Guyod (written commun., 1968), mentioned that three tacit assumptions are made when the method is applied: (1) the aquifer is clastic, (2) the aquifer has a relatively constant porosity and clay content both vertically and laterally, and (3) the apparent resistivities, measured by the 64-inch normal, approximate the undisturbed formation resistivities.

The aquifer should be composed of clastic rocks or, at least, should behave electrically the same as clastic rocks because pore geometry exerts a great influence on resistivity. According to Keller and Frischknecht (1966), rock can be categorized into three groups on the basis of pore geometry—intergranular porosity, joint porosity, and vugular porosity. The porosity of clastic aquifers consists mainly of intergranular pores saturated with water, and the bulk resistivity is proportional to the formation-water resistivity. Not only sand and sandstone, but also many porous limestones and dolomites behave electrically the same as clastic rocks. The porosity of dense igneous rocks, such as granite, may exist almost entirely in joints, with very little intergranular porosity. Because only the water-saturated joints carry the current, the resistivity of dense rock is dependent on joint geometry and may attain values of several thousand ohm-meters. Some carbonate rocks have vugular porosity, consisting of large irregular cavities linked together by smaller connecting pores. Rock with a high ratio of vugular porosity to interconnecting porosity will have a higher bulk resistivity than a rock of the same porosity that has a low ratio. Formation factors computed from resistivity measurements of jointed igneous or vugular carbonate rocks will give misleading results when used to compute the water quality.

The clay content of the aquifer is a significant factor because ion exchange by clay minerals makes water in the rock pores conductive, even though the water after extraction from the rock is very resistive. If the saturating water is highly saline, the increase in conductivity produced by ion exchange is relatively minor, but in fresh-water aquifers, ion exchange from the rocks may drastically alter the resistivity of the water (while it is in intimate contact in the rock pores). According to Keller and Frischknecht (1966, p. 25), "even in rock with very low exchange capacities, pore water resistivity rarely exceeds 10 ohm-m."

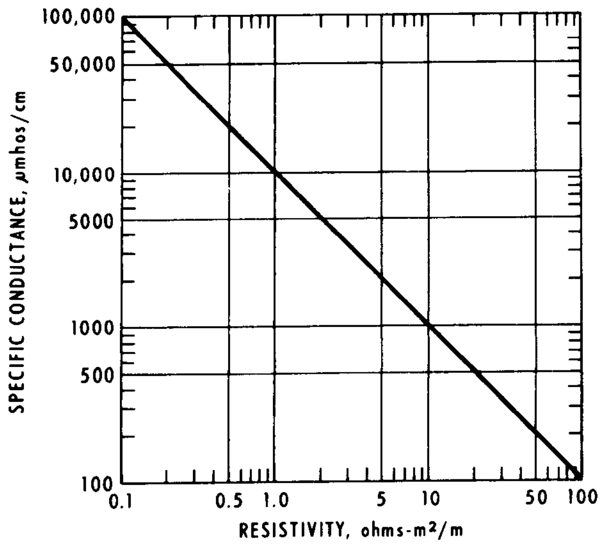
When applied to the fresh-water aquifer, the departure of apparent resistivity of the long normal from true aquifer resistivity will be approximately the same, provided the beds are relatively uniform both vertically and laterally and are more than 20 feet thick.

Turcan's (1966) method for estimating water quality from electric logs makes use of mathematical expressions which relate the following parameters: (1) Field-formation-resistivity factor and fluid resistivity, (2) fluid resistivity and specific conductance, and (3) specific conductance and dissolved solids. The rationale of the method is predicated on first establishing the field-formation factor[1] for an aquifer or for a hydrologic regime from preexisting electric logs and water analyses. When a new well is drilled into this aquifer and logged, the long-normal-curve resistivity is used to determine fluid resistivity in the aquifer. The value thus found is converted to specific conductance at standard temperature from tables or formula. The specific conductance is then converted to dissolved solids and chloride content by empirical relationships previously determined for the aquifer. By these determinations, reasonable estimates of total dissolved solids and chloride content can be made over broad areas, solely on the basis of electric logs in clastic rocks.

Using the Wilcox Group as an example will best illustrate the three steps required to apply the method described by Turcan.

1. Determine F_f from preexisting logs and analyses.
   a. Find fluid resistivity from the relationship
   $$R_w = \frac{10{,}000}{\text{Specific conductance}},$$
   or use graph shown in figure 24 (from Turcan, 1966).
   b. Find resistivity of the aquifer, R_o, at borehole temperature from the long-normal curve. Correct R_o to standard temperature by use of the Schlumberger chart (fig. 2, this manual), or use figure 10 of Jones and Buford (1951) or figure 12 of Olmsted (1962). (Also see R_o columns in the table in fig. 24, this manual.)
   c. Calculate F_f from the relationship
   $$F_f = \frac{R_o}{R_w},$$
   and see last table column in figure 24.
2. Determine relationship between specific conductance and total dissolved solids

[1] See section on "Formation Factor."



Field formation resistivity factors for aquifers of the Wilcox Group, northwestern Louisiana

Well No.	Specific conductance (μmhos/cm at 77°F)	R_w[1] (ohms-m²/m at 77°F)	R_o[2] (ohms-m²/m)	R_o (ohms-m²/m at 77°F)	F_f[3]
Bo–137	605	16.5	35	34	2.0
173	2,470	4.0	12	11	2.7
180	1,360	7.4	25	22	2.9
200	1,510	6.6	18	17	2.6
205	1,080	9.3	17	15	1.6
Cd–360	953	10.5	20	19	1.8
430	1,580	6.3	14	13	2.1
Sa–292	905	11.0	30	28.5	2.5
Na–54	1,280	7.8	17	16.1	2.1
55	1,040	9.6	35	31.4	3.2
58	2,270	4.4	15	13.8	3.1

[1] $R_w = 10^4$/specific conductance (K).
[2] Resistivity reading from long-normal curve on electrical log at field temperature.
[3] F_f (field formation factor) $= R_o/R_w$.

Figure 24. — Graph showing resistivity and specific conductance, and table of formation factors. From Turcan (1966).

and chloride content, both in parts per million.[2]

a. Use graphical plot, as shown in figure 25*A* (from Turcan, 1966).

b. Or, derive empirical formula for dissolved solids from relationship: $\log X = a \log Y$, or $X = Y^a$.

As parts per million is shown on the X axis, and specific conductance is shown on the Y axis, the relationship for the Wilcox Group becomes: Dissolved solids (in ppm) $= K^{0.93}$, where $K =$ specific conductance, in μmhos/cm. (See fig. 25*B*.)

3. Determine water quality from the newly made electric log.
   a. Read R_o value from the long-normal curve in a water-bearing bed ($R_o = 23$ ohm-meters, as shown in fig. 26*B*).
   b. Correct the 23-ohm-meter value at 69°F to 21.2 ohm-meters at 77°F (Standard temperature).
   c. Enter corrected R_o value and F_f value determined in Step 1, above, in formula $F_f = R_o/R_w$, and solve for R_w. $R_w = 21.2/2.4 = 8.8$ ohm-meters for the Wilcox group.
   d. Find 8.8 ohm-meters on upper X axis in figure 25*A*. Read straight down to find specific conductance of 1,100 μmhos/cm.
   e. Still using figure 25*A*, find intersection of the 1,100 μmhos/cm line with the two curves, and read dissolved-solids content of 650 ppm and a chloride content of 140 ppm.

Turcan showed that the dissolved-solids content from a chemical analysis of water from this well is actually 586 ppm, and the chloride content from analysis is actually 130 ppm. Figure 26*A* shows the type of areal map of field formation factor that can be drawn on the basis of electric logs and water analyses. Such a map makes spot estimation of water quality from electric logs relatively quick and accurate over wide areas, a large part of a State in this example.

Another potentially useful application of the normal-resistivity curves to hydrologic problems involves the calculation of the permeability of clastic aquifers. Croft (1971)

[2] The U.S. Geological Survey has reported water-quality data in milligrams per liter, in preference to parts per million, since 1968. If the dissolved-solids content is less than 7,000 mg/l, or if the specific conductance is less than 10,000 μmhos/cm, then parts per million values and the corresponding milligrams per liter values can be considered equivalent.

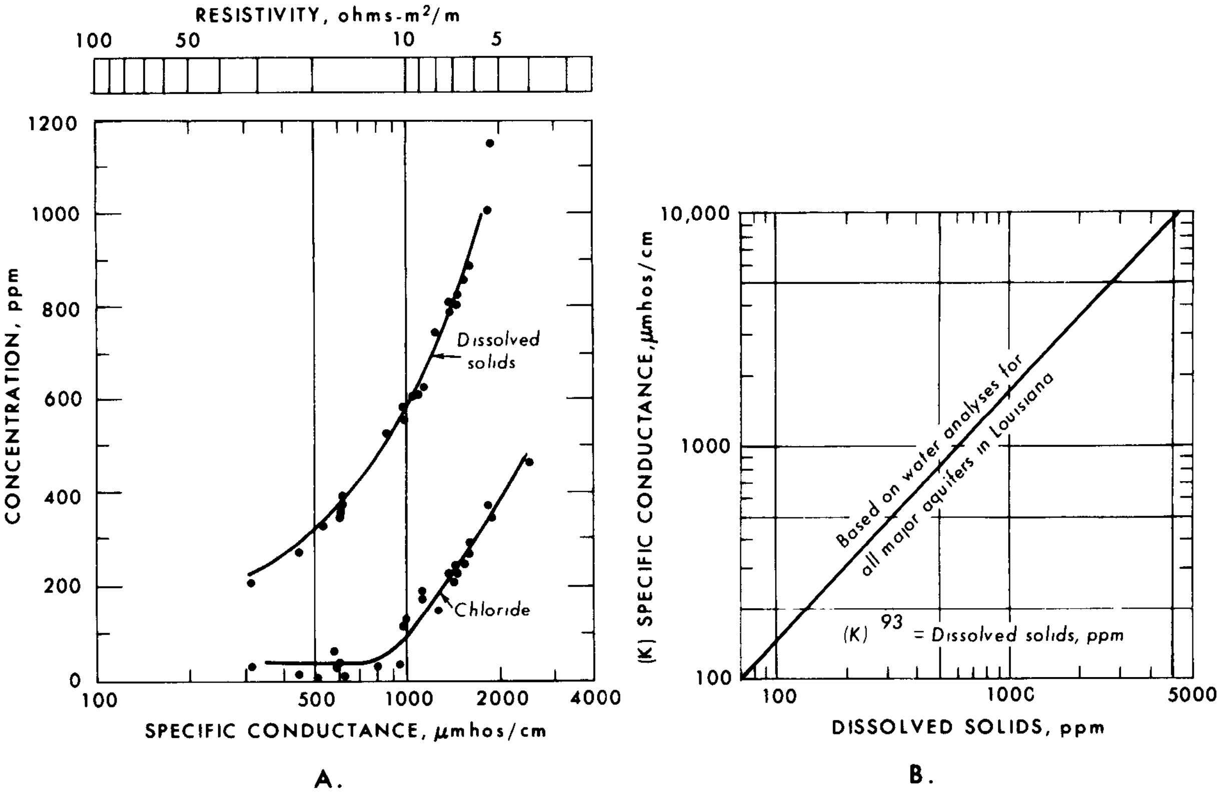


Figure 25. — Relation of dissolved-solids and chloride concentration, in ppm, to resistivity and specific conductance (A), and relation between specific conductance and dissolved solids (B). From Turcan (1966).

described a method he used for determining permeability in North Dakota. His method makes use of a graph by Alger (1966) which shows the relationship between permeability and formation factor. Alger's data were taken from original research by Jones and Buford (1951). Alger's figure 12 shows that there is a systematic increase in permeability with increase in grain size for graded sand samples. His figure 12 also shows an increase in formation factor with increase in grain size for each of the nine sand samples. By recombining the two graphs, he derived figure 13, which shows an increase in F with an increase in permeability. Because Croft was dealing with F values of less than 3, he had to extend Alger's curve across one additional log cycle.

The porosities of the graded-sand samples in Alger's paper ranged from 40.0 percent to 45.3 percent. Whether or not the plots for laboratory graded-sand samples will adequately duplicate natural sand deposits of various porosities, sorting coefficients, and clay content can only be determined by further laboratory analyses. However, Croft showed that his permeability values from electric logs agree well with those obtained by conventional methods. Inasmuch as the formation factor is the key to these permeability values, the inhomogeneities of aquifer sands may not be too restrictive on application of the method because the formation factor also accounts for tortuosity and cementation. In order to apply the method, we must determine the values of R_o and R_w for the particular aquifer. The electric log, (fig. 27, left; from Croft, 1971) shows the five zones selected for analysis. Zone C, for example, has a field R_o value of about 11.7 ohm-meters from the long normal. The water temperature is reported to be 56°F; hence, adjusting the log value to 77°F, with Schlumberger Chart A-6 (Schlumberger Well Surveying Corp., 1966) results in an R_o value of 8.5 ohm-meters. The R_w value was

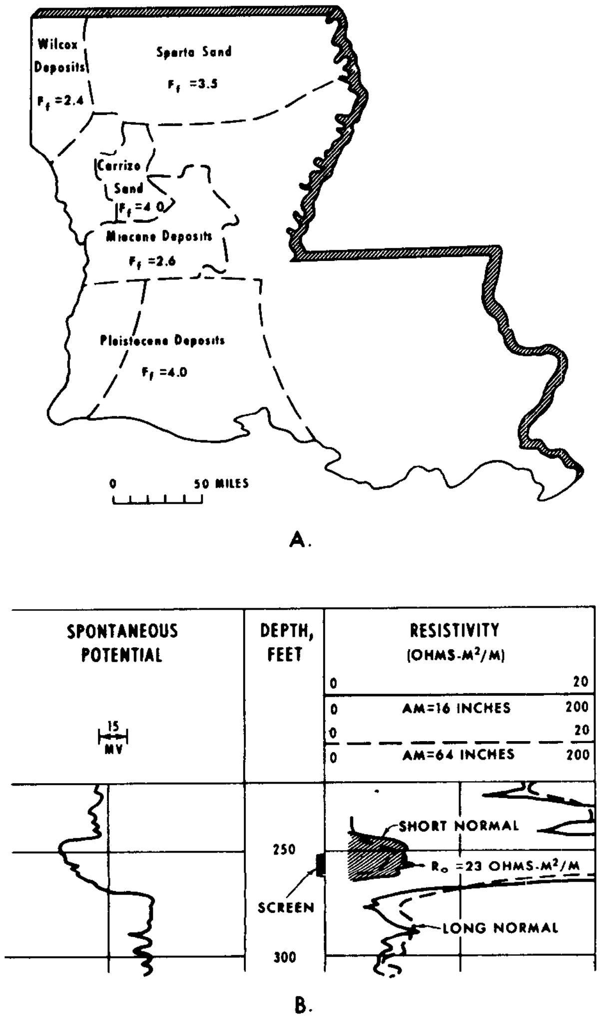


Figure 26. — Areal plot of formation factors *(A)* and electric log *(B)* of a well penetrating the Wilcox Group. From Turcan (1966).

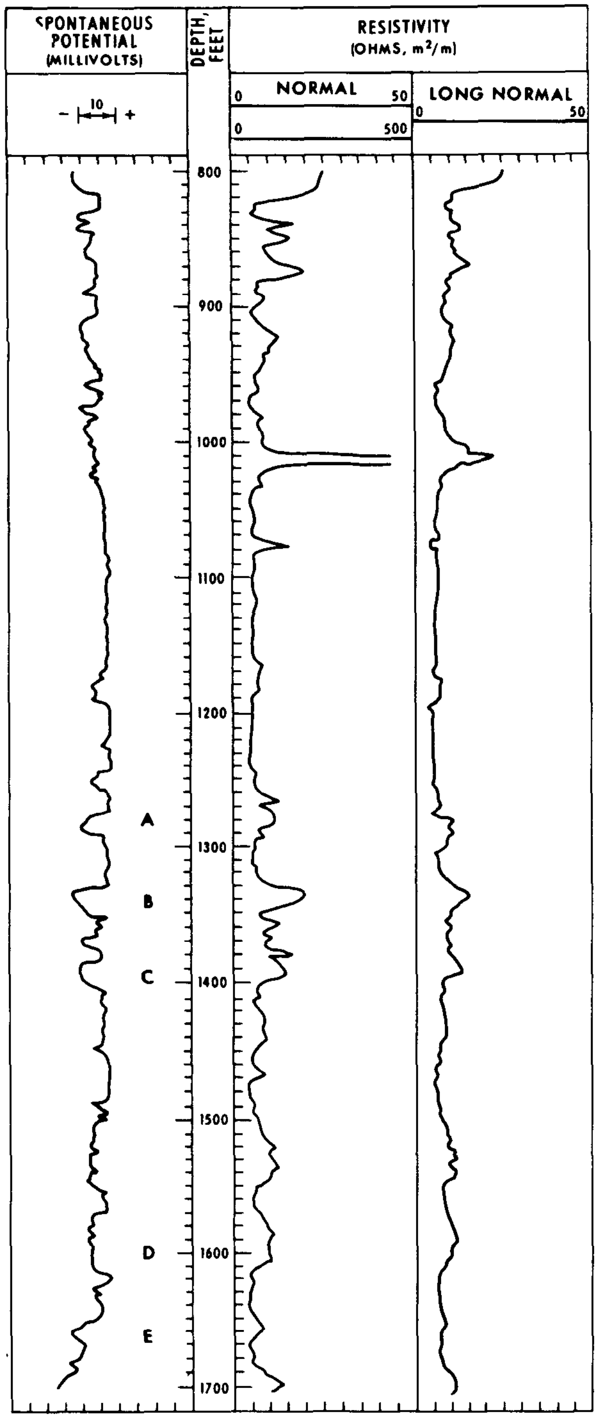
determined from the Schlumberger chart after converting the chemical analysis of formation water into an equivalent NaCl solution by use of the multipliers on page A–5 of the Schlumberger document. The R_w value is 3.5 ohm-meters. Solving for formation factor:

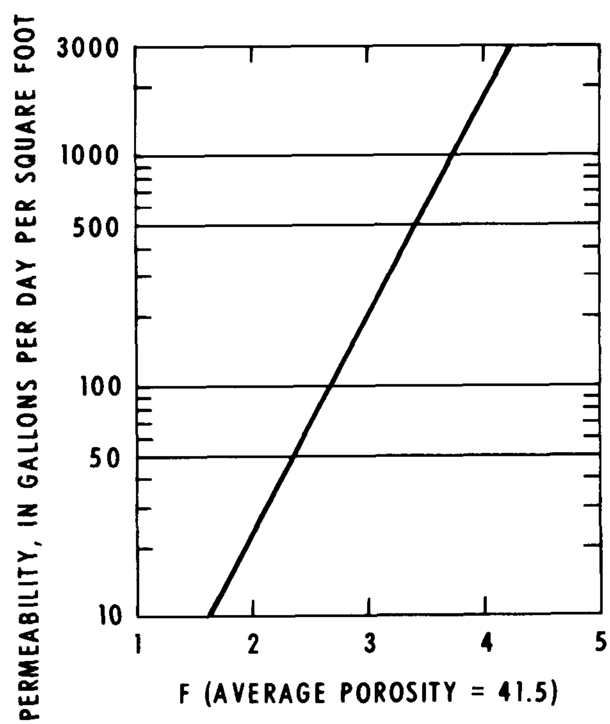
$$F=\frac{R_o}{R_w}=\frac{8.5}{3.5}=2.4.$$

Formation factor is converted to permeability by use of the graph in figure 27 (upper right), and gives a value of 60 gpd/ft³ (gallons per day per square foot). The permeability values of the other zones in the well are given in the table in figure 27 and agree with those determined by aquifer tests. Because anomalous formation factors result from resistivity measurements of rocks with only joint or vugular porosity, the method should be applied only to clastic rocks or to rocks that behave like clastics.

Instrumentation

The normal logs are generally run on multiple-conductor cable, so that two normals and the SP can be logged simultaneously. Commercial logging service companies often run a long-lateral curve along with the normals. The Water Resources Division four-conductor logger uses two conductors to carry the current down to the *A* and *B* electrodes and two conductors to carry the 16- and 64-inch potentials to the surface, with the SP picked off the 16-inch electrode. The two normal curves and the SP are displayed on a three-pen recorder. The Water Resources Division multielectrode-research logger employs the system shown on the left side of figure 22. Electrode *A* is at the bottom end of a rubber-insulated steel mandrel, about 7 feet long, with two *M* electrodes located 16 inches and 64 inches above *A*. These *M* electrodes pick up the voltage changes for the 16- and 64-inch normal curves. The cable head fastens to the top of the mandrel with a watertight threaded connection that is wrapped with insulated electrical tape. The armored cable is insulated with a rubber sleeve for 50 feet above the cable head. Since the cable armor is used as the current-return electrode, *B*, the taped cable head and rubber sleeve effectively move *B* more than 50 feet above the *AM* electrode group. The voltage-return electrode, *N*, is a lead sleeve on the end of a rubber-covered wire and is placed in the mud pit. Electrode *N* also is the ground return for the SP, which is measured on the lower *M* (16-inch) electrode. The reference point of the short-normal measurement is the midpoint between the electrode *A* and the 16-inch *M* electrode. Because the spacing *AM* is different for the short and long normals, the *AM* midpoints for the two curves do not coincide. The midpoint for the long normal is 24 inches above the short-normal midpoint. This difference





Formation factors and values for permeability at selected depths from the electric log shown.

Depth		$\frac{R_o}{R_w}$	Formation factor	Permeability $\left(\frac{\text{gallons per day}}{\text{foot}^2}\right)$
A........	1,205	$\frac{6.8}{3.5}$	1.9	20
B........	1,340	$\frac{10}{3.5}$	2.9	150
C........	1,395	$\frac{3.5}{3.5}$	2.4	60
D........	1,600	$\frac{6}{3.5}$	1.7	11
E........	1,655	$\frac{3.8}{3.5}$	1.1	5

Figure 27. — Electric log of water well (left), graph showing permeability and *F* (upper right), and table of formation factors. From Croft (1971).

is compensated at the surface by adjusting the long-normal recorder pen to read 2 feet higher than the short-normal pen. Other combinations of normals—4, 8, or 32 inches, inclusive—require different pen separations. Some commercial logging service companies use optical galvanometers to record the various traces. Generally, sufficient channels are available so that a backup trace can be utilized to record off-scale deflections. In figure 10, for example, the resistivities from the bottom of the hole to a depth of 510 feet are less than about 100 ohm-meters. Between 510 and 480 feet, the resistivity went off-scale, and the backup galvanometer (cross-hatched pattern) recorded the resistivity from 100 to 175 ohm-meters on the long normal and a little less on the short normal. From 480 to 450 feet, both traces are back on the 0- to 100-ohm-meter galvanometer. From 450 to 100 feet, the long normal is off-scale again, and is recorded on the backup galvanometer between 100 and 200 ohm-meters. The short normal is also off-scale from 450 to 100 feet, except for a small deflection back on the 0- to 100-ohm-meter scale from 230 to 200 feet.

Part of the instrumentation of a normal logging system is some provision to maintain constant current into the formation through the current electrodes for a given resistivity range and the option of selecting greater or lesser current for each resistivity range. Constant current can be maintained by putting a sufficiently high resistance between the power source and the current electrodes, so that, in effect, the same current will pass through the series circuit, regardless of the formation resistivity, within a limited range. An alternate method is to use a constant-current generator, generally of solid-state circuitry, to maintain current stability at the A and B electrodes.

Several systems have been designed to make normal curves with single-conductor loggers, but, to date, they have not been operational over a wide range of resistivities. One experimental system tried by the Water Resources Division used a local oscillator to generate current and used the potential from the 16- and 64-inch electrodes to program voltage-controlled oscillators. The resultant pulses were sent to the surface, where they were discriminated, integrated, and made into an analog signal. The inherent difficulty in this system, as with any single-conductor system, is the inability to select different currents for different resistivities in order to get an optimum potential from the pickup electrodes.

Calibration and standardization

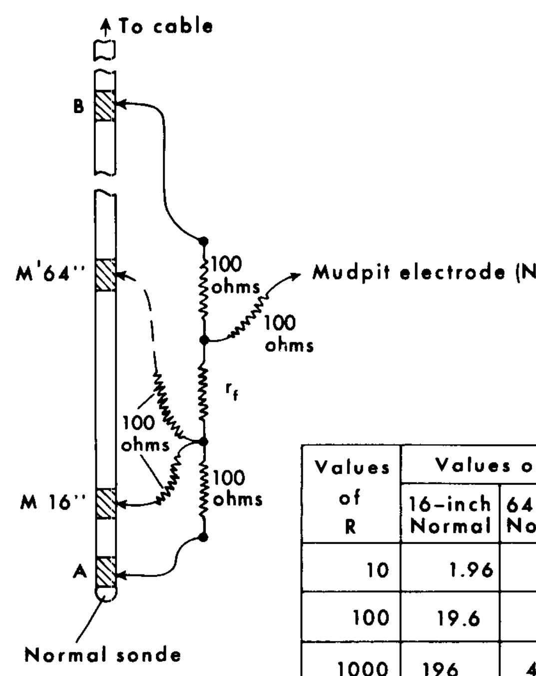
The normal logging systems, like other apparent resistivity devices, are calibrated in ohm-meters. A calibration device similar to the one used with single-point resistivity systems can be employed to establish a reference resistance for the normal curves. A calibrator that simulates both the contact resistance and the formation resistivity when attached to the normal electrodes is shown in figure 28. The equivalent resistance for the various resistivities is calculated from the formula

$$R_a = \frac{E}{I} 4\pi AM.$$

Because $\frac{E}{I} = r$, the formula is rewritten

$$r_f = \frac{4\pi AM}{R},$$

where r_f = equivalent resistance of formation;
$4\pi AM$ = geometric factor for normal device; and
R = resistivity, in ohm-meters.



Values of R	Values of r_f 16-inch Normal	64-inch Normal
10	1.96	0.49
100	19.6	4.9
1000	196	49.0
10,000	1960	490

Figure 28. — Normal-device calibrator.

For example, the value of $4\pi AM$ for the 16-inch normal is approximately 5.11. By using this value and substituting various values of R, one can derive values of r_f for each resistivity. For 10 ohm-meters, r_f equals 1.96 ohms; for 100 ohm-meters, r_f equals 19.6 ohms; for 1,000 ohm-meters, r_f equals 196 ohms; and for 10,000 ohm-meters, r_f is 1,960 ohms. The research logger uses a 300-volt DC supply, which is mechanically chopped into a square wave. This square wave is applied to current electrodes A and B (fig. 28) through high-series resistors in the uphole circuitry to achieve constant current. The series resistance is 6 kΩ in the 0–10 ohm-meter range, 60 kΩ in the 0–100 ohm-meter range, 600 kΩ in the 0–1,000 ohm-meter range, and 6 meg-ohms in the 0–10,000 ohm-meter range. In each range, the ratio of r_f to the total series resistance is so small (196 ohms to 600,000 ohms in the 1,000 ohm-meter range, for example) that a constant current in the system is maintained. Ohm's law shows the current to be 50 ma in the 10 ohm-meter range, 5 ma in the 100 ohm-meter range, 500 μa in the 1,000 ohm-meter range and 50 μa in the 10,000 ohm-meter range. Also from Ohm's law, the voltage drop across r_f is approximately 100 mv for 10, 100, 1,000, and 10,000 ohm-meters.

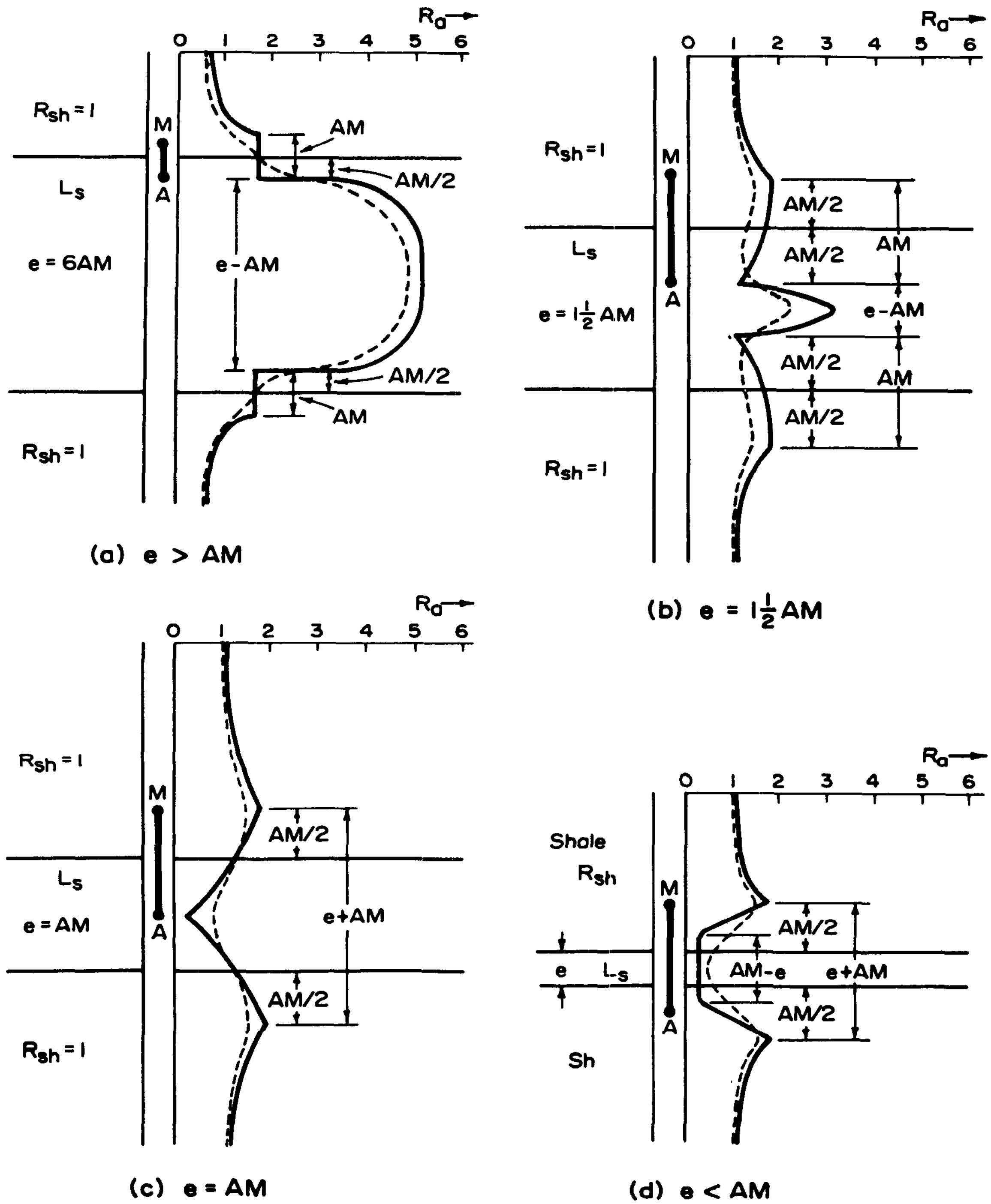
Contact resistance—the impedance to current flow that is caused by the contact between the tool electrodes and the surrounding fluid—depends on the surface area of the electrodes and the resistivity of the borehole fluid. In figure 28, contact resistance is shown by the 100-ohm resistors. Although this value appears to be suitable for low- to moderate-resistivity environments, in highly resistive rocks saturated with fresh water, contact resistance may be several thousand ohms.

To select the right current density for each resistivity range is imperative, as shown by the foregoing discussion. The lower the resistivity, the greater the current needed to get a useful potential drop across r_f, and conversely. If the current is too low in low resistivities, insufficient voltage drop will occur across r_f, and the log will be without character. If the current is too high in highly resistive rocks, excessive voltage will appear across r_f and will saturate the recorder inputs.

Bed-thickness effects

The curves produced by the normal devices are affected by bed thickness and resistivity. Figure 29 (Lynch, 1962) shows four fairly typical examples of resistive beds: bed thickness (e) = >6 AM; bed thickness = 1½ AM; bed thickness = AM; and bed thickness <AM. In the first example, where the resistive bed is more than 6 AM spacings thick, there is a gradual increase in resistivity until the M electrode on the sonde enters the bottom of the bed. This level of resistivity is maintained until the A electrode enters the bed. As the sonde continues (A and M both in the bed), there is a gradual increase in resistivity until the midpoint of the bed is reached. Thereafter, a gradual reduction occurs in resistivity, which is symmetrical with the curve below the midpoint of the bed, until the sonde passes out of bed. The recorded resistivity value approaches but does not fully equal the true resistivity of the bed. The bed also appears to be 1 AM spacing thinner than it actually is, the major resistivity deflections occurring ½ AM above the bed bottom and ½ AM below the bed top. As the bed thickness decreases, the resistivity peak at the center decreases in amplitude (fig. 29b). Further thinning of the bed to AM or less causes the resistivity deflection to disappear entirely, and the curve actually reverses, as shown in fig. 29c and d. The resistive bed now appears as if it were more conductive than the surrounding beds. Reflection peaks appear symmetrically on either side of the resistive bed, separated by a distance equal to bed thickness plus distance AM.

The reversal of the normal curve opposite thin resistive beds imposes a serious handicap in the use of this tool for some applications. Although the radius of investigation of any resistivity tool increases as the electrode spacing increases, the use of AM spacings longer than 64 inches is not practical because thinner beds not only are shown at less than the true resistivity, but they also may be



—— Theoretical Resistivity (Hole diameter infinitely small)

---- Actual Measured Resistivity

e Bed Thickness

Figure 29. — Response of a normal device opposite beds of various thicknesses. From Lynch (1962).

recorded as conductive beds if their thickness is equal to or less than the *AM* spacing.

Lateral devices

The lateral log measures the formation resistivity beyond the invaded zone by use of widely spaced electrodes. The lateral is a deep-looking device and gives best results in beds whose thickness exceeds twice the electrode spacing. Its efficiency is poor in highly resistive rocks. Like the normal device, commercial lateral-logging devices are long and heavy, and necessitate a derrick over the hole.

Principles and applications

The lateral devices consist of three effective electrodes actually present in the borehole. The potential-measuring electrodes *M* and *N* are positioned below the current electrode *A*. The electrode spacings on the lateral device are measured from current electrode *A* to the midpoint between electrodes *M* and *N*. This distance is called the *AO* spacing and has been standardized at 18 feet, 8 inches, although older logs may be seen with spacings of 4 feet, 8 inches; 6 feet; 9 feet; 13 feet; 15 feet; 19 feet; and 24 feet. The electrode *B* is located a remote distance from the group *AMN* and, therefore, has substantially no effect on the curve. Figure 30 shows the electrode arrangement for the lateral device. The geometric factor, *G*, for the lateral device is equal to $4\pi\ (AO)^2\ MN$, where distances *AO* and *MN* are in meters.

The prime objective of the lateral log is to measure true formation resistivity beyond the invaded zone by use of an electrode spacing large enough to insure that the invaded zone has little or no effect on the response.

The lateral device has its best response in beds that are more than twice the thickness of the *AO* spacing (more than 40 ft) and where the thick bed has contrasting beds above and below that are at least 1 *AO* space thick.

Instrumentation

Commercial service companies run the lateral device simultaneously with the short and long normals. The lateral curve generally appears in the third track of the recorder,

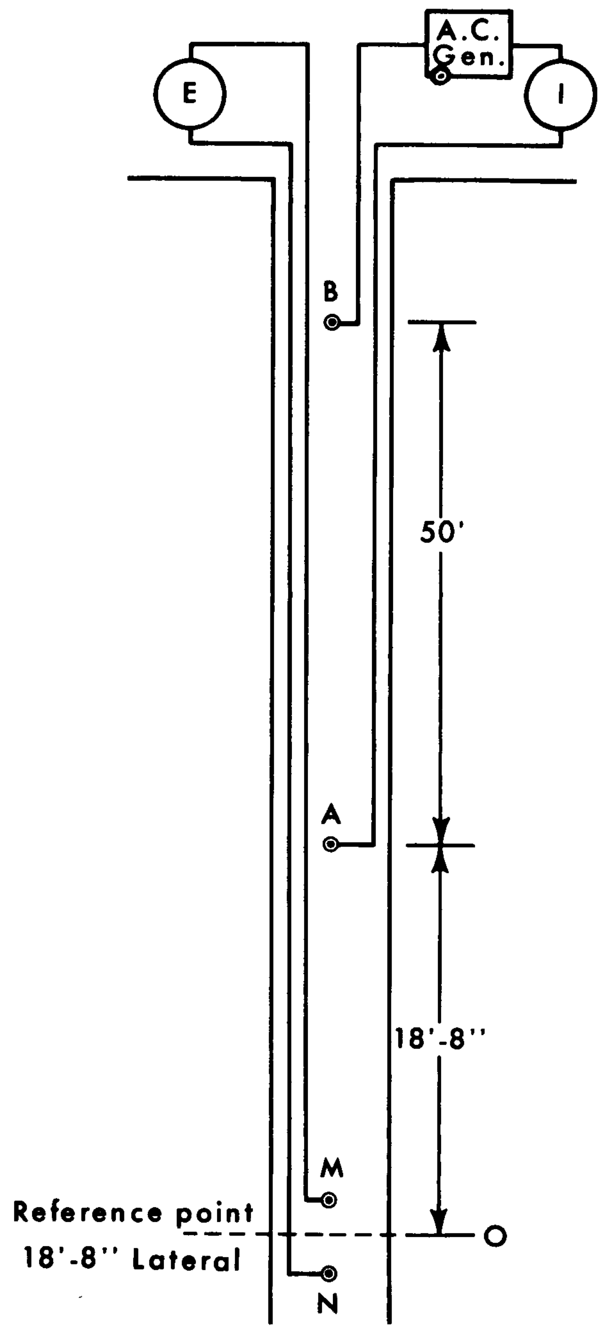


Figure 30. — Electrode arrangement for lateral device.

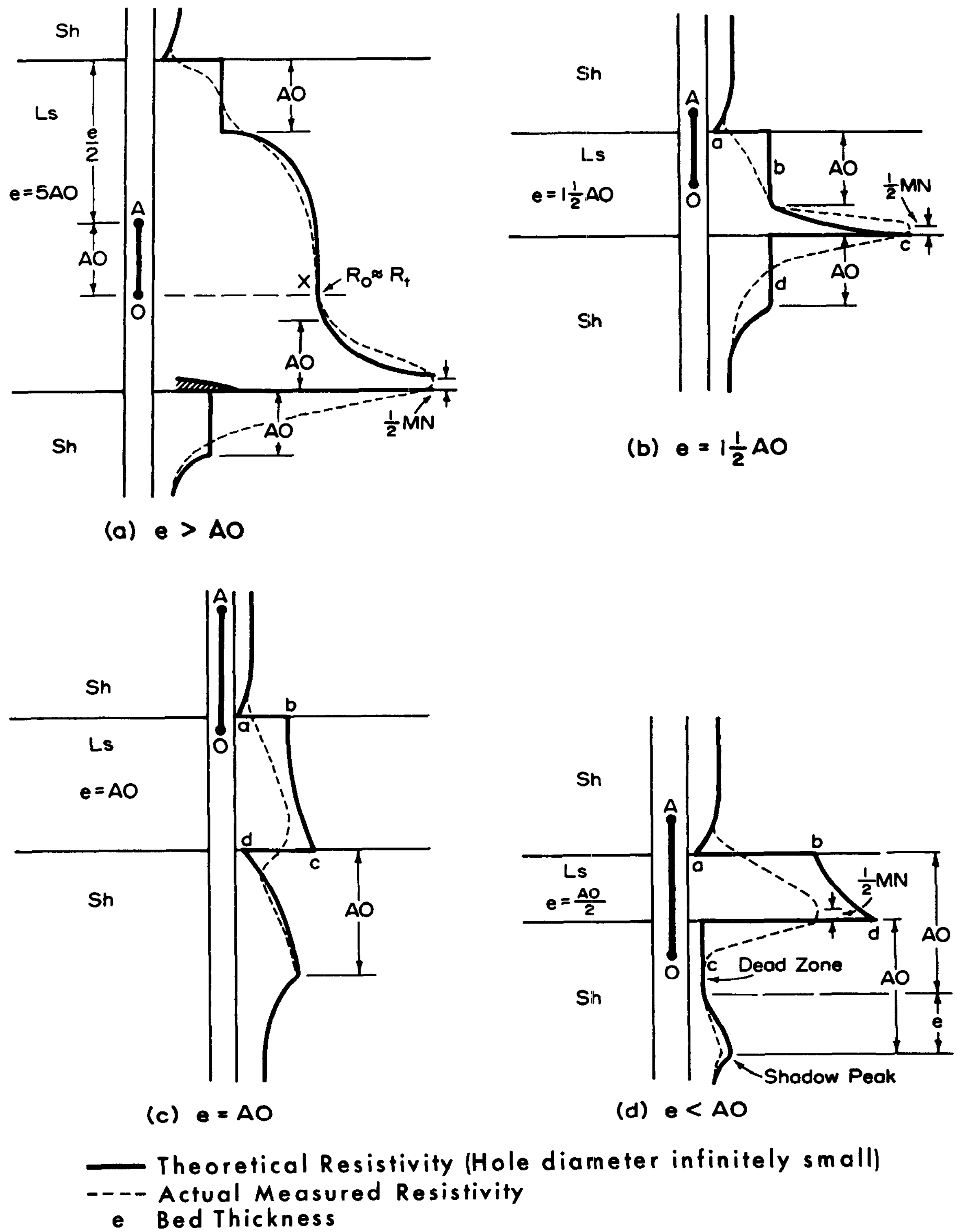


Figure 31. — Response of a lateral device opposite beds of various thicknesses. From Lynch (1962).

although on some logs it appears in the second along with the short normal. Like the normal curves, the lateral requires multiconductor logging cable.

As with the normal devices, the lateral curves are calibrated in ohm-meters, and external calibrators can be used to establish tool and instrumental response to various resistivities.

Bed-thickness effects

The most obvious characteristic of the lateral curve is its lack of symmetry about a given bed. Figure 31 (Lynch, 1962) shows four fairly typical examples of resistive beds. The curve is badly distorted by adjacent beds and by thin-bed effects. Not only do the apparent resistivities depart from the actual value, but shadow peaks and dead zones show up near thin resistive beds whose thickness is less than the distance *AO* (fig. 31*d*). Departure curves are necessary to correct lateral curves for thin-bed and adjacent-bed effects. Very salty muds and changes in hole diameter also affect the response of the lateral device and must be corrected using departure curves for quantitative-log interpretation.

Figure 32 is an electric log of a water well in Texas that penetrates thick limestone. The log is fairly typical of the conventional resistivity survey because it records SP, 16- and 64-inch normals, and the 18′8″ lateral. The response of the lateral to thin resistive beds is exhibited by the sharp deflections at 709 feet and at 791 feet. The 16-inch normal also shows sharp resistive peaks at these points. The two beds must be 64 inches or less in thickness because the long normal exhibits cratering at both of these beds. (See fig. 29*c* and *d*.)

Wall-resistivity devices

The unfocused wall-resistivity devices measure mainly the resistivity of the mud cake. They are used mostly to detect the presence or absence of a mud cake. Commercial wall-resistivity devices are about 5 feet long and more than 4 inches in diameter, and they weigh nearly 100 pounds. A rig tower or A frame generally must be used due to the great tension on the line caused by friction as the device is pushed against the wall of the hole.

Wall-resistivity devices are very short spaced multiple-electrode arrangements mounted on pads that hold the electrodes against the wall of the hole. They give fine lithologic detail and are also used to delineate porous versus nonporous formations on the basis of the presence or absence of a mud cake. Figure 33 (Schlumberger Well Surveying Corp., 1958) shows the electrode arrangement and current lines for a micronormal and microlateral device. The pad holds three dime-sized electrodes, 1 inch apart, designated A, M, and M_2, from bottom to top. The electrode group AM_2 provides a micronormal (two active electrodes) with AM equal to 2 inches, and the electrode group AMM_2 provides a microlateral (three active electrodes) with an AO equal to 1½ inches. The microlateral (called microinverse on some logs) measurement is affected mainly by the mud cake because it "sees" only 1½ inches into the wall of the hole. The micronormal measures the resistivities just beyond the mud cake and, thus, gives a resistivity that is mostly influenced by formation resistivities.

When the 2-inch normal continuously records a higher resistivity than the microlateral, it is indicative of a uniformly thick mud cake. In general, the uniform mud cake occurs on the more porous formations. In shale, there is no mud cake, and both microcurves read the same resistivity.

The utility of wall-resistivity devices is limited by the minimum diameter hole they will fit, generally about 6 inches, and the maximum diameter which the bow springs or presser arms will accommodate, generally about 16 inches. Mud cake thickness, mud cake resistivity, and depth of invasion all exert such a profound effect on the perfor-

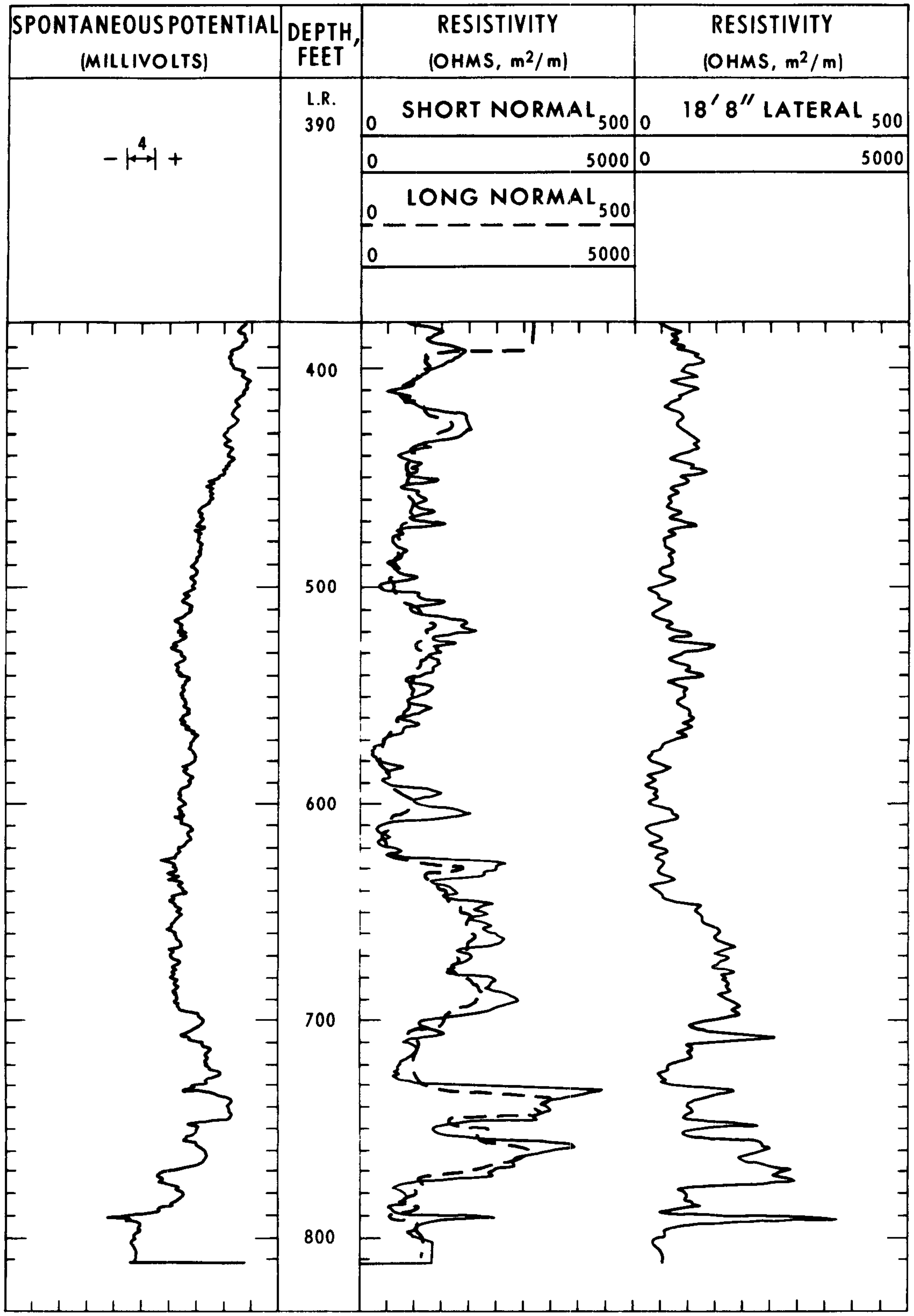


Figure 32. — Electric log of well drilled in limestone in Texas.

mance of this tool that it is sometimes regarded mainly as a mud cake detector.

Wall-resistivity logs appear under such trade names as Microlog, Minilog, Contact log, and Microsurvey log.

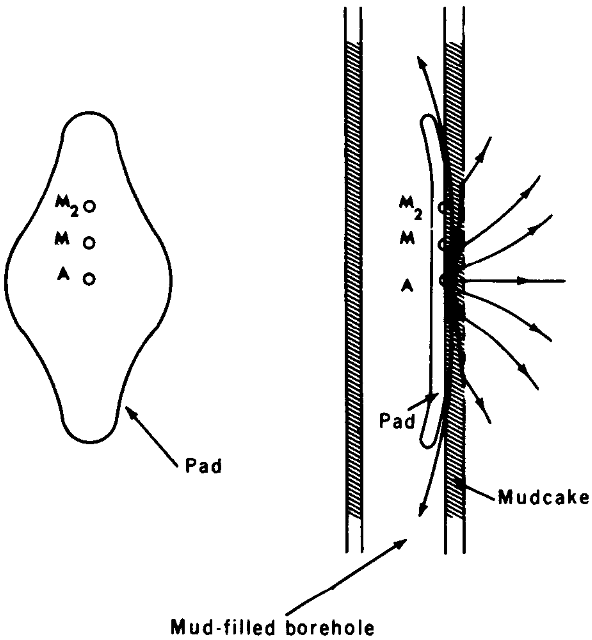


Figure 33. — Micronormal and microlateral device. From Schlumberger Well Surveying Corp. (1958).

Focused devices

Focused-current devices are used to measure relatively high formation resistivities through a conductive mud. Focused devices give good vertical resolution and great penetration, although their curves are seemingly distorted due to a nonlinear response at higher resistivities. (See fig. 20.) Commercial guard-log devices are 11 feet or more in length and 3⅝ inches in diameter, and weigh 150 pounds. A derrick or tower is required to handle this tool over the well bore.

All the conventional resistivity devices discussed so far yield anomalous results when they are used to log formations that are much more resistive than the borehole mud column. Electric current tends to follow the path of least resistance, and under the above conditions most of the current will flow in the mud column. For very high contrasts between the formation resistivity and the mud column, so little current enters the formation that the resistivity curves lack character, bed boundaries cannot be determined, and the apparent resistivities depart so radically from true resistivity that the latter cannot be determined.

The focused-resistivity devices were developed to overcome some of the limitations of the conventional resistivity systems. Focused devices include such electrode arrays as the guarded-electrode, laterlog, and the microfocused devices.

Figure 34 (Hubert Guyod, written commun., 1968) shows the design philosophy of the guarded-electrode system and the basic difference between it and the unfocused devices. In figure 34, the borehole is assumed to have penetrated a formation that is much more resistive than the mud column. Diagram *A* represents the current pattern about a short electrode, such as is used for the normals. The current tends to follow the conductive mud for a considerable distance relative to the length of the electrode. Where

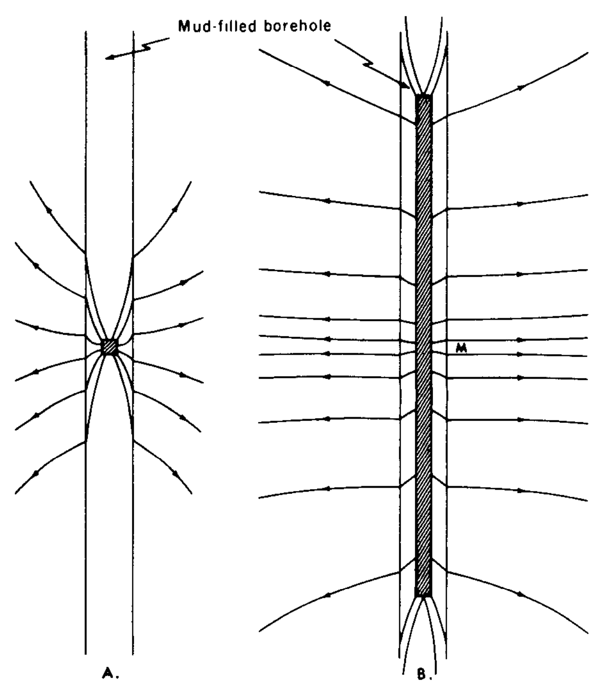


Figure 34. — Comparison of unfocused *(A)* and focused *(B)* devices (Hubert Guyod, written commun., 1968).

the resistivity contrast between formation and mud is very great, most of the current remains in the mud column. Diagram *B* shows the current pattern around the electrode if it were stretched out into a long cylinder. Near the center of the cylinder, the current is constrained to move at nearly right angles to the surface of the electrode, and it is only at the ends that the current has the tendency to fan up and down the borehole. If a measurement of resistivity were made at point *M*, the relatively flat beam of current could be utilized to penetrate deeply into the formation. The current focusing of the various guard systems is achieved in this manner by the expedient of cutting the cylinder in two sections, called guards, and inserting a measuring electrode at point *M*. Figure 35 (Doll, 1951) shows a typical guard-electrode system. The thickness of the current beam is approximately the length of

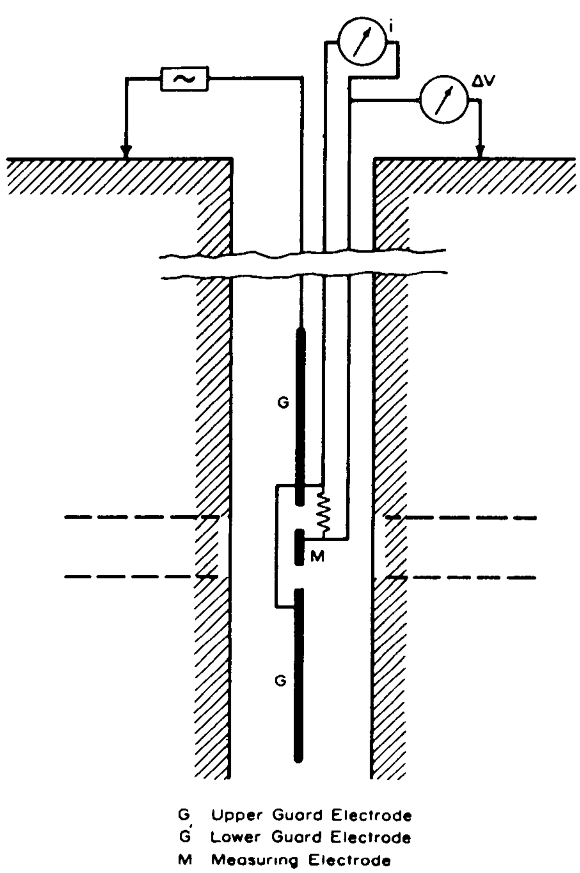


Figure 35.— Guard-logging system. From Doll (1951).

electrode *M* and, in commercial logging systems, ranges from 3 to 12 inches. These focused systems are especially useful for logging thin beds and for use in highly conductive mud. The length of the guard sections is generally 5 or 6 feet; the longer these guards, the flatter the current beam, and the greater the depth of penetration.

In general, the depth of penetration is about 3 times the length of one guard; thus, for a 6-foot guard (overall tool length is about 13 feet), the depth of investigation will be about 18 feet. One failing of the guard system is that no SP reading can be obtained within about 25 feet of the top of the uppermost guard when R_t/R_m is very high. For this reason, it is impossible to measure SP to the bottom of the hole when using guard systems.

Another focusing system is the laterolog method. Instead of the solid conductors of the guard method, the laterolog system employs a series of conventional electrodes A_1 A_2, M'_1 M'_2, and M_1M_2 to focus the current into a beam about 32 inches thick, the distance between O_1 and O_2 in figure 36 (from Doll, 1951). The depth of investigation is about the same as that of a guard tool whose guards are 5–6 feet long each. Owing to a thicker current beam than that of the guard tool, the bed definition by the laterolog is not so good as that by the guarded-electrode method. A log from a laterolog device is shown on the left in figure 20.

With the laterolog system, SP can be measured at the potential electrode almost to the bottom of the borehole because the metallic guards are eliminated.

Other types of focused equipment are currently in use in the petroleum industry, such as the microfocused devices. These devices are designed primarily to measure the resistivity of the flushed zone (R_{xo}) with the objective of obtaining the formation factor. The microfocused logs are wall-resistivity devices; they consist of small disk-shaped electrodes, less than 1 inch in diameter, which are pressed against the walls of the borehole. Figure 37 (Schlumberger Well Surveying Corp., 1958) shows the electrode arrange-

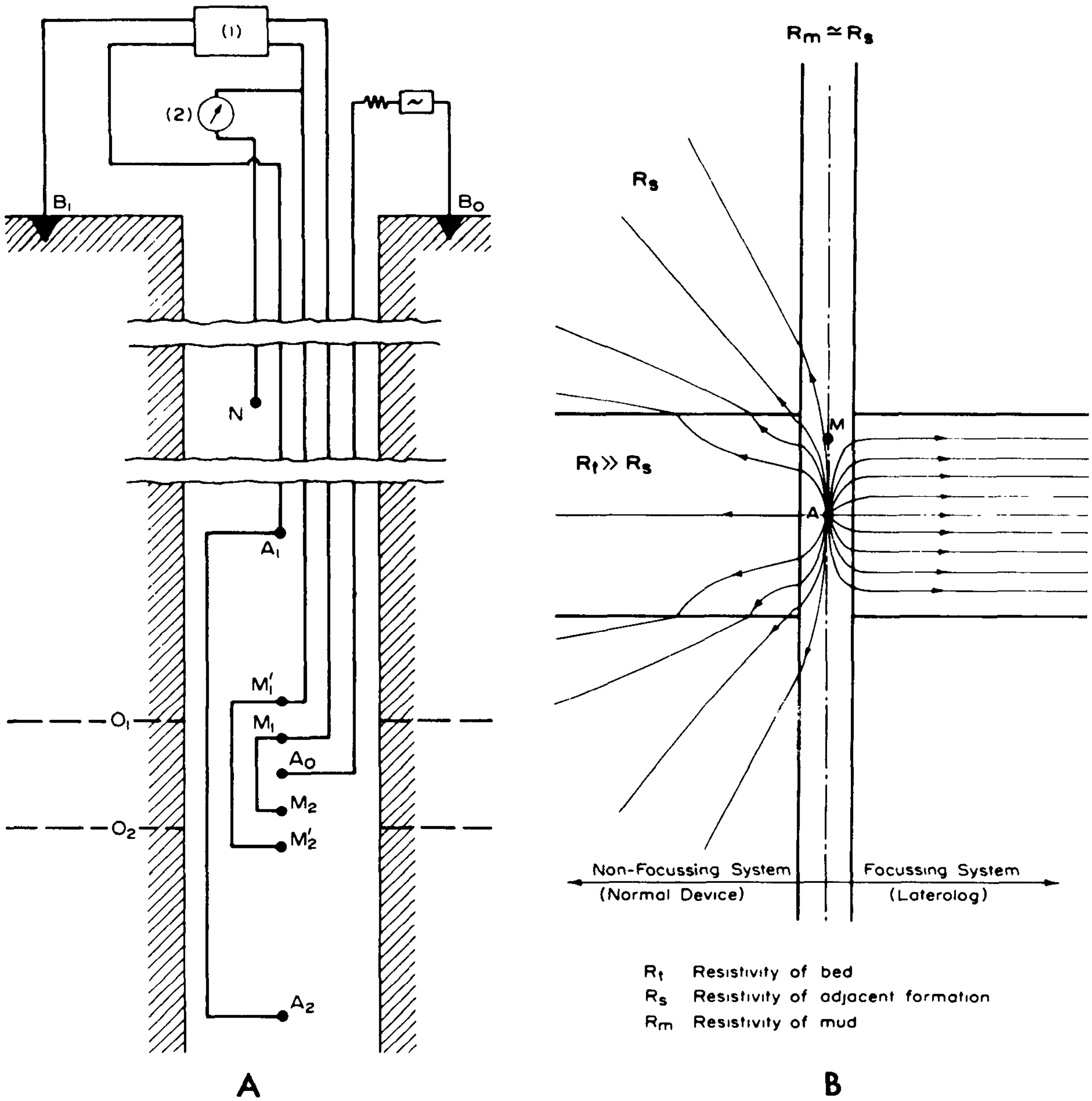


Figure 36. — Laterolog system, electrode arrangements, and comparison of current distribution for normal device and laterolog. From Doll (1951).

ment and current lines for the microlaterolog device. Compare this figure with figure 33 to see the effects of focusing on the current lines. These electrodes behave much as the point-electrode focusing technique used in the laterolog, but they have a depth of investigation of only about 5 inches; thus, the measurement is primarily related to the resistivity of the flushed zone.

Induction device

The induction device records the conductivity (reciprocal of resistivity) of rocks by inducing a current to flow in the rocks. Where invasion is shallow, the induction log measures true resistivity. Also, the device has the further advantage of working in either air- or oil-filled holes. The large resis-

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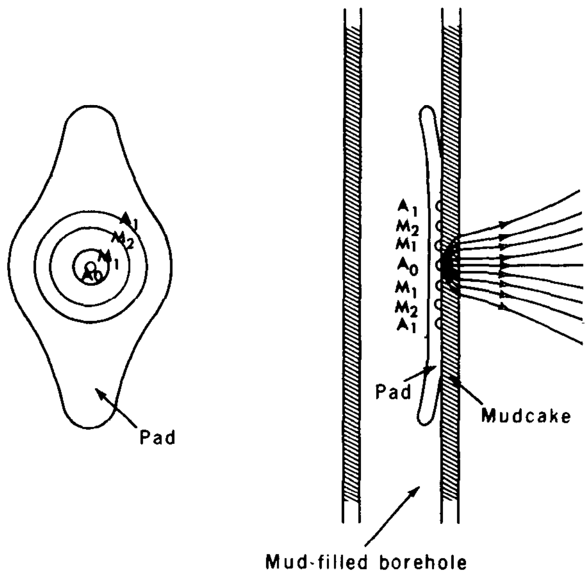


Figure 37. — Microlaterolog device. From Schlumberger Well Surveying Corp. (1958).

tivity contrast between formation water and borehole mud in fresh-water systems seriously limits the applicability of induction logs to hydrology. A further limitation is in the great size of the tool. A typical induction device is 3⅝ inches in diameter and more than 15 feet long, and weighs nearly 200 pounds. Tools of this size require a large mast, or drill rig, to get in and out of the hole.

Principles and applications

Conventional electrode-resistivity devices require a conductive medium in the borehole to carry the current into the formations; thus, they cannot be used in air-filled holes or in wells drilled with an oil-base mud. To overcome this problem, Schlumberger introduced induction logging in 1948. This method is based on the idea of using electromagnetic induction to couple a signal from the logging sonde into the formation and back to the sonde (Doll, 1949). This method has also proven extremely successful in fresh-water muds and is generally the best resistivity logging tool in fresh mud, except where formation resistivities are much higher than those of the adjacent shale beds.

In its simplest form, the induction sonde contains two coils of wire, one for transmitting an alternating current by induction into the formation, and the other for receiving the signal returned from the formations. The transmitting coil is driven by an oscillator (20 kHz), and the signal penetrates the formation in a torous-shaped pattern about the coil. Figure 38 (Schlumberger Well Surveying Corp., 1958) shows the arrangement for a single-transmitter single-receiver induction logging sonde. The electromagnetic field induces ground currents in the formation that flow along circular loops perpendicular to the axis of the borehole. One of these ground-current loops is shown in figure 38. The ground currents have an attendant magnetic field, the strength of which is dependent on the magnitude of the ground currents. The magnitude of the ground currents is proportional to the conductivity of the formation carrying this current. By instrumenting the receiving coil to respond only to the secondary magnetic field, which is due to the

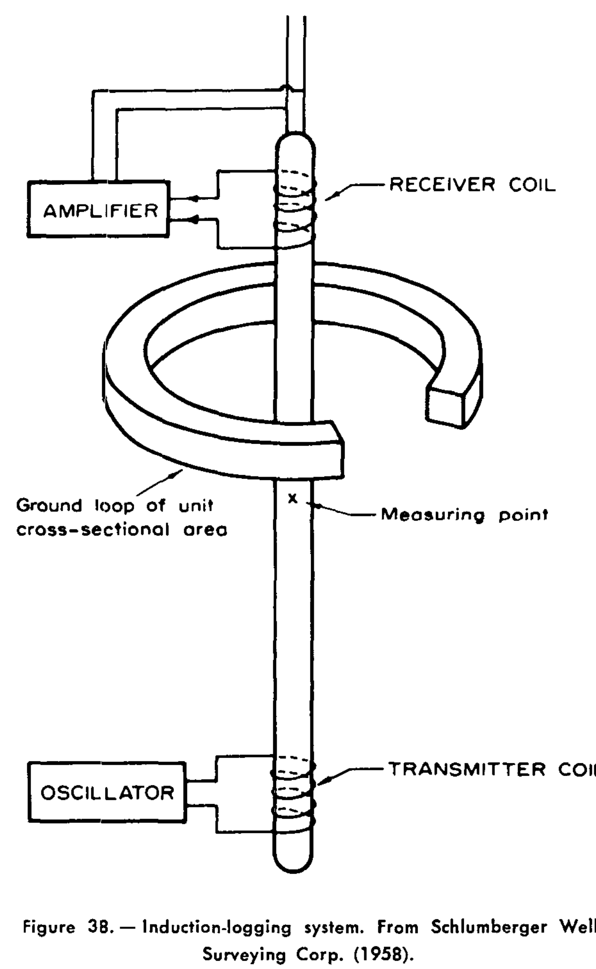


Figure 38. — Induction-logging system. From Schlumberger Well Surveying Corp. (1958).

ground currents, a curve proportional to formation conductivity is developed. Because resistivity is the reciprocal of conductivity, it is customary to electronically invert the conductivity log and display both resistivity and conductivity curves. In actual logging practice, focusing coils are also incorporated in the sonde to eliminate or minimize effects of variations in hole diameter, adjacent beds, and borehole-fluid invasion.

For many situations, in oil-base mud, fresh mud, and in empty holes (air or gas filled), the induction log virtually measures true formation resistivity.

The unit of electrical conductivity is called the "mho/meter." Conductivity equals 1/resistivity, and it would seem logical to use 1/ohm-meter (mho/meter) as the scale for induction logging. As this would result in a scale of fractions for all resistivity values greater than 1 ohm-meter, the induction-log scale is commonly calibrated in one-thousandth of a mho, or millimhos/meter. Using this scale, formation resistivities of 10, 100, and 1,000 ohm-meters would have conductivities of 100, 10, and 1 millimhos/m, respectively. The conductivity curve is displayed on the log, with zero on the right, which corresponds to an infinite resistivity. As conductivity increases, the curve trace moves to the left. In terms of resistivity, the curve is nonlinear, with the low resistivities emphasized and the high resistivities attenuated.

Figure 39, part of the log of a test hole in northwestern Colorado, shows the conductivity and resistivity curves for the 6FF40 induction device, as well as the 16-inch normal and SP curves. The conversion from conductivity to resistivity can best be illustrated by an example. The conductive peak at 2,850 feet reads 175 millimhos/meter from the right-hand curve of figure 39. Using the relationship millimhos/meter = 1,000/ohm-meters, we insert our value to get 175 =1,000/ohm-meters. Solving for ohm-meters gives 1,000/175 = 5.7 ohm-meters. Reading the electrically reciprocated curve (the dashed line in the center track of the log) at 2,850 feet gives a resistivity value of about 6 ohm-meters.

Because low-conductivity formations are inefficient electrical transformers, the induction log is insensitive to large changes in resistivity in a high-resistivity environment. The difference between 400 and 500 ohm-meters probably cannot be detected, and, therefore, the induction log should only be used where true resistivities are less than 100 ohm-meters or, better still, less than 50 ohm-meters.

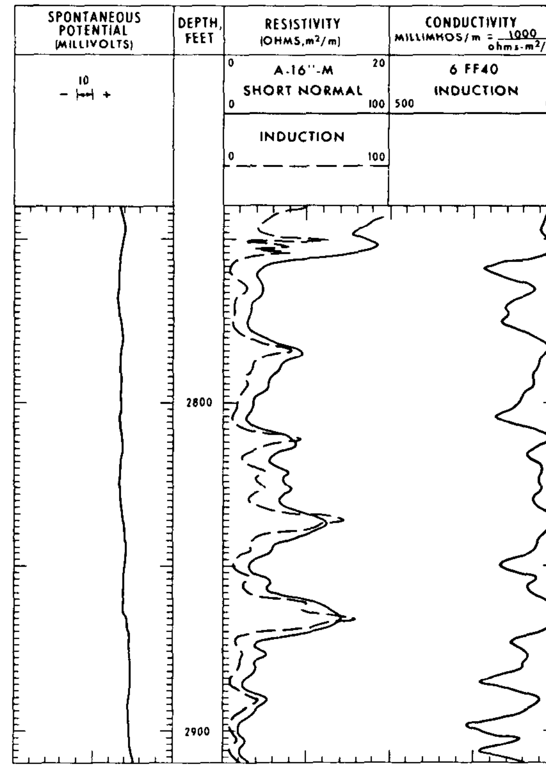


Figure 39. — Induction-electric log of a test hole in northwestern Colorado.

Instrumentation

Induction logs are customarily run by the logging service companies in the second and third recorder tracks, along with the 16-inch normal or a laterolog (Tixier and others, 1963). The induction log is displayed as resistivity, in ohm-meters, in the normal channel, and as conductivity, in millimhos/meters, in the third track. Ordinarily, SP or natural gamma, or both, are logged simultaneously in the first recorder track. Multiple-conductor logging cable plus both downhole and uphole electronics are necessary for induction logging.

Calibration and standardization

The zero conductivity in the third recorder track is determined by suspending the induction sonde in air above the ground and away from all conductors. If the receiving coil picks up no signal, the zero-conductivity point is established on the chart; however, in areas of high humidity, this procedure may not result in an accurate zero. The resulting error of a few millimhos in zero conductivity is not too critical in petroleum logging but can be very serious in fresh-water zones. Resistivity points are determined by suspending a copper hoop of known dimensions around the sonde (still in free air) and by adjusting the log display to agree with this known resistivity.

Radius of investigation

The radius of investigation of the induction log is a function of coil spacing. In the 5FF40 (service company nomenclature) sonde, the main coils are 40 inches apart, and the volume of investigation is a cylinder, 40 inches in diameter, surrounding the well bore. In the 6FF40 sonde, the main coils are also 40 inches apart, but the volume of investigation is a cylinder whose diameter is 1½ times the spacing, or 60 inches. For the 6FF40 tool, the effect of material within about 30 inches (borehole plus some of the invaded zone) is minimal. For this reason, where invasion is shallow, the 6FF40 induction log virtually responds only to true formation resistivity. If invasion is very deep, one or two supplemental resistivity curves are needed to obtain true formation resistivity.

Extraneous effects

Modern induction logs are relatively unaffected by changes in hole diameter. Early tools were adversely affected, and the logs had to be corrected by special charts. High to medium resistivity muds or an empty hole are necessary if the induction log is to have satisfactory response. If very conductive muds are used, the response from the mud and invaded zone will be relatively large, and the induction reading departs from true resistivity. Actually, it is the ratio of mud resistivity to formation-water resistivity that determines the applicability of induction tools. For example, assume we are logging a porous sandstone more than 10 feet thick. If the value of R_w does not exceed about 3 to 5 times R_m, the departure of apparent resistivity from true resistivity will be small for the induction tool. These are the conditions that generally occur in permeable formations containing petroleum. In fresh-water formations, however, the value of R_w may often exceed 5 R_m, and the departure of R_a and R_t becomes excessive. For this reason, the induction tool is generally not suitable for logging fresh-water aquifers.

Vertical resolution of the induction tool is adversely affected primarily when the bed being logged is less than about 6 feet thick and is several times as resistive as the adjacent beds. The induction-log response is susceptible to hole eccentricity, and for this reason, the sonde should be positioned in the borehole by centralizers.

In order to determine the depth of invasion, the resistivity of the invaded zone, and the true formation resistivity, a resistivity curve (such as a long normal) would be needed in addition to the short normal and the induction log. Commonly, the service companies run what is known as the "dual-induction logs." These consist of the 5FF40 and the 6FF40 induction logs plus either a 16-inch normal or a short laterolog. The use of cross-plot charts is required to solve for the correct values of resistivity and depth of invasion.

Nuclear Logging

Nuclear or radiation logs are all related to the measurement of fundamental particles or radiations from the nucleus of an atom. The commonly used nuclear logs are natural gamma, gamma-gamma, and neutron. Nuclear logs have a fundamental advantage over most other logs—they may be made in either cased or open holes that are filled with any type of fluid.

Fundamentals of nuclear geophysics

An understanding of some of the basic principles of nuclear geophysics is a prerequisite to the proper use of all types of radiation logs. Such basic information is not only a great aid to log interpretation but is necessary to appreciate the limitations and errors inherent in nuclear logs. A general lack of this knowledge is partly responsible for the limited use of nuclear logs in groundwater hydrology to date and for the misinterpretation of logs.

Characteristics of radiation

Basically, an atom consists of neutrons (n), with a mass of 1 and no charge; protons (p), with a mass of 1 and a positive charge; and orbital electrons (e^-), with a mass of 1/1,840 of a proton and a negative charge. The mass number, A, is the number of protons and neutrons in the nucleus, and the atomic number, Z, is the number of protons, ordinarily the same as the number of electrons. Isotopes are different states of an element, where A changes due to a change in the number of neutrons, but Z remains constant. For example, natural uranium consists of three isotopes with atomic weights of 234, 235, and 238. The term "nuclide" refers to each of the possible combinations of neutrons and protons.

Some isotopes are stable—that is, they do not change structure or energy. Unstable radioactive isotopes spontaneously change structure, emit radiation, and become different isotopes. Of almost 1,400 nuclides recognized, 1,130 are unstable, although only 65 occur naturally. Most radiation is emitted from the nucleus of an atom, but X-rays are derived from shell transitions by orbital electrons. The radiation emitted during radioactive decay consists of alpha particles, positive and negative beta particles, and gamma photons or rays. Of this group, only gamma rays are measured in well logging because of their unique ability to penetrate high-density materials. Neutrons produced by an artificial source are also used for well logging. They have the ability to penetrate dense material, but are slowed (thermalized) in hydrogenous materials.

Any of the processes involved in the transformation of unstable isotopes may leave the resultant nucleus with an excess of energy which may be emitted as high-energy electromagnetic radiation, called gamma rays or photons. Since gamma rays possess some characteristics of both particles and high-frequency waves, the term "photon" is also used to describe this bundle of energy. The energies of emitted gamma rays are characteristic of the nucleus and, therefore, of the isotope emitting them. It is this characteristic that is utilized in neutron-activation analysis and in natural-gamma spectrometry for the identification of elements. Energy of radiation is measured in electron volts (ev), thousands of electron volts (Kev), and millions of electron volts (Mev). The amplitude of the pulse emitted by a scintillation detector is a function of the energy of the impinging radiation. Radiation intensity is related to the number of pulses detected per unit time.

Radiation statistics

An important factor in the interpretation of all nuclear logs is the statistical nature of radioactive emission. Half life is the time required for one-half of the atoms in a group or source to decay to a lower state and varies from fractions of a second to millions of years. Although this time is known very accurately, it is impossible to predict how many atoms will decay or how many gamma photons will be emitted during a short period of time. Photon emission follows a Poisson distribution—that is, the standard deviation is equal to the square root of the number of disintegrations observed; therefore, experimental accuracy can be calculated. Time constant is the time, in seconds, over which radiation pulses are averaged, and is an important adjustment on all radiation-logging equipment. Pulse averaging is achieved by a capacitor (C) in series with a resistor (R). The time constant (tc) is equal to $R \times C$ and is defined as the time for the DC voltage, which drives the recorder pen, to rise to approximately 63 percent of the final value, or to fall to 37 percent of the initial value. From a practical standpoint, however, the

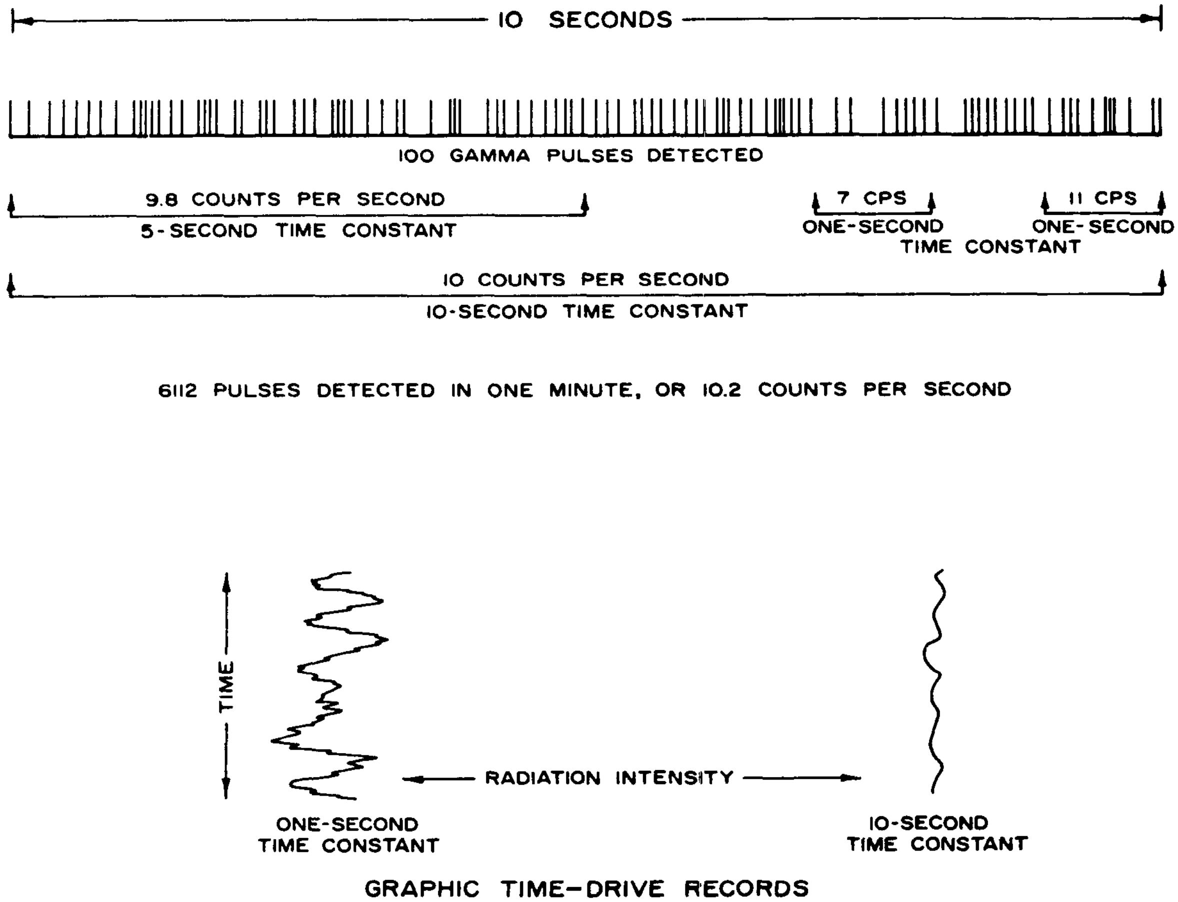


Figure 40. — Time constant and its effect on logging parameters.

time constant includes the averaging effects of the entire logging system—from pulse detection to pen travel. The upper part of figure 40 shows how the measured count rate can vary as the time constant is reduced from 10 seconds to 1 second. A larger time constant tends to reduce the magnitude of fluctuations on a log, as shown at the bottom of figure 40. However, if the time constant is too long with respect to the logging speed, the pen may not have time to record true radiation intensity before a rock unit with a different intensity enters the volume of investigation. Some random fluctuations are present on all radiation logs, and the logs will not repeat exactly. Repeat logging runs are a positive means of separating random changes from deflections related to lithology. The relationship of time constant and count rate to the standard deviation are well illustrated by the following computer analyses of Water Resources Division logs made by J. H. Dyck of the Saskatchewan Research Council (written commun., 1969). The figures, in order, are time constant and mean and standard deviation, in counts per second. Natural gamma log: 3 sec, 83.0±4.7 cps; 10 sec, 83.1±1.5 cps; and 20 sec, 83.0±0.8 cps. Neutron Log: 1 sec, 1818.7±33.1 cps; 3 sec, 1817.6±12.8 cps; and 10 sec, 1820.8±7.4 cps. Time constant of the system and detector efficiency vary among loggers, and, because the requirements for statistical accuracy and bed definition are not the same, rules for logging speed and time-constant settings cannot be given. Logging speed can be increased and (or) time constant can be decreased when a higher count rate is measured. The time constant and logging speed are usually determined as a result of experience with the equipment, on the basis of the amount of statistical fluctuation that can be tolerated and the thickness of the beds that are to be measured. For example, a logging speed of 60 feet per minute, using a time constant of 10 seconds, would mean that a nuclear log would theoretically record 63 percent of the correct value for a bed 10 feet thick. If a nuclear log is to be used quantitatively, these factors must be very carefully considered, so that log values will approach true values, and statistical errors will be minimized.

The following nuclear logging parameters are illustrated in figure 41: Logging direction and speed, time constant, and radiation intensity. The two neutron-gamma logs on the left in figure 41 were made with a 3-curie americium-beryllium (AmBe) source, and all other factors were constant while logs were made moving down and up the hole. The apparent differences between the logs are due to the random nature of radiation and, possibly, to a different probe position in the hole. The log on the right was made with a smaller plutonium-beryllium (PuBe) source, a longer time constant, and a higher sensitivity at the same logging speed. Fluctuations in signal were recorded on time drive at the bottom of the log. The rounded character of the deflections on the right-hand log was caused by an unsatisfactory ratio of time constant and logging speed. Lithologic contacts would be difficult to identify from this log. The logs on the left clearly distinguish thin beds that are not obvious on the right-hand log, and the bed contacts are more sharply defined. Although the lower emission of the PuBe source necessitated a longer time constant, a 10-second time constant was too long for the logging speed selected.

Radiation detection

In the past, geiger tubes have been used extensively for gamma logging, but in recent years they have been almost completely replaced by the more efficient scintillation crystal for both gamma and neutron detection at borehole temperatures below 150°F. The most commonly used phosphor—thallium-activated sodium iodide—emits flashes of light when exposed to nuclear radiation and is transparent to these flashes or scintillations. The sodium iodide or lithium iodide crystal is optically coupled to a photomultiplier tube, where a pulse of electrical current, amplified about 1 million times, is produced. This pulse is further amplified electronically in the probe, and then sent to the surface equipment. In the radiation-control module on a logger, the pulses are integrated over a preset time constant, and the DC-voltage output is used to drive the recorder. The sensitivity of a scintillation detector is mainly a function of crystal size and shape. More pulses are measured in a given radiation field if the crystal is larger.

An important feature of scintillation detectors is that the intensity of each flash of light in the detector is nearly proportional to the energy of the gamma photon that produced it. With the proper amplifying circuits, the height of each pulse sent up the cable is proportional to the energy of the detected radiation. This fact makes it possible to identify radiation according to its energy, by using scintillation equipment and a multichannel pulse-height analyzer. A single-channel analyzer, which discriminates against all pulses not within a preselected energy range, makes it possible to record a continuous log of a part of the energy spectrum, or to eliminate unwanted energy levels from a log.

Quantitative interpretation

Most laboratory measurements of nuclear radiation are made in terms of observed disintegrations, expressed in counts per second. Only a fraction of the total radioactive disintegrations per second from a source are observed, the size of the fraction depending on the efficiency of the detecting and counting system. The basic unit of radioactivity is the curie, which represents any source that is decaying at a rate of 3.7×10^{10} disintegrations per second. The roentgen is an exposure unit that is based on the ionizing effect of gamma or X-rays on the air through which they pass. A radiation detector in a given field of radiation will detect a percentage of the gamma-ray photons or particles present, depending on the geometric relation between the source and detector and on the

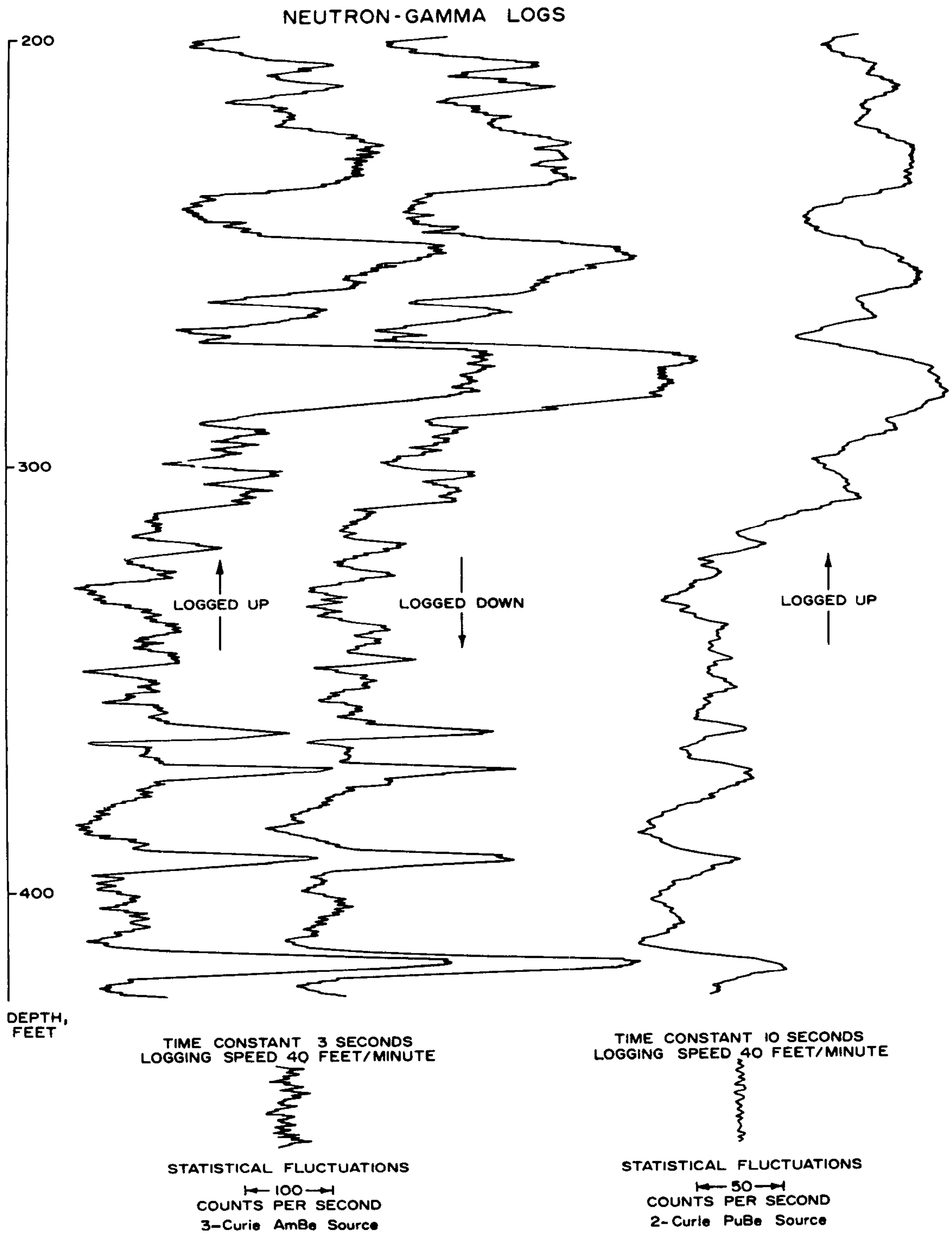


Figure 41. — Nuclear-logging parameters.

efficiency of the detector and associated electronics. Probably no two detecting systems will measure exactly the same number of pulses per unit time in the same field of radiation. However, they can be standardized to provide similar recorder deflections, whether the units are milliroentgens (1/1000 of a roentgen), percent porosity, bulk density, in grams per cubic centimeter (g/cc), or API gamma-ray units. Nuclear logs, recorded in counts per second, have the advantage that each pulse sent up the cable represents a detected neutron or gamma photon, and electronic counters and pulse generators reading directly in counts per second can be used for checking the linearity of response of the logging equipment and for correcting for dead time. Counts per second can then be converted to environmental units, such as porosity or bulk density, from calibration curves.

An important instrumental factor for which correction must be made on all nuclear logs is "dead time," or "resolving time." Coincidence error is caused by two pulses occurring in a time interval smaller than the resolving time of the equipment, so that only one pulse is recorded. This is the most significant cause of nonlinear response of radiation-logging systems at higher count rates. Count rates on logs may be corrected by means of a graph, a log overlay, or the formula: $N = n/(1-nt)$, where N is the corrected counting rate, n is the observed counting rate, and t is the dead time of the instrument, in seconds. The significance and calculation of dead time are described in detail in an article by Crew and Berkoff (1970).

Quantitative analysis of nuclear logs can be made only if the logging equipment is calibrated by using laboratory analyses of core samples from a logged hole or by using a model that is infinite with respect to probe response. Correction must also be made for the various borehole and instrumental effects present on all logs. Where nuclear logs are used for stratigraphic correlation, such corrections are not important. In quantitative applications of nuclear logs, calibration, standardization, and correction for extraneous effects are essential.

The radius of investigation, or volume of influence, is a concept essential to both interpretation and quantitative analysis of nuclear logs. The detector for natural-gamma logs and the source and detector for neutron and gamma-gamma logs are located within a roughly spherical shaped volume of material that is contributing to the radiation being recorded (fig. 42). The center of the volume of influence is at the detector for a natural-gamma sonde, and between the source and the detector for neutron and gamma-gamma logs. The volume of influence does not have sharp boundaries as illustrated; rather, there is a zone of maximum contribution to the total radiation measured and a gradual decrease in influence with distance away from the detector. The radius of investigation is here defined as including all the material that produces 90 percent of the signal recorded on the log. Inasmuch as the volume of influence extends for some distance above and below the detector, it follows that a rock layer begins to influence the log response before the detector enters the bed, and continues to influence response after the detector leaves the bed. Figure 42 shows that unless the bed fills the volume of influence, the neutron-log response will not reach a level representative of the lithology near the detector because part of the radiation recorded is due to the adjacent lithology. The true log response for a porosity of 1

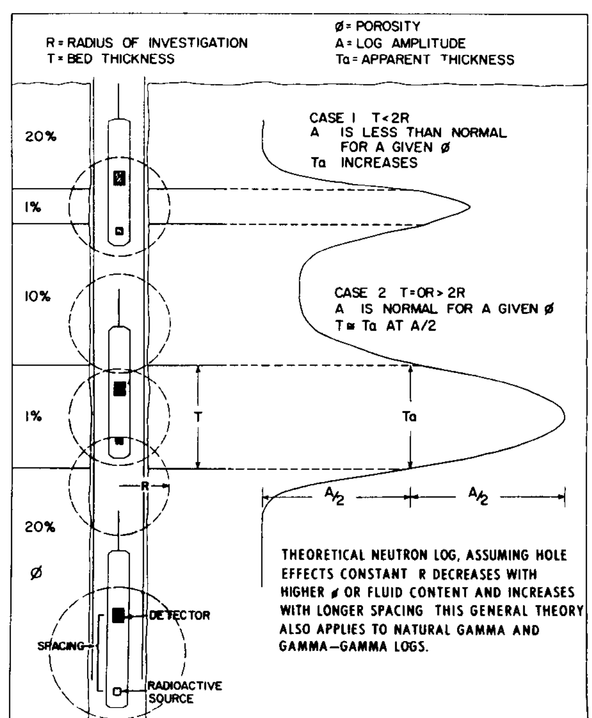


Figure 42. — Relationship of the radius of investigation and bed thickness to the quantitative interpretation of nuclear logs.

percent is only recorded for the thicker bed in figure 42. This same principle applies to natural-gamma logging or bulk density measured by gamma-gamma logging.

A widely used technique for the determination of bed thickness from nuclear logs is the measurement of thickness of the anomaly at one-half the maximum amplitude (fig. 42). Because the volume of influence is not filled by thin beds, their thicknesses measured from logs by this technique are generally too great.

An important concept in nuclear-log interpretation is emphasized here—that the area under the radiation curve is proportional to the product of the bed-thickness times, *Q* (quantity). *Q* is proportional to either the amount of radioisotopes present in natural-gamma logging or to the bulk density or porosity in gamma-gamma or neutron logging. At present, conventional quantitative-radiation log analysis utilizes only the relationship between maximum amplitude of the curve and the desired lithologic parameter.

The "area-under-the-curve" approach was described by Scott, Dodd, Droullard, and Mudra (1961). Their work dealt with the quantitative interpretation of natural-gamma logs in terms of grade and thickness of beds of uranium ore; however, the technique can and should be applied to the quantitative evaluation of other types of radiation logs.

As nuclear logs become more widely applied to ground-water investigations, the need for the standardization of log scales and for the calibration of equipment response will increase. It is hoped that a calibration facility for water-well loggers can be built; however, until such time, we recommend that the American Petroleum Institute neutron and gamma pits be used to facilitate comparison of water-well logs with commercial geophysical logs. These pits are located at the University of Houston, Tex., and rental is charged on a time-used basis. The neutron pit is constructed of limestone blocks of three different porosities and is only valid for limestone porosity (Belknap and others, 1959). The API gamma pit is constructed of an artificial mixture of uranium, thorium, and potassium; hence, differences in the energy response of logging equipment will hinder the quantitative comparison of logs made in any other mixture of radioisotopes. Until calibration models simulating other hydrogeological environments are available, core analyses must be used as a basis for the quantitative interpretation of nuclear logs. Field standards are also necessary to determine whether response changes with time or temperature and standards should be related quantitatively to response in calibration models.

Natural-gamma logging

Natural-gamma logs are records of the amount of natural-gamma radiation that is emitted by all rocks. The chief use of natural-gamma logs is for the identification of lithology and stratigraphic correlation in open or cased, liquid- or air-filled holes.

Principles and applications

The gamma-emitting radioisotopes normally found in rocks are potassium-40 and daughter products of the uranium- and thorium-decay series. The natural-gamma log run by most equipment does not employ energy discrimination to distinguish the various radioisotopes, and only gross gamma activity above a detection threshold is recorded. Gamma spectrometry is described on page 67. Some of the important characteristics of the three most important naturally occurring radioactive materials (Belknap and others, 1959) are as follows:

	Energy of characteristic peaks (Mev)	Number of photons per second per gram of element	Average content in 200 shale samples	Gamma intensity in shale samples (percent)
Potassium-40	1.46	3.4	2%	19
Uranium-238 series in equilibrium	1.76	2.8×10^4	6 ppm	47
Thorium-232 series in equilibrium	2.62	1.0×10^4	12 ppm	34

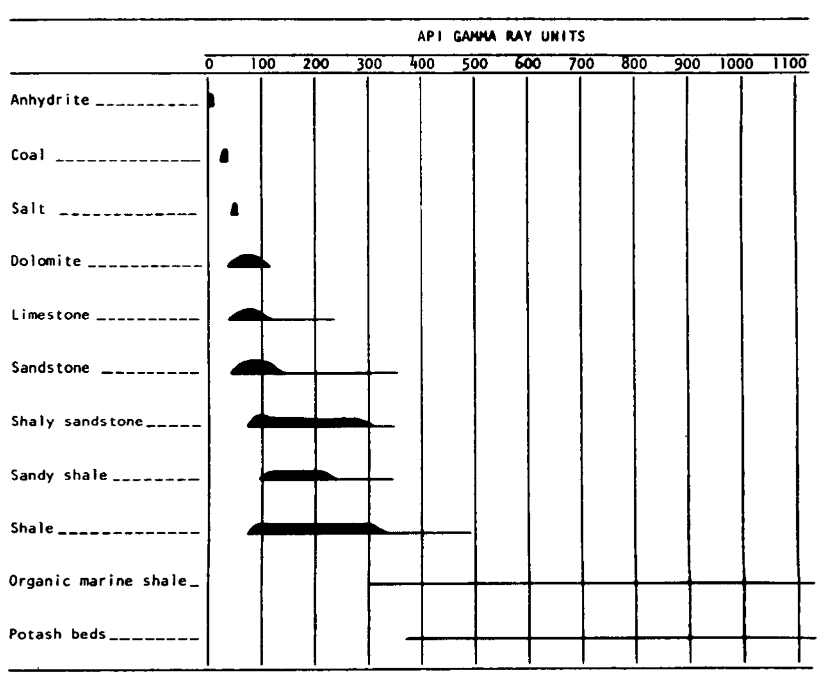
The actinium series is also present in rocks, but it starts with uranium-235, which has a concentration of only 1:139 parts of uranium-238 in natural uranium, and, therefore, its contribution to natural radiation is minuscule.

Even though the common gamma probe detects the several radioactive elements without distinguishing them, it does provide diagnostic lithologic information. Potassium, which contains about 0.012-percent potassium-40, is abundant in feldspars and micas, which decompose readily to clay. Clays also concentrate the heavy radioelements through the processes of ion-exchange and adsorption. In general, the natural gamma activity of clay-bearing sediments is much higher than that of quartz sands and carbonates. Russell and Steinhoff (1961) showed that inclusions of volcanic material can increase the radioactivity of sandstones and that some bentonite beds may be more radioactive than shales. Table 4, from Wood (1966), shows the relative gamma intensities of some sedimentary rocks.

From the range of gamma intensities shown in table 4, it can be seen that the interpretation of gamma logs depends to a large degree on experience in a restricted geologic environment. Probably the most important application in ground-water hydrology is in identification of clay- or shale-bearing sediments. Clay tends to reduce the effective porosity and permeability of aquifers, and the gamma log can be used to empirically determine the shale or clay content in some sediments. Figure 5 demonstrates how this relationship can be utilized. The neutron log and core analyses of this hole show a significant increase in average total porosity below a depth of 300 feet. The gamma log indicates that this zone has a higher percentage of clay and, therefore, does not have a higher effective porosity and permeability than the rocks above 300 feet. Laboratory analyses of particle-size distribution gave an average of less than 10 percent of clay-size particles (<0.004 mm) above 300 feet. Below 300 feet, the average content of clay-size particles is greater than 20 percent, and two samples exceeded 50 percent.

Rabe (1957) demonstrated an empirical relationship between natural-gamma radiation and permeability for clay-bonded sands

Table 4. — Range of radioactivity of selected sedimentary rocks



of the Denver–Julesburg basin. Rapolova (1961) reported his studies in Russia that indicated a relationship between the "specific yield" [permeability] of granular aquifers and the natural-gamma intensity from logs. Gaur and Singh (1965) showed a relation between the area under gamma curves and permeability from hydraulic tests. The data were for an Oligocene sand in India that contained an average of 26 percent of calcareous material, in addition to interstitial clay.

In summary, the natural-gamma log does not have a unique response to lithology. The response is generally consistent within a single geohydrologic environment. To date (1971), the widest use of gamma logs is for the identification of lithology, chiefly in detrital sediments, where the fine-grained units have the highest gamma intensity.

Instrumentation

Most of the newer equipment utilized for gamma logging of water wells employs thallium-activated sodium iodide crystals to detect gamma radiation. Older equipment and most oil-well sondes required to log in borehole temperatures greater than 150°F use gas-filled Geiger-Mueller (G–M) tubes as detectors. G–M tubes are considerably less efficient radiation detectors than scintillation phosphors and do not emit pulses with amplitudes related to the energy of the impinging radiation. Basically, the electronics in gamma probes consist of a high-voltage supply and pulse-amplification and shaping circuits. Power to operate the probes is either supplied by batteries in the sonde or transmitted from the surface. Four important controls at the surface affect the gamma log, and the settings of these controls should be recorded on every log—the time constant or pulse-averaging time, logging speed, recorder sensitivity or span, and zero positioning or basing. For natural-gamma logs, zero radiation is generally placed at the left margin of the paper. Changes in energy discrimination and high-voltage supply should not be necessary on routine logs.

Calibration and standardization

Most of the scale settings recorded on natural-gamma logs of water wells are meaningless. Furthermore, an unpublished study by Carl Bunker of the U.S. Geological Survey (written commun., 1960) indicated that no quantitative correlation between gamma logs made by various commercial service companies prior to 1960 can be accomplished with validity. Even though the API gamma pit (Belknap and others, 1959) has some shortcomings, the API gamma-ray unit is now being used by all the large service companies, and it does offer a semiquantitative means of relating gamma-log response. The only other pits available for calibration of gamma probes are maintained by the U.S. Atomic Energy Commission, and they relate gamma response to radiometric equivalent-uranium oxide (U_3O_8). In the past, the following units have been used on gamma logs: "Inches of deflection," "Standard units," counts per minute, counts per second, microroentgens per hour, milliroentgens per hour, and micrograms of equivalent-radium per ton. So long as the energy-dependence factor is recognized, the API gamma-ray unit is certainly an improvement over the multiplicity of terms used in the past. The following relationship of gamma units used by various logging service companies should only be used for the semiquantitative comparison of logs (Desbrandes, 1968).

Service Company	Units	Detector	API units
Schlumberger	1 microgram radium-equivalent/ton.		16.5 (11.7, GNT–J sonde).
Lane Wells (now Dresser Atlas)	1 unit of radiation	Scintillator	2.16
PGAC (now Dresser Atlas)	1 microroentgen/hour	Scintillator	15.0
McCullough	1 microroentgen/hour		10.4

Counts per second is the unit used for most laboratory radiation equipment, and it is recommended for logger scales because of the ease with which the equipment can be standardized and checked with pulse generators and nuclear counters. Counts per second do not have any meaning with respect to the intensity of a field of gamma radiation, except for a given measuring system. For this reason, counts per second should be related to API gamma-ray units and also to a field standard in which the response of the logging equipment is checked periodically. A small gamma source may be used as a field standard if it is always placed in the same position relative to the detector, and if background radiation is constant or only a small percentage of the total radiation. Two gamma field standards were built for the Water Resources Division logging equipment which utilize two grades of uranium ore in the annulus between telescoped aluminum pipes. The ore was sieved and mixed with cement until it was completely homogeneous; after the mix had solidified, covers were welded on to prevent the escape of radon, which would cause disequilibrium. Gamma probes are placed in the sleeves for field standardization. Standards of this type show no significant change with time, and they reduce background effects to a minimum.

Radius of investigation

The radius of investigation of a gamma probe is a function of downhole instrumentation, borehole fluid, borehole diameter, size of casing, density of the rock, and photon energy. Although the volume of the hole and the rock sampled by any radiation probe may be visualized as roughly spherical, note that a unit volume of material close to the detector will exert a much greater influence on the radiation intensity recorded than will the same unit of material farther away. Depending on the bulk density of the rock, 90 percent of the gamma photons detected probably originate within 6–12 inches of the borehole wall. Figure 42 illustrates how a radioactive bed is detected before the detector enters the bed. Beds with a thickness of less than twice the radius of investigation will not be recorded at full amplitude because the volume of influence is never completely filled by the bed.

Extraneous effects

The recorded natural-gamma intensity is decreased by any change in borehole conditions that either increases the distance traveled by gamma photons or increases the electron density of the material through which they must move. In general, however, these effects are much less than those caused by similar changes in borehole conditions on other types of nuclear logs. Shifts on gamma logs may be caused by changes in borehole media (air, water, mud), casing, hole diameter, gravel pack, grout behind the casing, or well development and are not necessarily related to changes in rock type. Increases in natural-gamma intensity with time were found in wells that produce large quantities of salt water (Campbell, 1951). Anomalies of this type may be due to the transportation and precipitation of uranium or potassium.

Gamma spectrometry

Gamma spectrometry is a means of studying the energy distribution of gamma photons and provides information that is not available on the natural-gamma log. Both natural and artificial radioisotopes emit radiation with energies characteristic of the isotope. When dealing with the identification and quantitative analysis of potassium, uranium, and thorium, one must recognize that each of these constitutes a radioactive-decay series. Isotopes in these series decay to the next nuclide by emission of alpha or beta particles and a loss of mass. Some of these nuclides or daughters also emit gamma radiation. The following are simplified decay schemes for the common natural radioisotopes with the source and energy of important gamma radiation indicated:

Potassium-40 γ1.46 Mev $\rightarrow$ Argon-40 (or calcium-40).

Uranium-238 → thorium-234 → proctactinium-234 → uranium-234 → thorium-230 → radium-226 → radon-222 → polonium-218 → lead-214 (or astatine-218) → bismuth-214 (0.6, 1.12, 1.76, and 2.20 Mev) → polonium-214 (or to thallium-210) → lead-210 → bismuth-210 → polonium-210 → lead-206 (stable).

Thorium-232 → radium-228 → actinium-228 (0.9 and 1.6 Mev) → thorium-228 → radium-224 → radon-220 → polonium-216 → lead-212 → bismuth-212 → polonium-212 (or thallium-208 2.62 Mev) → lead-208 (stable).

Each of these nuclides should be present in an equilibrium amount which depends on half life. Changes in this quantity, which may be caused by selective chemical removal from the system, produce disequilibrium. Gamma measurements of certain isotopes in a decay series not present in equilibrium amounts will give incorrect quantitative analyses for other isotopes in the series. The state of equilibrium in the radioactive-decay series is a potential source of information on water chemistry and movement in a ground-water system. Research underway suggests that disequilibrium in uranium can be detected by logging, but it is not known whether detection is possible in rocks having a low uranium content. However, potassium, uranium, and thorium, as well as gamma-emitting radioisotopes in industrial wastes can be identified with logging equipment. Spectral equipment to make this possible can be added to most water-well loggers.

The limitations and difficulties in utilizing inhole gamma spectrometry for quantitative analysis are numerous. Although the gamma photons from potassium-40 are essentially monoenergetic, approximately 80 gamma-energy peaks have been found in the uranium series and 60 were found in the thorium series (Belknap and others, 1959). Degradation of photon energy by Compton processes is one of the most serious limitations in gamma spectrometry. (See p. 70.) For this reason, the low-energy spectrum probably will not be informative. Rhodes and Mott (1966) presented calculated departure curves for correction of spectral-gamma logs due to: The position of the detector in the borehole, the diameter of the hole and the density of the fluid, the thickness of the casing and cement, and the thickness of the formation.

Figure 43 shows energy peaks for naturally occurring potassium and daughter products of uranium and thorium as they might appear on the oscilloscope of a multichannel-spectrum analyzer. The abscissa represents energy, increasing to the right, and the ordinate is the number of counts, or photons, detected. Counts are accumulated in channels on the abscissa that are subdivisions of the energy range selected. Spectra of this type must be accumulated over a period of time. The length of time for accumulation depends on the gamma intensity. To obtain inhole spectra, a linear-amplifier system for transmitting variable height pulses up the logging cable must be used.

To make continuous logs or stationary measurements that provide spectral data, a single-channel analyzer with a variable threshold or "window" adjustment is required. This means that the energy range of pulses to be recorded per unit time on a log can be selected. Figure 44 shows three selected thresholds to distinguish between the

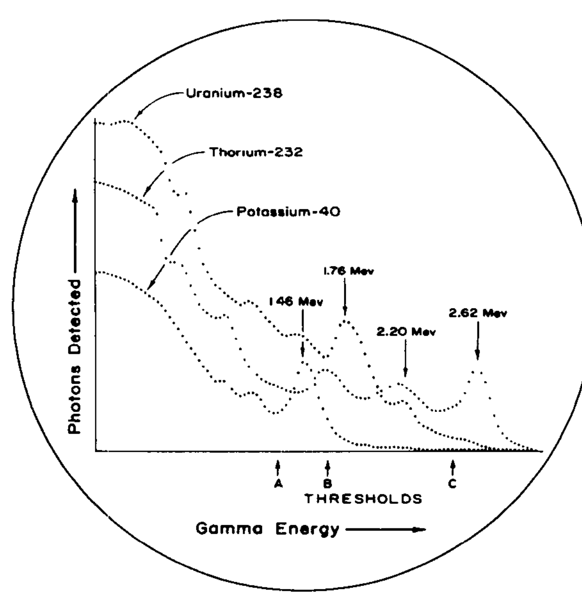


Figure 43. — Gamma spectra — potassium, uranium, and thorium.

uranium, thorium, and potassium peaks. Recording all pulses in the energy "window" between thresholds *A* and *B* should give a value that is related to the potassium-40 content, if the uranium and thorium contributions are subtracted. The gamma activity between *B* and *C* should indicate the uranium content, if the thorium contribution is removed, and the count rate above *C* is related to the thorium content. Figure 43 shows how the variable height pulses, representing the various energies of detected gamma photons, appear on the oscilloscope in relation to the thresholds selected. Continuous gamma logs can be made from the number of pulses that occur in each of these "windows," but, of course, the count rate will be relatively low unless very large crystals are used.

The applications of inhole gamma spectrometry are several. The relative distribution of potassium, uranium, and thorium can be determined by running successive logs, using different "window" settings. Diagnostic ratios of natural radioisotopes can be a significant aid to stratigraphic correlation and to the identification of lithology. Using inhole spectrometry, Brannon and Osaba (1956) found that a limestone in west Texas had a lower concentration of potassium relative to uranium and thorium than the shales tested. In the Ogallala Formation of west Texas, the zones containing more than 35-percent calcium carbonate were found to have a much higher radium-potassium ratio than did the sands and clays having a lower carbonate content (Keys and Brown, 1971). Analyses of radioactive elements in ocean-bottom marine sediments indicated that concentrations of thorium and radium steadily increase through silts to clay oozes, but the uranium content remains constant and is apparently unrelated to grain size (Baranov and Kristianova, 1966). These investigators also found that red ocean clays contain the highest concentrations of radioisotopes, and that both thorium-230 and, less distinctly, thorium-232 increase from the ocean margins toward the open ocean. The possible relation of certain radioisotopes to grain-size distribution and depositional environment would, of course, be extremely useful in identifying aquifers. The suggestion that zircon can be used as a tracer in sedimentary petrology was made as a result of a study of a Triassic sandstone in England that contained two types of zircons with widely different radioactivity (Rankama, 1963).

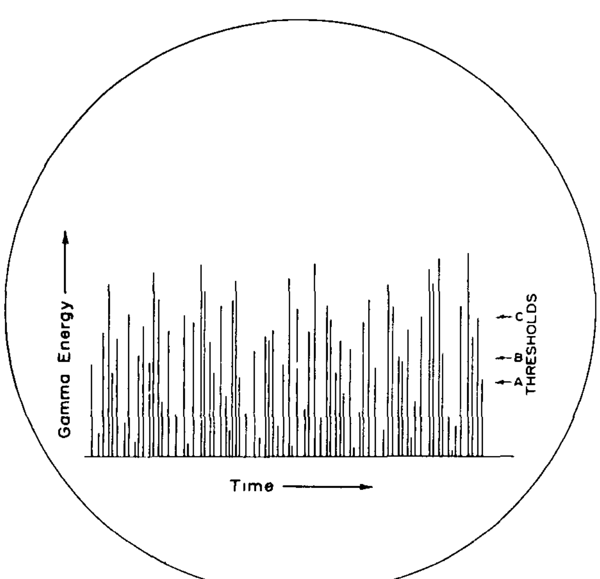


Figure 44. — Pulse-energy discrimination.

Gamma spectrometry has been found to be an accurate method of analyzing samples for potassium content (Bunker and Bush, 1967), based on the fact that potassium-40 makes up about 0.012 percent of all potassium. It is not known whether accurate inhole quantitative analysis of potassium can be made because of borehole effects and scattering and attenuation within the rock; however, accurate uranium analysis is possible with gamma logs if the content is high enough. Clay minerals are selectively efficient in fixing potassium, and potassium is a major constituent of such clay minerals as illite and of feldspars and micas. The mineralogical source and isotopes causing radioactivity in sediments are not well known. Their distribution in igneous rocks has been more widely studied. Such accessory minerals as zircon, biotite, sphene, and apatite contain most of the uranium and thorium, and the content generally increases from basic to granitic rocks. Gamma spectrometry in wells has been successfully used to identify artificial radioisotopes in liquid wastes. Gamma spectrometry also has considerable application in neutron-activation logging. (See section on "Neutron Logging.")

Gamma-gamma logging

Gamma-gamma logs are records of the intensity of gamma radiation from a source in the probe after it is backscattered and attenuated within the borehole and surrounding rocks. The main uses of gamma-gamma logs are for identification of lithology and the measurement of the bulk density and porosity of rocks. These logs may also be used for locating cavities and cement outside the casing of a well.

Principles and applications

The gamma-gamma probe contains a source of gamma photons, generally cobalt-60 or cesium-137, shielded from a sodium iodide detector by Mallory-1,000 metal or lead spacers (fig. 45). Gamma photons from the source penetrate and are scattered and absorbed by the fluid, casing, and formation surrounding the probe. Gamma radiation is absorbed and (or) scattered by all material through which it travels. Degradation of photon energy takes place by three main processes: (1) The Compton scattering, in which a gamma photon loses part of its energy to an orbital electron, is proportional to the number of electrons (Z) and occurs with gamma photons from 0.1 to 1 Mev. (2) The photoelectric effect, in which an ejected orbital electron completely absorbs the photon energy, is proportional to Z^6 and occurs with photons of 0.1 Mev or less. (3) Pair production, which occurs as the photon approaches the nucleus and completely converts itself into a pair of electrons, is proportional to Z^2 and requires gamma energy greater than 1.02 Mev. Compton scattering is probably the most significant process taking place in gamma-gamma logging. Some photoelectric absorption also takes place because of degradation of photon energy by scattering, but the effect on a log may be reduced by energy discrimination. In the Compton range, the gamma radiation absorbed is proportional to the electron density of the material penetrated, but it is affected by the chemical nature of the medium. Electron density is approximately proportional to the bulk density of most materials penetrated in logging; however, for salt and gypsum, a Z/A correction should be made (Tittman and Wahl, 1965). A Z/A correction should be made for any material that does not have the same ratio of atomic number to atomic mass as the calibration environment. After correction, the count rate recorded on a gamma-gamma log is inversely proportional to the bulk density. The gamma-gamma log has also been called the density log; however, this implies a quantitative interpretation and correction for all interfering factors.

Gamma-gamma density is widely used in the petroleum industry for the determination of total porosity by application of the following equation:

$$\text{Porosity} = \frac{\text{Grain density} - \text{Bulk density (from log)}}{\text{Grain density} - \text{Fluid density}}.$$

Grain density can be derived from laboratory analyses of cores or cuttings, or, for quartz sandstone, a value of 2.65 g/cc is used. The fluid density in most water wells may be assumed to be 1 g/cc, or, if the fluid is highly saline, laboratory measurement of density may be necessary. If the same lithologic unit is present below and above the water table, or if gamma-gamma measurements can be made after drawdown, it should be possible to derive specific yield from gamma-gamma logs (Davis, 1967). Specific yield should be proportional to the difference between the bulk density of saturated and drained sediments, if the porosity and grain density are not changed.

Bulk density may be read directly from a calibrated and corrected log or derived from a chart providing correction factors. Errors in bulk density obtained by gamma-gamma methods are on the order of ± 0.03–0.04 g/cc. Errors in porosity calculated from log bulk densities depend on the accuracy of grain and fluid densities used. For certain source to detector spacings and over a limited

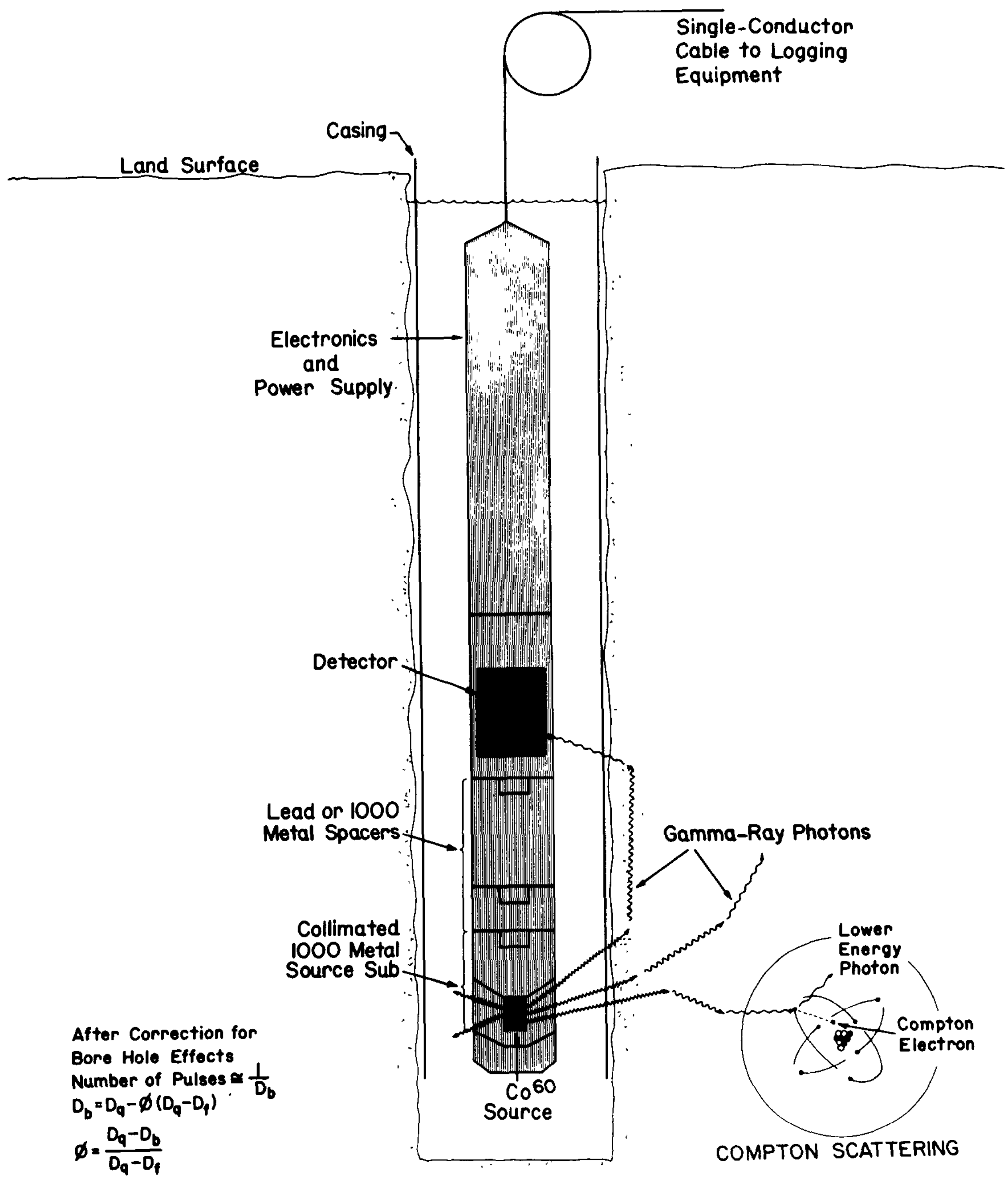


Figure 45. — The equipment, principles, and interpretation of gamma-gamma logs.

density range, a linear relationship is obtained when bulk density is plotted against the logarithm of count rate. Most commercial gamma-gamma logs are reversed, so that radiation increases to the left, rather than to the right as on natural-gamma and neutron logs. The purpose of this reversal was to make porosity increase to the left, as on long-spaced neutron logs. Confusion can be eliminated by remembering that radiation recorded on a gamma-gamma log increases with increasing porosity.

In addition to determining porosity, the gamma-gamma log may be used to locate

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casing or collars or the position of grout outside the casing. Figure 46 shows the use of the gamma-gamma log to locate the position of cement or grout behind the casing. The gamma-gamma log made prior to cementing indicated the sediment beds, between depths of 350 and 450 feet, which are also shown on the caliper and gamma logs. These beds were not detected by the postcement gamma-gamma log shown on the figure because of shielding by the cement-filled annulus. The gamma-gamma log can also be used to identify hole enlargements through casing as shown in figure 46. The water level and significant changes in fluid density will also be apparent on gamma-gamma logs.

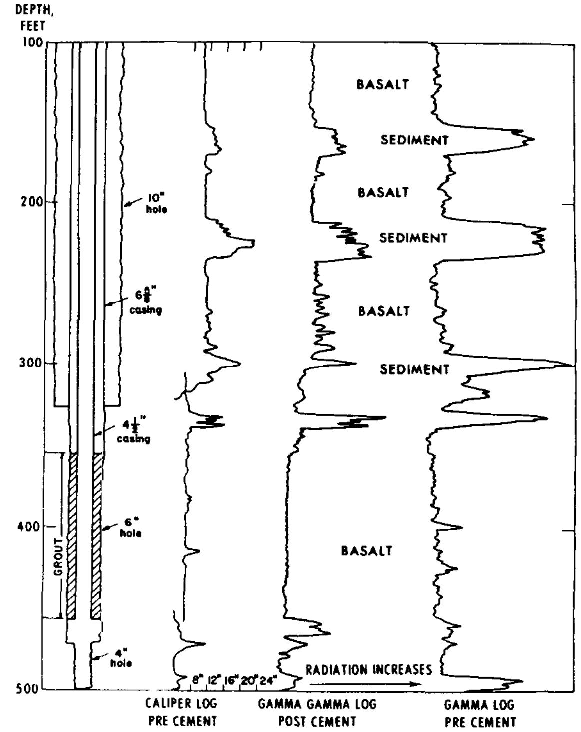

Figure 46. — Gamma-gamma logs, used to interpret position of grout behind casing, and caliper logs, used to select depth for grouting and to estimate volume required.

Instrumentation

Qualitative gamma-gamma logging can be done most economically with a gamma source, such as cesium-137 or cobalt-60, attached to a conventional natural-gamma sonde by heavy-metal spacers. The relative percentage of gamma photons absorbed and scattered depends to a large degree upon the type and size of the source, spacing between the source and detector, and the hole diameter. The radius of investigation depends on these same factors in addition to the bulk density (fig. 45). In general, source strength and spacing must be increased to obtain proper logs in large-diameter holes, except when a decentralized tool is used. Spacing that is too short may cause partially reversed log response because of increased backscattered effect, and will emphasize the hole-diameter changes. Cobalt-60 has a half life of 5.3 years, so that radioactivity decreases about 1 percent per month, and correction must be made for the quantitative interpretation of logs.

Both an axially symmetric and decentralized side-collimated tool are used in the Water Resources Division research-logging program. With the axially symmetric tool illustrated in figure 45, 5–50 millicuries of cobalt-60 is used, with spacings of 10–35 inches. These parameters depend on borehole conditions and rock density. This tool is not positioned in the hole, nor is it directionally collimated. The decentralized sonde employs two motor-driven arms to force the tool against the wall of the hole. Mallory-1,000 metal is used as a shield around the source and detector, so that most of the recorded radiation is from the part of the borehole wall in contact with the tool. The decentralized tool has the advantage of being much less affected by changes in drill-bit size, sonde position in the hole, or density of fluid in the hole. It is, however, still affected by any borehole rugosity between the source and detector. Some commercial logging sources employ two detectors at different distances from the source in order to compensate for mud-cake and borehole-diameter changes. However, this system does not completely eliminate the effect of borehole rugosity.

Calibration and standardization

Gamma-gamma logging equipment can be calibrated in the API limestone pits, but this does not provide correction for the significant borehole effects or Z/A effects. Until additional pits constructed of various earth materials are available, it is highly desirable that core samples of the various lithologic units penetrated be used for calibration of gamma-gamma logs that are to be interpreted quantitatively. Accurate measurements of grain density from samples are also needed if porosity calculations are to be made. Field standardization of logging equipment with blocks of various densities is desirable because this method accounts for changes in detector sensitivity, source decay, and spacing; however, such standards are heavy and, consequently, difficult to transport. The alternate solution is to use a radioactive source, such as the natural-gamma field standards, and to calculate radioactive decay and correct for spacing. With proper standardization, gamma-gamma logs can be related to calibration runs in either pits or cored holes.

Radius of investigation

The radius of investigation of gamma-gamma logging devices is reported to be about 6 inches, with 90 percent of the signal coming from the material within this volume. Note that the bulk density of the rock being logged and fluid or casing between the sonde and rock will affect the radius of investigation. Furthermore, the spacing between the source and detector will significantly alter the volume of material measured. It was found experimentally that effects caused by casing collars or the position of a second string of pipe on the outside can be emphasized by short spacing and can be reduced by longer spacing. In very high porosity rocks, such as tuffs, a very long spacing is necessary, and the radius of investigation probably exceeds 6 inches. In a recent Water Resources Division experiment, radiation from a cobalt-60 gamma source in a hole was measured in another hole through 4 feet of moist sand. A technique is now being employed to log the material between two holes by synchronously moving a source in one hole and a detector in the adjacent hole. This greatly increases the volume of material investigated and reduces borehole effects. Absolute values for bulk density cannot be obtained unless the distance between the holes is accurately known.

Extraneous effects

Because the gamma photon is affected to some degree by all media along its path from source to detector, changes in borehole parameters must be evaluated for quantitative-log interpretation. Factors which will cause a shift or anomaly on the gamma-gamma log are as follows: Water level, change in fluid density, mud cake, casing, collars, grout, and most important of all, hole diameter. A decrease in measured radiation generally occurs below the water table, and a smaller magnitude increase occurs in an open hole below the casing. Diameter effects are greater in air-filled holes than in fluid-filled holes. If washouts, or changes of hole diameter are probable, a caliper log should be run. If the hole is already cased, or if a caliper log cannot be run, zones of suspected enlargement should be omitted from quantitative evaluation. The decentralized sonde should nearly eliminate the effects of changes of bit size but not of borehole rugosity. Figure 60 shows axially symmetric gamma-gamma logs and caliper logs in adjacent holes on the upper Brazos River. The lithology is almost identical, so differences between the gamma-gamma logs are nearly all due to hole-diameter effects. Hole C–1 is a core hole where considerable circulation was maintained to increase core recovery; therefore, the walls are badly washed. Rotary hole T–14 was drilled rapidly to minimize washing effects.

Charts to correct for borehole conditions are available for commercial gamma-gamma logs, and the newer devices are said to provide a log that is electronically compensated for borehole parameters. Some of the more recent logs have a bulk-density scale, in grams per cubic centimeter, on the log. Probably none of these techniques can accurately compensate for borehole rugosity or thin washed-out zones between the source and detector. Figure 47 shows examples of gamma-gamma, neutron, and caliper logs made in the same hole by a commercial service company, *A*, and logs made with Water Resources Division equipment, *B*. The Water Resources Division gamma-gamma log was made with an axially symmetric tool, and

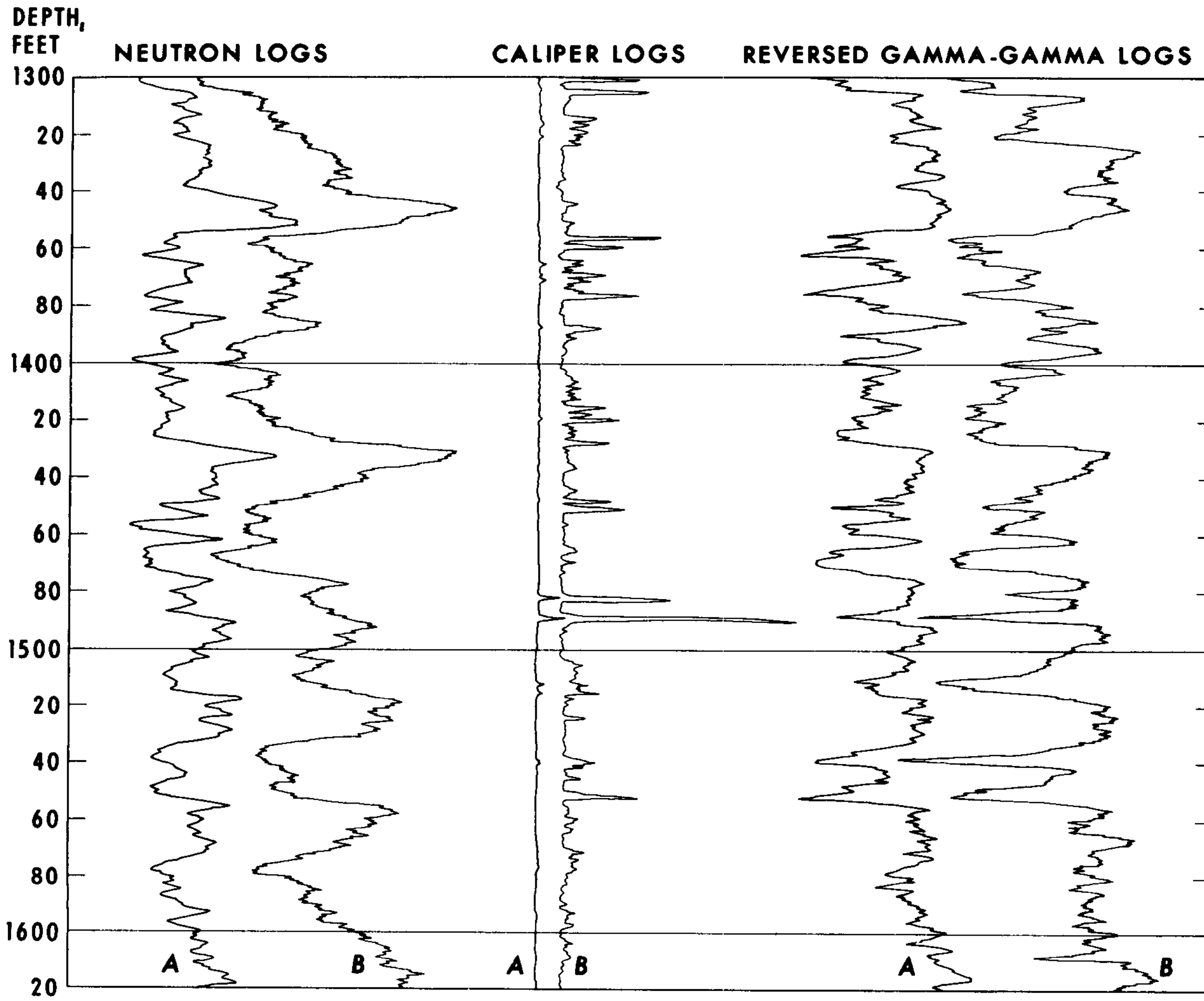

Figure 47. — Examples of logs made by (A) commercial oil-well logging equipment and by (B) small water-well logging equipment.

the service company log was made, using a decentralized side-collimated tool with the output corrected for borehole effects. Deflections caused by hole rugosity are apparent on both logs. Borehole corrections have removed some of the rugosity effects, as at 1,485 feet, but not others, as at 1,490 feet.

Neutron logging

A neutron source and a detector are arranged in a probe so that the output is primarily a function of the hydrogen content of the borehole environment. Neutron logs are used chiefly for the measurement of moisture content above the water table and of total porosity below the water table.

Principles and applications

The various types of neutron logs are potentially the most useful techniques in borehole geophysics, as applied to groundwater investigations, because most of the probe response is due to hydrogen and, therefore, also to water. Neutron logs also have advantages peculiar to other radiation logs; they can be used in liquid-filled or dry holes or in cased or open holes, and they have a relatively large volume of influence. The basic principles of deep well neutron-porosity logging and the conventional neutron-moisture logging are the same; however, the equipment and log interpretation differ. Most older neutron-moisture meters provide only point measurements instead of logs, although continuous moisture loggers are now available. The moisture probes utilize a much smaller source and a shorter source-to-detector spacing that causes the count rate to increase with a higher moisture content, rather than decrease as on a conventional neutron-porosity log. For accurate quantitative results, the moisture devices must be used in a small-diameter access tube that fits the probe tightly, in contrast to the conventional neutron-porosity logs, which can be made in large-diameter open or cased holes. Table 5 summarizes the characteristics of the two general types of neutron-logging systems.

Neutrons for most logs are derived from alpha particles impinging on beryllium. The alpha emitter is intimately mixed with beryllium inside a sealed source. The first Water Resources Division research on neutron-porosity logging was done with a leased 2-curie plutonium-239 beryllium source. A 3-curie americium-241 beryllium source, having an emission of 8.62×10^6 neutrons per second, has been found to give superior logs under most conditions and is now standard on many oil- and water-well loggers. Americium-241 has a half life of 458 years, so the decay-correction factor is small. These sources emit fast neutrons (greater than 10^5 ev or 0.1 Mev). Many of the older neutron-logging devices and most of the thermal-neutron moisture meters utilize radium-226 beryllium sources. The latter type of source has the disadvantage of strong gamma radiation that may produce gamma-gamma effects on log response under certain conditions. Most recently, a californium-252 source was used for experimental neutron logging and inhole neutron-activation analysis. The 50-millicurie californium source used emits 2.1×10^8 neutrons per second by spontaneous fission, which is sufficient to activate several isotopes in boreholes; however, its expected high cost and short half life will probably limit the use of this source to specialized applications.

In well logging, neutrons are artificially introduced into the rock-fluid system, and the effect of the environment on the neutrons is measured (fig. 48). The neutron has a relative mass of 1, and no electric charge; for this reason, the loss of energy when passing through matter is caused by elastic collision. Materials which slow down neutrons are called moderators, and the effectiveness of naturally occurring elements as moderators is the most important factor in neutron logging. Neutrons from the source pass through the walls of the source and source sub, fluid column, casing, and rock and are slowed down by collisions with atomic nuclei. The most effective element in moderating neutrons is hydrogen because the nucleus of a hydrogen atom has approximately the same mass as a neutron. Neutrons must be slowed to energies below 0.025 ev (thermalized) before they can be captured. The neutron may be visualized as a ping-pong ball rolling across a billiard table. It loses but little energy in striking a billiard ball, but will lose most of its energy in a direct collision with another ping-pong ball. It takes fewer collisions with

Table 5. — Comparison of neutron logging techniques

	Neutron "*moisture meter*" widely used for point measurements of moisture content.	Neutron "*porosity*" log available on all oil-well and some water-well loggers.
Source-to-detector spacing	Usually less than 5 inches.	Usually more than 15 inches.
Source size	Millicurie range.	Multicurie range.
Type of detector	Usually sensitive to thermal neutrons.	Sensitive to thermal or epithermal neutrons or gamma rays.
Usual application	Moisture measurement.	Saturated porosity and moisture measurements.
Limitations	Usually restricted to small-diameter holes above the water table or air-filled pipe below the water table.	Useful in large- or small-diameter holes above or below the water table.
Advantages	Lower cost and reduced radiation exposure to personnel.	Wider application; reduced borehole effects; lower statistical error.
Graphic readout-neutron intensity	Increases to right.	Increases to right.
Moisture content	Linear response — moisture increases to right.	Logarithmic response— moisture increases to left.
Saturated porosity	Linear response — porosity increases to right; water in hole causes significant error.	Logarithmic response— porosity increases to left.

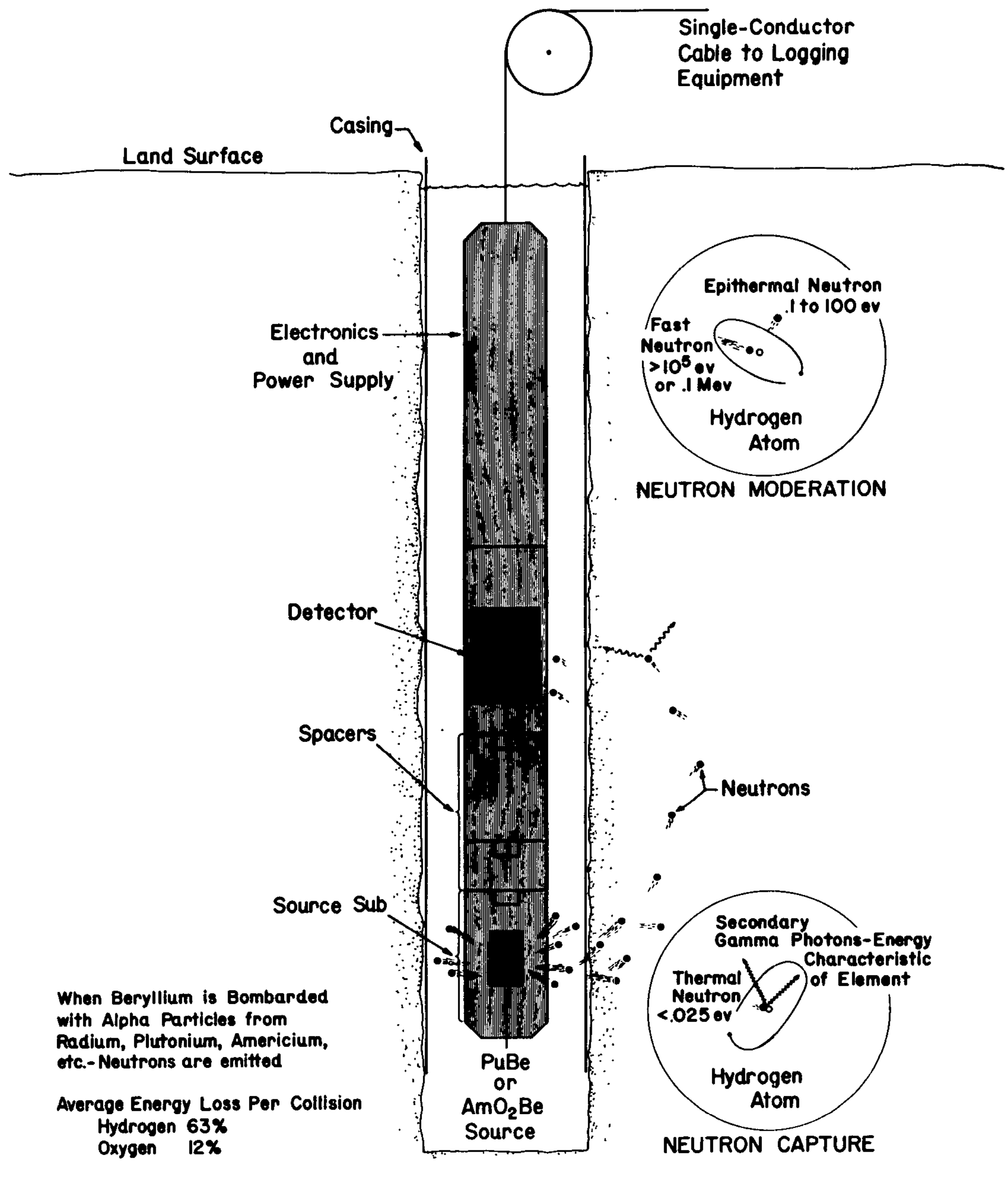

Figure 48. — The equipment, principles, and interpretation of neutron logs.

hydrogen nuclei to thermalize a neutron than with the nuclei of other elements. The average energy lost by a neutron in a collision with the nucleus of a hydrogen atom is 63 percent, as compared to 12 percent for a collision with the nucleus of an oxygen atom. In addition, hydrogen also has a higher neutron-scattering cross section than common elements found in sedimentary rocks. This means that there is a greater probability that a neutron will collide with a hydrogen atom. Cross section is the probability that a neutron reaction will occur. For these reasons the range of a neutron is largely a function of the hydrogen content of the material through which it passes.

Various types of neutron logs are made by counting the number of neutrons present at different energy levels or counting the gamma photons produced by neutron reactions. The type of radiation measured is a function of the type of source and detector, energy discrimination, shielding material, and spacing between the source and detector. However, most neutron logs are hybrids, and their names are derived from the type of radiation that causes most of the measured response. The term "neutron-gamma log" indicates that most of the radiation detected are gamma photons resulting from neutron reactions. The neutron–thermal–neutron probe responds chiefly to thermal neutrons, and the neutron–epithermal-neutron tool responds mostly to neutrons between 0.1 and 100 ev.

The gamma photons produced when neutrons interact with matter are classified as prompt, capture, or activation. Prompt gammas are derived from the inelastic scattering of fast neutrons by nuclei; capture gammas arise from decay or excited energy levels of a neutron; and activation-gamma photons result from the decay of an unstable nucleus caused by fast-neutron reactions or by the capture of thermal neutrons. Prompt and capture gammas occur only during and immediately after the neutron reaction that produced them. Activation gammas may be produced for a long period of time, dependent upon the half life of the unstable isotope that was created.

In a drill hole, the neutron source and detector may be visualized as a roughly spherical cloud of neutrons that decrease in energy and number from the source outward. The detector is located in the region of lower energy neutrons at a distance dependent on the spacing that is selected. With long spacing, in a medium with a high percentage of hydrogen, most neutrons will be thermalized and captured prior to reaching the detector; whereas in very low porosity material, the range of neutrons will be much greater and more will be counted. In a tool designed for moisture measurement, the detector, which is located near the source, measures the increase in thermalized neutrons that results from the increase in water content. Thus, the number of neutrons measured with a long-spaced probe decreases with increasing water content, and the number of neutrons measured with a short-spaced moisture probe increases with increasing water content. If the short-spaced probe is used below the water table, the access pipe should be sealed to exclude water.

In most rocks the hydrogen content is directly proportional to the interstitial-water content; however, hydrocarbons, chemically or physically bound water, and (or) any other hydrogenous materials can give anomalous values. For example, gypsum has a large percentage of water of crystallization which can be erroneously interpreted as material having a high porosity. In the upper Brazos River basin, Tex., it was found that this fact could be used to distinguish gypsum and anhydrite and, thus, locate the depth of hydration, which has a bearing on the hydrologic history of the area and the position of an interface between brine and fresh water. Gypsum and anhydrite both emit very low intensity natural-gamma radiation, but anhydrite gives a high neutron count rate, and gypsum gives a low neutron count rate. Figure 49 illustrates the combined use of natural-gamma and neutron logs for stratigraphic correlation and for distinguishing gypsum from anhydrite. In figure 49 the anhydrite bed shown at an elevation of 1,700 feet in hole T–14 may have been partly altered to gypsum in well T–21. The anhydrite bed registered a similarly low natural-gamma intensity in all four wells; however, the low-porosity deflection to the right on the neutron logs is somewhat reduced in well T–21.

Although a neutron log cannot be used for measuring porosity above the water table, it is very useful for measuring changes in the moisture content. Figure 50 shows how the perched source of contaminated water (which was ultimately reaching the water table) was located behind an 8-inch steel casing in a well at the National Reactor Testing Station in Idaho. The neutron log shows a gradual decrease in moisture downward through the clay "perching" bed, and the clay is clearly indicated as a deflection, to the right, on the natural-gamma log.

Meyer (1963), described how neutron-logging devices can also be used to determine the specific yield of unconfined aquifers. His

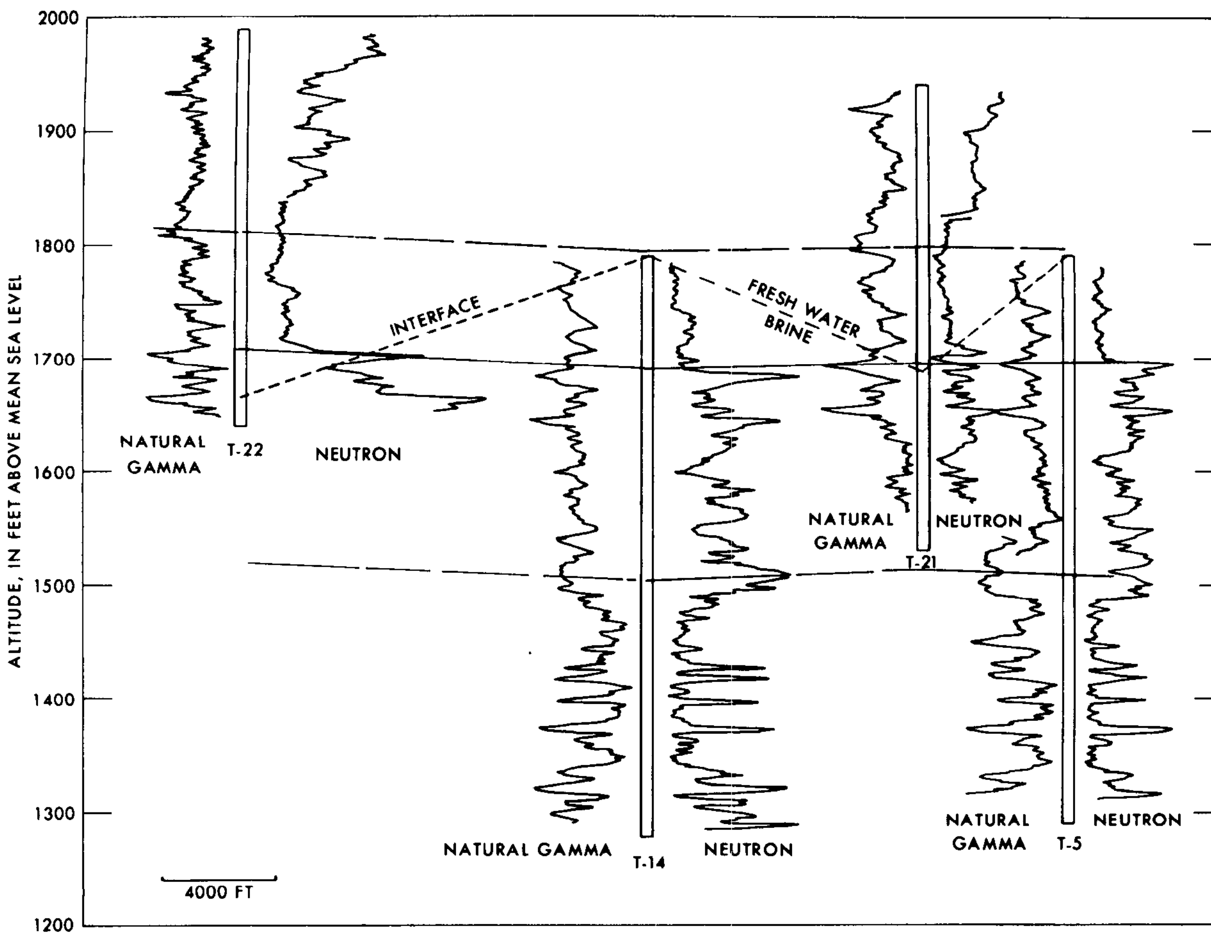

Figure 49. — Correlation with gamma and neutron-*N* logs.

method utilizes a neutron probe to measure the difference between the moisture content of saturated material and the moisture content of the same material after it has been drained. A conventional pumping test and neutron methods were used simultaneously to determine the specific yield of alluvium near Garden City, Kans. Before the pumping test was started, the percent-moisture by volume was determined with a neutron probe for each foot of depth of saturated material. The amount of water drained by volume was then measured during the pumping test. The Thiem equation (Wenzel, 1942) and a modified form of the Theis nonequilibrium equation (Cooper and Jacob, 1946) were used to calculate specific yields of 0.19 and 0.21, respectively, on the basis of drawdown data. The average of the specific yields calculated for the three depths measured with a neutron probe is 0.205. Thus, the two methods appear to be equally reliable for determining the specific yield for unconfined aquifers.

Epithermal neutrons are those in the energy range from 0.1 to 100 ev—that is, they are above the thermal energies at which neutron capture and activation are possible. Epithermal-neutron measurements provide the highest percentage of response due to hydrogen and are least affected by the chemical composition of rocks and contained fluids. Boron and chlorine are two elements, having high-neutron-capture cross sections, which might interfere with quantitative moisture or porosity measurements. For these reasons, selective detection of epithermal neutrons should provide the most accurate neutron log for measuring porosity in rocks saturated with fresh water.

A neutron-gamma log can be made with

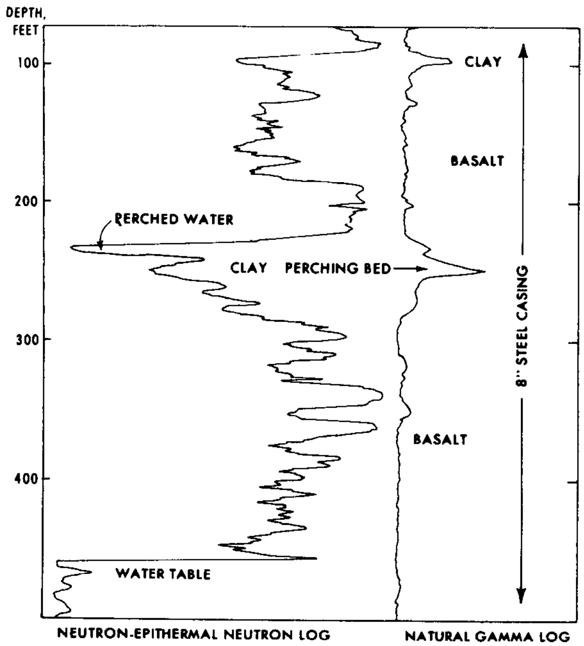

Figure 50. — Interpretation of a neutron log and a gamma log indicates that water is perched on a clay bed. From Keys (1967).

the same source, spacers, and electronic section used for neutron–epithermal neutron logging. However, the detector is a thallium-activated sodium iodide phosphor that is very sensitive to gamma photons and is also sensitive to neutrons. A removable boron carbide shield around the crystal was used experimentally to reduce the sensitivity to neutrons. When thermal neutrons are captured, the nucleus of the unstable atom created emits gamma photons that have energies characteristic of the irradiated element. Measurement and identification of activation-gamma photons in the laboratory is known as neutron-activation analysis, and it is a most effective means of detecting and measuring minute quantities of various elements. Unfortunately, in a drill hole many factors interfere with the use of neutron-activation analyses as a quantitative tool. Not the least of these is the degradation of gamma energies from the point of emission to the detector. Another serious problem is the interference of various elements with similar energy peaks—particularly those elements in the hole and in the tool that might not be abundant in the rocks, such as iron. Fortunately, activation analysis also permits the measurement of half life as an aid to identifying isotopes.

A recent feasibility study demonstrated that a 50-mc californium-252 source can be used for both stationary- and continuous-activation analysis in boreholes (Keys and Boulogne, 1969). The continuous-activation log was made using a 5.5-foot spacing between the source and the detector.

With this spacing, practically no radiation from the vicinity of the source reaches the detector, and activation logs can be made only with the source moving ahead of the detector down the hole. Aluminum-28 was identified as the chief radioisotope contributing to the log response. Use of this new technique may provide a log more closely related to clay content than the natural-gamma log because the clay minerals are mainly hydrous aluminum silicates, and there is a significant increase in the percentage of aluminum with decreasing grain size from fine sand to clay. In stationary-activation experiments made using a californium-252 source, both sodium-24 and manganese-56 were readily produced and identified in a borehole. The technique provides a method for identifying water that is rich in sodium chloride in open holes or behind casing. Also, the quantity of oxygen, carbon, calcium, and iron can be estimated from in-situ neutron activation (Ferronsky and others, 1968). Limitations of these techniques for use in a borehole include the difficulty of determining whether the nuclide is present in the rock matrix or in the fluid, and problems associated with maintaining the constant conditions necessary for quantitative analysis. The gamma activity produced by neutron irradiation is related to the neutron flux and to the nuclear characteristics of the parent and product nuclides, and this activity may be calculated (Lyon, 1964). Table 6 provides data on some common nuclides easily activated by thermal-neutron capture.

The neutron-gamma probe has been found experimentally to be very sensitive to chlorine content; hence, a comparison of neutron–epithermal-neutron logs, which are relatively insensitive to chemical composition of fluids, and of neutron-gamma logs, which are mostly

Table 6. — Data on common nuclides

[After Senftle and Hoyt (1966), with additional data from Goldman and Stehn (1961)]

Parent nuclide	Abundance (percent)	Daughter nuclide	Counts per second per gram after 2 min irradiation[1]	Half life	Energy of major gamma peaks (Mev)
^{27}Al	100	^{28}Al	2.7×10^4	2.3 min	1.78
^{37}Cl	24.5	^{38}Cl	8.1×10^2	37.5 min	2.16, 1.63
^{41}K	6.88	^{42}K	1.9×10^2	12.4 hr	1.53
^{26}Mg	11.2	^{27}Mg	3.1×10^2	9.5 min	0.84, 1.02
^{55}Mn	100	^{56}Mn	1.2×10^4	2.58 hr	0.84, 1.81, 2.13
^{23}Na	100	^{24}Na	2.1×10^2	15.0 hr	1.37, 2.75
^{30}Si	3.09	^{31}Si	5.9	2.62 hr	1.26

[1] Based on 10 percent counting efficiency, a flux of 10^8 n/cm^2 sec, and a normal abundance of nuclides.

a record of prompt-gamma photons, gives a theoretical basis for measuring the chlorine content in place and through casing. Of course, most of the chlorine present will be due to common salt, NaCl. Chlorine has a high-capture cross section for thermal neutrons, and emits gamma rays of 7.4 and 7.77 Mev, compared with capture-gamma rays of 2.2 Mev for hydrogen. Also, hydrogen is most effective in thermalizing the neutrons, so that capture can take place. Most of the chlorine detection in petroleum logging is done by direct comparison of neutron-neutron logs with neutron-gamma logs. Increases of count rate on the neutron-gamma log are supposed to be due to chlorine and are therefore related to saline interstitial fluid. In our research, we found that brine of 200,000 parts per million, which is common in the upper Brazos River basin, Texas, produced a shift on both types of neutron logs, although of different magnitude (fig. 51). The neutron–epithermal-neutron and neutron-gamma logs shown in figure 51 coincide fairly well above the interface, but not below. On the neutron–epithermal-neutron log, this difference may be due to the lower hydrogen content of brine. That is, sandstone with 25-percent porosity, saturated with a sodium chloride brine, is logged

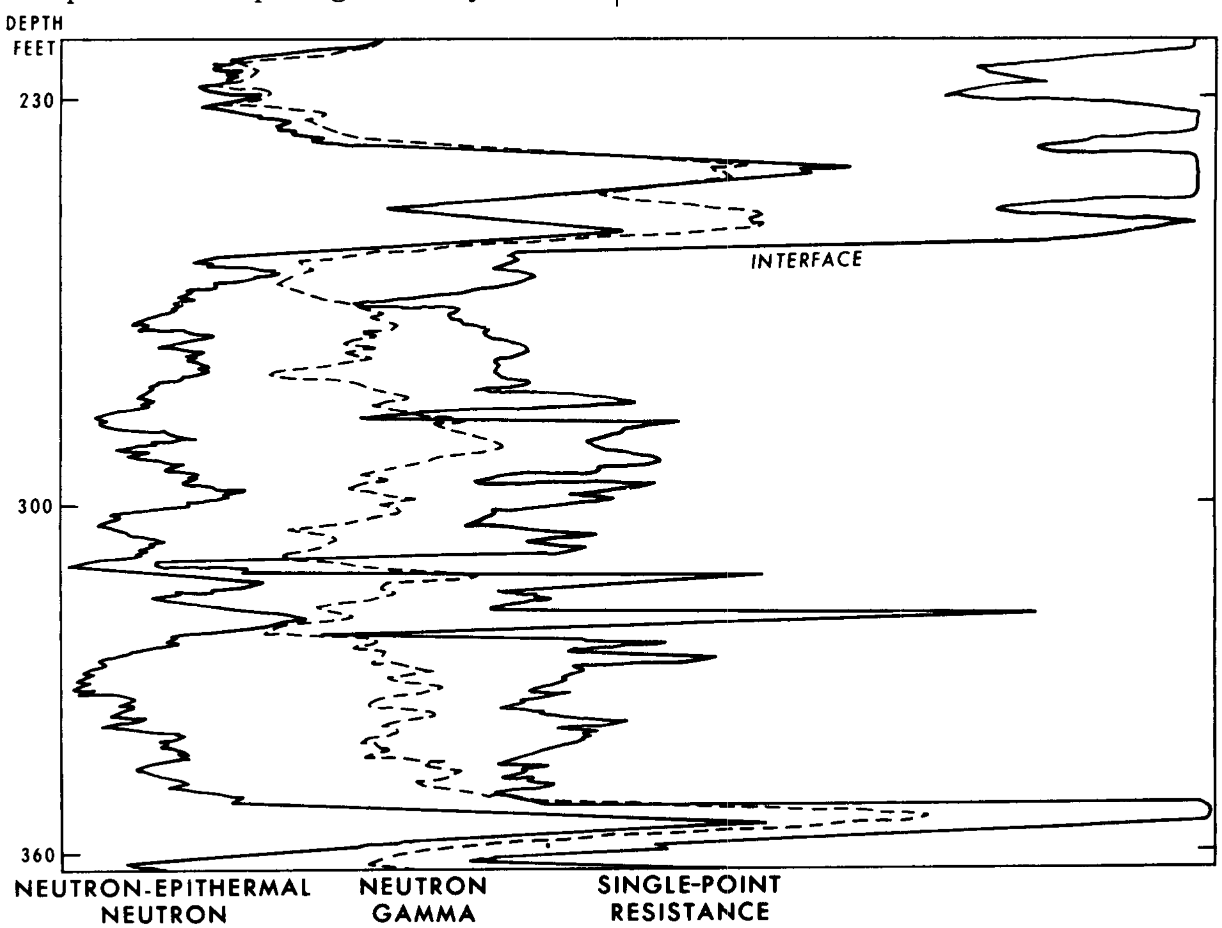

Figure 51. — Location of the brine–fresh-water interface from geophysical logs, hole T–18, upper Brazos River basin, Texas.

as rock having a lower porosity due to the substitution of chlorine atoms for hydrogen atoms. There will be a greater increase in count rate on the neutron-gamma log than on the neutron–epithermal-neutron log because the decrease in hydrogen and the increase in chlorine both raise the neutron-gamma count rate. This is balanced to an unknown degree by the smaller number of thermal neutrons available for capture, owing to the reduction in hydrogen content. At present, neutron-chlorine logging serves only as a qualitative technique for locating the interface between fresh water and brine through casing under the proper conditions. Inhole neutron activation of sodium may provide a more positive means of doing this.

A potential use for neutron, gamma and gamma-gamma logging is to locate the source of fine-grained material produced during the development of a well by pumping. Presumably, most of the fines will be removed from that part of the aquifer where the fluid velocity is highest, if all other factors are equal. The difference between a neutron log made prior to the development of a well and a second log made after well development should indicate zones of higher porosity produced by the pumping and the consequent removal of fines. Preliminary investigations in Alaska and Texas have indicated that changes in porosity caused by both well development and artificial recharge can be detected by logging.

Figure 52 illustrates the use of successive neutron logs to detect porosity changes due to development of a well. The well, which was drilled for oil exploration near Anchorage, Alaska, was lined with 9⅝-inch casing, plugged at 960 feet, and pressure-cemented back to the surface. It was decided to perforate the casing at four deep zones selected from geophysical logs, develop the well, and then selectively test with a pump and packer. Log *A* in figure 52 was made before perforating. The shallowest zone perforated was at 507 feet. Log *B* was made after several days of surging and bailing. It recorded a zone showing a significant increase in porosity from 103 to 122 feet and a decrease in porosity from 130 to 138 feet. The mate-

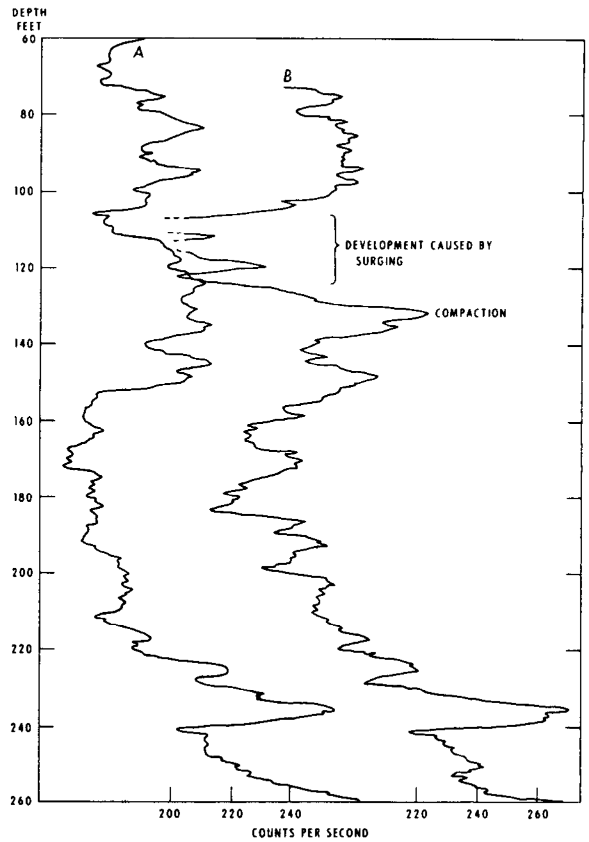

Figure 52.—Neutron logs, Yukon Services well, Anchorage, Alaska.

rial developed from this zone (103–122 ft) consisted mainly of silt containing some coarser particles. The increase in porosity could only have been caused by a leak in the casing within this depth interval. Brine-tracer logs, temperature logs, and neutron logs indicated that development and subsequent production from the deeper aquifers was small. (See fig. 62.)

Instrumentation

The downhole and surface electronics for making neutron logs can be exactly the same as that utilized for making natural-gamma and gamma-gamma logs. This equipment must be capable of handling a somewhat higher count rate than is typical for natural gamma, and pulse-energy discrimination is desirable. Considerable latitude in zero positioning and sensitivity is necessary because of the high-amplitude deflections on the logs and the shift in count rate at water table. A

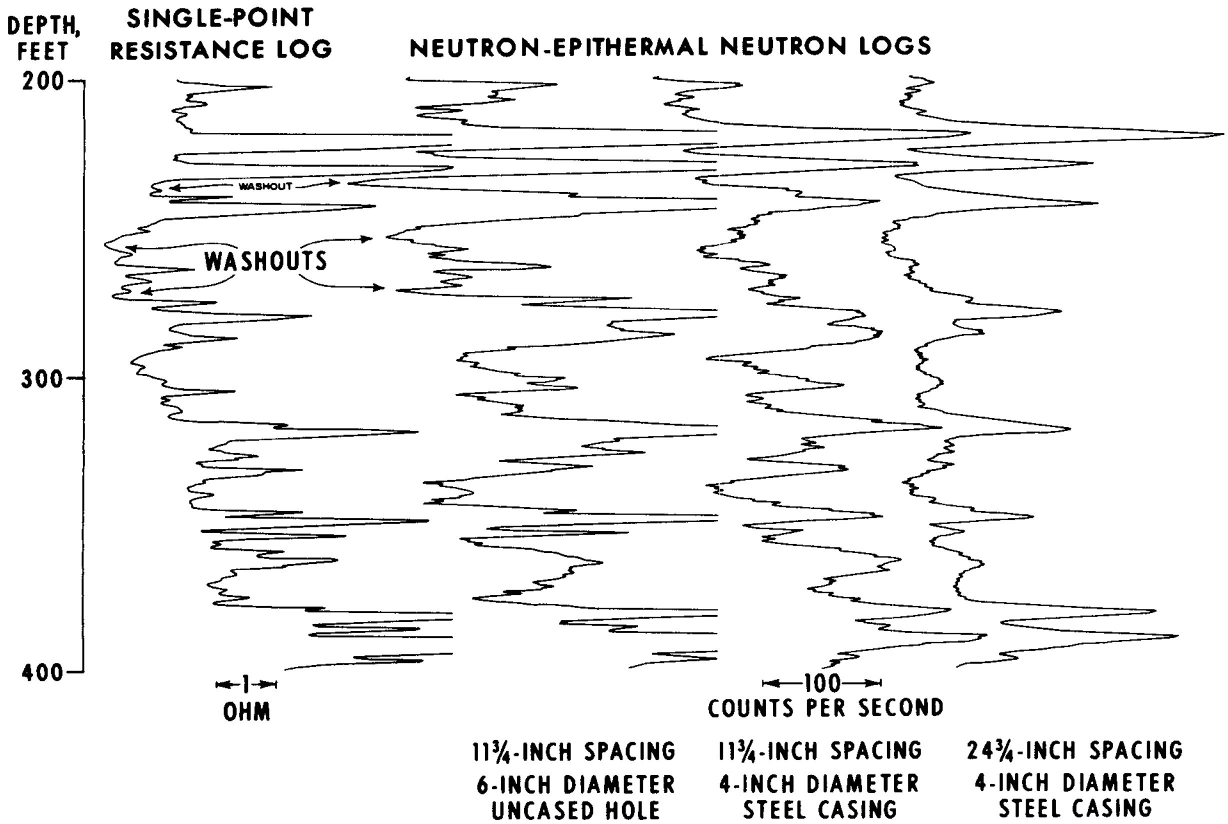

Figure 53. — Neutron logs made with various spacings between source and detector and under different hole conditions.

europium-activated lithium iodide crystal enriched in lithium-6 may be used for neutron detection at temperatures below 150°F. Gas-filled tubes are commonly used at higher temperatures. Similarly, sodium iodide crystals and Geiger-Mueller tubes can be used for the detection of gamma photons. In the low-temperature epithermal-neutron tool, cadmium is used as a thermal-neutron shield, and energy discrimination is used to reduce sensitivity to neutron-produced secondary-gamma photons to a low level. Character of the log is not affected by the spacing between the source and detector, but spacing does affect the quantitative relation between the log and the hydrogen content. Figure 53 illustrates the manner in which sensitivity is affected by casing and by spacing between the source and the detector. Note the decrease in detail and the reduced effect of washouts with the longer spacing.

Calibration and standardization

The API limestone pits in Houston, Tex., are the only readily available models for calibrating neutron-logging equipment at various porosities. Neutron-moisture-logging equipment can be calibrated with smaller models, available in many areas, or in boric acid solutions of different concentrations. Core samples provide the only other means of calibration. The count rate can be related either to API neutron units from the limestone pits or to percent porosity from core samples. Regardless of how the equipment is calibrated, it should be standardized frequently—preferably after, or before and after logging each hole, if the equipment has shown any tendency to drift. A neutron field standard can consist of an unvarying high-hydrogen environment. The standard can be constructed with water, paraffin, or plastic, and should be large enough that changes in moisture in the environment will have no effect on the probe output. Where possible, the use of two standards having different hydrogen densities is preferable, so that recorder span, as well as pen positioning, can be measured.

Calibration should be done in full-scale models that have different porosities and that closely approximate borehole conditions. The models, containing built-in neutron access tubes of various diameters, are filled with a water-saturated homogeneous sand. Models 20 inches in diameter were found to be less than infinite with respect to the radius of investigation of our neutron-porosity probes. An infinite model is defined as one that can be increased in size with no change in the radiation measured. To change fluids in a sand model is difficult, and it is expensive to construct the number of large models needed to represent the various porosities, casing sizes and types, and diameters of open hole. A heterogeneous model that permits changes in interstitial fluid, porosity, and casing size appears to be an alternate solution. Such changes can be made with movable rods of limestone or novaculite (Allen and others, 1965).

The American Petroleum Institute has constructed neutron-calibration pits of saturated limestone blocks with porosities of 1.9, 19, and 26 percent (Belknap and others, 1959). Because of possible instrument drift, these pits should be used for calibration of logging equipment only if a portable field standard is available for comparison. Calibration of neutron devices in these pits and the use of a field standard provide a basis for quantitative comparison of logs. Note, however, that calibration in a limestone model is not directly applicable to a sandstone environment because of matrix effects.

Figure 3 shows how the porosity of more than 200 core samples compares with a neutron log. Note how much easier the log is to interpret between depths of 200 and 300 feet deep than are the many core samples from this interval. The common practice of selecting a few pieces of core for laboratory analysis would have produced meaningless data in a sedimentary section exhibiting such inhomogeneities. Laboratory analyses of the core were done by Core Laboratories, Inc. of Dallas, Tex., and the Hydrologic Laboratory of the U.S. Geological Survey in Denver. Some of the samples sent to the two laboratories were duplicates, and some were split for two analyses by one laboratory to determine the confidence that could be placed in core samples as a means of calibrating logs. The analyses of some duplicated samples varied by more than 100 percent, whereas others tested exactly the same. This difference does not necessarily indicate a problem in the laboratory, as the same piece of core could not be used twice; also, detailed sampling in some sections indicated a porosity variation that was not apparent from examination of the drill core. A recent article on a gamma-gamma method for making a continuous measurement of core porosity suggests that variations in porosity are much greater than suspected, and that a small plug cut from a drill core does not provide a representative sample for most areas (Evans, 1965; Harms and Choquette, 1965). Also, some differences apparently exist between the analytical techniques used at the two laboratories, as we noted a relatively consistent difference in the higher porosity range. A further difficulty in comparing core analyses with logs is caused by depth inaccuracies on samples from zones with lost core.

Radius of investigation

The volume of influence, or radius of investigation, is an important factor in the analysis of any neutron logs (fig. 42). The radius of investigation is a function both of the spacing between the source and the detector and of the type of material within the volume of influence. Figure 42 is somewhat idealized in that the true shape of the volume of material investigated is not known, and the radius of investigation decreases at higher saturated porosities, or greater percent-moisture, because of the reduced range of neutrons prior to capture. Inasmuch as the recorded response is an integration of the varying porosities present within a rather large sample volume, it follows that a bed having 10-percent porosity but that does not fill the volume of influence will not give the same neutron value as that for a bed having 10-percent porosity that more than fills the sample volume. Thus, very thin beds are not accurately measured by neutron logging.

The radius of investigation of neutron devices is reported to be from 6 inches for high-porosity saturated rocks to 2 feet for low-porosity or dry rocks. These estimates may be conservative, for when we placed the neutron sondes in 20-inch-diameter models that had a saturated-sand porosity of greater than 30 percent, the sondes exhibited significant changes in count rate when the hydrogen density outside each model was changed. An experiment run in two holes, which were drilled 4 feet apart in damp sand and gravel, indicated that significant numbers of neutrons from a 3-curie americium source could be detected at that distance. However, this is not directly comparable to logging in a single hole.

Extraneous effects

Neutron logs are affected by changes in borehole parameters, although to a lesser degree than most other geophysical logs that measure the properties of rocks. Figure 54 shows that little difference exists between neutron logs made in an open hole and those made through two types of casing installed later in the same hole. The one major difference between these logs occurs at a depth of 80 feet, and is probably due to the caving of an anhydrite and shale unit, which occurred when the plastic casing was being drilled out.

The most marked extraneous effect on neutron logs is that caused by changes in hole diameter. Such error can be reduced by maintaining a side-collimated tool against the wall of the hole. The effect of changes in bit size, or average hole diameter, would theoretically be eliminated by a decentralized tool. A decentralized tool probably would not reduce the effect of hole rugosity because of the small vertical dimension and the considerable horizontal extent of most washouts. The best solution to this problem is not to attempt quantitative-log interpretations where hole washouts are known or suspected. This is one reason why a caliper log is such an important tool in borehole geophysics. Figure 47 provides a comparison of a commercial decentralized neutron log, on the left, and a log made with an axially symmetric tool by the Water Resources Division research project, on the right. The gamma-gamma logs of the same hole are much more sensitive to the washouts shown on the caliper logs. Figure 55 shows a neutron and a gamma-gamma log with a resistance log. Because the hole was caving, the radiation logs were made through drill rods. Joints in the drill stem apparently have very little effect on the neutron log, but they have a marked effect on the gamma-gamma log. Note the similar character of the neutron and the single-point resistance logs.

Mud cake and invasion will also have a minor effect on neutron logs and will decrease with pumping and development of a well. Multiple-electrode electric-logging techniques or dual-spaced neutron or gamma-gamma logs may provide data on the invaded zone. This is a potentially important field because of the close relation between the depth of invasion and the formation permeability.

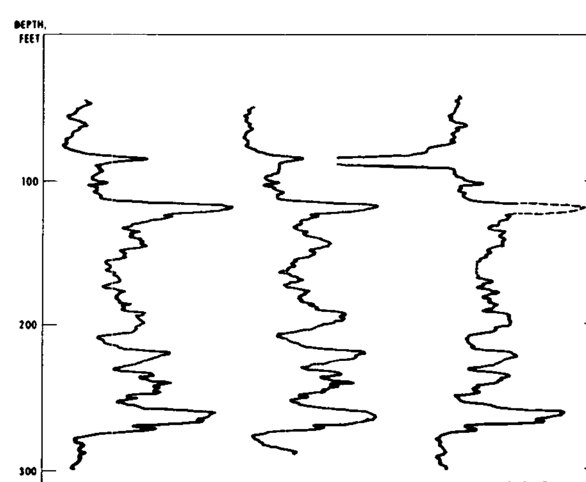

Figure 54.—A comparison of neutron logs made in the same hole uncased and through PVC and steel casing.

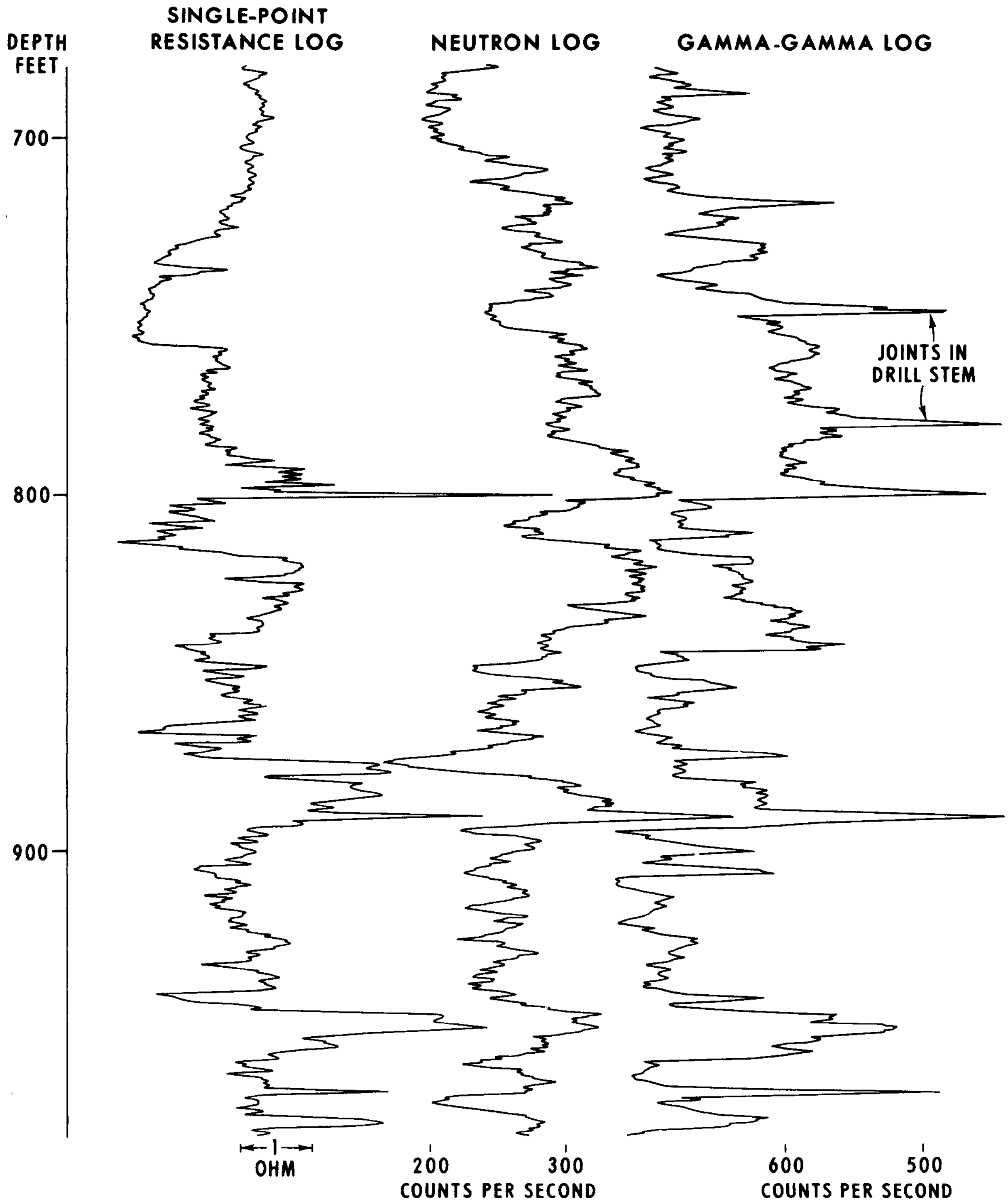

Figure 55. — Neutron and reversed gamma-gamma logs, made through drill rods, and a single-point resistance log. Compare the effect of joints on the radiation logs.

The media in a drill hole has a considerable effect on a neutron log. The marked shift at the air-water interface is useful for approximating the water level at the time the log is made. Likewise, a water-brine interface or a water-mud interface in the hole is apt to cause a shift that is not always readily recognizable. Fortunately, the fluid-conductivity log will give exact locations of these fluid-column interfaces without showing interference from hole effects.

The use of radioisotopes in well logging

All types of nuclear logging except natural gamma utilize radioactive materials or sources. However, natural-gamma logging equipment is calibrated, or standardized, with natural or artificial radioactive materials. Most neutron-logging devices use either radium-beryllium, plutonium-beryllium, or americium-beryllium sources or electronic-neutron generators. Gamma-gamma logging devices generally contain cobalt-60 or cesium-137 sources. Downhole radioactive tracer techniques utilize a wide variety of gamma-emitting liquid or solid radioisotopes. (See section on "Fluid Movement Logging.") Therefore, anyone planning a logging program must be cognizant of the regulations and procedures necessary to use radioisotopes. The purpose of this brief description is to minimize personnel exposure and the risk of accident or loss of a source.

Radium and small quantities of other naturally occurring radioactive materials, as well as microcurie sources as specified in title 10, Code of Federal Regulations, Chapter 1, Part 30.72, do not require a license from the U.S. Atomic Energy Commission or from those States that have instituted formal regulation of radioactive materials. Higher levels of the specific radionuclides listed in Part 30.72 of the code and all other radioactive materials are regulated by the U.S. Atomic Energy Commission or the States. The following quotation is from the U.S. Geological Survey, Water Resources Division Memorandum No. 68.98, dated January 16, 1968, which should be read by everyone planning to utilize radioactive materials. "Federal regulations (U.S.A.E.C., Division of Materials Licensing, 1966, Conditions and Limitations on the General License Provisions of 10 CFR 150.20) prescribe the limits governing exposure of personnel to radiation, concentrations of radioactive material that may be discharged to the environment, authorized disposal practices, and precautionary procedures and administration controls. All WRD [Water Resources Division], personnel authorized to handle radioactive materials, or in charge of activities requiring use of these materials, are required to be familiar with the A.E.C. regulations and the contents of NBS [National Bureau of Standards] Handbook No. 92, entitled "Safe Handling of Radioactive Materials," and IAEA [International Atomic Energy Agency], "Guide to the Safe Handling of Radioisotopes in Hydrology." WRD memorandum No. 68.98 also establishes the position of the Regional Radiation Protection Officer, who "will ensure that only qualified personnel, properly trained and licensed, oversee use of or handle radioactive materials and equipment * * * ." Because of the importance of nuclear-logging techniques, some of the procedures for the proper utilization of radioactive materials in wells will be briefly described. Specific handling procedures will depend on the size and nature of the source and the application, and should be developed only by experienced personnel in compliance with local regulations.

Training and experience in radiation monitoring and the safe handling of radioisotopes is a prerequisite to obtaining a permit or license. Initial training should be designed to provide an understanding of the nature of radiation and its potential hazards; permissible doses, radiation levels and concentrations, precautionary procedures, and waste disposal should be included. Courses in "Radiological Monitoring for Instructors," offered by the Office of Civil Defense, are adequate for initial training. On-the-job training must include the specific equipment and procedures to be used in well logging. Periodic refresher training is also necessary to bring personnel up to date on changes in regulations, equipment and procedures.

Before radioisotopes are purchased or utilized, the Regional Radiation Protection Officer should be contacted for information on licensing, film-badge service, wipe testing, and monitoring equipment. Either an A.E.C. license or a permit covered under one of the existing broad licenses is necessary prior to the purchase of regulated radioactive materials. A monthly film-badge service for all personnel using the sources and portable monitoring equipment must be obtained before the sources are purchased. Shields that can be locked should be selected on the basis of maximum-radiation attenuation; however, they must also be portable. Shields should conform with Interstate Commerce Commission regulations so they can be shipped.

Despite high manufacturing standards, sealed sources occasionally do leak; therefore, when sources are received, they should be wipe tested, and procedures should be set up for at least semiannual wipes. The sources are wiped with filter paper, which is first checked with portable monitoring equipment and then sent to a laboratory capable of detecting the presence of 0.005 microcuries of removable contamination. Any suspected leaky sources should be reported immediately, and steps should be taken to prevent the spread of contamination. Sources and other radioactive materials should always be stored in locked shields in a locked room or vehicle. Approved radiation signs and labels are required on both the shield and the outside of the room or vehicle. Radiation levels outside transporting vehicles and storage rooms must not exceed the prescribed limits.

Source-handling procedures and equipment should be designed on the basis of minimum personnel exposure necessary to do the job, not on the basis of maximum permissible exposure. Use the proper combination of time, distance, and shielding to reduce exposure to a minimum. Sources should never be handled directly. Forceps or other remote-handling devices should be designed for rapid manipulation of the source, as well as increasing the handler's distance from it. Whenever possible, sources should be stored in a shield in the same sub used for logging. In this manner, the sub can be attached directly to the logging sonde, which makes extra loading and unloading of the sub unnecessary. The sonde should be placed in the well as soon as the sub is securely attached. Source subs should be metal, labeled "Caution—Radioactive Materials," so they can be identified if lost. Shields should be labeled as to type and amount of radioactive material contained. Monitoring equipment may be used to measure radiation levels during handling; in addition, all personnel utilizing or transporting sources must wear film badges. Care must be taken to assure that the general public and visitors to a logging project do not receive exposure above acceptable levels. Visitors in the immediate area of operations for more than a cursory examination of a project should be required to wear film badges furnished by the project.

Logging sondes containing radioactive materials should never be lowered in a well until at least one other sonde has freely traversed the full depth interval to be logged. If any caving is experienced or anticipated or any obstruction is found, radioactive materials should not be put in the hole. An expensive effort is required to recover a lost source, and if it is not recovered, it may be necessary to cement the well. For these reasons, it is recommended that the radiation logs be run in the drill stem or temporary pipe if any difficulty is anticipated in the hole. If a radioactive source is lost, the Regional Radiation Protection Officer and the nearest A.E.C. Licensing Office must be notified immediately, and all attempted recovery methods must be nondestructive. Various types of "fishing" tools are available commercially.

Work with radioactive tracers requires extensive preparation and planning, as well as protective clothing and decontamination facilities. Procedures will depend on the type and amount of tracer used, the application, the ground-water environment, and the distance to nearest point of use. For these reasons, they will not be described here. The Regional Radiation Protection Officer should be consulted for this type of work, and the regulations and references cited herein must be followed. Broad licenses to permit use of radioactive tracers in ground-water hydrology have not been issued; instead, a separate license is required for each application of a radioactive tracer. Considerable information is needed on the ground-water environment

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before such licenses will be issued. This requirement has tended to discourage the use of radioactive tracers in ground-water studies to date. The less strict regulations that have permitted a much wider use of radioactive tracers in oil wells may also permit application to deep waste-disposal investigations in the future.

Acoustic Logging

Generally, an acoustic log is a record of the transit time of an acoustic pulse between transmitters and receivers in a probe. The chief uses are for the measurement of porosity and the identification of fractures.

Principles and applications

Acoustic-velocity logs are widely used in the petroleum industry for the measurement of porosity. Amplitude logs are often applied to finding the location of fractures in a borehole and the determination of the character of cement bonding between the casing and the formation. Acoustic logging, also called sonic logging, utilizes many frequencies not audible to the human ear. Basically, all acoustic-logging devices contain one or two transmitters that convert electrical energy to acoustic energy, which is transmitted through the environment as an acoustic wave. One to four receivers reconvert the acoustic energy sensed to electrical energy for transmission up the cable. The tool is constructed so that the shortest path for the acoustic wave is that through the rock surrounding the well and then refracted along the borehole wall. The hole must be filled with water or mud to permit transmission of the elastic waves from transmitter to formation, and from formation to receiver.

Two general types of measurements may be made in acoustic logging:

1. Interval transit time, which is the reciprocal of velocity.
2. Amplitude, which is the reciprocal of attenuation.

The continuous acoustic- or sonic-velocity log is a record of transit time (Δt) of an elastic wave through the media being logged. Figure 56 schematically illustrates a single-receiver probe and a two-receiver probe. In the single-receiver system, the sonic path is T–A–B–R and includes the transit time in the mud. In the two-receiver system, the transit time B_1–B_2 is recorded. Spacing T–R is usually greater than 2 feet, and the spacing between receivers is 1 foot or more. Velocity logs are recorded in microseconds per foot. Figure 57 shows an acoustic-velocity logging probe that is compensated or adjusted for borehole-diameter changes, oscilloscope presentation of the received signals, and a typical acoustic-velocity log.

Because of the complex character of acoustic waves and the effect of various rock properties on these waves, a great potential exists for determining in-situ lithologic properties by use of acoustic techniques. Much useful data is available in the received-wave train. The types of acoustic waves received after transmission through the rock are classified as compressional, or P waves;

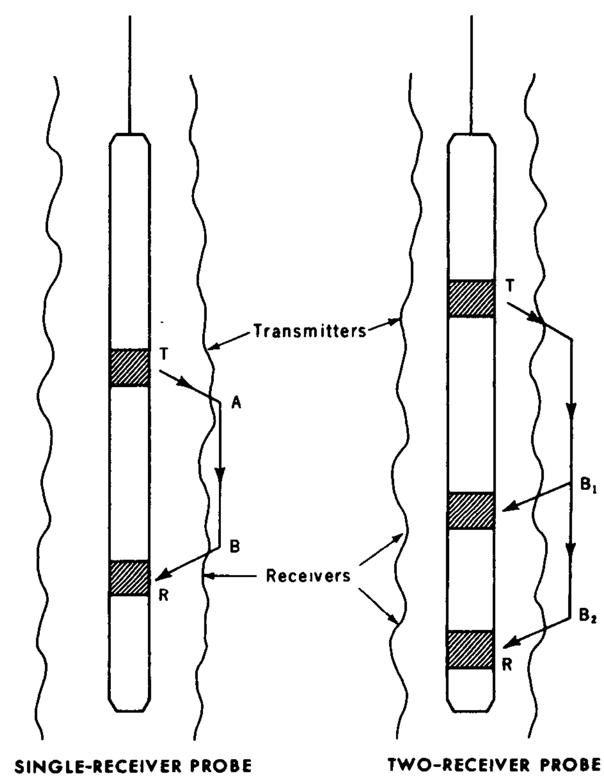

Figure 56. — Uncompensated acoustic-velocity probes.

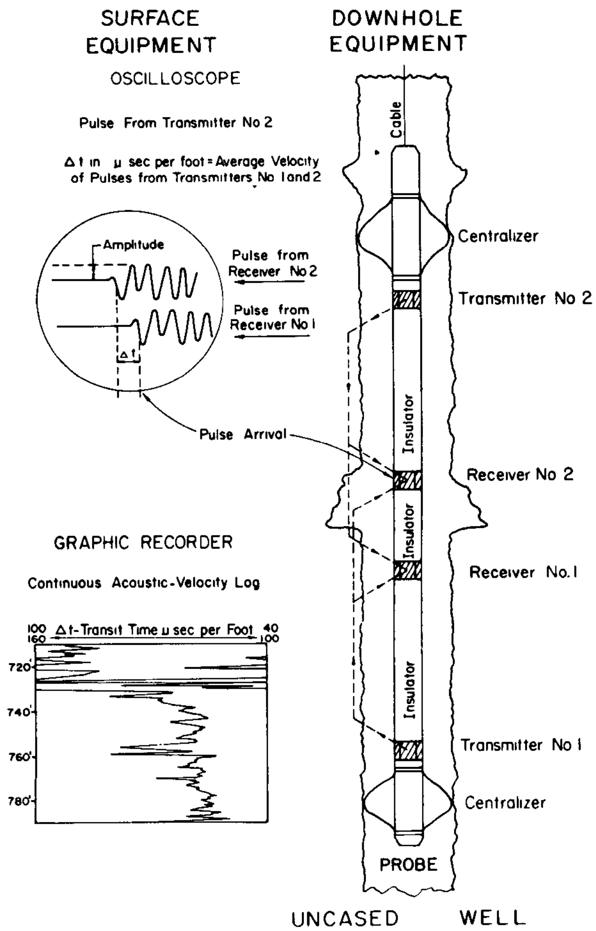

Figure 57. — Principles and equipment for making borehole-adjusted acoustic-velocity logs.

shear, or S waves; and boundary, or surface waves (Guyod and Shane, 1969). The P waves are propagated by the movement of particles in the medium in the direction of wave propagation; these waves arrive first and are characterized in consolidated rocks by a lower amplitude than the S waves. The S waves have a velocity about one-half that of P waves and are characterized by particle movement perpendicular to the direction of wave propagation. S waves are not transmitted through the fluid directly, but are transmitted by means of an intermediate P wave. The amplitudes, or heights, of the P and S waves received are related to the porosity, the degree of consolidation, the fracturing of the rocks traversed, and the orientation of the fractures (Morris and others, 1964). Boundary waves are only transmitted along the wall of the borehole by particle movement both perpendicular and parallel to the direction of wave movement, and their velocity is less than that of the S wave. Therefore, the acoustic waves arrive in the following sequence: P wave, S wave, and boundary wave.

The frequency, or wave length, of transmitted and received pulses is another important characteristic. Certain rock types exhibit frequency-selective acoustic characteristics (Chaney and others, 1966). For example, limestone transmits the higher frequency waves better than poorly consolidated sands and shales. As shown in the previous discussion, the following acoustic-wave parameters and the ratios between them can be measured: P- and S-wave velocity; P- and S-wave amplitude, or attenuation; and frequency. Research is presently underway in the petroleum field on the relationship between permeability and the various acoustic parameters. Khalevin (1960) indicated that porous fractured limestone is more readily identified by wave-amplitude attenuation than by wave-velocity changes and suggested using continuous-amplitude logging for porosity measurement. Taylor (1968) used sonic logs to estimate the vertical compressibility of an artesian aquifer. He then used the values of compressibility to plot the effect of changes in net stress on the storage coefficient of the aquifer. This use of acoustic logs in ground-water hydrology should be investigated further.

At present, the continuous-acoustic-velocity log is used mostly for the measurement of rock porosity in open holes (Pickett, 1960). Recently, some acoustic-porosity logs were also run in cased holes that have at least 40- to 50-percent cement bonding between the casing and the formation (Muir and Zoeller, 1967).

The basis for porosity calculation from acoustic logs is the time-average equation:

$$\frac{1}{V_r} = \Delta t = \frac{\phi}{V_f} + \frac{1-\phi}{V_m},$$

where

Δt = interval transit time, in seconds per foot;

ϕ = porosity fraction;

V_f = velocity of signal in fluid, in feet per second;
V_m = velocity of signal in matrix, in feet per second; and
V_r = velocity of signal in rock, in feet per second.

This equation is obtained by considering that the path of an acoustic pulse through saturated rock consists of two velocities, in series, V_f and V_m. The length of the path in fluid is equal to the porosity (ϕ), and the length of the path in the rock matrix is equal to $(1-\phi)$. Because the equation is valid only for rocks with uniformly distributed intergranular pore spaces, it can be considered to provide values for effective porosity. The velocity of elastic waves in water or drilling mud is 5,000–5,400 feet per second (transit time 200–185 μsec/ft), and following are velocity and transit-time ranges for the matrix of some common rocks:

Rock	Velocity (ft/sec)	Transit time (μsec/ft)
Sandstones	15,000–18,000	66.7–55.6
Shales	6,000–16,000	167.0–62.5
Limestone	19,000–21,000+	52.6–47.6
Dolomite	21,000–24,000	47.6–42.0

The graph in figure 58 can be used to determine porosity from an acoustic-velocity log when the acoustic velocity through the rock matrix is known. If the matrix velocity of a limy sandstone is 50 μsec/ft, and if Δt from a log is 78 μsec/ft, the porosity is approximately 20 percent. The acoustic-velocity log should only be used for porosity calculation in rocks having uniformly distributed

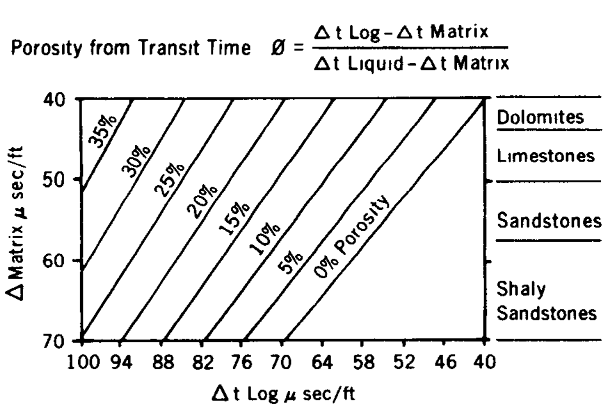

Figure 58. — Graph based on the time-average equation for the determination of porosity from acoustic velocity. From Welex (1968).

porosity. Secondary porosity, due to vugs and fractures, will not be accurately measured because the elastic waves that give the first arrival apparently travel through the matrix around the openings. Furthermore, correction factors must be applied for unconsolidated or shaly sediments (Lynch, 1962).

The effect of secondary porosity on the various elastic-wave parameters can be used to locate fracture zones near wells (Walker, 1962). Fractures may also cause "cycle skipping" on sonic-velocity logs. This is due to attenuation of the pulse to below the detection level. A subsequent pulse not attenuated below that level is sensed as the first arrival; thus, the recorded velocity is very low. Cycle skipping is not uniquely caused by fractures; poor consolidation, gas, sands, and material added to the mud to reduce circulation loss can also cause it. P waves and S waves are attenuated to different degrees by fractures, and the angle at which a fracture intersects the drill hole affects the wave amplitude. Therefore, the total signal received must be available for visual examination. The selective effect of fracture orientation on P- and S-wave arrival and amplitude was discussed in detail by Morris, Grine, and Arkfeld (1964). They were able to locate fractures and interpret their primary orientation from P- and S-wave amplitudes, but they were not able to determine fracture density.

Similar interpretation of a full acoustic signal provides the best means of determining the bonding of cement between the casing and the formation (Muir and Zoeller, 1967). Sonic velocity in steel casing is very high. When the casing is centralized in the hole and not bonded to the formation, only a symmetrical casing signal will be recorded. Decentralized unbonded casing will be recognized by a distorted casing signal, and bonding of cement to the casing but not to the formation will produce a very low amplitude casing signal but produces no formation signal. The amplitude of the casing signal is decreased by good bonding between cement and casing, and the amplitude of the formation signal is increased by good bonding between the cement and formation. Sufficient cement bond to permit signal transmission to and from the formation will allow the recording of a log of acoustic velocities of rock. A good casing-formation bond can be determined by comparing the velocity log made after the hole is cased with an open-hole velocity log or a neutron log.

Acoustic-transit time has also been related to the engineering properties of rocks by Carroll (1966). Plots of transit time versus static Young's modulus and ultimate compressive strength show a correlation with transit time. The in-situ elastic properties of rock salt were calculated by Christensen (1964) from acoustic-log values of *P*- and *S*-wave velocities, and density was calculated from gamma-gamma logs. The properties calculated, assuming that the medium was isotropic, were the bulk-compression modulus, Young's modulus, the shear modulus, and Poisson's ratio. The values obtained through logging compared very favorably with average laboratory measurements on rock salt. These characteristics are useful in studying the influences of underground nuclear explosions and should also be useful in the interpretation of surface seismic records.

Another presentation of acoustic-log data is most useful in the identification of lithologic units causing seismic reflections. The integrated travel time is recorded along the side of the standard acoustic-velocity log. The time required for a seismic pulse to travel through any depth interval may be obtained by adding the time pulses that appear along the side of the log for the interval of interest.

Instrumentation

There are three general types of acoustic-logging sondes. The earliest sondes developed consisted of a single transmitter and a single receiver. Any change in the length of the wave path, such as that caused by a washout, drastically affected the Δt that was measured. The first step in improving this tool was to add a second receiver. With the two-receiver sonds, which are still in use, Δt is measured from the time of arrival at the first receiver (R_1) until the time of arrival at the second receiver (R_2). With this arrangement, differences in acoustic path between the transmitter and the first receiver do not change the Δt. However, even with this system, anomalous deflections occur on the log when the edge of a cavity or washout in the borehole is located between the receivers. These deflections are in the opposite direction at the top and bottom of a cavity. Figure 57 illustrates the above explanation; when the edge of a cavity is located between receivers, there is a difference in length of the travel path from the formation to the receivers. The latest development in acoustic-logging devices incorporates two transmitters and either two or four receivers, and is termed "borehole compensated" or "corrected" (Kokesh and others, 1965).

Most transmitters and receivers used at the present time consist of a roll of thin magnetostrictive alloy wrapped with a coil of wire. Various types of piezoelectric crystals are also used. A pulse of current through the wire causes the metal to oscillate by means of rapid contraction and expansion. This vibrational energy is transmitted through the fluid in the hole to the rock and back through the fluid to the receivers. This type of transducer emits a range of frequencies from about 5,000 to over 40,000 hertz; the center frequency is usually about 20,000 hertz.

So that the first arrival detected will be the formation signal, the body of an acoustic-logging sonde must be constructed of rubber, or of similar low-velocity high-attenuation materials, so that the amplitude of the elastic wave propagated through the tool is less than the amplitude propagated through the formation. Acoustic-logging tools should be centered in the hole with bow springs or rubber fingers so that the signal path length is consistent.

The electronic equipment required to make acoustic logs is very complex. Power and timing circuits pulse the transmitters. Gating and amplifying circuits send the proper sequence of pulses up the cable. Adjustable trigger circuits are used to select the proper point for first-arrival timing. For this purpose, an oscilloscope presentation in the logging truck is essential. Also, scope presentation allows observing and photographing of wave amplitude and frequency, as well as arrival time. Circuits average the transit times and convert them to a DC voltage, which drives the recorder pen.

Continuous or periodic pictures of the oscilloscope trace of the wave form or full-wave recording (Muir and Fons, 1964) constitute another type of data output that is used for fracture-finding and cement-bond logging. Borehole-corrected sondes can be run on single-conductor cable, but the electronics is simplified and the cost is reduced when a multiconductor cable is used.

Calibration and standardization

Interval transit time, in microseconds per foot—the standard unit for all acoustic-velocity logs—can be read directly from a calibrated oscilloscope, which should be a part of every acoustic-logging system. Assuming that there are no electronic errors in transmission of the triggering, or transmitter, pulse and the receiver signal, the transit times from the scope can be written on the graphic analog record when the sonde is stationary in the hole. This can be done at the same time that the operator is selecting the first *P*-wave arrival. The transit time measured at these points in the hole is, of course, subject to the judgment of the operator in selecting arrivals. Use of several built-in calibration signals that can be recorded on the log at any time is desirable, in order to check uphole circuits and to provide standard points on each log for determination of pen-zero positioning and span, or sensitivity. Calibration points should appear on every acoustic log, preferably before and after the run, as an indication of uphole system drift. No convenient field standard for checking the response of the total acoustic-logging system is, as yet, available.

Theoretically, transit times from acoustic logs can be converted to porosity values if both the matrix and the fluid-velocity values are known. As with most other logs, environmental calibration is desirable, to reduce the possibility of extraneous effects on logs. Because of the difficulty of building environmental sonic models, the relation of core samples to log deflection is probably the simplest method of calibration. To construct a model having a given porosity is a relatively simple matter, but to simulate the acoustic response of a certain rock type in an open hole would probably require a large, water-saturated block of that type of rock with a hole drilled in it and pressure to simulate inhole conditions.

Acoustic velocity, as well as porosity on core samples, can be measured to determine some of the reasons for errors in acoustic measurement of porosity (Jenkins, R. E., 1960). Jenkins noted that, in quartz sandstone, the best 30 percent of data points obtained showed a deviation of only ±1 percent porosity from the theoretical time-average line. The best 90 percent showed a deviation of ±5 percent. In contrast to neutron logs, acoustic-velocity logs are the most accurate for logging consolidated rocks of a higher porosity but are inaccurate for logging rocks in which porosity is less than 5 percent.

Both acoustic-velocity and porosity measurements on core samples are recommended if the logs are to be used for quantitative interpretation. Core samples used for this purpose should be undisturbed and, if possible, saturated with native fluids. Determining the relation between acoustic velocity and porosity in the laboratory provides another means of learning the effects of such inhole conditions as confining pressure.

Radius of investigation

The radius of acoustic investigation varies with the wave length and frequency of the elastic wave, as well as with the sonic velocity. The radius investigated is reported to be about 3 times the wave length, λ (Pirson, 1963).

$$\lambda = \frac{V_r}{n},$$

where

V_r = velocity in rock, and
n = frequency.

At a frequency of 20,000 hertz, the radius of investigation should be about 0.75 feet for soft rocks having a velocity of 5,000 ft/sec, and should be about 3.65 feet for hard rocks having a velocity of 25,000 ft/sec. Reducing the transmitter frequency will increase the radius of investigation.

Extraneous effects

Cycle skipping on acoustic logs, an extraneous effect which is fairly obvious (fig. 59), occurs when the detecting circuits miss the first arrival, so that time is measured to the next detectable arrival. It is caused either by excessive signal attenuation in the fluid or the formation or by equipment malfunction. The cycle skipping on the acoustic log made with four receivers in figure 59 is probably due to the rugosity of the wall of the hole, as shown on the caliper log. Proper electronic gating in the equipment can greatly reduce this problem. The acoustic logs in figure 59 also recorded deflections at depths of 920 and 1,030 feet, which may be due to changes in the hole diameter, as shown on the caliper log. A borehole-adjusted acoustic tool should greatly reduce this error. Also, if a logging sonde is not properly centered, it can cause signal attenuation due to phase shift and can result in missed arrivals. Receiver span should always be considered when interpreting acoustic logs: the shorter the span, the greater the resolution of thin beds, and the more detailed the log.

The greatest problem in the interpretation of acoustic-velocity logs or acoustic-wave records is the variability in environmental factors affecting the transmission and attenuation of elastic waves. Acoustic velocity in porous media is dependent on such lithologic factors as the type of matrix, the density, size, distribution, and type of grains and pore spaces, and the degree of cementation,

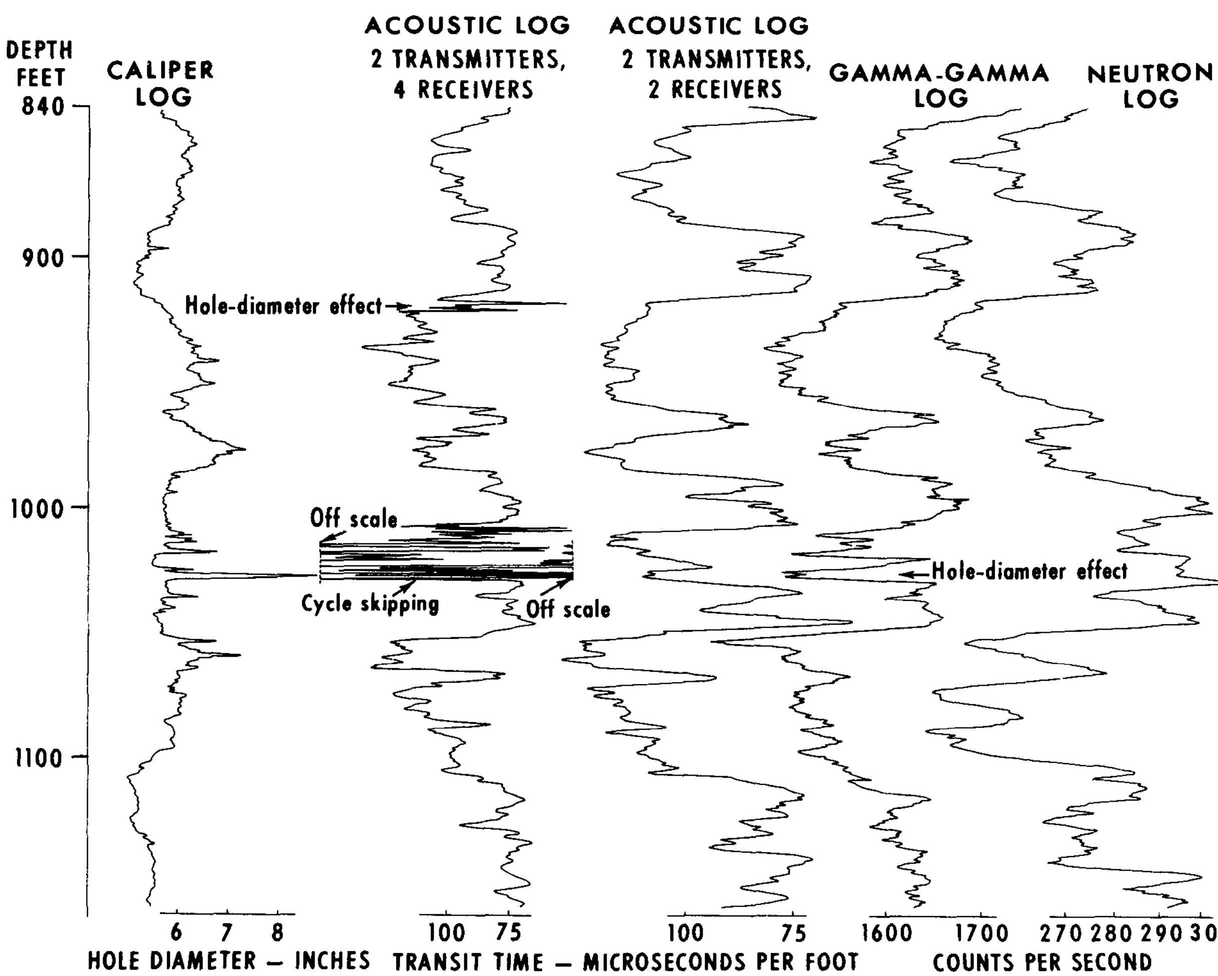

Figure 59. — Three porosity-related logs. Note the cycle skipping on the commercial acoustic log and the hole-diameter effect on the USGS gamma-gamma log.

and upon the elastic characteristics and properties of the interstitial fluids (Jenkins, R. E., 1960). The widely used time-average equation (p. 89) has been criticized because it does not account for most of these factors. Most of these characteristics are unknown unless considerable sample analysis has been done, and, therefore, calculation of correction factors would be impossible even if the necessary equation were available. The time-average equation is an approximation; nevertheless, it has been found to produce satisfactory porosity figures under most conditions. The time-average equation is recommended to be used only after the results have been checked by means of adequate samples in each geologic environment. Correct values for porosity are most likely to be ascertained when several types of porosity logs are run, as shown in figure 59.

Caliper Logging

The caliper log is a record of the average diameter of a drill hole. Its major use is to evaluate the environment in which other logs are made in order to correct them for hole-diameter effects and to provide information on lithology.

Principles and applications

Continuous logging of the average diameter of drill holes is one of the most useful and simplest techniques in borehole geophysics. Most caliper sondes consist of one to four pads, or bow springs, or feelers which follow the wall of the hole. The graphic record, calibrated in inches, is the average hole diameter. Averaging is generally done so that an increase in hole radius in one direction will not cause the recorded increase in diameter to be as great as an equal radial increase that is symmetrical around the axis of the hole. Some commercial calipers have only one feeler and, so, may not give a true picture of an asymmetrical hole. In an elliptical hole, none of the usual feeler configurations will necessarily give a correct measurement of the area of the hole, and independently recording arms are needed. (Hilchie, 1968).

Caliper logs are utilized for the identification of lithology and stratigraphic correlation, for the location of fractures and other openings, as a guide to well construction, and to correct the interpretation of other logs for hole-diameter effects. Most changes in hole size are caused by a combination of drilling techniques and lithology. Drilling factors which can cause changes in hole diameter include: Drilling technique; weight and straightness of the drill stem; volume, pressure, and type of fluid circulated; and length of time the drilling equipment is in the hole. Lithologic factors which will affect the hole diameter include: Type and degree of cementation or compaction; porosity and permeability; bed thickness and vertical distance to adjacent hard beds; size, spacing, and orientation of fractures and vugs; and the swelling or hydration of clay.

Figure 60 illustrates the differences in hole diameter in beds of the same lithology caused by changes in drilling technique. The solid line on the left is the caliper log of a core hole C–1, in the upper Brazos River basin in Texas. The hole was badly washed out during drilling operations, which were designed for maximum core recovery. An adjacent offset hole was drilled rapidly with a tricone rotary bit. The reduction in hole-diameter changes can be seen on the dashed log of T–14. The same lithologic units can be identified on both logs despite the difference in drilling techniques. Note the three anhydrite beds between depths of 100 and 150 feet, which are shown as hard layers where the hole diameter is less than 5 inches. A major fracture system just above 200 feet was recorded as a zone of thin washouts that attained a maximum diameter of 14 inches. The importance of making caliper logs to aid in the interpretation of other logs is demonstrated by the hole-diameter effects on the gamma-gamma logs in figures 47 and 60.

The repeatable detail that can be detected by a sensitive caliper sonde is shown on the right side of figure 61. The two logs were made of core hole C–1 on different dates by

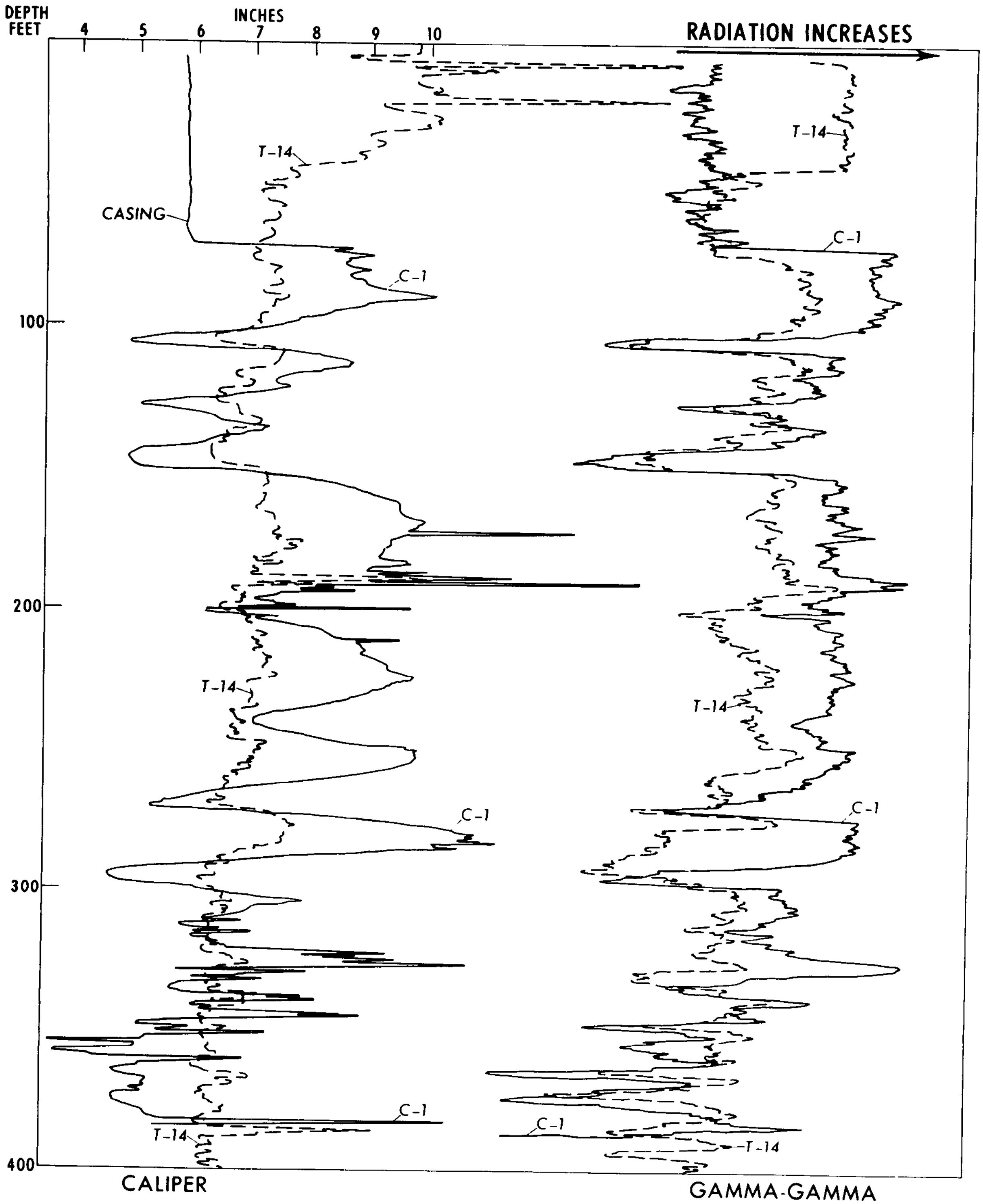

Figure 60. — Effect of drilling technique on hole diameter, and effect of hole diameter on gamma-gamma logs.

different logging operators. Rotary hole T–5 is approximately 3 miles from C–1; yet, a fracture zone was recorded in approximately the same stratigraphic position. The difference in the drilling techniques is evident from a comparison of the caliper logs. In both holes, however, the very hard anhydrite beds in the upper part of the holes remained approximately bit size. The fracture zone also caused similar amplitude deflections on the caliper logs, even though there were differences in drilling technique. The fracture zone in T–5 was found to be the main source of brine and gas in the hole. Correlation, using caliper logs, of the lithology and fractures is substantiated by the single-point resistance logs shown on the left in figure 61. Anhydrite beds are interpreted from logs by their high resistance and small hole diameter, and fractures are interpreted by their low resistance and large, irregular hole diameter.

The location of fractures in igneous and metamorphic rocks and of solution openings in limestone is an important use for the caliper log. Figure 14 shows several logs made in a hole cored in granite in Clear Creek County, Colo. Information on the fault and fracture zones and the water-bearing zones (right of the spontaneous-potential log) was obtained from core, pump, and packer tests. The caliper sonde detected most of the fracture zones found in coring and was particularly effective in showing the main water-bearing zone between 680 and 800 feet deep. The fracture zones on the electric logs that were not detected by the caliper might have been recorded, if shorter arms and a higher sensitivity had been used. In the Snake River Plain, Idaho, the sensitivity of a three-feeler caliper was found to be sufficient to detect the scoria and vesicles which mark the top of basalt flows. Further, a caliper log can be run with enough sensitivity to pick joints in casing and to distinguish between smooth, new casing and rough, corroded casing.

Caliper logs were one of the first successful means of identifying and correlating aquifers in the Snake River Plain (Jones, 1961). Cinder beds and unconsolidated sediments in this area cave badly during cable-tool drilling. Vibrations of the drill bit cause caving of sediments that occur above layers of hard basalt. Beds of unconsolidated sediments above the water table continue to cave

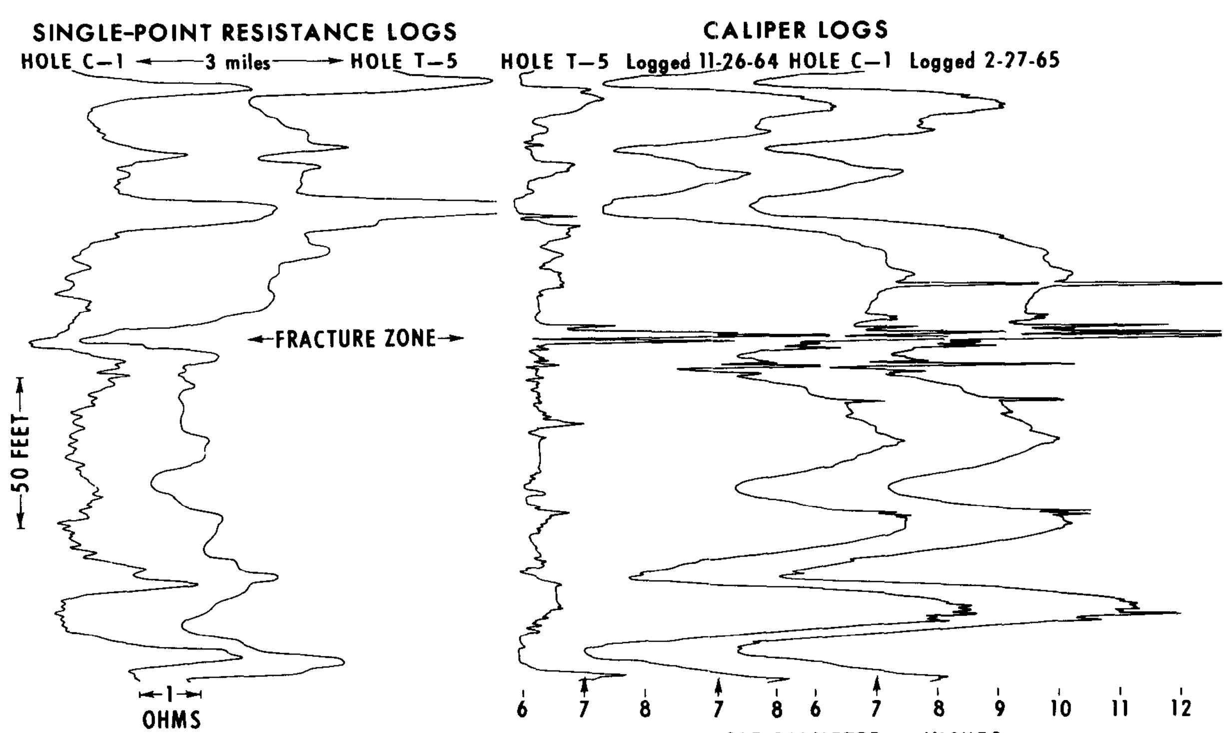

Figure 61.—Correlation of fracture zones between rotary hole T–5 and core hole C–1 from caliper logs. Note the repeatability of caliper logs made on different dates in hole C–1.

as a hole is deepened because of the water poured in the hole during drilling. In the Snake River Plain, caliper logs were also used to determine the best place to seat the casing for cementing and to estimate the volume of the annulus to be filled (Keys, 1963). The caliper logs in figure 46 were used to select a depth of 460 feet for seating the casing to be cemented because only a few caved sediment zones were found just above this depth. The high permeability of some sediment zones allows lateral movement of grout and prevents fill-up of the annulus.

An accurate caliper log can be used to determine the size of casing a hole will accept, and to what depth it can be set. Caliper logs are also extremely useful for calculating the annulus volume for effective gravel packing. Annulus fill-up with much less than the calculated volume of gravel would be indicative of gaps not properly filled with gravel. An accurate caliper log is also essential for selecting seats for straddle or isolation well packers. All packers have an effective operational range of hole diameters. A packer either will not set, will blow out, or will leak when inflated in a portion of the hole that is too large. Furthermore, a caliper log will locate fractures in hard rock that may permit flow to bypass the packer or cause it to blow out. Packers should never be set in rough, irregular parts of a hole.

Caliper logs are essential for quantitative interpretation of flowmeter logs or tracer work measuring vertical flow. All vertical in-hole flow measurements must be corrected for changes in the hole or in the casing diameter.

In sequences of detrital sediments that are poorly to fairly well consolidated, the massive sands and sandstones are generally closer to bit size and produce a smoother hole than do the clays and shales. Thin beds are partly responsible for the sharp, closely spaced caliper deflections that are common in shale. Shale and compacted clay tend to become hydrated and to swell and slough into a hole that is drilled with water-base mud (Jones and Skibitzke, 1956). Processes of this type may continue long after a hole has been completed and cause progressive changes in the hole diameter. Mud squeezes can be recognized on the caliper log by the areas that are significantly smaller than bit size, and, frequently, the mud squeezes cause the caliper arms to close all the way. In addition, mud squeezes can completely close a drill hole and can even cause the loss of logging sondes. Mud rings or mud cake build-up can also cause hole diameters to be less than bit size, but do not necessarily indicate a caving hole.

Mud cake build-up on the wall of the borehole may be related to the porosity and permeability of the rocks, and thick mud cake can be detected with a caliper log. Most drilling muds are a suspension of clay particles in water, and higher pressures in the hole cause the water to invade the rock and leave a layer of clay or mud cake on the wall of the hole. Whether a caliper will cut through or ride on top of a mud cake depends on the pressure exerted on the springs or feelers. Some pad-type devices are designed to ride on top of the mud cake.

One of the most important applications of caliper logs is aiding in the correct interpretation of other logs. Most logs that respond to lithology are also affected by changes in hole diameter. Figure 61 shows this effect on gamma-gamma logs. Changes that are consistent over a thick interval, such as those caused by a change in bit size, can be corrected by use of empirically derived charts. In general, the changes in the log response caused by borehole rugosity cannot be corrected, and very rough zones seen on caliper logs should be eliminated from quantitative-log interpretation.

Instrumentation

Two basic types of measuring systems are used in caliper tools—arms or feelers hinged at the upper end and maintained against the hole wall by springs, and bow springs fastened at both ends. The arm-type device is much more sensitive than the bow-spring device, which may span washed out or fracture zones. Most feelers also exert a higher pressure than bow springs. The caliper logs in the center of figure 47 can be compared with a log on the left, made with a one-arm pad-type caliper, and with a log made with the three-arm probe used on most Geological Survey loggers. Devices employing small-diameter feelers have a much greater vertical resolution than either the pad or bow-spring probes. If a hole is round, all types of calipers should give the same log. In asymmetrical holes, one- or two-arm calipers will generally measure a larger diameter than three- or four-arm calipers. If asymmetry is important, dual-type calipers that make independent measurements should be used (Hilchie, 1968). Both types of tools use the feelers to change the resistance of a potentiometer, which is monitored by voltage changes at the surface.

Motor-driven feelers have proved to be the most dependable means of opening the arms, although heavy mud or sand in the mechanism will occasionally prevent them from opening. A DC motor in the tool can be operated at any position in the hole, and a light on the caliper module indicates when the arm-drive mechanism has reached the end of its travel. By reversing the DC polarity, the arms can be closed at any time, thus permitting the tool to travel downhole and to relog without returning to the surface. An early device that opened the feelers when the sonde was bounced on the bottom of the hole was not satisfactory because the bottoms of drill holes are generally filled with soft mud and loose drill cuttings. Another type of caliper tool uses an electric blasting cap to break an arm-retaining wire, thus permitting the arms to open. This system does not always work, and any relogging necessitates returning the tool to the surface for time-consuming rewiring. A system that does not permit closing the feelers in the hole means that the open caliper must be dragged through the entire cased part of the hole, causing excessive arm wear. Also, it is not always possible to pull an open caliper into a small-diameter pipe or drill stem with the arms open. In addition to the controls for opening and closing the feelers, preselected scales, or a variable scale having independent zero positioning and span, are provided.

Caliper tools are available for small loggers that will measure hole diameters up to 42 inches; however, arms that are longer than necessary reduce the sensitivity. In addition, with long arms, the measuring point or depth will differ significantly from the nearly closed position to the fully open position. Feeler-type calipers are generally provided with interchangeable arms of several different lengths. The arms should be selected on the basis of the hole-diameter range expected and the type of information desired, and the basing and span adjustments should be made to satisfy these same requirements.

Spring pressure on the feelers is a factor in caliper tools, inasmuch as inadequate pressure will not force the arms to a fully open position in heavy mud. Spring pressure will also affect the degree of penetration of mud cake. Obviously, long arms will require a stronger spring pressure in the tool to achieve the same force at the ends of the feeler.

Calibration and standardization

Calibration of caliper tools should be done in cylinders of different sizes that contact all the feelers. Because it generally is not feasible to carry many cylinders in a logging truck, a board-type standard may be used, instead. The board consists of a large hole, to fit the body of the sonde, and small holes, drilled to accept a single feeler, in order to simulate the various hole sizes. Rings may also be used, but if they are made of rod stock, they are difficult to use. The correction factor between the field standards and the use of a one-feeler calibration board and calibration cylinders must be established if very accurate measurements are required.

Before logging a hole, the basing and sensitivity adjustments and field standard should be used to set up or to verify the logging span desired. One inch of chart width per inch of hole diameter was found to be sufficiently sensitive for fracture location and is an easy scale to use. Standard measurements should be plotted directly on the log, and enough points should be plotted to establish the linearity of system response. If any system drift is suspected, several points should also be plotted on the caliper log after the tool is removed from the hole. It is also desirable to log at least 20 feet of casing before closing the tool as a further check of the calibration and as an indication of the electronic noise on the log.

Radius of investigation and extraneous effects

The radius of investigation of a caliper is the point at which the feeler touches the borehole wall. The caliper has a more nearly unique response than most other logging devices. Instrumental malfunctions are more likely to cause spurious log response than are the borehole parameters. Heavy mud can prevent the tool from opening, and mud cake can prevent the feelers from reaching the wall of the hole. However, temperature drift and cable leakage are much more frequent sources of anomalous log response.

Temperature Logging

Temperature logs are the continuous records of the temperature of the environment immediately surrounding a sensor in a borehole. They can provide information on the source and movement of water and the thermal conductivity of rocks.

Principles and applications

Most temperature logs are continuous records of the thermal gradient of the fluid in a borehole, and are made with a single sensor moving down the hole. Most commercial logs are recorded in degrees Fahrenheit. Recently, some of the WRD logging equipment has been calibrated in degrees Celsius. The temperature recorded is only that of the fluid surrounding the sensor, which may or may not be representative of the temperature in the surrounding rocks. The geothermal gradient may be derived from a temperature log if the fluid in the well is in thermal equilibrium with the adjacent rocks and if there is no vertical circulation of fluids in, or adjacent to, the well bore. Such static conditions are unusual, but where they occur, the temperature gradient is largely a function of the thermal conductivity of the rocks. Thermal conductivities (calories per second-centimeter-°C) vary from as high as 10 for some types of sandstone, and range from 4.8 to 8.1 for limestone, and from 2.2 to 3.9 for clay. In most wells the geothermal gradient is considerably modified by fluid movement in the borehole and adjacent rocks. A geothermal gradient measured under completely static conditions is one extreme, and no gradient produced by a very high flow rate through the hole is the other extreme. All logs fall between these extremes. In general, the geothermal gradient is steeper in rocks with low permeability than in rocks with high permeability, possibly because of ground-water flow. This relation offers a potential interpretation of thermal data to determine lithology or the relative magnitude of permeability. Typical geothermal gradients are between 1° and 1.3°F per 100 feet of depth. The depth-temperature relation is also reported as reciprocal gradient, or the depth interval per degree.

Seasonal recharge to the ground-water system may be reflected in cyclic-temperature fluctuations, and the vertical movement of water in the unsaturated zone can be investigated with very sensitive temperature sensors (Stallman, 1965). Temperature logs may also be used to identify aquifers or perforated sections contributing water to a pumped well. Water in different aquifers is seldom the same temperature. Where two aquifers contribute water of different temperatures to a well, it may be possible to estimate the relative contribution of each zone from the temperature of the well discharge.

Figure 62 shows a series of temperature logs of an unsuccessful oil well that was drilled and then plugged near Anchorage, Alaska. It was decided to jet-perforate the casing at intervals, selected from geophysical

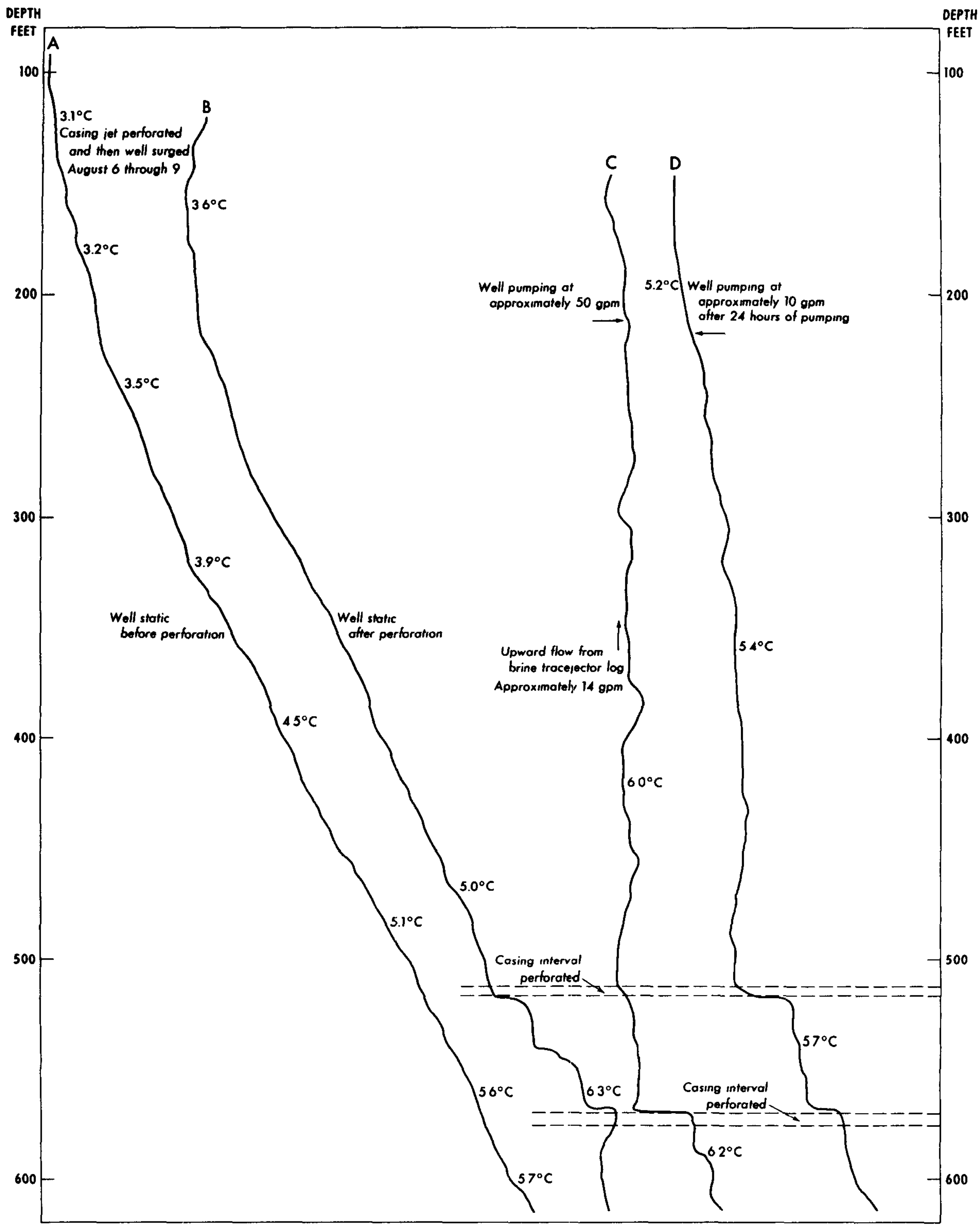

Figure 62.—Temperature logs, Yukon Services well, Anchorage, Alaska.

logs, for selective aquifer testing with a pump and packer. Log *A* was made after the 9⅝-inch casing had been filled with water and allowed to stabilize for several months. Above 150 feet, the temperature gradient was small, apparently because of significant ground-water circulation. The gradient below this interval was typical of that logged in oil wells in the Cook Inlet field. Log *B* was made after the casing had been perforated and after the well had been surged and bailed for several days. The perforated intervals between 500 and 600 feet are clearly distinguished; however, temperature log *B* did not indicate two deeper intervals that were also perforated. Nonetheless, logs *B* through *D* suggested that some warmer water from the deeper aquifers did move up the well during development and pumping. Log *C* shows that most of the water moving up the casing at 14 gpm was coming from the 575-foot-deep aquifer. The flow rate was determined from brine tracejector logs. (See section on "Fluid-Movement Logging.") Brine-tracer logs and neutron logs showed a casing leak at about 115 feet that was contributing most of the water pumped. (See fig. 52.) Temperature log *D* shows that, after pumping for about 24 hours, the aquifer at 515 feet had developed and was contributing some water.

Temperature logs can be extremely useful in identifying recharge water or liquid wastes discharged to the ground. Olmsted (1962) mapped the temperature distribution of ground water from wells logged at the NRTS (National Reactor Testing Station) in Idaho. He attributed the zones of warm water, some of which are coextensive with chemical changes, to hot-spring sources, lower permeability rocks, and (or) recharge from excess warm irrigation water. Zones of cooler ground water in the Snake River Plain aquifer may be related to recharge from cold surface water. Temperature logs permit the identification of warm waste water, discharged through a well at the NRTS, as it moves downgradient in the aquifer (Jones, 1961). Water injected into a well at a temperature of 62°F attains the normal ground-water temperature of 52°F within 1.5 miles downgradient. Temperature logs clearly show the horizontal and vertical dispersion of warmer water from the discharge well. Temperature logs can be used to locate an unknown source of thermal pollution. Further, the temperature distribution around a disposal pond at the NRTS is apparently related to the velocity of the ground-water movement.

Figure 63 shows a series of temperature logs made during artificial recharge of the Ogallala Formation near Lubbock, Tex. The recharge water was obtained from a nearby playa lake and fed to a well by gravity at 100 gpm for 24 hours. The recharge water contained about 700 ppm suspended sediment and had an initial temperature of 22°C compared with 17°C for the ground water. The casing in the recharge well was slotted for its entire length, and the well was gravel packed. Auger holes were drilled at various distances from the well and cased with 2-inch-diameter pipe equipped with well points. The logs shown in figure 63 were made in auger hole H–3, which was 6.5 feet from the injection well. Recharge was started at 1600 hours, and temperature logs *A* and *B* show that the water reached auger hole H–3 between 1615 and 1628 hours. The zone of maximum velocity at 105 feet coincides with the interval of lowest clay content indicated by the low natural-gamma intensity. The recharge water gradually spread vertically through the sand until it reached the top of the underlying clay (logs *C* and *D*). The well lost approximately one-half of its specific capacity during the test, and gamma-transmittance logs made before and after recharge suggested significant plugging by sediment at a depth of 105 feet.

Because of the effect of temperature on electrical resistance, temperature logs are necessary for the correct interpretation of resistivity logs. Alger (1966) showed the magnitude of this correlation (fig. 2). Spe-

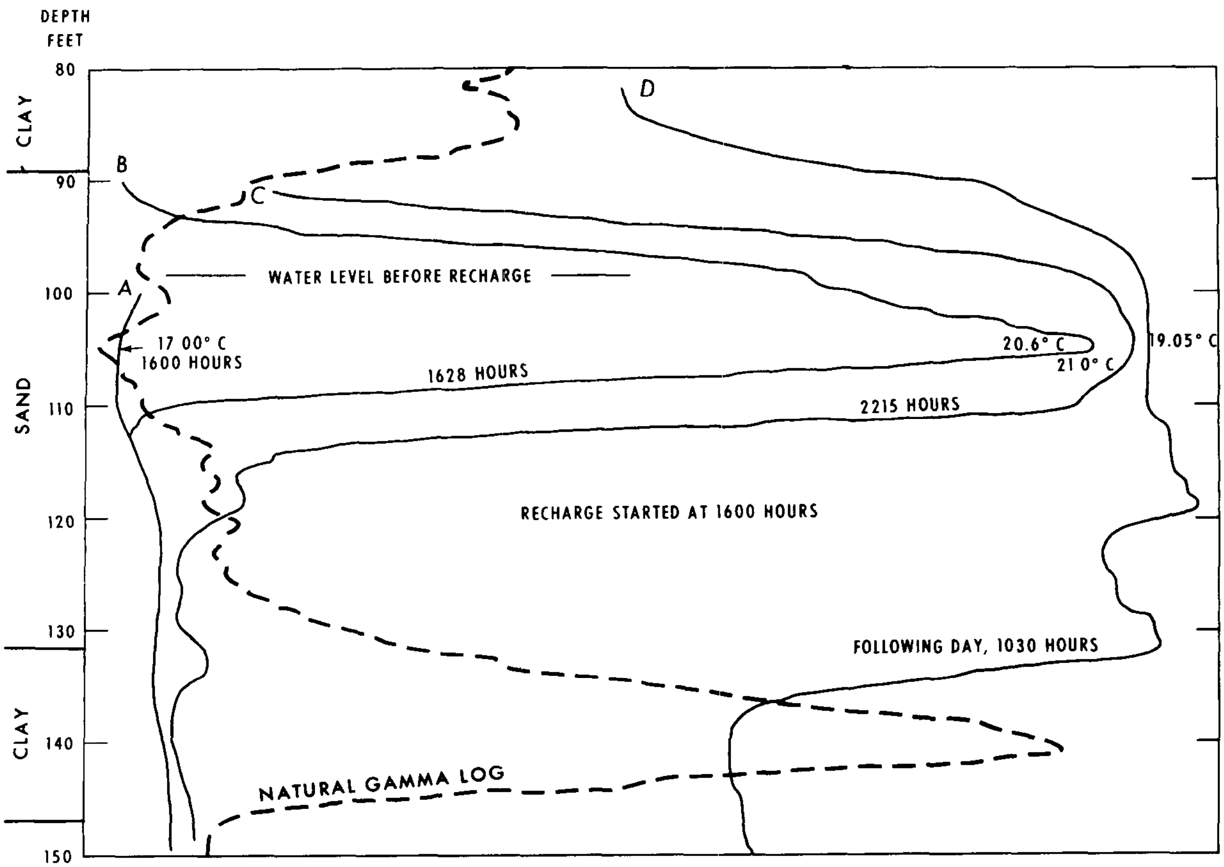

Figure 63. — Temperature logs during artificial recharge, auger hole H–3, Hufstedler well, near Lubbock, Tex.

cific conductance may be calculated from fluid resistivity and temperature logs. The density and viscosity of water are very important characteristics affecting its movement, and they are related to temperature (figs. 64, 65; Olmsted, 1962). The importance of viscosity is emphasized by Jones and Skibitzke (1956) who pointed out that an aquifer having an effective permeability of 2,000 meinzers at 60°F has an effective permeability of about 3,200 meinzers at 100°F.

Temperature logs are also used to determine the location of grout outside the casing after cementing a well (Keys, 1963). For this purpose, the well should be filled with water to a level considerably above the expected top of the grout, and a temperature log should be run within 24 hours of cementing. With a temperature tool, it is possible to detect grout for several days after cementing. Anomalous temperatures may prevail for longer periods, but log interpretation becomes more difficult. The temperature anomaly should be greater where there is more cement behind the casing. A neat portland-cement grout should have a temperature of 160°F after 4 to 8 hours and should have a temperature of 100°F after 8 to 12 hours at shallow depths, where the normal borehole temperatures are considerably below 100°F.

The differential-temperature log utilizes a different measuring principle than the temperature log and offers a potentially greater sensitivity. The differential system detects the difference in temperature over a fixed interval of depth. Differential-logging systems are of two types. One system uses two thermal sensors that are spaced from 1 to several feet apart along the axis of the sonde (Basham and Macune, 1952). This type of tool is shown on the right in figure 66. The differential-temperature log illustrated is a record of the temperature difference between the two sensors. Another type of differential

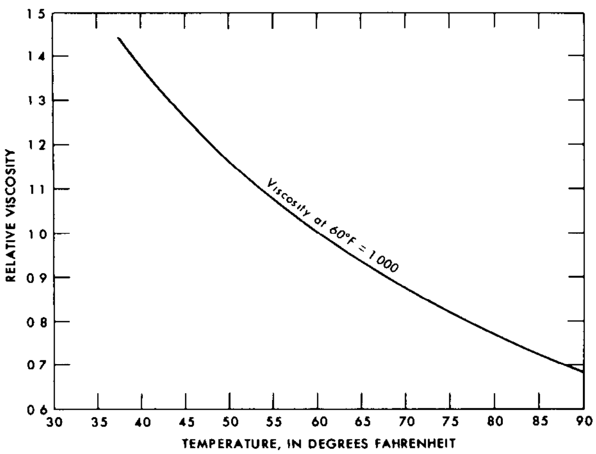

Figure 64. — Relation of viscosity of water to temperature. From Olmsted (1962).

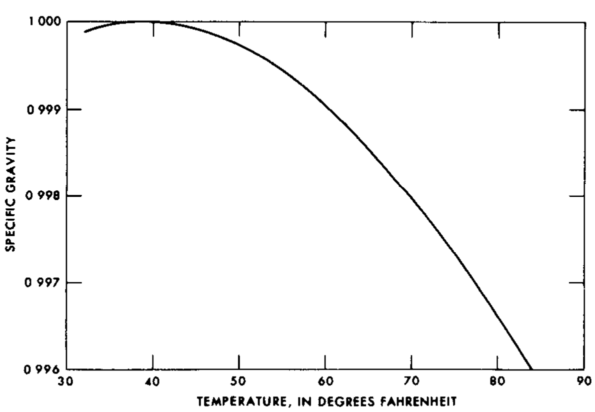

Figure 65.—Relation of specific gravity of water to temperature. From Olmsted (1962).

system uses one sensor and an electronic memory, so that the temperature at one time can be compared with the temperature at a selected previous time (Johns, 1966). With either tool the recorder response may be set at zero in a reference-temperature gradient in the borehole. In this way the log will demonstrate a passive response to the reference-temperature gradient and an active response to changes in gradient. Any changes from reference gradient should be recorded as sharp deflections from a baseline, as shown on the hypothetical curve in figure 66. The differential log can be considered as the first derivative of the temperature. Note the difference in sensitivity between the temperature log and single-sensor differential-temperature log run near Roswell, N. Mex. The sharp change in gradient at a depth of about 340 feet seems to be related to the increase in porosity shown just below this point on the neutron log.

A temperature log should always be run simultaneously with a differential-temperature log. This not only provides the actual temperature values, but often the first log made down the hole is the only one that is correct because passage of the tool disturbs the fluid column. Preselecting the temperature range for logging is difficult because the temperature is generally not known; yet, a sensitive scale is desirable. Figure 67 shows repeat temperature logs and dual-sensor differential-temperature logs in a deep well in Colorado. The left trace shows the temperature log on a sensitive scale. The numerous changes in zero positioning, or basing, necessary to prevent the pen from going off-scale, make the log very difficult to decipher. The log was reconstructed in the office to produce the smooth trace shown (second curve from left). The depth interval from 1,780 feet to 2,100 feet is shown as the third enlarged curve from the left. Both the temperature gradient and the differential-temperature logs repeated very well from the first to the fourth logging traverse through the interval. All the temperature logs had to be reconstructed to be interpreted, but the differential-temperature logs are understandable as is. The gradual changes on the temperature log are sharply accentuated on the differential-temperature log, and the repeatability of minor changes is good. Good log repeatability suggests that disturbances by the logging sonde had a negligible effect on temperature distribution. In many holes the thermal logs do not repeat very well, and the fluid must be allowed to return to equilibrium before logging is repeated. Gas entering a well generally produces a significant thermal anomaly, and, although this is not a common occurrence in water wells, gas-produced thermal anomalies occasionally occur in deeper test holes (Van Orstrand, 1918). This may be the explanation for the low-temperature anomaly shown at a depth of 1,750–2,100 feet in figure 67.

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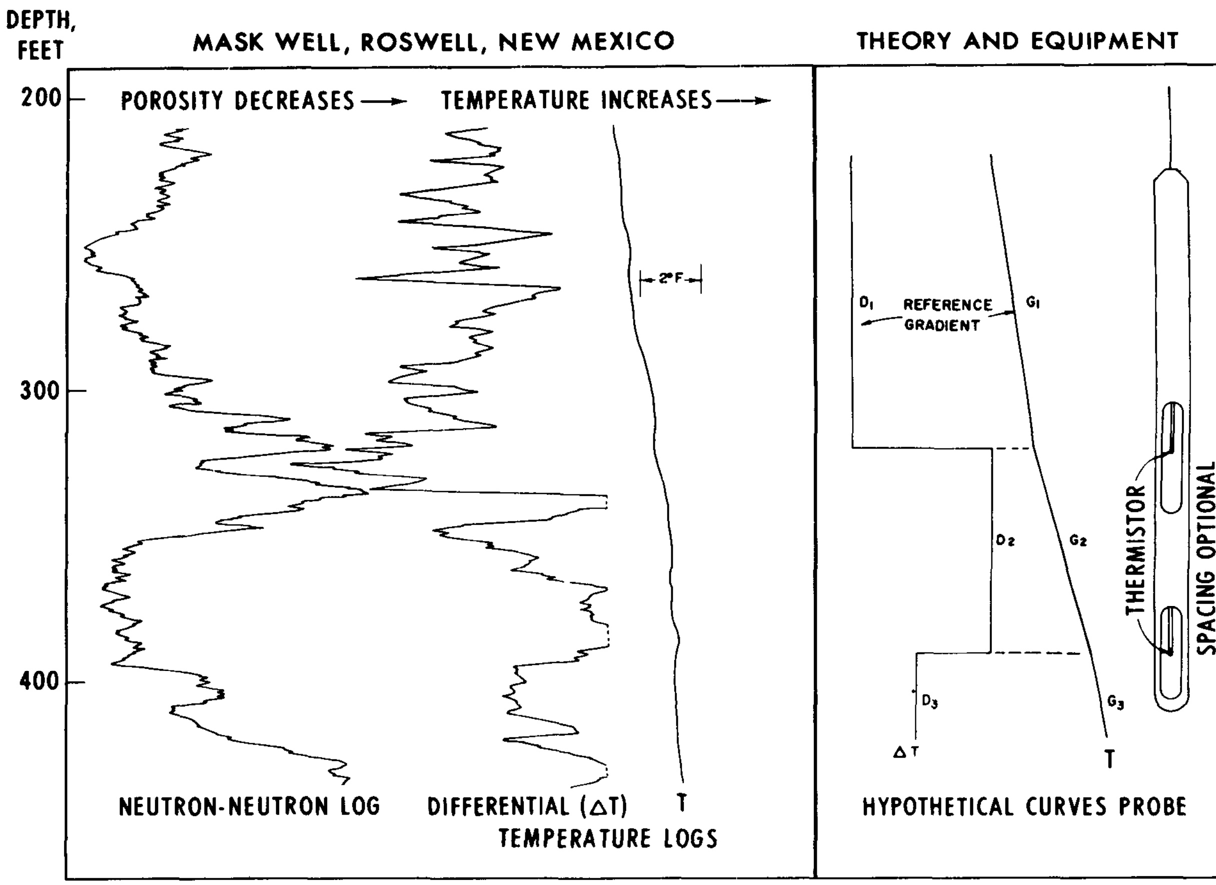

Figure 66. — Principles, equipment, and examples of differential-temperature logging.

The greater sensitivity and the sharp deflections provided by the differential technique suggest the possibility of using water as an inhole tracer. Water may be injected in a well and a series of time-lapse differential-temperature logs used to locate the zones accepting the water. Basham and Macune (1952) reported that the difference in temperature between the cooler, injected water and the water of normal temperature below an aquifer is proportional to the total flow accepted by the aquifer. Their tests also showed that the differential system was sensitive to a flow of a fraction of a gallon per minute leaving the borehole. Temperature logs made shortly after a well is drilled may indicate the location of deeply invaded zones by means of temperature anomalies. Similarly, a series of time-lapse logs before, during, and after a pumping test will at least indicate the base of the lowest producing aquifer. (See fig. 62.)

Instrumentation

Basically, temperature-logging sondes contain a thermistor whose internal electrical resistance changes in response to temperature changes. A thermistor is a glass-insulated semiconductor that has a negative temperature coefficient of resistance. A small current must be fed through the thermistor, in order to measure changes in resistance, and if this current is too high, self heating will occur, and, consequently, an error will be introduced. Any material used to enclose the thermistor or other sensor should have a high thermal conductivity and a small mass in order to reduce the thermal-response time. Furthermore, thermal conductivity between the sensor and body of the probe must be minimized. The sensor is generally mounted inside a cage or tube to protect it and to channel the fluid past the sensor. These tubes are usually constructed such that they are

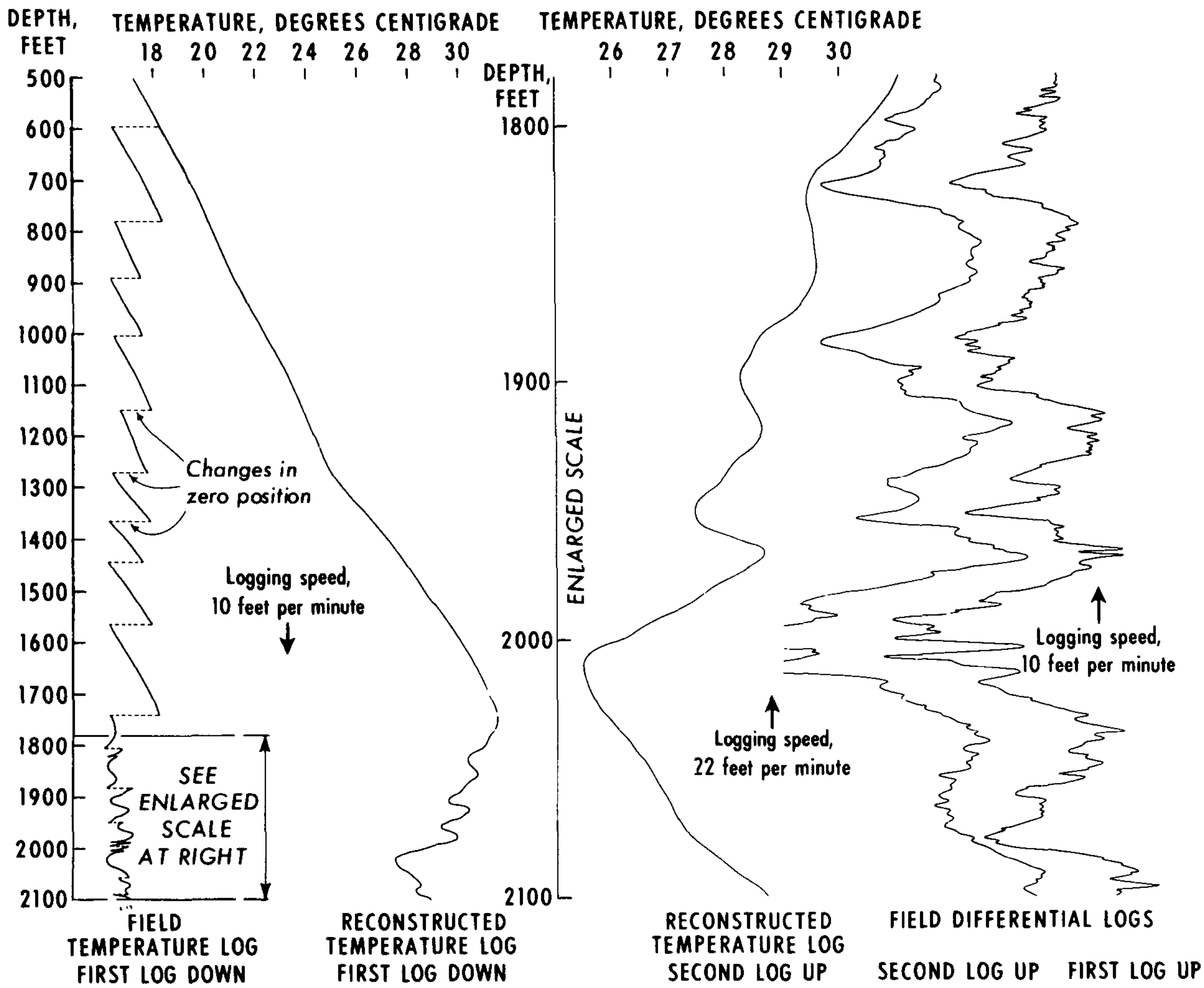

Figure 67. — Field- and reconstructed-temperature logs (left). The interval from 1,780 to 2,100 feet is enlarged (right) to show the detail and repeatability of differential-temperature logs.

more effective in channeling the fluid past the sensor when logging down a hole. Electronics should be designed so that the changes in resistance elsewhere in the circuit or logging cable have a negligible effect on the readout. Important controls are zero positioning and sensitivity or span, which may either be continuously adjustable or be included in a scale-selector switch.

Each temperature sensor and probe has an inherent response lag, or time constant, so that logging speed must be constant and slow enough that temperatures are accurately reflected at true depths on the log. A single tool that makes simultaneous logs of fluid temperature and resistivity is now available commercially and offers the advantage of measuring both of these fluid parameters before they are disturbed by subsequent passes of the sonde.

Calibration and extraneous effects

Many thermistors and other types of temperature sensors are supplied with calibration data in terms of resistance as a function of temperature. An accurate thermometer is used in a stabilized fluid bath to determine whether these values are correct. When the relation between temperature and resistance is properly determined, a single standardization technique will suffice for accurate logs. A resistance-decade box can be substituted for the thermistor to check the response of the entire logging system and to place standardized values on each log. Field standardization is particularly important because of the possibility of drift of the electronics in the hole or at the surface in response to changes in environmental temperature or AC voltage, or frequency.

In addition to instrumental effects, such as thermal lag, selfheating, and drift of electronics, borehole conditions can cause significant errors in the interpretation of temperature logs. Drilling, cementing, and testing disturbs the thermal environment of a borehole, and considerable time (up to several years) may be necessary for equilibrium to be attained. Furthermore, the borehole fluid is disturbed during logging. Consequently, fluid-temperature and fluid-conductivity logs should always be run down the hole before any other logs are run. If more than one log is run, the first log down the hole should be considered the most nearly representative of equilibrium conditions.

Convection in a well can cause significant disturbance of the thermal gradient, particularly in large-diameter wells. Krige (1939) indicated that the critical temperature gradient above which convection occurs in the absence of viscosity is

$$\frac{g \alpha T}{cp},$$

where

g = acceleration due to gravity;
T = absolute temperature;
α = coefficient of thermal expansion; and
cp = specific heat at constant pressure.

When viscosity is considered, the critical gradient becomes

$$\frac{Cvk}{g \alpha a^4} + \frac{g \alpha T}{cp},$$

where

v = kinematic viscosity;
k = thermal conductivity;
a = radius of the borehole; and
C = a constant, which is 216 for a hole whose length is great compared to its diameter.

Sammel (1968) plotted critical thermal gradients as functions of temperature, dissolved-solids content, and well diameter. He also reported the results of field and laboratory tests and concluded that convection may cause temperatures in the upper zone of deep wells to depart widely from ambient temperatures in the formations penetrated.

This relationship is not only important in temperature logging, but can be responsible for introducing an error in tracer measurements of very slow flow in a hole.

Differential-temperature logs can display two unique types of errors. The log from a two-sensor probe can be inaccurate because the first sensor disturbs the thermal environment of the fluid through which it passes. The memory type of differential device is based on the principle that time between the stored and the actual temperature is a function of the depth interval traversed. Error is introduced if the logging speed is not constant.

Fluid-Conductivity Logging

Fluid-conductivity logs provide a measurement of the conductivity of the inhole liquid between electrodes in the probe. After appropriate corrections, the logs provide data on the chemical quality of fluid in a borehole.

Principles and applications

Fluid-conductivity logs are a continuous record of the conductivity or resistivity of the fluid in the borehole, which may or may not be related to the conductivity of fluids in the adjacent rocks. The most common sonde measures the AC-voltage drop across two closely spaced electrodes, which is a function of the resistivity of the fluid between the electrodes. Fluid resistivity is generally measured in ohm-meters, the same unit used for rock-resistivity logs. Use of the same units simplifies calculations involving the two logs. Logs may also be recorded as the reciprocal of resistivity—that is, conductivity. Conductivity is measured in micromhos per centimeter, which is equal to 10,000 divided by the resistivity, in ohm-meters. Logs of the borehole fluid are called fluid conductivity in this manual to avoid confusion with resistivity logs, which measure the rocks and their interstitial fluids. A temperature log made simultaneously with the fluid-conductivity log allows the most accurate conversion to specific conductance because it eliminates the possibility of measuring a fluid column disturbed by the first trip down the hole. Conductivity can be converted to specific conductance at the standard temperature of 25°C or 77°F, using figure 68 (from Olmsted, 1962). For example, a conductivity of 700 μmhos/cm at 50°F would equal a specific conductance of about 1,000 μmhos/cm for a NaCl solution. Jones and Buford (1951) presented a similar graph to convert resistivity to standard temperature.

The relationship of resistivity and temperature for a pure NaCl solution is shown in figure 2 (Alger, 1966). The NaCl content, in milligrams per liter (mg/l), can be read directly from the chart if both the fluid resistivity and the temperature are known. A resistivity of 10 ohm-meters indicates a NaCl concentration of 375 mg/l at 100°F and 760 mg/l at 50°F. A list of factors to convert other salts to a NaCl equivalent is given on page 8.

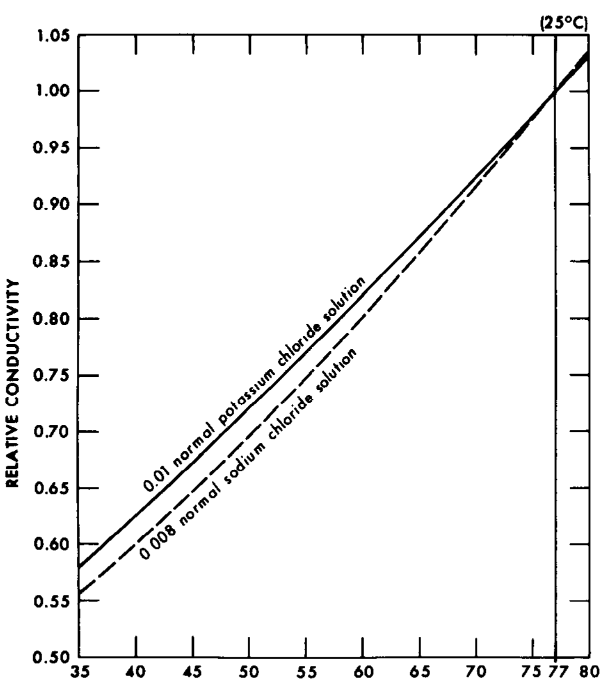

Figure 68. — Relation of electrical conductivity to temperature in dilute solutions of potassium chloride and sodium chloride. From Olmsted (1962).

Fluid-conductivity logging was first used in ground-water investigations by Livingston and Lynch (1937) of the U.S. Geological Survey in 1930. They developed and used conductivity equipment to locate salt water leaking into artesian wells in Texas. Fluid-resistivity or conductivity logs are widely used to determine water quality in wells and to aid in the interpretation of standard electric logs. Spontaneous-potential logs and most types of resistivity logs are affected by differences in the conductivity of fluid in the borehole. Electric logs are generally made shortly after the drilling of a well has been completed. Rotary-drilled holes are filled with a mud, which may be segregated by gravity; therefore, the fluid column will exhibit a gradual change in resistivity with time and depth. The resistivity of samples of circulated mud does not give information on this condition, which can seriously affect the quantitative interpretation of electric logs.

Olmsted (1962) gave some excellent examples of the relationship between the chemical character of ground water and the sources and movement of that water. There is no known way to directly calculate the concentration of specific dissolved ions in water from conductivity. However, if water samples analyzed in the laboratory show a consistent relation between dissolved solids and specific conductance for a given aquifer, the correlation may be useful in interpreting regional water-quality patterns from logs (Jones and Buford, 1951). Conductivity logs also provide a rational basis for selecting depths for the collection of water samples. Information from fluid-movement and (or) multielectrode-resistivity logs is necessary to determine whether the water measured by fluid-conductivity probes is representative of the water in the surrounding rocks. Logs also provide a convenient and inexpensive way of vertically and horizontally extrapolating water-sample data from a well, and they indicate temporal changes in quality.

Fluid-conductivity logs may be used in

the same general way as fluid-temperature logs to locate the source of water in producing wells, or to locate the most permeable zones under injection conditions. The source of water can be determined only if detectable differences exist between the conductivities of water in several aquifers. Injecting saline water in a well and following it with a fluid-conductivity probe is an inexpensive means of determining the relative magnitude of permeabilities, if corrections are made for head. This technique is described in the section on "Fluid-Movement Logging."

Inviolable rules for the interpretation of fluid-conductivity logs cannot be given; the logs must be analyzed on the basis of all available data. For example, a fresh-water–saline-water interface in a well might be at the same depth as a similar interface in the aquifer system, or it might be a residual condition caused by drilling, cementing, or pumping operations. Due to cross flow between aquifers in a multiaquifer well, the fluid-column interface may be related to an interface in the rock at a different depth. Setting of screens at the wrong depth can cause the measurement of fluid conductivities that are not representative of fluid in the aquifer. Figure 69 shows a very sharp interface between the overlying brackish water and the brine. This interface is not shown on the temperature log but can be identified on the neutron log, and it is probably located at the same depth in the fluid column as in the adjacent rocks.

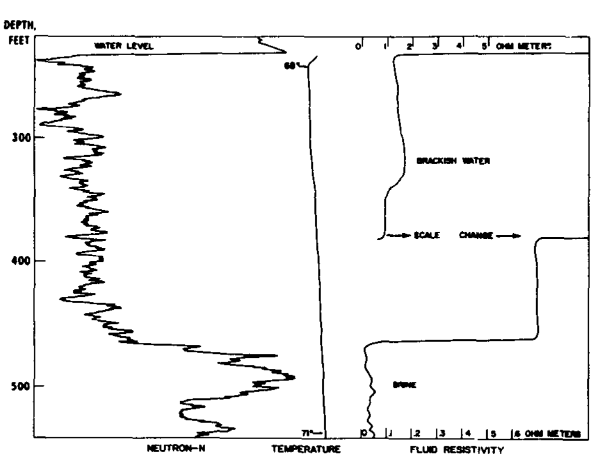

Figure 69. — A brine–brackish-water interface, shown by fluid-resistivity and neutron logs.

Instrumentation

The usual fluid-conductivity probe utilizes two or four ring-type gold or silver electrodes, spaced several inches apart, inside a tube through which the water flows. Gold electrodes are preferable, as they reduce the changes in contact resistance caused by chemical reaction at the electrodes. Probes for multiconductor cable utilize a four-electrode arrangement, as in formation-resistivity logging, and probes for single-conductor cable use two electrodes.

Alternating current instead of direct current across these electrodes tends to reduce electrode polarization. The voltage drop across these electrodes is related to the resistance or conductance of the fluid. An empirically determined constant can then be used to determine the resistivity or conductivity of a unit volume of fluid. Like the temperature sonde, the circuit should be designed so that changes in temperature of the electronics or changes in resistance of the logging cable do not cause inaccurate logs. Pulses can be used to transmit the data from the probe to a frequency-to-voltage converter in the module at the surface, so that cable length will have no effect on the recorded signal.

Fluid-conductivity probes should be run at slow logging speeds to assure the proper flow of fluid through the tool.

Calibration and extraneous effects

Calibration of the fluid-conductivity sonde should always be done in fluids of known conductance and corrected to standard temperature. After the relationship of logger response to conductivity or resistivity is determined, a resistance-decade box can be used for standardization of the logging-system response in the field. Standardization before and after logging is particularly important until the stability of both surface and downhole electronics is known. Recalibration with fluids of known conductivity is necessary only if a change occurs in the contact resistance of the electrodes.

The most common extraneous effect on fluid conductivities recorded on logs is caused by a disturbance of the fluid in the borehole. Fluid-density differences and thermal convection can cause movement of fluid in a completely sealed casing. (See section on "Temperature Logging.") Water in a well may require months to attain chemical equilibrium with the surrounding rocks after drilling or cementing operations are completed. Unlike thermal equilibrium, the changes in water chemistry and, thus, in conductivity require the actual movement of water or ions. It may take longer to reestablish chemical equilibrium than thermal equilibrium after some disturbance. If there is much internal movement of water in the well, equilibrium may never be established.

Fluid-Movement Logging

Fluid-movement logging includes all techniques for measuring natural and (or) artificially induced flow within a single borehole. Data on inhole flow is related to well construction, differences in head, and the relative magnitude of permeability of the water-bearing units open to the well.

Principles and applications

Devices used to measure the vertical and horizontal components of flow in a single well include impeller flowmeters, thermal flowmeters, and various systems for injecting and detecting radioactive and chemical tracers. The impeller flowmeter transmits pulses, which indicate the number of revolutions of the impeller per unit time, whereas the thermal flowmeter detects water heated by an element in the tool. Various tracers are injected in the column of water, and their movement to a detector is timed. (Techniques for measuring flow rate between wells are not considered to be in the field of borehole geophysics and are not discussed here.) Techniques for measuring the natural or induced vertical movement of fluids in boreholes have been widely applied in both oil and water wells. The interpretation of all types of vertical-fluid-movement logs is similar, regardless of whether they are made with impeller, thermal, or tracer probes. Techniques for measuring the horizontal movement of fluids through a single borehole are new and little used to date, but have considerable potential for application to ground-water hydrology.

One of the most common applications of the measurement of vertical-fluid movement is in wells that are open to a multiaquifer artesian system (Bennett and Patten, 1960). If there are differences in head between aquifers, flow will occur within the well. Such flow lowers the head in the contributing aquifer and may result in either thermal or chemical pollution of the aquifer having the lower head. Vertical flow in a well may invalidate pump-test data if not detected. Vertical flow will also complicate sampling for water quality and the interpretation of fluid-conductivity or temperature logs.

An example of the measurement of natural flow in a well with an impeller-type flowmeter is shown in figure 70. This same well was logged with a radioactive-tracer sonde, and the results were similar. The left side of figure 70 shows continuous integrated-flowmeter logs made to locate the zones of flow. In this mode of operation, the logs were run with the sonde moving down and up the hole at a relatively constant logging speed of 40 feet per minute. The individual pulses on these logs are caused by rotation of the impeller. The pulses are integrated, so that a deflection of the trace to the right indicates an increase in revolutions per unit time. If it were possible to maintain the same constant logging speed up and down a hole, and if the position of a symmetrical sonde in the hole were consistent, logs made up and down in a stagnant column of water would be the same. Therefore, the zone of maximum curve separation in figure 70 represents a zone of upward flow. The impeller revolutions increased when the sonde was moving against the upward flow and decreased when the sonde was moving in the same direction as the flow. The deflections on one log not matched by deflections in the opposite direction on the other log were probably caused by changes in logging speed or by the probe bouncing off the casing. When the logs were repeated, only the curve separation between

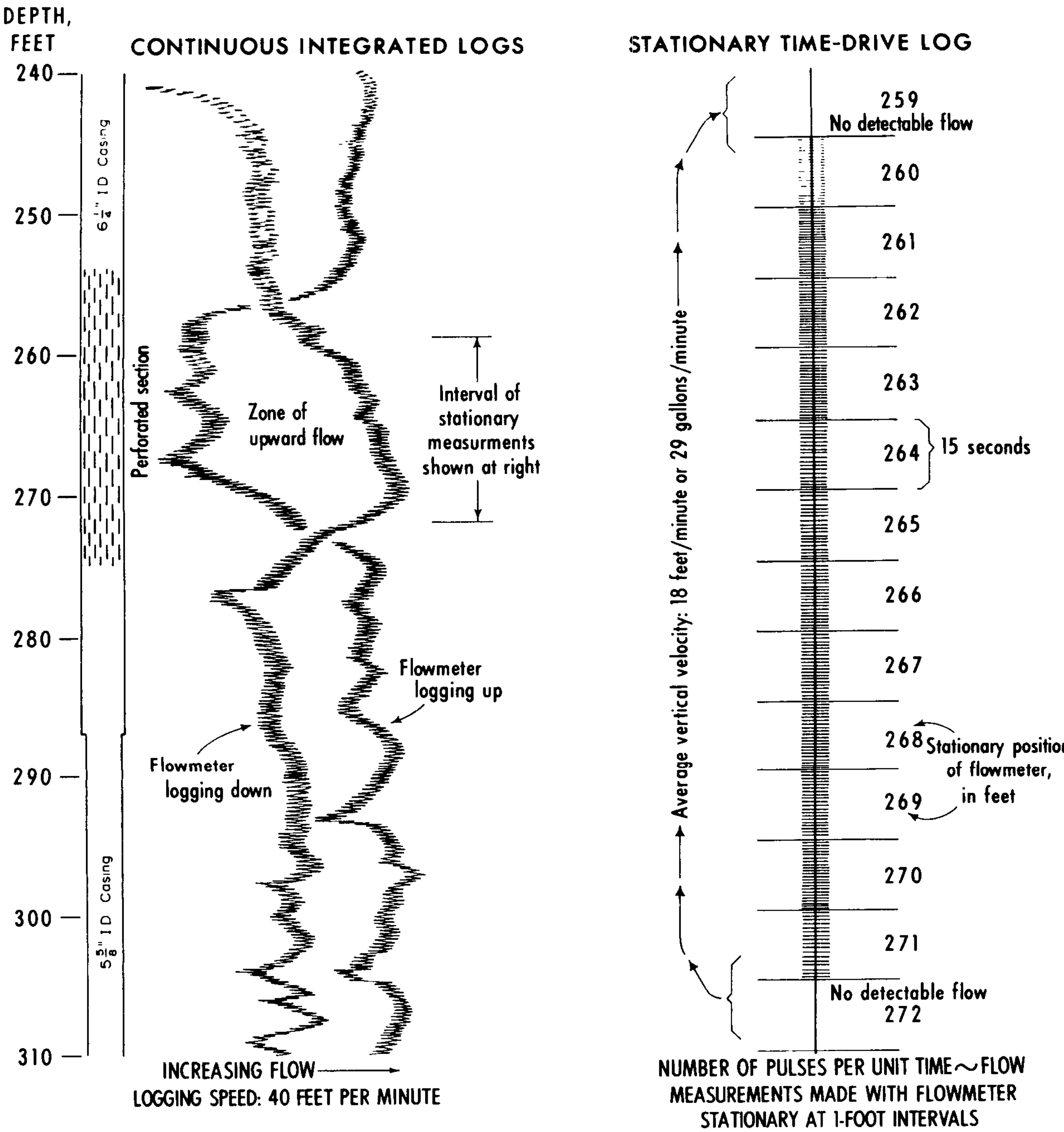

Figure 70. — Continuous flowmeter logs, used to locate the zone of flow (left) and to determine stationary time-drive measurements across that interval (right).

259 and 272 feet were duplicated. By moving the flowmeter, flow can be detected that is too slow to detect with a stationary flowmeter. When the velocity of flow is equal to the logging speed, the impeller ceases to rotate.

The right-hand log in figure 70 shows stationary-flowmeter measurements made through the same zone. In this mode, the recorder on the logger is set to operate on time drive—4 inches per minute on this log—and individual pulses caused by rotation of the impeller are recorded. Note on this log that only minor changes in velocity occurred across the zone of interest. The average velocity, indicated by the movement of radioactive tracers, in the zone from 272 to 259 feet was 18 feet per minute, or 29 gallons per minute. Apparently, all the water was entering and leaving the screen in two very thin zones separated by relatively impermeable material.

A second broad category of application for inhole-flow measurement is to determine the relative magnitude of permeabilities under an imposed hydraulic stress. In the petroleum industry, this is termed "injectivity profiling" and is done during injection or recharge of water into a well. An injectivity profile is made by plotting the water lost within each depth interval of hole where vertical-velocity measurements are made. Several studies of this type have shown a poor correlation between injectivity and horizontal permeability measured on core samples (Kaveler and Hunter, 1952; Piety and Wiley, 1952). This lack of correlation is suggested to be due chiefly to two factors: (1) the sands in these studies showed a difference of as much as 300 percent in the horizontal permeability of adjacent samples, and (2) the vertical permeability showed wide variations and equalled as much as one-half of the horizontal permeability; hence, it could contribute significantly to the actual flow pattern, as could fractures not present in the small core samples. Lack of correlation between sample data and injectivity profiles may also be due to failure to correct for head differences, to lower permeability caused by drilling mud, or to plugging of the formation from organic matter in the recharge water. Nonetheless, inhole-flow data can show the relative amounts of water moving into an aquifer system under injection conditions designed to simulate artificial recharge. Similarly, a flow-measuring device can be placed in a well beneath a pump during a test, and the relative contributions of various aquifers can be determined at various discharge rates.

When permeability and flow rates are extremely low, tracer techniques are the best means of measuring water movement in a hole. Figure 71 illustrates a technique used to analyze the vertical distribution of permeability in fractured crystalline rocks at the AEC Savannah River Plant in South Carolina, where vertical flow in wells was as low

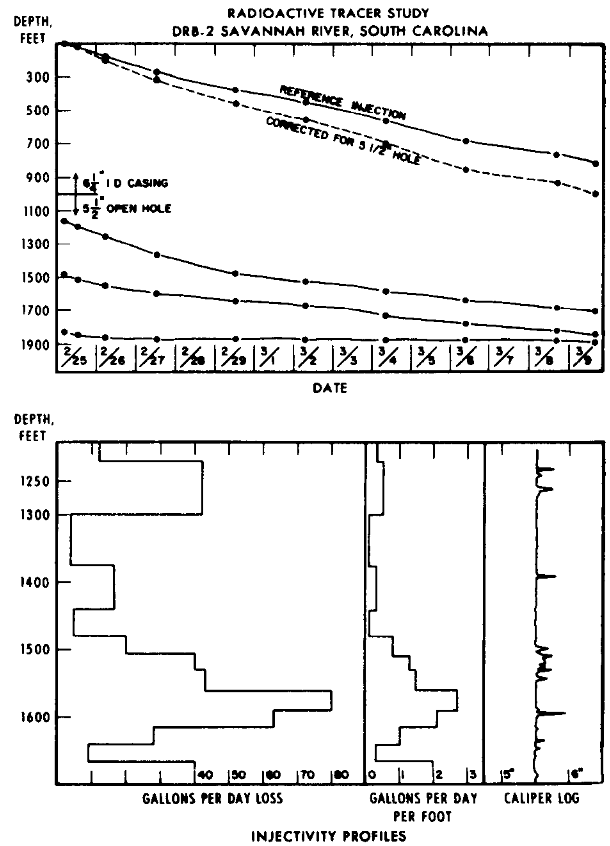

Figure 71. — The movement of slugs of radioactive tracer under injection conditions (upper half) and injectivity profiles and their relation to a caliper log (lower half).

as a few feet per day. The curves in the upper half of this illustration show the movement of four injections of an aqueous solution of iodine-131, from February 25 to March 9. These slugs of tracer were located by periodic gamma logs, and are indicated by dots in figure 71. Because no system was available for maintaining a constant injection head, it was necessary to place a reference slug of tracer in the 6¼-inch I.D. (inside-diameter) casing. The dashed curve shows the velocity of this reference slug corrected for a 5½-inch hole. Two types of injectivity, or water-loss profiles, were calculated; "gallons per day" and "gallons per day per foot." This was done by comparing the volume of water moved through the casing with the volume moved through a given depth interval of open hole for the same period of time.

At the National Reactor Testing Station in Idaho, a radioactive tracejector and other

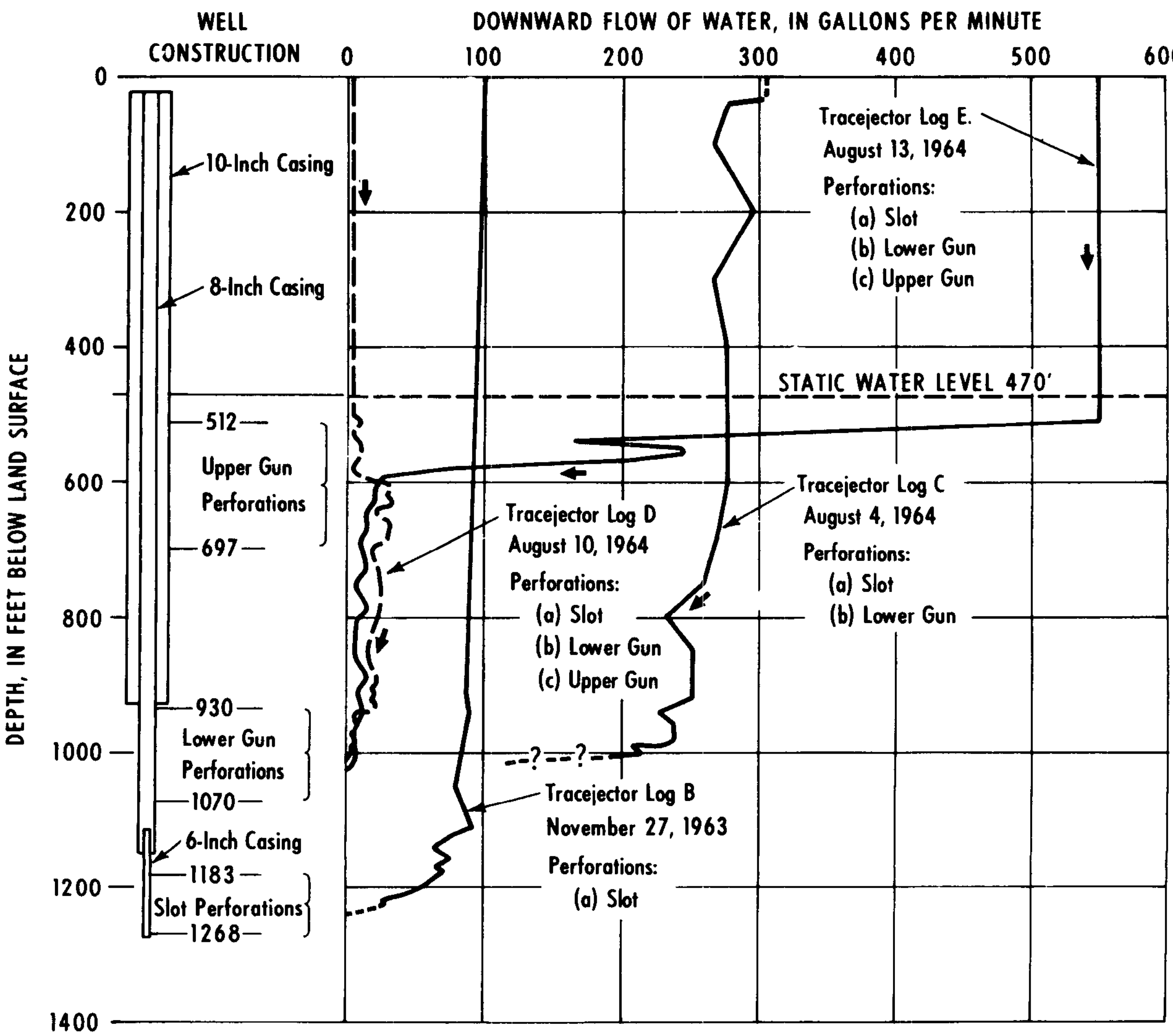

Figure 72. — Radioactive-tracejector logs, National Reactor Testing Station, Idaho. From Morris and others (1965).

nuclear logs were used to determine the reason for inadequate capacity and to guide the recompletion of a waste-disposal well (Morris and others, 1965). The waste-disposal well was originally drilled to a depth of 1,275 feet, with slot perforations from 1,182 to 1,267 feet (fig. 72). The specific capacity of the well was not adequate for the disposal anticipated, and it decreased with time. Tracejector log *B* showed that about 30 percent of the water injected at 100 gpm left the well through the annulus between the 6- and 8-inch casing. The casing was then gun perforated between 935 and 1,070 feet. An improvement in specific capacity was noted, but the well was bridged at 1,005 feet, and tracejector log *C* showed part of the water leaving through the bottom of the hole. On the basis of caliper, gamma-gamma, and natural-gamma logs, it was decided to gun perforate the casing interval from 512 to 697 feet. Tracejector log *E* showed that this zone took practically all the water injected at 550 gpm and that the head rise was insignificant. Tracejector log *D* was run during a period of no injection, and a natural-downward flow of about 25 gpm was noted.

In addition to measuring vertical velocities, there are several techniques, which have received only limited use in ground-water hydrology to date, for measuring horizontal movement in a single well. However, these techniques may only provide data on local velocities and direction of movement, and it may be necessary to repeat the procedure in several wells to establish an areal pattern. One method for measuring velocity is to inject a liquid radioisotope into a well and make in-situ measurements of the dilution, as untagged water moves through the well (Raymond and Bierschenk, 1957). The equation for analysis of this data is based on horizontal flow, so dilution must be measured in a section of the well that is isolated by packers. The velocities calculated are greatly affected by well loss due to the screen, gravel pack, or mud cake; therefore, they are closely related to the yield of that interval of the well. Lewis, Kriz, and Burgy (1966) utilized nonradioactive tracers and a dilution-sampling technique to determine the hydraulic conductivity of fractured rock. Hydraulic conductivities of 0.02 to 0.5 feet per day determined in small wells agreed favorably with similar conductivity values obtained from pumping tests.

The single-well pulse technique utilizes a radioisotope dissolved in the stream of water injected into a well (Borowczyk and others, 1967). Water injection continues until the tracer moves some distance out into the aquifer. The well is then pumped, and the time of recovery for 50 percent of the injected tracer indicates the velocity of movement in the aquifer under injection conditions. The technique is most successful in a single, homogeneous aquifer. A gamma probe can be used to measure concentration and to determine the zone that is taking the water and tracer. The hydraulic conductivity, calculated from pumping tests in the area, averaged 0.4 cm/sec, and the transit time between two observations wells, as determined by tracer study, was 0.47 cm/sec. Hydraulic conductivity calculated from the single-well pulse technique was 0.45 cm/sec.

Another single-well technique utilizes directional detectors to determine the azimuth of movement of a liquid-radioactive tracer. One method employs a shielded detector that may be rotated from the surface in order to determine the direction of exit of the injected radioisotope (Payne and others, 1965). Another possibility is the use of a number of radially spaced detectors, which may be recorded individually, with the whole device oriented by compass. A device of this type has been used for measuring the horizontal component of flow in lakes. Selecki and Filipek (1966) proposed a method that relied on the neutron moderation in a saturated solution, containing lithium, boron, and cadmium, which is introduced into the well. The direction of maximum movement of the tracer was measured by means of a rotating collimated-neutron detector.

Gamma-emitting radioactive tracers that are water soluble have the following advantages over chemical tracers: They are detectable at very low concentrations so that density effects are minimized, they are easily detected in a well bore and outside the casing, and they are obtainable in numerous chemical and physical forms suited to the specific test requirements. Relative cost and difficulties in obtaining a Government license for use in ground-water environments are the chief drawbacks to the use of radioactive tracers. (See page 86, section on "The Use of Radioisotopes in Well Logging.")

A brief discussion of radioactive tracers that can be used is germane to the selection of a flow-measuring system. A radioactive tracer that has a short half life and is detectable at low concentrations should be selected so that the concentration at the nearest point of reuse does not exceed limits (recommended by the U.S. Public Health Service) for drinking water. Iodine-131 is commonly used because it has an 8-day half life and a high specific activity of energetic gamma photons. However, other tracers can be used, such as bromine-82 with a 36-hour half life. The possible sorption or delay of tracers must always be considered when measuring flow through aquifers, but this is not an important factor in determining velocities in a fluid column. An attractive possibility is the use of neutron-activated tracers. Radioisotopes formed in this way generally have a very short half life and are not subject to stringent regulation. In general, however, an intense neutron flux is required to produce a radioisotope that has a long enough half life, a high specific activity, and a high enough gamma energy to penetrate the fluid and sonde. The half life needed is a function of the velocity to be measured. A californium-252 source recently used for well logging was found to have sufficient neutron flux to produce activated radiotracers in a relatively short time (Keys and Boulogne, 1969).

Another type of inhole-tracer technique utilizes fine particulate or insoluble radioisotopes, such as gold-198 or cobalt-60. They are introduced into the well under injection conditions and are filtered out on the face of aquifers in proportion to the relative permeability of the units. Gamma logs made after injection correspond closely to the permeability profiles measured by other methods. Soluble tracers may also be introduced into the water during its injection into a well. Periodic gamma logs made during subsequent pumping of the well locate the zones where the greatest amount of tracer has entered.

Instrumentation

The various methods of flow measurement in wells, with the exception of radioactive tracers, are discussed in detail by Patten and Bennett (1962). Their discussion and new developments are summarized here. The most widely used device for the measurement of flow in water wells utilizes an impeller, a rotor, or vanes housed inside a protective cage or basket. The Price current meter was first used by Meinzer (1928) to locate zones of leakage in wells in Hawaii. Fiedler (1928) described the use of the Au deep-well current meter in wells in the Roswell artesian basin. Recent work by the research project in borehole geophysics has been done with flowmeters designed for work in oil wells. This type of flowmeter was used to make the logs shown in figure 70. The earlier devices used a mechanical switch, attached to the rotor, which completed an electrical circuit through a battery. An audible click was detected on earphones, and the clicks per unit time, measured with a stopwatch, were empirically related to flow. The oil-well-type flowmeter has some improvements, but still exhibits the shortcomings described under "Calibration" and "Extraneous Effects." Friction on the shaft is reduced by filling the switch chamber with oil or by allowing it to fill with water. A very sensitive magnetic switch and a rotating magnet eliminate friction caused by a mechanical switch, but they introduce some magnetic bias. Pulses can be coded so that the direction of rotation can be ascertained without moving the flowmeter. Recording of data has been considerably improved over the stopwatch and notebook method. Pulses from the flowmeter can be integrated in a standard gamma-logging module, and the time constant can be adjusted so that a smooth integrated trace, or an integrated trace with pulses superimposed, can be recorded (fig. 70). Loggers with time drive on the recorders also permit the graphic recording of pulses per unit time. In this manner, all data from either continuous or stationary flowmeters is automatically recorded. The oil-field flowmeter is also available; it has a number of interchangeable baskets and impellers of different diameters. The chief advantages of an impeller flowmeter are its simplicity and its relatively low cost. Disadvantages include nonlinear response, lack of sensitivity at low velocity, and poor accuracy at high velocity; also, none are available for very small diameter holes.

A significant improvement can be made in the performance of any type of flowmeter by the addition of a device to force all or most of the flow through the cage or basket. Commercial service companies have inflatable-packer flowmeters that operate on loggers. The packer may be inflated at any point in the hole that is within the size range of the packer to provide a reading with all the fluid channeled through the flowmeter. Such equipment is not available for purchase at present (1971); however, the performance of most flowmeters can be improved with a simple centralizing flange. A thick rubber flange and an annular bristle-type brush have both been used successfully. The rubber flange can be cut to fit the hole diameter, as determined by a caliper log. This method has been used to increase the sensitivity of a flowmeter sufficiently to detect the movement of air out of a well in response to falling barometric pressure.

The thermal flowmeter, developed by H. E. Skibitzke (1955), has promise of offering improved flow measurement, but it has not yet received wide use. A resistance heating element is located between two thermistors in a small-diameter tube. The amount of water heating that is achieved is inversely related to the fluid velocity through the tube. The upstream thermistor is at ambient temperature, and the downstream thermistor measures the higher temperature due to heated water reaching it. The imbalance caused in a Wheatstone bridge circuit is measured on a meter. Because of nonlinear response, thermal convection, and internal and external flow variables, this device must be calibrated empirically. Patten and Bennett (1962) reported a functional velocity range of 2 to 75 fpm, with errors likely to be less than 0.5 fpm at low velocities and less than 1 fpm at high velocities. The thermal flowmeter is readily adaptable to small-diameter tools and can probably be improved to measure velocities less than 2 fpm. Variations of the system developed by Skibitzke include the measurement of changes in voltage required to heat a single thermistor, which should be related to the velocity of the fluid removing the heat. Similarly, the changes in resistance of a hot-wire or hot-film anemometer have also been used to measure fluid flow.

Radioactive-tracer techniques for inhole flow surveys are widely used in the petroleum industry and in ground-water investigations in Europe, but have only had limited use in this country. Basically, the downhole equipment consists of a device for injecting a gamma-emitting radioisotope in the well and one or several gamma detectors (Edwards and Holter, 1962). The tracejector detector described here was developed for injectivity profiling of oil wells and was first used in ground-water investigations by the senior author at the National Reactor Testing Station in 1961. Figure 73 shows the double-detector probe and some logs made at the station. This probe may be used to measure velocity with the tool stationary, as shown, and then the slug of tracer can be followed up or down the hole to the point of exit. If the velocity is extremely low, the hole may be relogged periodically to determine movement. Moving the tool through a slug of tracer does tend to spread it out to some extent.

A common type of tracejector used in both oil wells and water wells consists of a positive-displacement piston-type pump that will eject from a fraction of a milliliter to 20 milliliters of a water-soluble tracer, such as iodine-131. The ejector is operated by direct current from the surface. The module for operating a motor-driven caliper may be used. The radiation probes used for natural-gamma logs may be attached to the ejector in any one of a number of combinations. When direction of flow is not known, they may be placed above and below the ejector. When direction is known, they may both be attached above or below the ejector to increase the accuracy of measurement, as shown in figure 73. The recorder is operated on time drive, and an event marker is automatically triggered when the switch is depressed to eject a drop of iodine. The upper left part of figure 73 shows the repeatability of single-detector logs. Note the sharp arrival front of the slug of iodine at about 22 seconds, and the gradual decrease in concentration. The lower left part of figure 73 shows an actual double-detector log. In this mode, traveltime is measured between the arrival of a slug of tracer at the first and the second detectors. This measurement is considered to be more accurate because the slug of tracer is well formed by the time it reaches the first detector, and errors caused by dispersion and actual time of ejection are eliminated. Note in figure 73 that a higher velocity is recorded between detectors than from the injector to detector No. 1. With this system, natural vertical flows as high as 30 feet per minute have been measured in wells at the National Reactor Testing Station in Idaho. Horizontal flow in some of these aquifers removes all of the tracer from the well within several seconds. In contrast, vertical velocities of a few feet per day were measured in

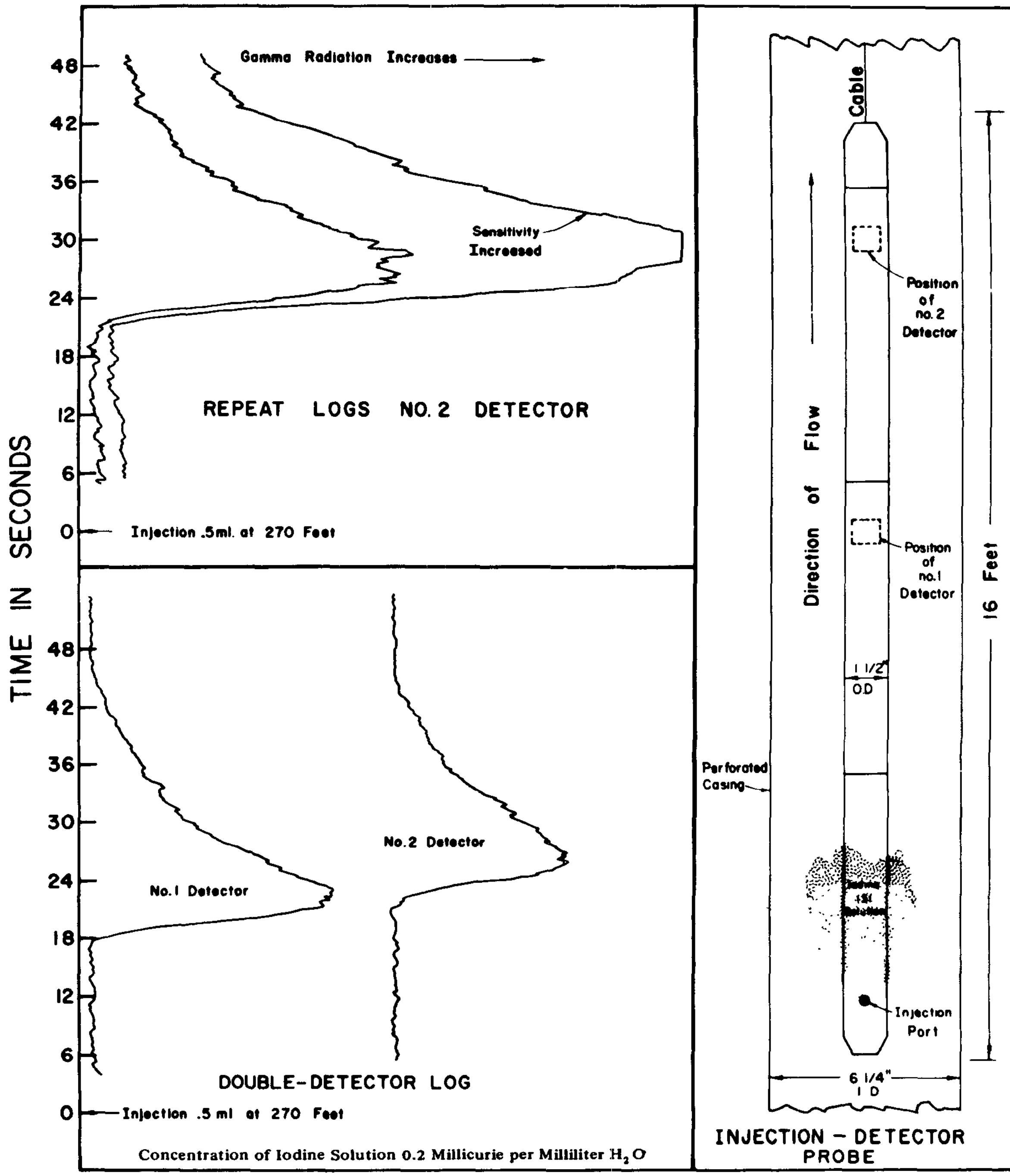

Figure 73. — Double-detector radioactive-tracejector (right) and logs of iodine-131 injections (left).

fractured crystalline rocks at the A.E.C. Savannah River Plant in South Carolina. The advantages of this method are that it operates over a wide velocity range with very small quantities of tracer; it should not be directionally sensitive; it will detect flow behind casing; and all data are automatically plotted.

A brine ejector-detector system, utilizing the radioactive-tracejector and one or sev-

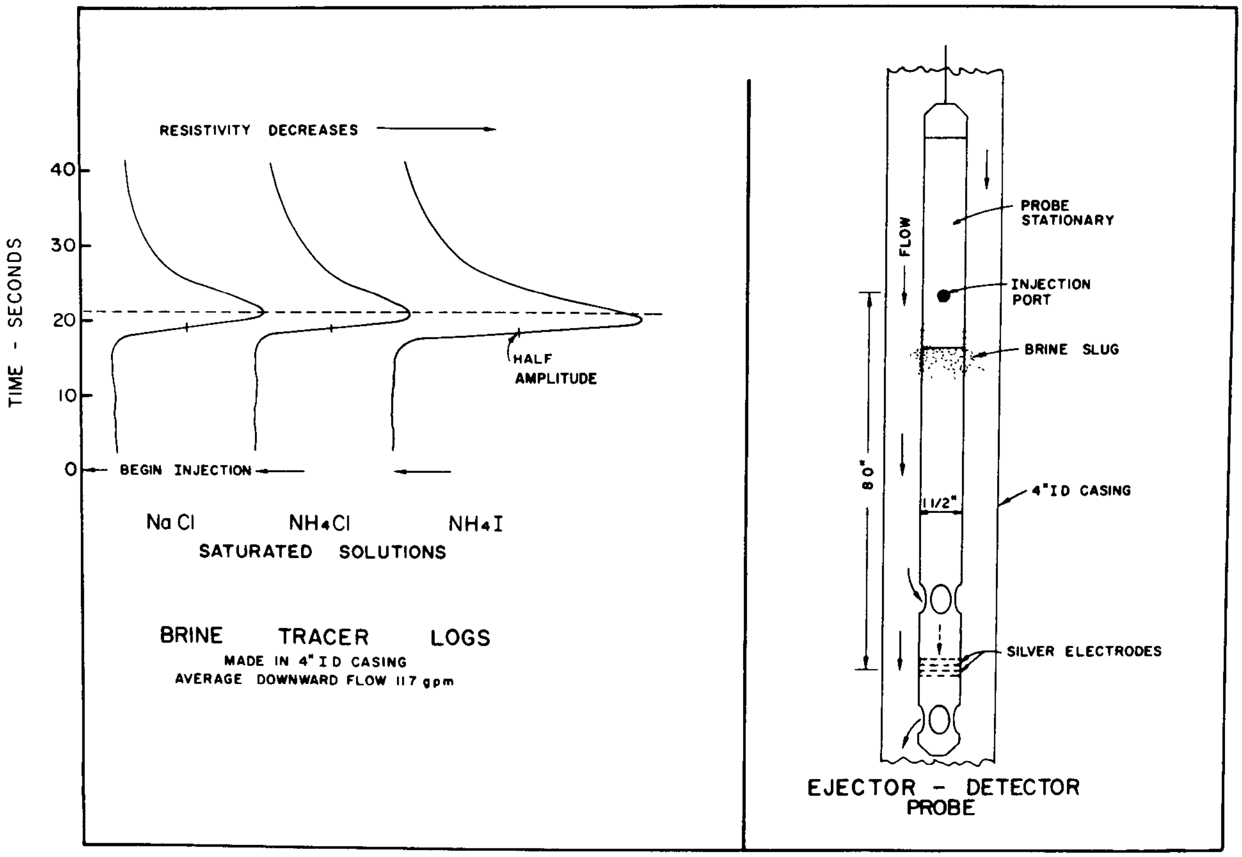

Figure 74. — Brine ejector-detector probe (right) and logs of three different salts used as tracers (left).

eral fluid-conductivity tools, has recently been developed (fig. 74). The system has the advantage of utilizing a less expensive, more readily available tracer that does not require licensing. However, chemical tracers have disadvantages in that results are more affected by the specific gravity of the solution; they have a lower detection sensitivity; and they are not detectable through casing. The tool shown on the right in figure 74 is set up to measure downward flow. On the left are actual time-drive logs of three different salt tracers in the same flow system. Note how the NH_4I solution indicates a higher downward velocity because of the greater specific gravity of the solution. Recording is done exactly the same as for the radioactive tracer, and the logs look nearly the same. An event marker records the instant of ejection, and a plot of fluid conductivity versus time is made automatically. After the slug of tracer has passed the detector, the tool may be moved to follow it, but this causes some mixing and disturbance in the flow system. A new tool uses two sets of electrodes for tracer detection above or below the ejector. Patten and Bennett (1962) described a brine-tracer system utilizing a plastic hose for tracer ejection and a fluid-conductivity probe and stopwatch for velocity measurement. They pointed out that the method is inherently accurate and usable at low velocities, but that certain improvements in instrumentation are needed as follows: An automatic and repeatable brine-release system incorporated in the same tool with two detectors, an automatic time-recording system, and the capability of making stationary measurements. The brine ejector-detector system now available meets all these requirements and is probably the most useful flowmeter presently available for a wide variety of borehole conditions.

Calibration and extraneous effects

All the flow-measuring devices described are subject to extraneous effects; hence, they must all be calibrated by empirical methods. Aside from the disadvantages mentioned for each tool, a problem common to all is the apparent change of fluid velocity caused by varying the probe position radially within the borehole. The velocity of a fluid moving through a smooth cylinder is lowest near the wall, and is a fairly constant maximum across most of the central part of the conduit. Thus, a flow-measuring device that measures the velocity of only a small part of the total cross-sectional area can give low results if it is located near the wall. For this reason, use of centralizing devices, channeling flanges, or packers improves the accuracy of flow measurement. Transparent plexiglass cylinders, used to calibrate flow sondes for the research project on borehole geophysics, permit observation of this effect. Dye was mixed with other tracers in order to study their behavior. The greatest error was achieved with the ejector port located against the side of the cylinder. Lateral dispersion of the tracer into the central zone of maximum velocity took place along with vertical movement. The directional effect on the output of a flow-measuring sonde is significant if the upper and lower parts of the sonde are not mirror images. Generally, a symmetrical tool is not feasible to construct because of the cable connector. Directional errors due to specific-gravity differences between tracers and water are only significant at low velocities and can be checked in a stationary column. If spacing between sensors is too great, a depth interval with varying fluid velocity may be averaged; however, constant water flow across the interval being measured must be assumed for quantitative interpretation. Tools that have a large diameter in relation to the diameter of the well will cause the greatest vertical dispersion when they pass through a slug of tracer.

Flow-measuring devices should be calibrated in the size of casing or hole in which they are to be used. Open-hole flow surveys should always be checked against a caliper log. The research project facility for testing and calibration of flow sondes consists of plexiglass cylinders of different diameters that can be connected to a recirculating pump in a tank. A system of valves and a calibrated Sparling meter allow the flow to be measured and the flow direction to be reversed. Calibration should be done for both flow directions, if possible. Field standardization, or calibration, for one hole size can be done either when a well is being pumped or when water is being injected into the well at a known rate. With careful calibration and field standardization, errors at low-flow velocities can be reduced to 10 percent, and errors can be reduced to as low as 1 percent at higher velocities.

Casing Logs

The casing-collar locator is a useful and inexpensive device that can be added to any geophysical logger. The continuous-collar log can also be interpreted to accurately locate perforations and screens in a well. Accurate information on a well's construction is very important for pumping tests and as a guide to the correct interpretation of other geophysical logs. The simplest type consists of a permanent magnet wrapped with a coil of wire. Changes in the magnetic properties of material moving through the lines of flux from the magnet cause a small direct current to flow in the coil of wire, and the resulting voltage can be used to drive the recorder pen. In collar and perforation logging, DC-voltage fluctuations are caused by changes in the mass of metal cutting the lines of flux and by changes in the velocity of the tool. Commercially, the typical collar log is run simultaneously with radiation logs as a means of providing depth reference in the hole. The CCL log is generally recorded as "event marks" on the left side of the log (fig. 75). This is accomplished by adjusting an event marker so that it trips only when the DC

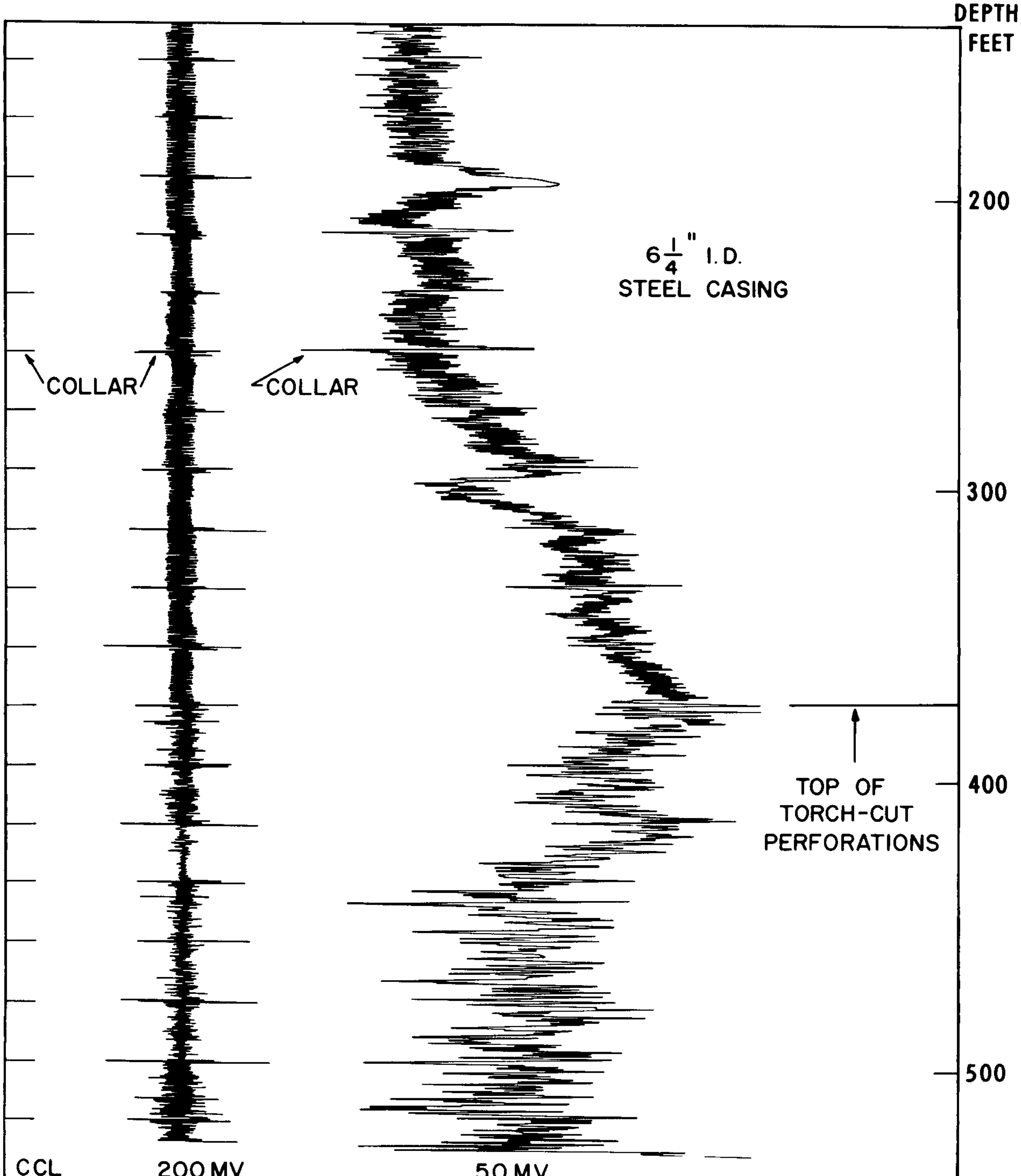

Figure 75. — A typical CCL log, made with an event marker (on the left of the log), and continuous logs, at two different potential scales, which were used to locate perforations in the well casing.

voltage exceeds a certain predetermined level. The continuous-collar logs shown in figure 75 were run with the same tool. The signal was fed through a spontaneous-potential module at sensitivities of 50 and 200 millivolts. Extraneous effects that may cause misinterpretation of CCL logs include changes in response due to logging speed, direction, and position of the sonde in the hole. In some holes, it may be helpful to decentralize the sonde. Where interpretation is questionable, repeat logs should be run in order to distinguish real from extraneous deflections.

The effect of casing on other geophysical logs is described in the sections on "Borehole Effects" and "Extraneous Effects." Gamma-gamma logs have also been used to locate joints and one string of casing outside another. (See fig. 53). The caliper log is particularly useful for measuring casing size and for locating joints and screens; it can even be used to identify badly corroded pipe. The spontaneous-potential sonde has also been used in casing to locate differences in anodic activity in wells where there is active corrosion (Kendall, 1965). This method can only be used to locate areas of active corrosion and cannot determine the extent of corrosion. Of course, both the SP and single-point resistance log will generally provide an accurate depth to the bottom of the casing, and sometimes they can also be used to locate screens.

At least one commercial logging service is available for detecting corroded pipe. An electromagnetic casing-inspection log measures the changes in metal mass between two coils (Edwards and Stroud, 1964). The log indicates possible total metal loss and, therefore, does not indicate whether the corrosion has occurred on the inside or the outside of the pipe.

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