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

Chapter E2

BOREHOLE GEOPHYSICS APPLIED TO GROUND-WATER INVESTIGATIONS

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Book 2

COLLECTION OF ENVIRONMENTAL DATA

ter have been compared in terms of providing information on the location, orientation, and character of fractures, the acoustic televiewer has been found to provide an understanding of complex fracture systems, whereas the dipmeter was not (Keys, 1979).

Test 2.—ELECTRIC LOGGING

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

Nuclear Logging

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

Fundamentals of nuclear geophysics

An understanding of the basic structure of the atom and of the energy that may be emitted is as important to the use of nuclear logs as Ohm's law is to resistivity logs. The principles essential to the interpretation of gamma, gamma-spectrometry, gamma-gamma, and various types of neutron logs include the nature of subatomic particles and the particles and photons emitted by unstable isotopes.

The nucleus of an atom consists of protons with a mass of 1 and a positive electrical charge and neutrons with a mass of 1 and no electrical charge. Electrons orbiting the nucleus have a negative charge to balance the positive charge of the protons and a mass equal to $1/1{,}840$ of the mass of a proton. The mass number (A) is equal to the number of protons plus the number of neutrons in the nucleus. The atomic number (Z) is equal to the number of protons; Z is usually the same as the number of orbital electrons and determines the chemical characteristics of the elements. Isotopes are one of two or more different states of an atom; they have the same atomic number but different mass numbers, because of a difference in the number of neutrons. Isotopes of a given element have the same chemical characteristics but a different mass. For example, uranium present in rocks consists of three isotopes with mass numbers of 234, 235, and 238; these isotopes can be separated by differences in their weight. Of the 104 known elements, 83 have more than two isotopes. The term "nuclide" refers to each of the possible combinations of protons and neutrons.

Stable isotopes are those that do not change structure or energy over time. Unstable or radioactive isotopes (also called radioisotopes) change structure and emit radiation spontaneously as they decay, and become different isotopes. Almost 1,400 isotopes are known; 1,130 of these are unstable, although only 65 unstable isotopes occur naturally. Most of the radiation emitted during decay originates in the nucleus of an atom; X-rays are derived from shell transitions by the orbital electrons. Radiation from the nucleus consists of alpha particles, positive and negative beta particles, and gamma photons or rays. Alpha particles are stopped by a sheet of paper; beta particles are stopped by $1/25$ in of aluminum. Several inches of lead, however, are required to stop gamma radiation. Of the three types of radiation, only gamma photons are measured by well-logging equipment, because they are able to readily penetrate dense materials such as rock, casing, and the shell of a logging probe.

Neutrons also are able to penetrate dense materials; however, they are slowed more effectively and ultimately are captured in materials, such as water, that have a substantial content of hydrogen. Neutrons produced by a source in a logging probe are measured after they pass through material in and adjacent to the well. Gamma photons produced by neutron reactions are measured by some types of logging equipment. Neutron reactions that produce gamma radiation include scattering, capture, and activation. Neutron activation produces a new isotope, which may be identified on the basis of the energy of the gamma radiation it emits and its half-life. Half-life is the time required for a radioisotope to lose half of its radioactivity by decay.

The processes of transformation of one isotope to another may leave the resulting nucleus with an excess of energy, which may be emitted as electromagnetic radiation in the form of gamma photons or gamma rays. Because photons have some characteristics of both particles and high-frequency waves, the term "gamma photon" is more technically correct than "gamma ray"; both terms are used in logging literature. The energy of gamma photons can be used to identify the isotope that emitted them; this is the basis for gamma-spectral logging and neutron-activation logging. Scintillation detectors emit flashes of light that produce electrical pulses; the amplitude of these pulses is proportional to the energy of the impinging radiation. These pulses can be sorted and recorded as a function of energy by a pulse-height analyzer. The energy of radiation, both neutrons and gamma photons, is measured in electronvolts (eV), thousands of electronvolts (keV), and millions of electronvolts (MeV). Radiation intensity is measured directly as the number of pulses detected per unit time, which may be converted within the logging equipment to some other unit of measurement, on the basis of calibration.

Detection of radiation

Radioactivity is measured by converting it to electronic pulses, which then can be counted and sorted as a function of energy. The detection of radiation is based on ionization, which is directly or indirectly produced in the medium through which radiation passes. Three types of detectors currently are used for nuclear logging: scintillation crystals, Geiger-Mueller tubes, and proportional counters. Scintillation detectors are laboratory-grown crystals that produce a flash of light, or scintillation, when traversed by radiation. The scintillations are amplified in a photomultiplier tube to which the crystal is optically coupled, and the output is a pulse whose amplitude is proportional to that of the impinging radiation. These pulses can be used for spectral logging. The pulses from a photomultiplier tube are small enough that they require additional amplification before they can be transmitted to the land surface and counted. The number of pulses detected in a given radiation field is approximately proportional to the volume of the crystal, so probe sensitivity can be varied by changing crystal size. Scintillation crystals probably are the most widely used detectors of gamma photons and neutrons in nuclear logging. Sodium-iodide crystals are used for gamma logging, and lithium-iodide crystals are used for many types of neutron logging systems. These crystals are much more efficient than Geiger tubes, but standard crystals cannot be used at temperatures greater than about 65 °C.

Geiger detectors are gas-filled glass tubes that contain two electrodes at different potentials. The electrodes collect the charged ions that are produced in the gas by radiation; the output pulse is so large that additional amplification is not required. Geiger-Mueller tubes were used extensively in early gamma probes, but they have been replaced largely by crystals, because the crystals are much more efficient. Geiger tubes also have the disadvantage that the amplitude of the output pulse is not proportional to the energy of the radiation detected. Geiger tubes may be more resistant to breakage from mechanical shock than crystals, but shock-resistant crystals now are available for well logging. Geiger tubes also can operate at higher temperatures than most scintillation crystals.

Helium-3 proportional counters also are gas-filled tubes, but the amplitude of the pulse produced is proportional to the energy of the ionizing radiation. Neutrons produce a higher amplitude pulse than gamma photons, so energy discrimination can be used to eliminate unwanted gamma contribution to the recorded signal. Helium-3 detectors commonly are used for neutron logging.

Most detectors used for neutron and gamma-gamma logging are side collimated with appropriate shielding material, so most of the radiation measured comes from the side of the borehole against which the logging probe is being decentralized. Both borehole diameter and the position of the detector within the borehole have an effect on the response of the system; these effects are discussed in the sections on the various types of nuclear logs. Detector length also is an important factor that affects the vertical resolution of a logging probe. A longer detector averages the signal from a greater volume of material, thereby decreasing the vertical resolution of lithologic changes.

Instrumentation

Nuclear probes contain power supplies for the photomultiplier or gas-filled tube and electronics to amplify, shape, and discriminate the pulses detected. In most modern probes, the power is sent down the logging cable to be regulated and divided into the voltages needed in the probe. Pulse amplification is needed in most probes; the pulses may need to be shaped, to optimize transmission up the cable. If two detectors are operated on a single-conductor cable, the output of the two will be segregated into positive and negative pulses for separate recording at the land surface. Except for spectral probes, all pulses are transmitted at the same height, so information on the energy of the radiation is not available.

In the logging truck, the pulses coming up the cable are received by ratemeters. An analog ratemeter converts the pulses per unit time to an analog voltage that is used to drive a graphic recorder. A digital ratemeter counts the pulses that arrive during a preselected time interval and transmits a proportional signal to a digital-recording system. The pulses usually pass through an adjustable discriminator before they are counted, so that unwanted noise can be eliminated. Analog ratemeters incorporate scale-selection controls that permit adjustment of the sensitivity of recorder response. They also have a time-constant switch, which controls the time period during which the pulses are counted. Time constant is so important to the proper recording and interpretation of nuclear logs that it is described in detail in the section on counting statistics.

When the count rate is rapid, dead-time or resolving-time corrections must be made on nuclear logs that are to be used quantitatively. Coincidence error is caused by (1) the equipment feature that causes two pulses that occur in a time interval shorter than the resolving time of the equipment to be counted as one pulse, or (2) positive and negative pulses that cancel. The coincidence error causes a nonlinear response at rapid count rates. If the dead time of the instrumentation is known, count rate can be corrected using the following equation:

$$N=n/(1-nt) \qquad (8)$$

where

N=corrected count rate, in pulses per second;
n =measured count rate, in pulses per second; and
t =dead time, in seconds.

Dead time can be calculated by using two sources of equal size. The procedures have been described by Crew and Berkoff (1970). Dead-time corrections usually are not significant for count rates of less than several thousand pulses per second.

If information on the energy distribution of the pulses is desired for spectral logging, or if variable-height pulses are being transmitted from the probe, the pulses are routed to single-channel or multichannel analyzers in the logging truck. A single-channel analyzer discriminates against all pulses not within a preselected energy range, and the resulting signal can be used to make a continuous recording of the count rate within that energy range. The signal from the probe can be transmitted to several single-channel analyzers, so that logs representing different energy ranges can be recorded simultaneously. A multichannel analyzer permits analog or digital recording of a spectrum that represents the chosen energy range; the measurement usually is made at selected depths in the borehole while the probe is stationary.

Counting statistics and logging speed

The statistical nature of radioactive decay should be considered when making or interpreting nuclear logs. Half-life is the time required for half the atoms in a radioactive source to decay to a lower energy state. Half-lives of the different radioisotopes, which vary from fractions of a second to millions of years, have been accurately measured. In contrast, it is impossible to predict how many atoms will decay or gamma photons will be emitted during the few seconds that commonly are used for logging measurements. Photon emission has a Poisson distribution; the standard deviation is equal to the square root of the number of disintegrations recorded. Therefore, the accuracy of measurement can be calculated; accuracy is greater at rapid count rates and for a long measurement period. The statistical variations in radioactivity cause the recorder pen to wander, even when the probe is stationary; these variations have produced the mistaken impression that nuclear logs are not repeatable. If the count rate is rapid enough and the measuring time is long enough, the statistical error will be small and the logs will be repeatable.

Time constant (*tc*) is an important adjustment on all analog nuclear-recording equipment. Time constant is the time, in seconds, during which the pulses are averaged. Pulse averaging is done by a capacitor (*C*) in series with a resistor (*R*), so that $tc=R\times C$. Time constant is defined as the time for the recorded signal level to increase to 63 percent of the total increase that occurred, or to decrease to 37 percent of the total decrease that occurred. Thus, if the probe moved opposite a bed where the long-time average-count rate changed to 200 p/s from a previous average of 100 p/s, and the time constant was 4 s, the recorder will show only 163 p/s after 4 s, 186 p/s after 8 s, and 195 p/s after 12 s. The true value nearly is equaled after five time constants, if the probe is opposite the same bed that long. If the probe moves too fast, or if the time constant is too long in thin-bedded materials, the true value never will be recorded before the probe moves away from a unit of interest. Specific time constants for each type of log cannot be recommended, for several reasons. Time constants labeled on the switches on some logging equipment are quite inaccurate, and loggers differ considerably. The logging speed, the count rate being measured, the vertical resolution required, and equipment variations have such a substantial effect on the selection of a time constant that recommended values would have very limited application.

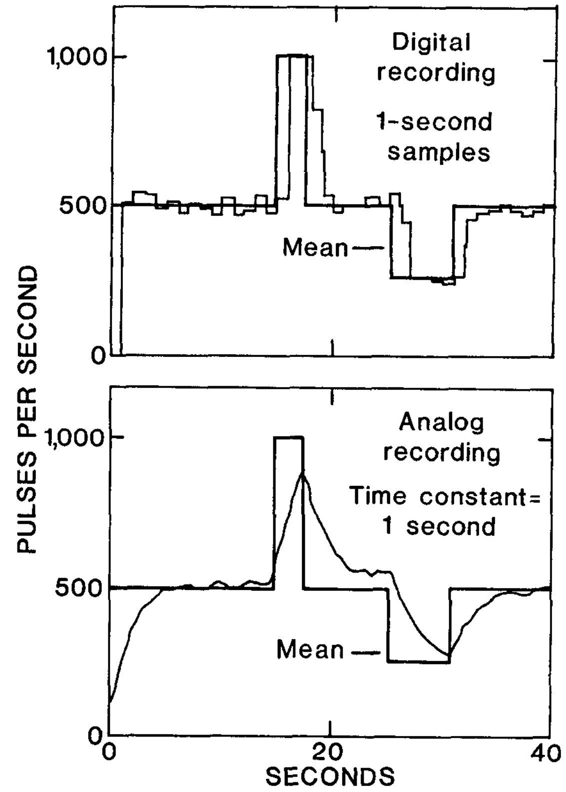


Figure 40.—Comparison of a digital recording of a gamma signal with 1-second samples and an analog recording with a 1-second time constant.

The difference between a digital recording with a sample time of 1 s and an analog recording with a time constant of 1 s is shown in figure 40. The average, or mean, radioactivity is shown as the wider line. Note that the digital system changed more rapidly because the time window used does not have a memory like the RC circuit used to determine the time constant in analog measurements. Note also that the analog measurement did not equal the mean value for short time periods.

The results of a study using U.S. Geological Survey research equipment is shown in figures 41 and 42 (Dyck and Reich, 1979). The gamma and neutron probes were stationary at different depths in a borehole while analog records were made of the varying count rate at different time constants. Means and standard deviations were calculated for all but the 1-s time constant. Note that standard deviation generally decreased as the time constant increased. At a time constant of 1 s, changes in gamma count rate would have to exceed 20 p/s (which is about 25 percent of the mean value) to be significant. In contrast, changes of about 10 percent of the mean may represent real lithologic changes on a neutron log run at a 1-s time constant in this borehole. At a 10-s time constant, the standard deviation of the gamma record is nearly 2 percent of the mean while the deviation of the neutron record is less than 1 percent of the mean. The differences are the result of the faster count rate on the neutron log. At a time constant of 50 s (not shown), the gamma record showed only minor variations. The recorder sensitivity could be decreased to decrease the apparent magnitude of the statistical fluctuations, but this also would decrease the amplitude of changes caused by lithology.

The effect of logging speed in the same study is shown in figure 43. The differences between the logs, run at 5 and 40 ft/min, are very significant. Both amplitudes and depth to contacts are much more accurate on the log run at 5 ft/min.

Some commercial logs are recorded at a minimal sensitivity, long time constant, and rapid logging speed so that real changes are small; the curve is quite smooth, and thin beds are not detected. The difference between a gamma log recorded this way (log A) and a log recorded on an amplified scale with a shorter time constant (log B) is shown in figure 44. Even though the log run at a greater sensitivity shows some statistical variations, the resistivity log indicates that the major deflections result from changes in lithology. If the log on the left had been digitized onsite, much of the lost detail could have been recovered by replotting the data on an amplified scale with a computer; however, information lost by running a log at excessive speed cannot be recovered. The more sensitive log was run at 25 ft/min; no information on the logging speed was written on the commercial log, but it probably was run at least twice as fast.

The effect of a time constant so short that it makes the log difficult to interpret is shown in figure 45. The log on the left and the repeat log were made with an 8-s time constant and a logging speed of 10 ft/min. The log on the right was run with a 1-s time constant and a logging speed of 20 ft/min using different equipment. Note that the left log repeated well and that the real changes are much easier to distinguish from the statistical variations than on the right log. Interpretation of the right log, with the short time constant, is complicated further by the fact that the operator repositioned the pen at four different depths, which are not labeled. The effects of two extremes—a time constant that is too long and a logging speed that may be too fast, contrasted with a time constant that is too short—are shown in figures 44 and 45. If a long time constant is used to improve repeatability, then a slow logging speed is best. If time is an important factor, as it often is on an oil well where standby time is being paid, then 10 ft/min may be too costly.

Bed thickness and lag are additional factors related to the speed at which nuclear logs should be run. Lag (L'), in feet, is the distance the detector moves during one time constant:

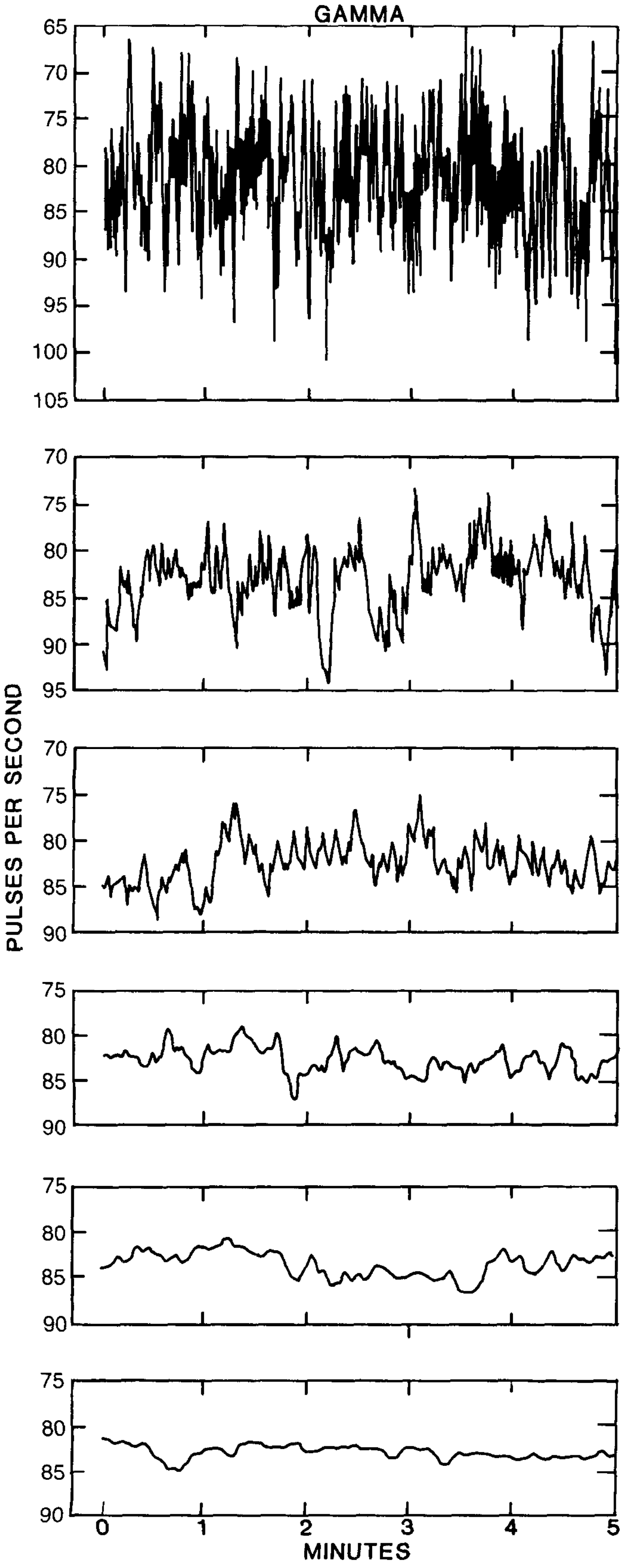
$$L'=(ls\times tc)/60 \qquad (9)$$

where ls is logging speed, in feet per minute.

Note that on some commercial logs, speed is recorded in feet per hour. The contacts between lithologic units on a nuclear log are shifted by about the length of the lag. Furthermore, beds that are thinner than L' are not defined. Both ls and tc can be controlled by the logging-equipment operator, but the count rate cannot. The resolution of thin beds that is needed is a decision that may be made by the ultimate user of the logs. The log analyst needs to be in the logging truck to help in the selection of optimum logging parameters.

If the count rate is slow, then tc may have to be increased to decrease statistical fluctuations and speed will have to be decreased to permit the proper response to thin beds. Full log response to the lithology of a thin bed will not be attained if ls is too fast or if the tc is too long. Bed-thickness effects are further described in the section on neutron logging.

The general practice for locating lithologic contacts on nuclear logs is to place them at one-half of the maximum log amplitude for a given bed. Thus, if the average count rate for a gamma log in a sandstone unit was 100 p/s, and the average count rate for a shale unit was 200 p/s, the contact would be placed at 150 p/s, using the half-amplitude rule. The true depth of the contact would be deeper by the amount of lag. Morland (1984) has demonstrated by computer analysis of the theoretical response of a gamma probe that, for beds less than 4 ft thick, the measured amplitude of the log deflection is substantially less than that for an equivalent thick bed. He also determined that both the half-amplitude and inflection-point methods of



TIME CONSTANT	MEAN	STANDARD DEVIATION
1 second	Not calculated	
3 seconds	83.0	4.7
5 seconds	82.9	2.5
10 seconds	83.1	1.5
15 seconds	83.8	1.4
20 seconds	83.0	0.8

Figure 41.—Effect of time constant on data from a gamma probe at one position in a well (modified from Dyck and Reich, 1979).

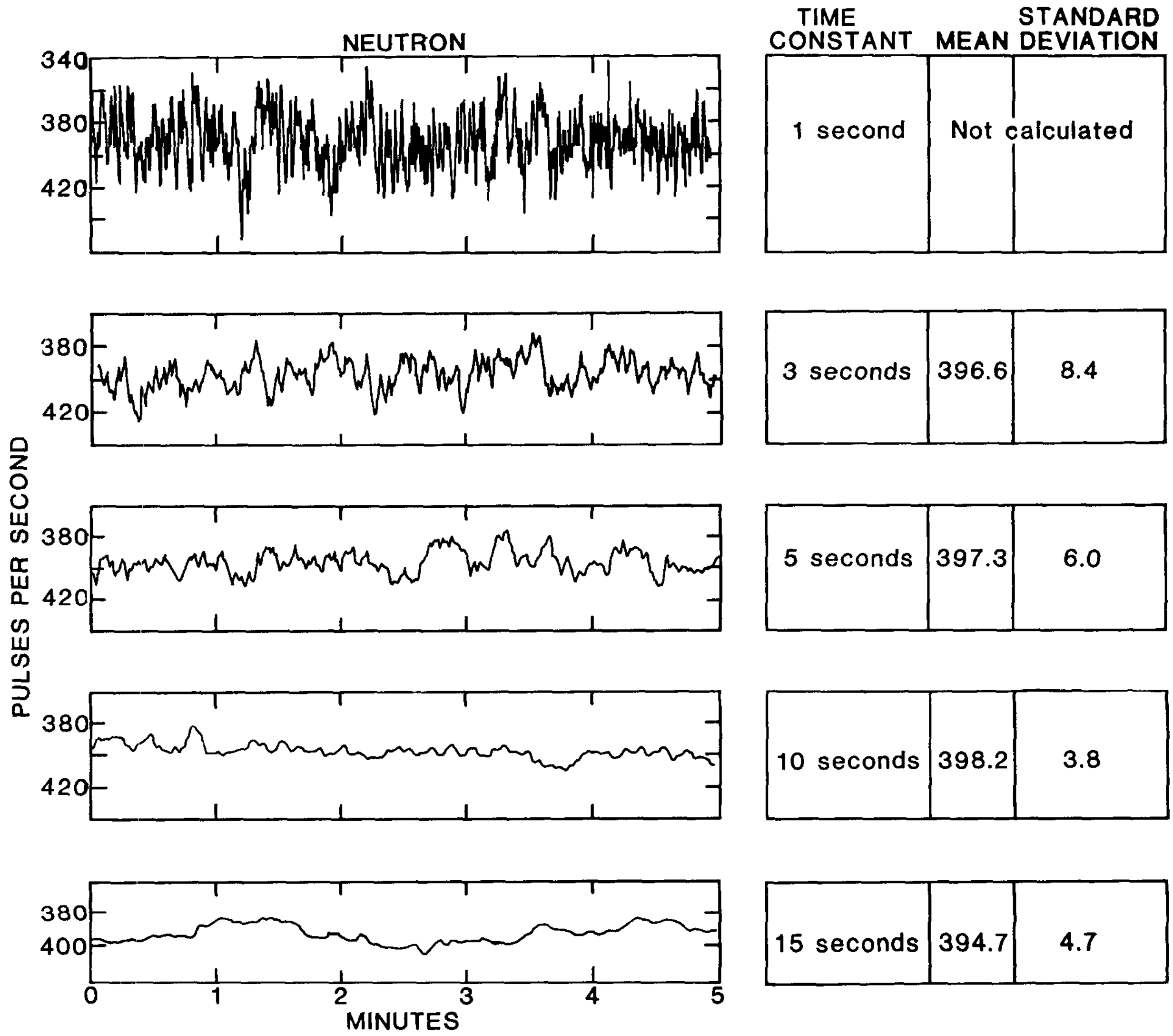


Figure 42.—Effect of time constant on data from a neutron probe at one position in a well (modified from Dyck and Reich, 1979).

locating contacts indicate thicknesses that are too large for beds less than 4 ft thick, and that the contacts were located about 6 in below their true positions, after correction for lag using detectors either 4 or 8 in long. Errors in bed thickness and the location of contacts can be significant, if logs are used to determine the length and placement of screens in water wells. Morland (1984) provided an example of a sand unit that is 1.5 ft thick, with shale above and below. A gamma log would indicate that this sand is 2 ft thick, and the decrease in radioactivity would be only 65 percent of the true difference; therefore, interpretation of the log would indicate a greater clay content than is actually the case. He provided equations for making corrections for beds thinner than 4 ft. Although he did not model the response of neutron and gamma-gamma probes using the computer, the same conclusions apply; thin-bed deflections will be decreased, and the thicknesses will appear too large.

Use of radioactive sources in well logging

Radioactive sources are placed in probes used for making gamma-gamma, neutron, and some types of tracer logs, and for calibrating various nuclear probes. No source is needed to make gamma logs, but one may be used for onsite standardization of the probe. The use and transportation of artificial radioisotopes for these purposes is regulated by various government agencies; individuals involved in making nuclear logs must be aware of the applicable laws. Even more important are the needs to avoid exposure of personnel to more radiation than is necessary to do the job

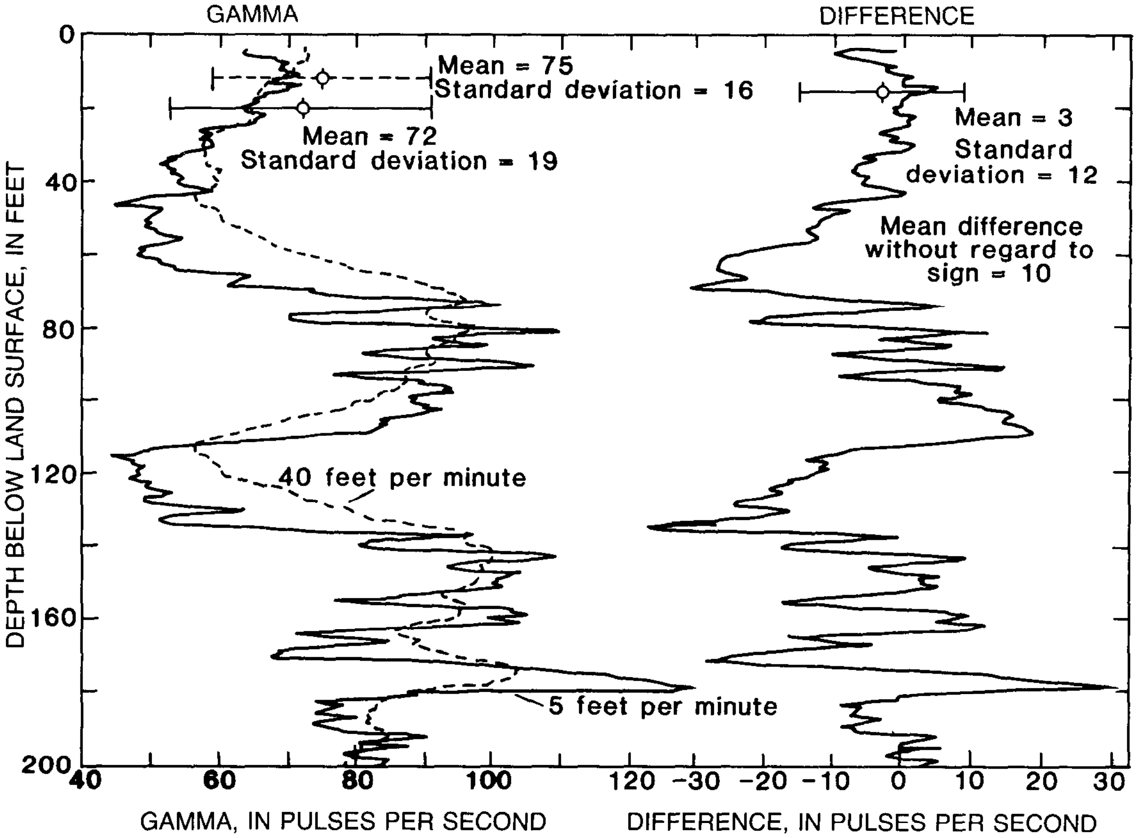


Figure 43.—Difference between gamma logs made at 5 and 40 feet per minute (modified from Dyck and Reich, 1979).

and to prevent contamination of ground water. Neither of these potential problems has proved to be significant in ground-water applications of borehole geophysics because, in general, radioactive sources have been used with care. Radiation-exposure risks to logging personnel have been described by Fujimoto and others (1985).

The use and transportation of radioactive materials is regulated by both Federal and State government agencies. Because of the numerous agencies involved and the frequent changes in regulations, specific information on the subject cannot be provided in this manual. A potential user must consult the appropriate government agency for regulations that apply to the specific type and area of use. Purchase and use of radioactive sources requires a license from either the U.S. Nuclear Regulatory Commission (NRC) or the counterpart State agency, or both. A specified duration and type of training and experience are required to qualify for such a license. Courses on handling logging sources are available from private companies. Information on these courses and licensing requirements can be obtained from local NRC offices or the counterpart State agency.

Transportation of radioactive sources is governed by the U.S. Department of Transportation (DOT) and counterpart State agencies. Radioactive sources for logging may be transported across the country, and it is difficult to be aware of all State regulations. For example, particularly in the Eastern United States, numerous bridges, tunnels, and toll roads cannot be used to transport radioactive materials. A private company has compiled and sells a publication that includes a tabulation of State regulations on the transportation of radioactive materials and a compendium of regulations on bridges, tunnels, and toll roads. Information on reports of this kind is available from the DOT. Most States have adopted the DOT's rules, but many exceptions exist.

Radioactive materials used in water-well logging are available in two forms: water-soluble tracers and sealed sources. Although radioactive tracers provide an excellent method for determining the direction and velocity of ground-water movement, they have not been used widely because regulations require a permit for each application and much information about a ground-water system is needed before a permit will be issued. Ground-water users are protected by the use

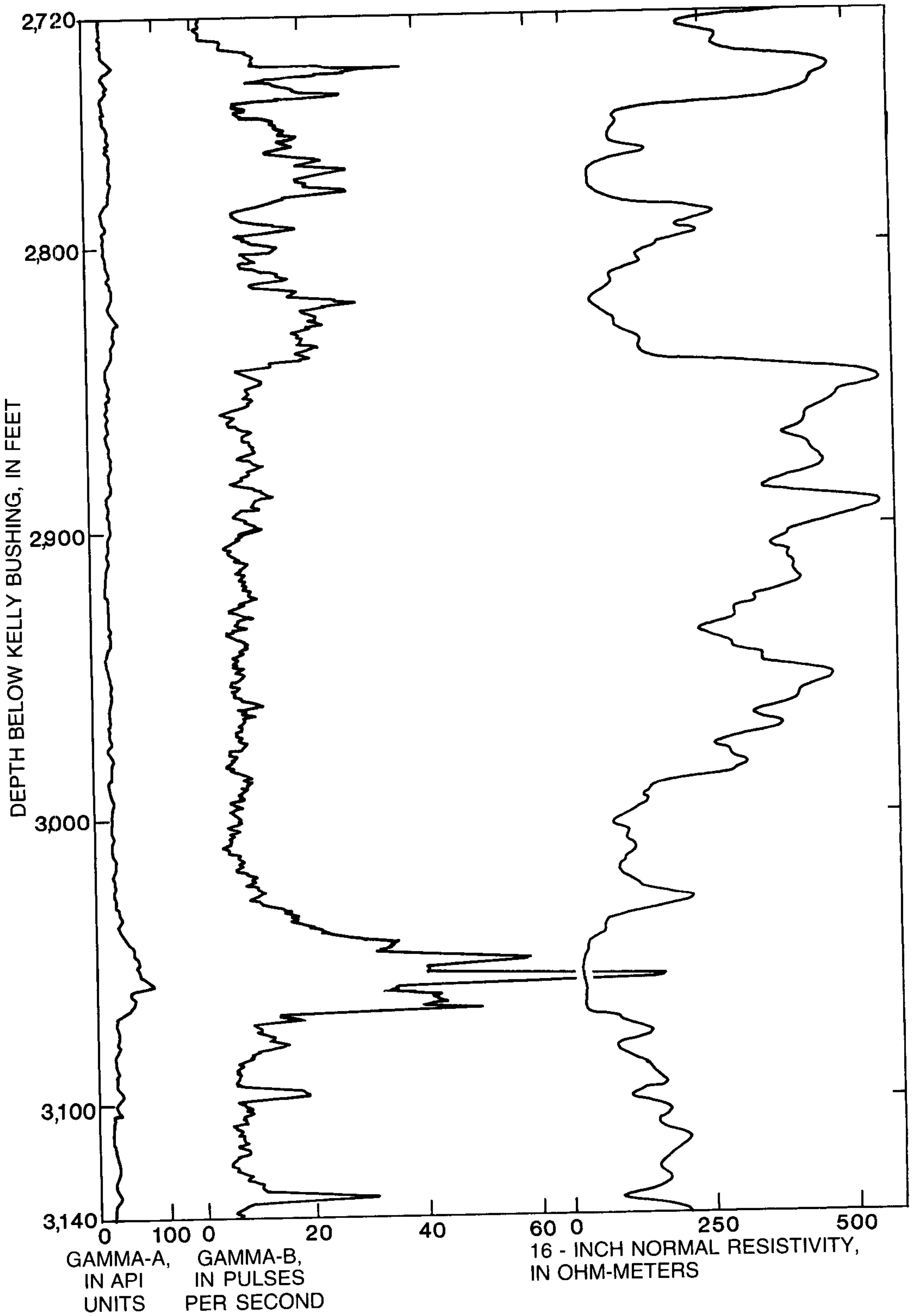


Figure 44.—Gamma logs made by a commercial service company (log A) and by the U.S. Geological Survey (log B), and a resistivity log to aid in identifying lithology, Madison Limestone test well 1, Wyoming.

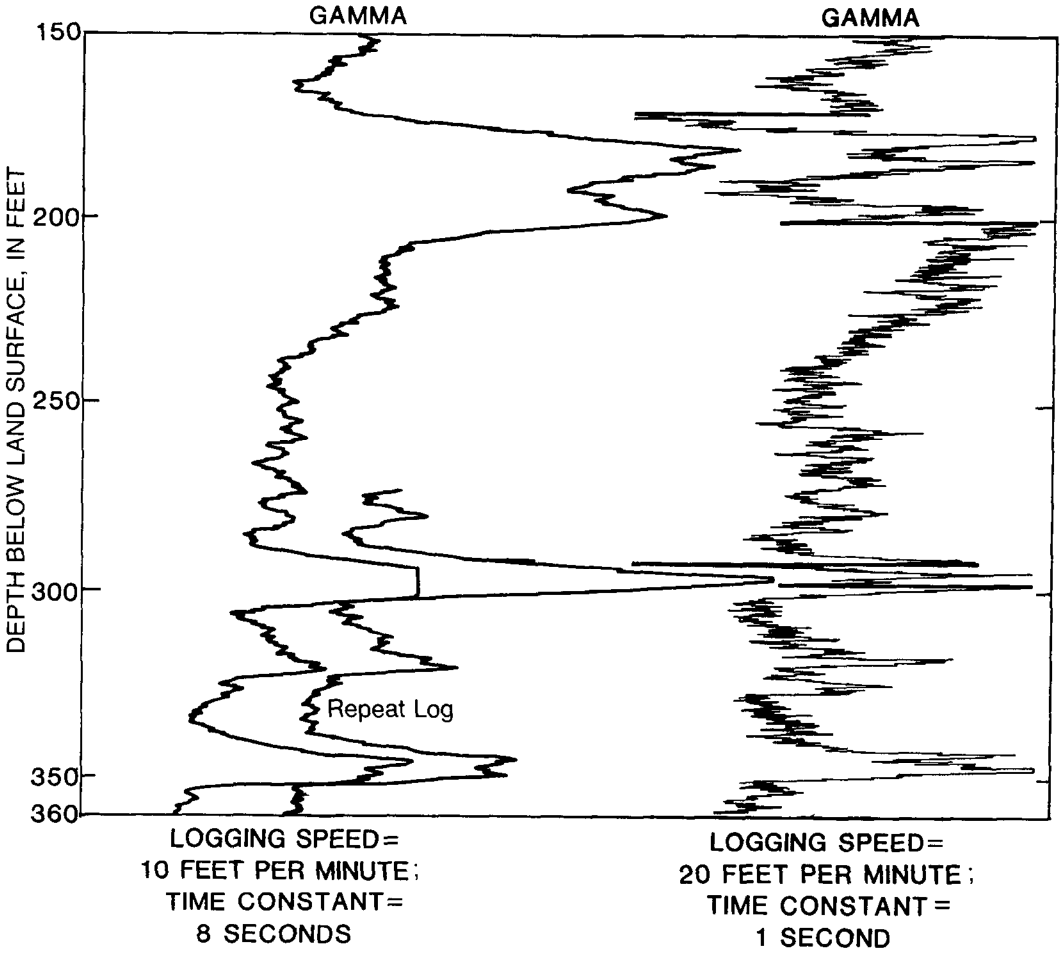


Figure 45.—Gamma logs recorded at two different logging speeds and time constants, well EX-1, Guam.

of short half-life tracers that will decay before reaching a supply well. All radioactive sources used in neutron and gamma-gamma probes are sold in welded stainless-steel capsules that have double walls. The sources are protected further by a source sub, which is a removable section of the probe containing the source. There is little danger of the radioisotope entering the ground water unless both the capsule and the source sub are crushed.

All sources must be transported and stored in a shield (the shield is removed when the source is being used for well logging). Shields for neutron sources are filled with hydrogenous materials, such as plastic. Shields for gamma sources are filled with heavy material, usually lead. Shields must be attached securely to transporting vehicles, and they must be labeled and locked. The size of a source determines the size of the shield required; shields for large sources may weigh several hundred pounds. The radiation level measured outside a shield determines whether, by regulation, a sign warning of radioactive contents must be placed on the logging truck. Shields should be as thick as practical to decrease exposure to personnel. The radiation that might be measured on the outside of a shield can be estimated, based on tables of half-value thickness for various materials and the energy of the radiation emitted by the source. Half-value thickness is the thickness that will decrease radiation of a given energy to half its original value. The half-value thickness of lead is about 0.25 for cesium-137 and 0.50 for cobalt-60, which emits more energetic gamma radiation. Probes containing sodium-iodide crystals should not be stored near neutron sources, because the crystals can be activated so that they emit gamma radiation.

Most regulations specify that radiation-monitoring equipment must be carried on a truck that transports sources. Monitoring equipment must be capable of measuring the kinds of radiation emitted by the sources being used, and the equipment must be calibrated periodically. Hand-carried counters commonly have interchangeable probes for measuring alpha, beta, gamma, and fast and slow neutrons. They are used to make periodic radiation checks of logging equipment and logging sites. The sources also must be wipe-tested periodically to determine if they are leaking. The wiping usually is done with a piece of filter paper, which is sent to a laboratory for analysis. Sources rarely leak, unless they have been physically damaged. Regulations require that records be kept noting the use of the sources, the monitoring of vehicles and sites, and the use of wipe tests.

Exposure of personnel to radioactivity during logging operations can be controlled by three important factors—time, distance, and shielding. All personnel involved with logging operations that use radioactive sources must wear film badges to record the dosage of radiation of different types that they have been exposed to during a specified time, usually 1 month. Film badges are read at the end of the specified time, and a record of the exposure for each individual is maintained by private companies under contract. The exposure to ionizing radiation recorded on the film badge is a function of time and of the kind and energy of radiation. Limits have been established for personnel exposure; if they are exceeded, no further on-the-job exposure is permitted for a specified period. Self-reading pocket dosimeters also are available so personnel can check exposure during a logging operation in which radiation might be expected to be unusually high.

Time probably is the most useful control of the dosage of radiation received by personnel involved with a logging operation. All procedures for removing sources from shields and loading them in probes should be designed to minimize the amount of time the source is out of the shield, before the probe is placed in the well. When the probe is a few feet below the ground surface, logging personnel will receive no radiation. The length of time personnel are close to sources in shields also adds to their total exposure.

Radioactivity decreases with the square of the distance. Distance can be controlled to some extent when loading a source by the use of long-handled devices, but sometimes remote-handling devices significantly increase the time needed to complete an operation. Although sources are not manipulated with the hands directly, the length of the handling device should be selected to permit rapid completion of the operation. If possible, source subs are designed so they can be attached to the probe while the sub and contained source are still in the shield. Using this method, exposure is limited to the time required to pull the probe and sub from the shield and lower it into the hole. Sources also can be handled from behind small shields, such as lead bricks for a gamma source, or under water for a neutron source, but such shields usually are not practical. During these operations, all unnecessary personnel and visitors should be kept a safe distance from the source.

The loss and subsequent rupturing of a radioactive source in a well constitute the greatest single danger in using such sources for logging. Although radioactive sources in shields have been lost out of the back of logging trucks through carelessness, they usually are recovered. Radioactive sources that are lost in wells may not be recovered even by the expensive retrieval attempt that is required by law. If the radioactive source is not recovered, the well must be filled with cement, and a plaque describing the lost source must be mounted permanently at the top of the well. The publicity and expense of such a loss might deter some groups from further use of radioactive sources. The author was involved in a retrieval operation that lasted 16 days and nights after a large neutron source was lost at a depth of 1,000 ft. The neutron source finally was recovered and put back into use; however, using care during logging to prevent such losses is much better than depending on good luck or skill in attempting to retrieve lost sources.

If a source is lost, nondestructive retrieval techniques (called fishing) are required by law; that is, the probe and contained source cannot be drilled out. Time is a factor, because of the possibility of a rock falling on top of the probe. Drawings and dimensions of the top of the probe and cable head should be kept in the logging truck to facilitate onsite construction of an overshot device that might permit fast recovery by using the logging winch and cable. Such fishing tools have been constructed at a local welding shop, and lost probes have been recovered within 1 day; however, the loss of a radioactive source must be reported to the appropriate agency immediately. If fishing with locally constructed devices is not successful and help is needed, a call to the nearest logging-company office will provide the telephone number of a company that specializes in such services. These companies will either provide or rent fishing tools, and will provide an expert to operate them. Usually a rotary-drill rig is needed to use commercial fishing devices. Complete instructions on fishing techniques are beyond the scope of this manual; if a logging operator has no experience in retrieving lost sources, help should be obtained as soon as possible.

The loss of most probes can be prevented if proper logging procedures are followed. Probes containing radioactive sources should be the last to be used in an uncased well; they should never be used if the use of other probes indicated problems. The driller should be consulted prior to logging to determine if caving or other problems will prevent free access to the entire depth of the well. If any drilling or logging equipment (junk) has been lost in the well, all logging should proceed with caution, and the probe should not be lowered all of the way to the bottom of the well. Damaged casing or key-slotted casing in deviated wells can cause the cable to be caught. Swelling clay can cause probes to become stuck in a well. The weight indicator should be watched closely, and the probe should be pulled rapidly from the hole if it appears to be sticking. A high-resolution caliper log may indicate hole conditions that would make logging with a radioactive source unsafe. The individual in charge of the logging equipment is never overruled if he or she thinks logging is not safe.

Many precautions and procedures are needed to make nuclear logs using a radioactive source. The logs are useful, but for some organizations it may not be economically justifiable to run their own logs; the use of a commercial service company might be considered.

Gamma logging

Gamma logs, also called gamma-ray logs or natural-gamma logs, are the most widely used nuclear logs in ground-water applications. The most common uses are for identification of lithology and for stratigraphic correlation. Gamma logs can be made with relatively inexpensive and simple equipment, and they provide useful data under a variety of borehole conditions.

Principles

A gamma log provides a record of the total gamma radiation detected in a borehole that is within a selected energy range. In water-bearing rocks that are not contaminated by artificial radioisotopes, the most significant naturally occurring, gamma-emitting radioisotopes are potassium-40 and daughter products of the uranium- and thorium-decay series—hence the name natural-gamma log. If gamma-emitting artificial radioisotopes have been introduced by humans into the ground-water system, they will produce part of the radiation measured, but they cannot be identified unless spectral-logging equipment is used. Some characteristics of the three most important naturally occurring radioactive materials that affect logging are listed below (Belknap and others, 1959). These concentrations, which are averages from 200 shale samples, were used to establish the concentrations of radioisotopes in the American Petroleum Institute calibration pits for gamma logs (see table 2).

Material	Energy of major gamma peaks (million electronvolts)	Number of photons per second per gram	Average content in 200 shale samples	Percentage of total gamma intensity of shale samples
Potassium-40	1.46	3.4	2 percent (of total potassium)	19
Uranium-238 series in equilibrium	1.76	2.810	6 parts per million	47
Thorium-232 series in equilibrium	2.62	1.010	12 parts per million	34

Note that in these 200 shale samples, collected from various localities around the United States, the uranium series contributed almost half the gamma radiation even though the average content was 6 ppm. This is because of the substantial specific activity of the uranium series. The average potassium content was 2 percent, of which potassium-40 constitutes only about 0.012 percent. Potassium is abundant in some feldspar and mica that decompose to clay. Uranium and thorium are concentrated in clay by the processes of adsorption and ion exchange. For these reasons, fine-grained detrital sediments that contain abundant clay tend to be more radioactive than quartz sand and carbonate rocks, although numerous exceptions occur. Rocks can be characterized according to their usual gamma intensity, but knowledge of the local geology is needed to identify the numerous exceptions to the classification shown in figure 46.

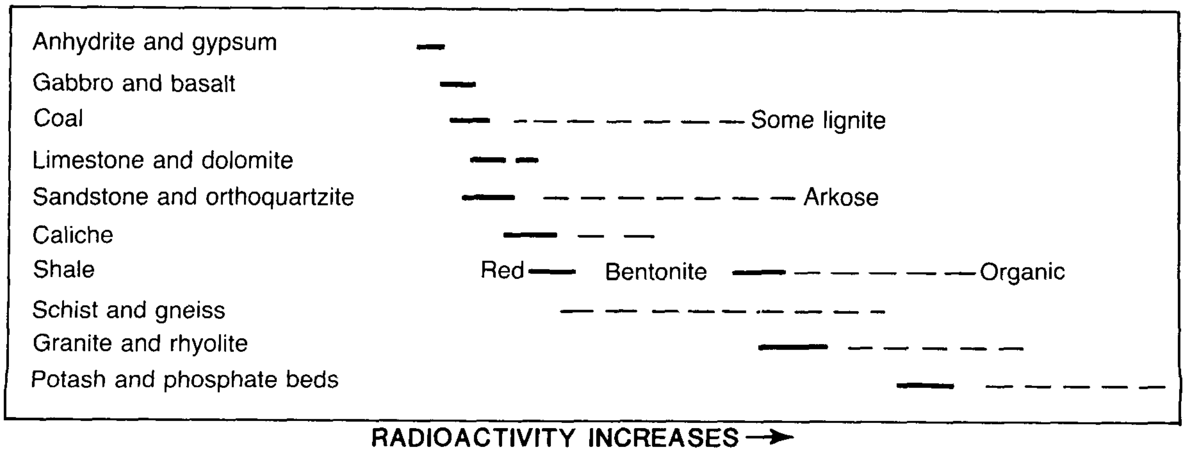


Figure 46.—Relative radioactivity of some common rocks.

Coal, limestone, and dolomite usually are less radioactive than shale; however, all these rocks can contain deposits of uranium and be quite radioactive. Basic igneous rocks usually are less radioactive than silicic igneous rocks, but exceptions are known. There are several reasons for the considerable variability in the radioactivity of rocks. Uranium and thorium are trace elements and are not important in the genesis of rocks. Uranium also is soluble in ground water under some conditions; thus solution, migration, and precipitation may cause redistribution with time. Separation of uranium from its gamma-emitting daughters during migration may cause disequilibrium, which will result in a gamma-log response that does not indicate correctly the quantity of uranium present.

Calibration and standardization

The petroleum industry has adopted the American Petroleum Institute (API) gamma-ray unit as the standard for scales on gamma logs, but the unit has not been widely used in water-well logging to date. A number of different units have been used in the past, including milli-roentgen per hour, "inches of deflection," and "standard units." Conversion between some of the older units used by commercial service companies is included in Desbrandes (1968); however, in general, if logging probes have not been calibrated in the same pit, the accuracy of scale conversion is questionable.

Most laboratory radiation-counting equipment provides a direct reading in pulses or counts per second or minute; because this is a direct reading, these units have been adopted for many of the small loggers used for water wells. Pulses are convenient units to work with because readily available pulse generators can be used to establish and display scales on logs, and pulses are recorded using digital ratemeters for onsite digitizing of logs. Unfortunately, although convenient to work with, pulses per unit time cannot be used for comparing logs quantitatively and have no meaning with respect to the actual flux in a radiation field. For example, gamma probes having different-size crystals or different electronics probably will produce markedly different count rates in the same well at the same depth. The entire logging system should be calibrated in a pit or well with a known intensity of radiation or a known concentration of radioisotopes.

The U.S. Department of Energy maintains a number of calibration pits for gamma probes; separate pits are maintained for each of the naturally occurring gamma emitters—uranium, thorium, and potassium. These pits are not suitable for calibrating most gamma probes used in water-well logging, because the contents of the radioelements in the pits tend to be much greater than the average content of these radioelements in most aquifers and related rocks. In contrast, the API's calibration pit for gamma probes contains these radioisotopes in concentrations typical of shale; this pit has become the worldwide standard for all logging related to petroleum. For this reason, adoption of the API gamma-ray unit for use in ground water would seem logical. The API gamma-ray unit is defined as 1/200 of the difference in deflection of a gamma log between an interval of negligible radioactivity in the pit and the interval that contains the same relative proportions of radioisotopes as an average shale, but about twice the total radioactivity.

One or more field standards are needed when calibrating in a pit or well and when calibrating frequently during logging operations to ensure that a gamma-logging system is stable with respect to time and temperature. Field standards may be radioactive sources that can be held in one or more fixed positions in relation to the detector while readings are made. If this approach is used, the probe is best located at least several feet above the ground and distant from a logging truck that contains other radioactive sources that could contribute to the background radiation. Radiation measurements taken around the logging truck can be used to determine the proper distance. Another approach is to fabricate sleeves consisting of two concentric pipes with welded endpieces. After one end is welded to the pipes, the annular space between the pipes is filled with a radioactive cement slurry that is allowed to set up before the other endpiece is welded to the pipes. The standard is not used for a month to allow radon to reach equilibrium. The advantages of this method are that a more uniform radiation field is produced, the sleeves tend to shield the background contribution, and proportions of radioisotopes can be selected to approximate those in the API's calibration pit or other calibration facility. If natural uranium, thorium, and potassium are used, the half-lives are so long that no correction need be made for radioactive decay, which would be necessary for many artificial sources.

Volume of investigation

The volume of material investigated by a gamma probe is related to the energy of the radiation measured, the density of the material through which that radiation must pass, and the design of the probe. Dense rock, steel casing, and cement will decrease the radiation that reaches the detector, particularly from a greater distance from the borehole. Wahl (1983), using a computer model, demonstrated that the effect of rock density is negligible. Higher energy gamma radiation, such as that from uranium and thorium, will travel farther than the lower energy radiation from potassium-40; however, Wahl (1983) determined that,

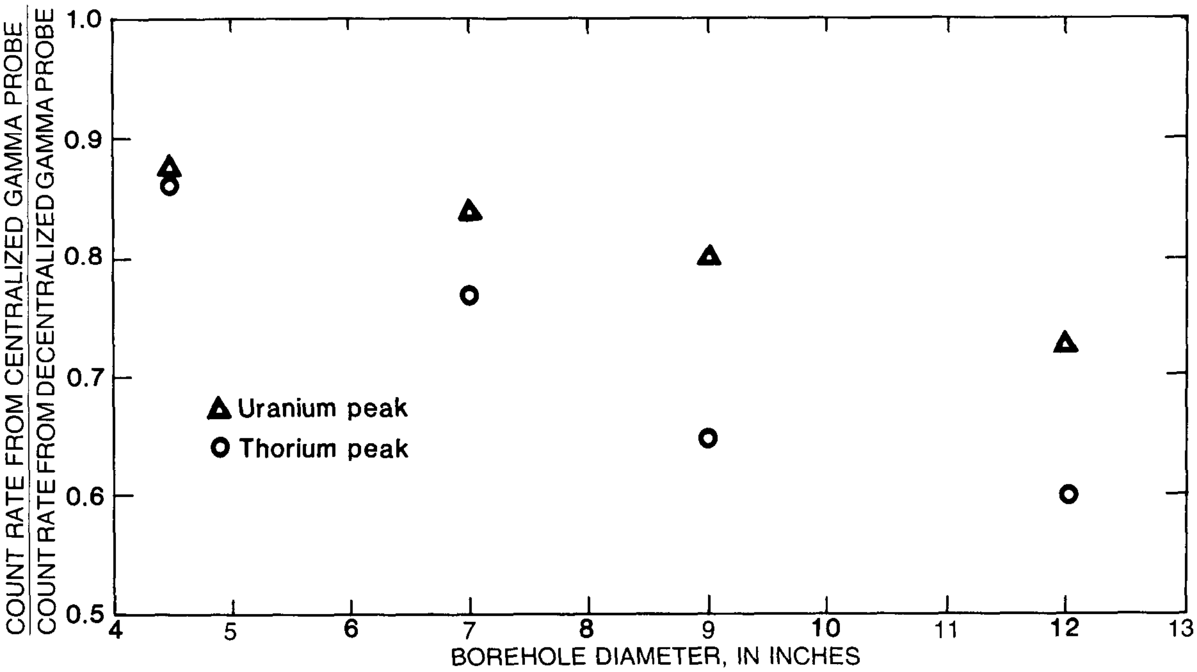


Figure 47.—Effect of position of a gamma probe in a borehole as a function of borehole diameter for uranium and thorium radiation (Ulrich Schimschal, U.S. Geological Survey, written commun., 1981).

from a practical standpoint, there is little difference in the volume of investigation for uranium and thorium. This lack of difference probably is attributable to the fact that although thorium has a higher energy peak than uranium, more of its activity comes from low energy peaks. Energy discrimination used in the probe, together with a dense or thick housing around the detector, may decrease the low energy radiation detected. Under most conditions, 90 percent of the gamma radiation detected probably originates from material within 6 to 12 in of the borehole wall. The volume of material contributing to the measured signal may be considered approximately spherical, with no distinct boundary at the outer surface. The vertical dimension of this volume also depends on the length of the crystal, and this will affect the resolution of thin beds. Because the detector is at the center of the volume investigated, radioactivity measured when the detector is located at a bed contact will be an average of two beds. The actual radioactivity of beds having a thickness less than twice the radius of investigation will not be recorded.

Extraneous effects

The amplitude of gamma-log deflections is changed by any borehole conditions that alter the density of the material through which the gamma photons must pass or the length of the travel path. Thus, casing and cement will decrease the recorded radiation, as will large well diameters. The type of borehole fluid has a minor effect unless the borehole is large in diameter or the mud contains radioactive clay or sylvite. Heavy drilling mud also can attenuate gamma radiation. All these extraneous effects are less on gamma logs than they are on other types of nuclear logs. Thick gravel pack in the annular space behind the casing may limit the usefulness of gamma logs. If the gravel pack is composed of a rock, such as dolomite, that is minimally radioactive, the gamma response from the aquifer will be reduced. If a granitic or arkosic material is used, gamma-log response will be anomalously large. Changes in gamma-log response over time are common. Increases in gamma radiation have been detected in oil wells that produce large quantities of saltwater. Changes in gamma response during 1 year, which apparently were caused by migration of uranium daughter products along fractures, have been reported (Keys, 1984). Radon distribution, determined from gamma logs, has been used to identify intervals of water entry or loss and to calculate the rate of water inflow in boreholes in igneous rock (Nelson and others, 1980).

The position of a gamma probe in a well may introduce an error in the count rate measured. Unless they are centered intentionally, probes slide along the wall of most boreholes because the boreholes usually are deviated enough to prevent the probe from remaining in the center. The ratio of the count rates from a centralized gamma probe to those from a decentralized gamma probe is plotted in figure 47

(Ulrich Schimschal, U.S. Geological Survey, written commun., 1981). Note that the difference is small for a hole approximately 4.5 inches in diameter, but quite large for a borehole 12 inches in diameter; the difference is greater for thorium than for uranium.

Interpretation and applications

Because of numerous deviations from the typical response of gamma logs to lithology, some background information on each new study area is needed to decrease the possibility of errors in interpretation. The typical gamma-log response in a hypothetical well that penetrates a sedimentary sequence and bottoms in granite is shown in figure 48. (See fig. 7 for the responses of other logs in this rock sequence and fig. 8 for the response of gamma and other logs in igneous rocks.) Note that coal, gypsum, and anhydrite all are recorded as a decreased gamma intensity on the log in figure 48, so that other logs are needed to distinguish between these rock types. Shale tends to be more radioactive than sandstone, which usually is more radioactive than limestone. Quartz sandstone usually is less radioactive than sandstone containing other minerals, and arkose tends to give a greater gamma deflection than either. Granitic basement rocks are likely more radioactive than any of the other rocks shown. Note that no effect occurs on the gamma log from the change in water quality and that borehole-diameter effects are minor. The 10-in casing in alluvium does decrease the gamma-log response; however, the magnitude of the effect is not known because the lithology changes at the bottom of the casing.

Gamma logs are used for correlation of rock units; however, this approach can result in erroneous correlation if the gamma-log response within the area being studied is not understood. For example, gradual lateral change in grain size or increase in arkosic materials in a sandstone may change the response of gamma logs. Gamma logs and spontaneous-potential logs of the same area may be interpreted similarly if the spontaneous-potential log was made under the right conditions. The similar response of these two logs in a sequence of detrital sediments is shown in figure 29.

In igneous rocks, gamma intensity is greater in silicic rocks, such as granite, than in basic rocks, such as andesite. Orthoclase and biotite are two minerals that contain radioisotopes in igneous rocks; they can contribute to the radioactivity of sedimentary rocks if chemical decomposition has not been too great. A relation between gamma-log response and the content of orthoclase and biotite in a borehole drilled in igneous rocks is demonstrated in figure 49.

Gamma logs are used widely in the petroleum industry to establish the clay or shale content of reservoir rocks; laboratory data from ground-water studies also support a relation between gamma logs and clay or shale content. The relation between the percentage of silt and clay from core analyses and the gamma-log response in a series of valley-fill sediments is demonstrated in figure 50. The increase in radioactivity from an increase in fine-grained materials has been the basis for a number of studies relating gamma-log response to permeability in various parts of the world, such as Colorado (the Denver-Julesburg basin), Russia, India, and Texas (Rabe, 1957; Raplova, 1961; Gaur and Singh, 1965; Keys and MacCary, 1973). If gamma logs are to be interpreted quantitatively, then using the amplitude of the gamma response is not correct. Scott and others (1961) demonstrated that the area under the gamma curve is proportional to the bed thickness multiplied by the quantity of radioisotope present. If gamma logs are to be interpreted quantitatively, other references should be consulted; a number of considerations that are beyond the scope of this manual have been described well by Killeen (1982). The usefulness of gamma measurements to establish clay and shale content and for other ground-water applications probably will be increased by using borehole-gamma spectrometry.

Gamma-spectrometry logging

Gamma-spectrometry logging permits identification and quantitative analysis of the radioisotopes that contribute to the gross count rate that is recorded on a gamma log. Gamma spectrometry in boreholes can provide much more diagnostic information on lithology than a gamma log, and can be used to identify natural and artificial radioisotopes migrating in ground water. The equipment required to make gamma-spectrometry logs comprises a probe designed to transmit variable-height pulses up the cable and a multichannel analyzer. Determining the concentration of radioactive elements requires computer analysis. Gamma-spectrometry logging is used widely in the petroleum industry, but it has not been used to the extent justified in water-resources investigations, even though this author applied it to ground-water-contamination problems more than two decades ago.

Principles

As described in the section on the fundamentals of nuclear geophysics, radioisotopes emit particles and gamma photons that have an energy characteristic of the isotope. In the section on gamma logging, the radiation measured was described as coming from the decay series of uranium, thorium, and potassium. The following are simplified decay series for these naturally occurring radioisotopes; the energy of the most

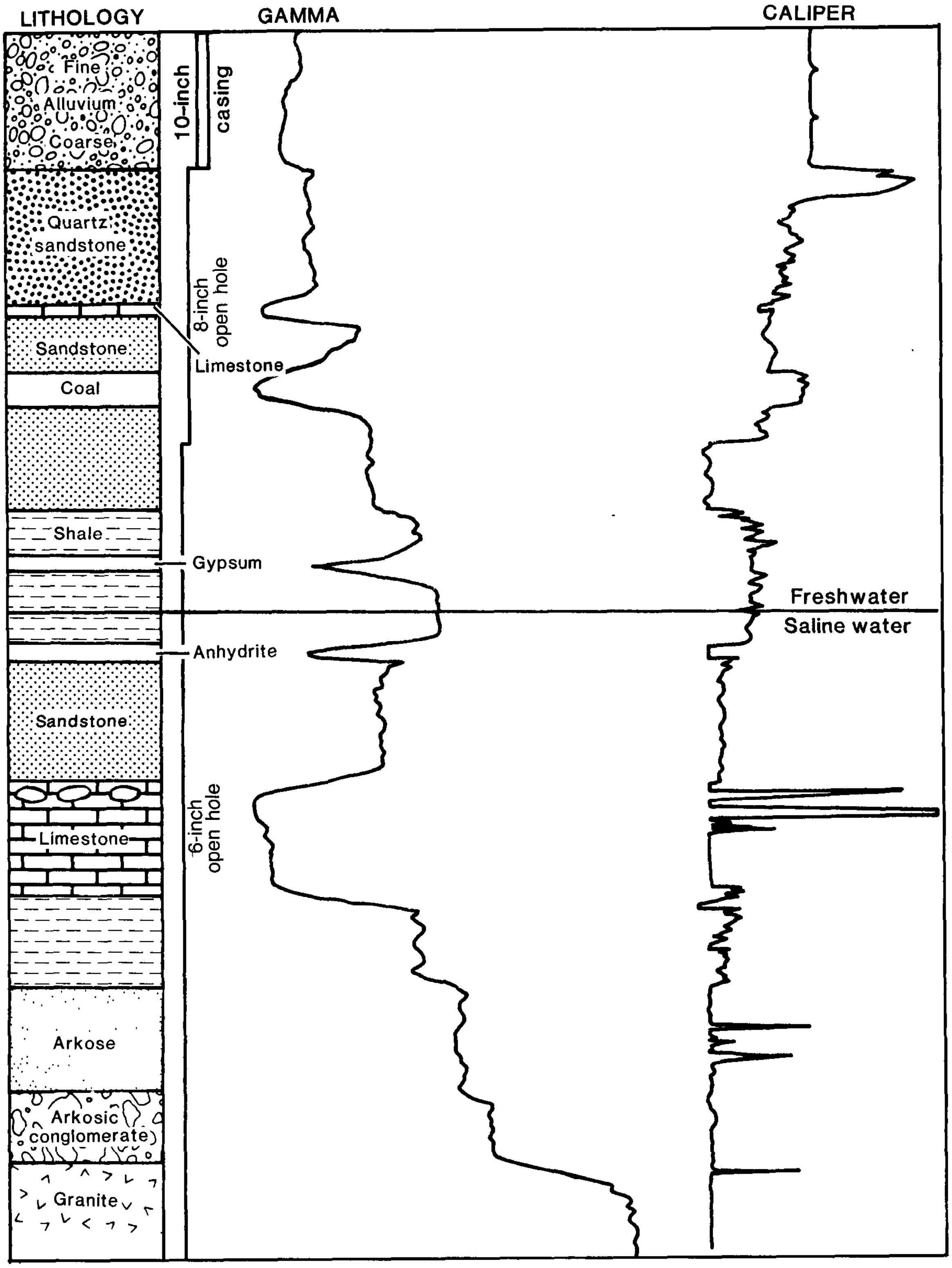


Figure 48.—Typical responses of gamma and caliper logs to a sequence of sedimentary rocks.

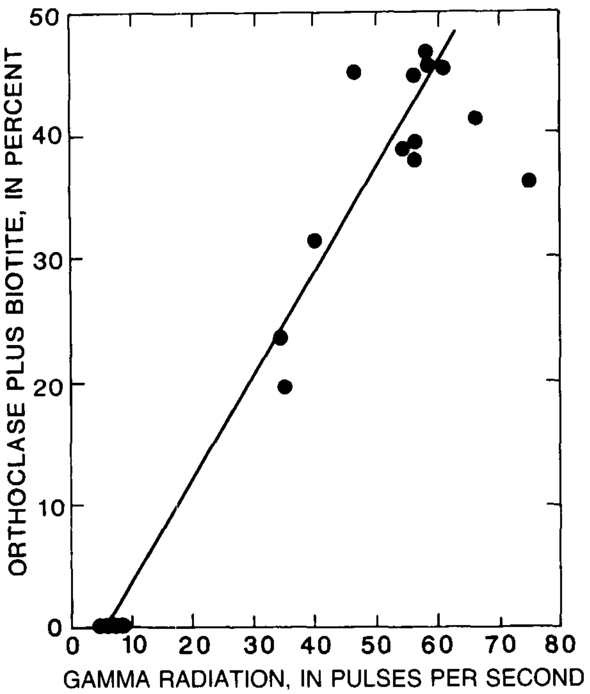


Figure 49.—Percentage of orthoclase and biotite versus gamma-log response in borehole CR-6, Ontario, Canada.

important gamma peaks is shown in parentheses, following the isotope from which it is emitted:

Potassium-40 (1.46 MeV) → argon-40 (stable).

Uranium-238 → thorium-234 → protactinium-234 → uranium-234 → thorium-230 → radium-226 → radon-222 → polonium-218 → lead-214 → bismuth-214 (0.6, 1.12, 1.76, and 2.20 MeV) → polonium-214 (or 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 the radioisotopes in these decay series is present in a quantity related to its half-life if the system is in equilibrium. Secular disequilibrium is caused by selective removal of any of the isotopes in the series; measurement of the quantity of gamma emitters by standard spectrometry techniques will not permit calculation of the correct quantity of other isotopes that are present in the series. For this reason, gamma-spectral analyses of samples for uranium content usually are reported as radium-equivalent uranium.

Gamma-spectral data can be recorded in boreholes on a continuous basis or at selected depths with the probe stationary. To record a full spectrum of the naturally occurring gamma emitters, the multichannel analyzer usually is set to record the energy range 0 to 3 MeV. The way individual spectra for the three series would appear, measured by a sodium-iodide crystal, if they were distinguishable on the analog display of a multichannel analyzer is shown in figure 51. A catalog of gamma spectra recorded for 277 radioisotopes using a sodium-iodide crystal permits identification from such an analog display, if there are not too many interfering isotopes (Heath, 1964). Gamma spectra usually are recorded in both analog and digital format. In practice, the pulses recorded in each channel are superimposed; a composite spectrum is produced that is the sum of the spectra shown. If the concentrations of uranium, thorium, and potassium are sufficient, the energy peaks at 1.76, 2.62, and 1.46 MeV will be distinguishable in a composite spectrum, along with other lesser peaks. These are the peaks that are used most often to identify the three naturally occurring series.

To estimate the quantity of radioisotopes present, the area under a peak must be calculated; however, it should be apparent (see fig. 51) that both uranium and thorium contribute significantly to the 1.46-MeV potassium peak. Similarly, thorium, if much is present, makes a major contribution to the 1.76-MeV uranium peak. To remove these unwanted contributions, a technique called spectral stripping is used. Spectral stripping and counting the number of pulses within a peak may be done in most multichannel analyzers that are computer based. Careful equipment calibration permits selective removal of the thorium spectrum, based on the 2.62-MeV peak; then the uranium spectrum can be stripped out, based on the 1.76-MeV peak. This stripping process may be done at individual depths or on a continuous basis. For a more complete description of the quantitative analysis of gamma-spectral data, see Killeen (1982).

To do continuous spectral logging, which records separate curves representative of the content of selected radioisotopes, energy windows are employed. Single-channel analyzers are set to record all pulses within the energy ranges representative of the three peaks shown in figure 51. They may be stripped in real time with a computer. The result is plotted as a spectral log, or KUT log, which usually has at least four traces, a gamma log and curves that should represent the quantities of potassium (K), uranium (U), and thorium (T) that are present. The count rates in the channels selected may be quite small, so a large crystal is needed and logging must be done at a slow speed. Because of the complexity of the real-time

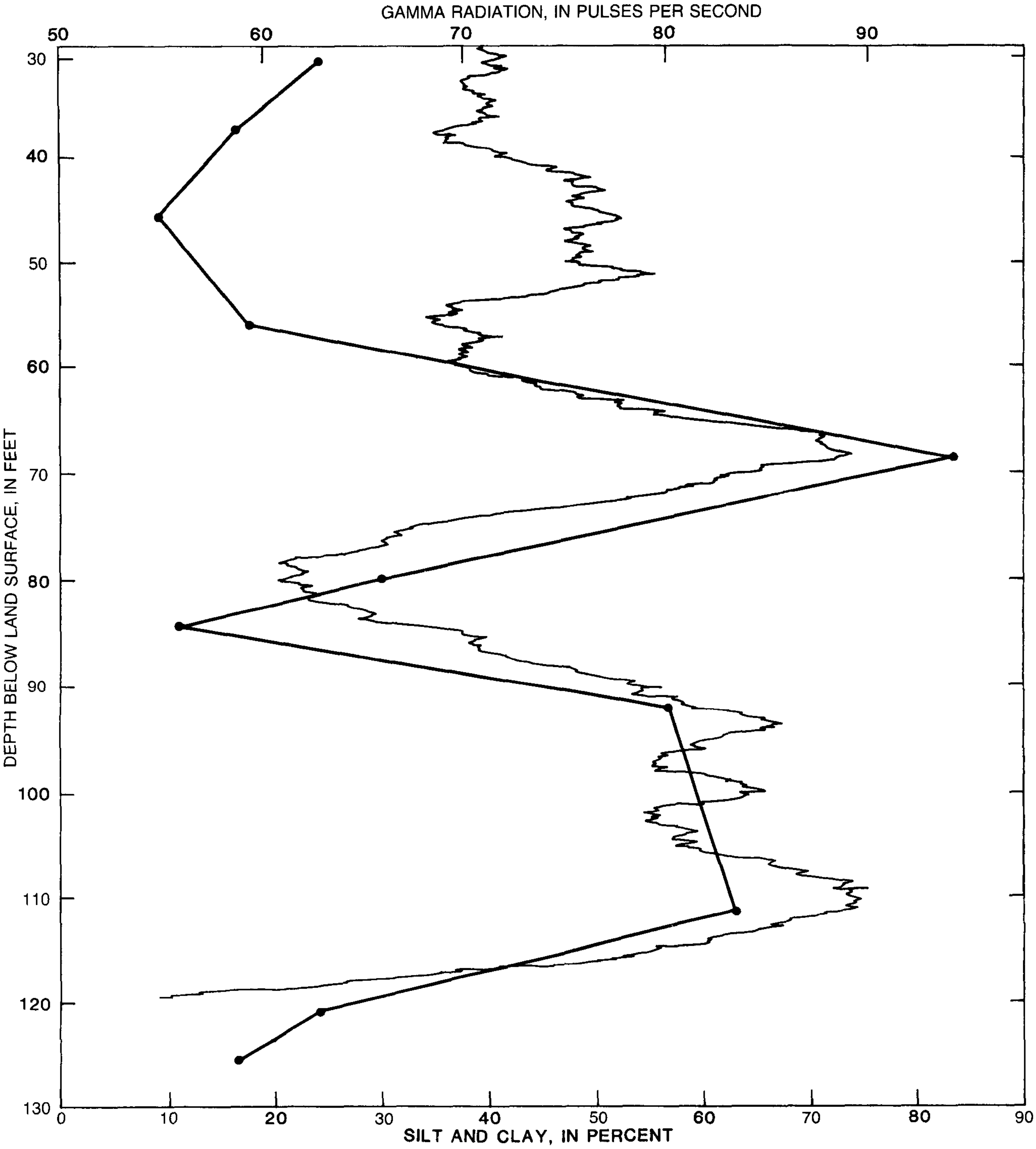


Figure 50.—Relation between percentage of silt and clay and gamma radiation from analyses of core samples from near Bear Creek, Colo.

calculations to produce a spectral log, substantial errors in the quantitative results are common. The logs should be checked against laboratory analyses of core and stationary spectral measurements. Spectral-logging equipment now is available from large commercial service companies; the equipment can be purchased, but it is expensive.

Although most spectral equipment for logging currently uses sodium- or cesium-iodide crystals, solid-state detectors are available that increase resolution

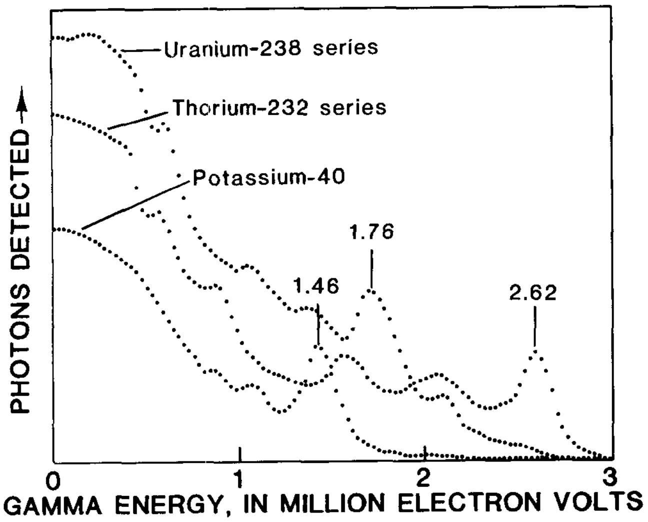


Figure 51.—Gamma spectra for the uranium-238 series, thorium-232 series, and potassium-40.

and make it possible to identify disequilibrium. A comparison of a spectrum run in a test hole at Oak Ridge, Tenn., with a sodium-iodide crystal and with a solid-state germanium detector (Keys, Senftle, and Tanner, 1979) is shown in figure 52. Note that the solid-state germanium detector has much greater resolution and permits identification of peaks not resolved by the sodium-iodide crystal. Solid-state detectors do have several disadvantages, however: they are expensive to buy and operate; some detectors (as the one used in this example) must be operated at cryogenic temperatures; and most of these detectors have minimal efficiency, particularly at greater energies. For this reason, count rates may be small in the upper half of a natural-gamma spectrum.

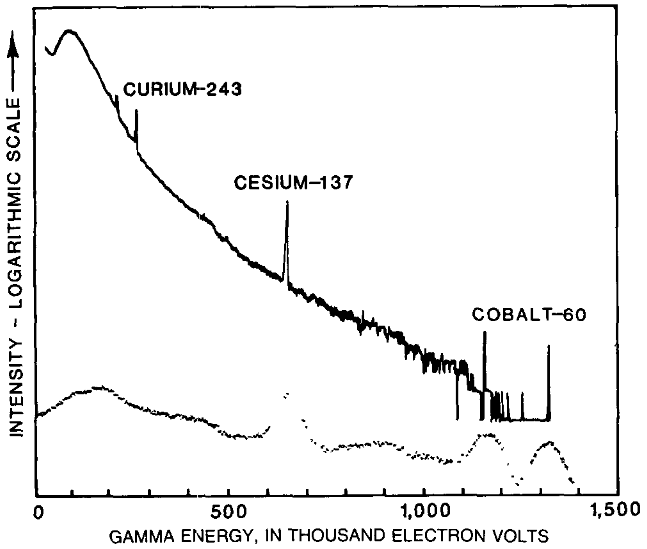


Figure 52.—Gamma spectra recorded in test hole 5-T83-5, Oak Ridge, Tenn. Upper spectrum recorded with a germanium detector; lower spectrum recorded with a sodium-iodide crystal (modified from Keys, Senftle, and Tanner, 1979).

Calibration and standardization

The U.S. Department of Energy's pits described in the general section on calibration and standardization can be used to calibrate spectral-logging equipment, and a new pit for spectral probes has been constructed at the American Petroleum Institute's facilities at the University of Houston, although analytical data are not available at this time (1985). The U.S. Department of Energy's pits offer different hole sizes and different concentrations of radioisotopes, with an emphasis on uranium. Commercial well-logging companies also have calibration pits for spectral equipment; these may be available by special arrangement. The only other procedure for calibration is comparison with laboratory analyses of core. Field standards should be used frequently during both calibration and spectral logging. The U.S. Geological Survey has developed bucket standards for checking spectral equipment onsite. Tubes that fit the probe tightly are placed in the center of each of two 5-gal buckets. One bucket is filled with quartz sand, and the other with potassium hydroxide for a potassium standard. Four or five small uranium or thorium sources are taped to the outside of the sand-filled bucket to simulate the scattering that takes place near a borehole. Natural radioisotopes could be mixed in the sand with cement, and a lid welded on after the cement has set. The material in the standard can be analyzed in a laboratory, or the concentration can be determined by comparison with calibration pits; however, buckets of this size may not simulate an infinite source, with respect to probe response. A model or standard may be considered to be infinite when an increase in size produces no change in the measurement. Field standards are designed so that the crystal is in the center of the standard when measurements are made and the counting periods are long enough to produce a small statistical error.

Volume of investigation and extraneous effects

The volume of investigation and extraneous effects for gamma-spectrometry logs are similar to those for gamma logs, except that the former must be considered more rigorously because the results usually are analyzed quantitatively. Ninety percent of the pulses recorded probably originate within 6 to 12 in of the borehole wall. Borehole diameter, fluid in the borehole, casing, and material in the annular space introduce errors that may be correctable within a limited range. Instrument drift as a function of time or

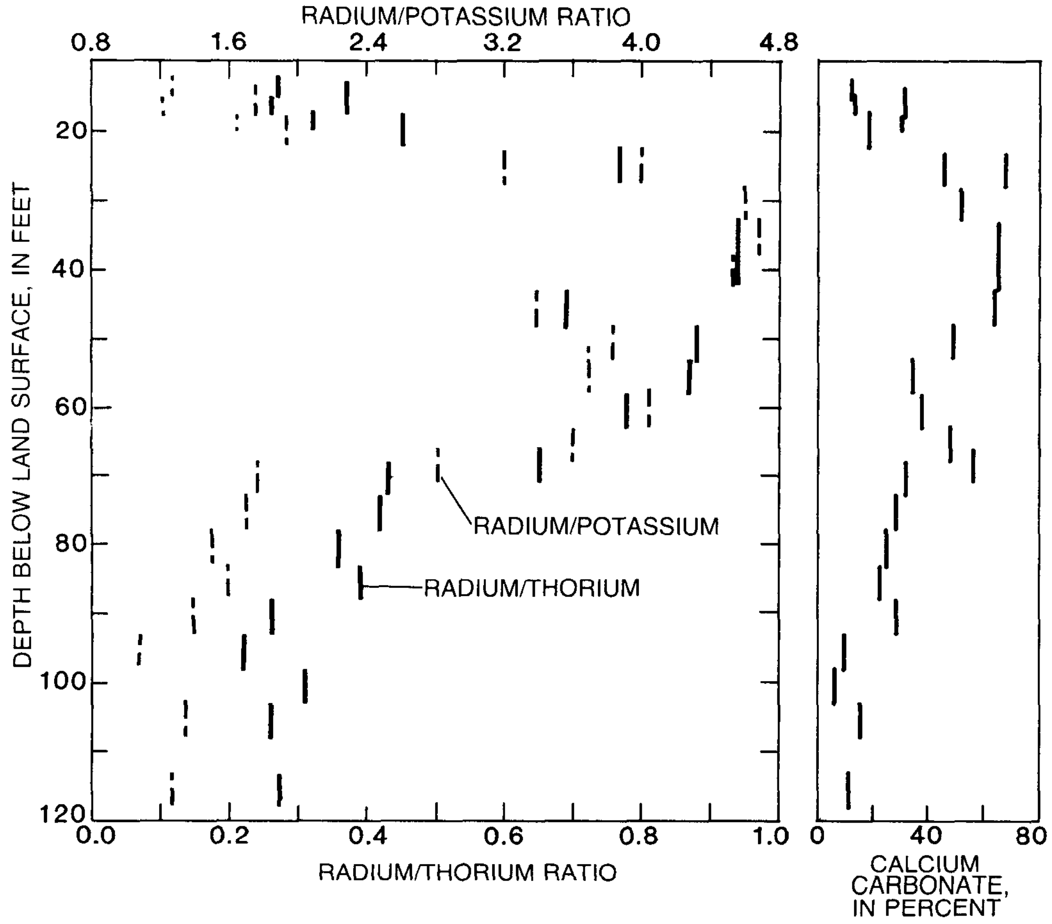


Figure 53.—Relation of calcium carbonate to radium/thorium and radium/potassium ratios from analyses of gamma spectra, Lubbock, Tex. (modified from Keys and Brown, 1971).

temperature is common. Many spectral systems incorporate a small, low-energy source and a spectrum stabilizer that locks on the peak from that source and automatically makes drift corrections. The term "drift" refers to changes in the apparent energy scale that result from changes in the ambient conditions of the measuring equipment, such as temperature and humidity. Other spectral systems lock the stabilizer on a peak from a naturally occurring radioisotope. Temperature drift of peak locations is common; drift caused by rapid count rates also can take place.

Interpretation and applications

Not only the methods, but also the interpretation and applications, of gamma-spectrometry logs are quite different from gamma logs, because the sources of the radioactivity can be identified. Gamma-spectral data from boreholes provide much more diagnostic information on lithology, because the concentration of each of the three naturally occurring radioisotopes can be determined under the proper conditions. Gamma-spectrometry logging also permits identification of artificial radioisotopes that might be contaminating ground-water supplies or that are produced by neutron activation. The latter application is described in the section on neutron logging.

The practical application of gamma spectrometry to a problem in artificial recharge near Lubbock, Tex. (Keys and Brown, 1971), is illustrated in figures 53 and 54. Laboratory analyses of core samples from below a site being considered for a recharge pond indicated that sediments of the Tertiary Ogallala Formation having the smallest content of clay and calcium carbonate had the largest permeability. Caliche intervals with calcium carbonate contents greater than 35 percent had a lesser permeability that would prevent the downward movement of recharge water. Neither the gamma nor the neutron logs had a diagnostic response that aided in identifying these caliche intervals. Gamma-spectral analyses permitted the plotting of ratios of radium to thorium and radium to potassium. Radium equivalent is reported here, because disequilibrium may occur in these sediments. The large ratios correlate well with the intervals of

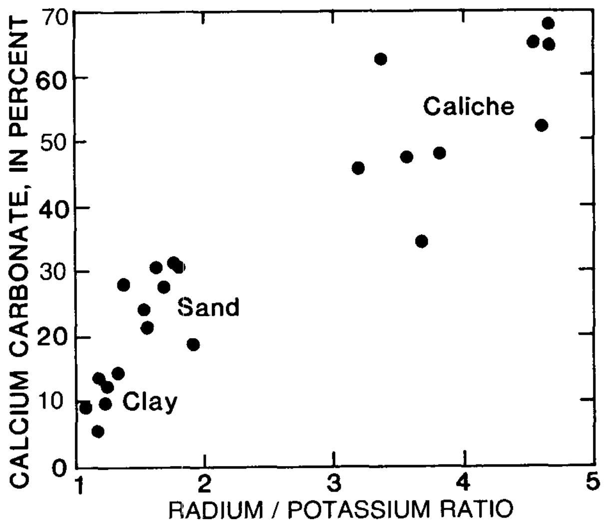


Figure 54.—Calcium carbonate versus radium/potassium ratio for a borehole in the Ogallala Formation (modified from Keys and Brown, 1971).

large calcium carbonate content (fig. 53). The radium/potassium ratio can be used to identify clay, sand, and caliche at this site (fig. 54). At other sites underlain by the Ogallala Formation, caliche was determined to have an anomalously large concentration of uranium or its daughter products, although the permeability of these intervals was not always small. Isotopes in the uranium series may have been transported relatively recently by ground water and precipitated in the caliche. Disequilibrium caused by selective transportation of uranium daughter products is relatively common.

Radiometric ratios have been used to distinguish clay or shale from other rocks more accurately than the total gamma intensity because of the possibility that the uranium contribution may be the result of postdeposition migration. Secondary concentrations of uranium and daughter products may indicate the presence of fractures, but such concentrations may not be related to lithology. Fractured calcareous and cherty shales, which yield large quantities of oil because of secondary porosity and permeability, have been identified using gamma-spectral logs (Fertl and Rieke, 1979). Some of these fractured shales have an anomalously large uranium content, and much less thorium and potassium. Nonproductive shales in the same section have approximately the same total gamma activity, but all three radioelements occur in their usual relative abundance.

The ratio of thorium to potassium has been reported to be related to the mineralogical composition of shale (Quirein and others, 1982). This ratio can be correlated with the percentage of illite clay in shale. These authors classified clay, feldspar, and mica minerals as a function of expected thorium and potassium concentrations. Gamma-spectrometry logging has been used to identify fractured and altered intervals in a geothermal well penetrating sedimentary rocks and in a nongeothermal well penetrating igneous rocks (Keys, 1982). Water moving through fractures apparently leached out much of the potassium deposited near the margins of the permeable intervals.

A probe housing with a small atomic number has been developed so that low-energy gamma radiation in the photoelectric region can be measured with a spectral probe (Gadeken and others, 1984). Reportedly, the photoelectric portion of the spectrum provides additional information on lithology; measurements of casing thickness can be made with this probe. The photoelectric factor (Pe) is derived from the ratio of counts in the higher energy Compton window to counts in the photoelectric window. The reported values of Pe are 1.81 for quartz, 3.14 for dolomite, and 5.08 for calcite.

Borehole-gamma spectrometry has considerable application to the selection of sites for the disposal of radioactive waste and the monitoring of waste migration. A table of gamma-emitting radioisotopes that might be present in such waste and examples of their identification are included in Keys, Senftle, and Tanner (1979). An example of the use of gamma spectrometry to identify artificial radioisotopes through casing in a monitoring well is given in figure 55. The well is located near the boundary of the commercial radioactive-waste disposal site at Maxey Flats, Ky. Water samples collected periodically from the bottom of the well indicated slight contamination by several radioisotopes. The gamma log on the left side of the figure indicates a significant radioactivity anomaly at a depth of 43 ft, which was identified through casing and cement as being caused by cesium-134 and 137 and cobalt-60. This contamination was not present when the well was drilled, and a spectrum at a depth of 56 ft did not indicate the presence of significant quantities of artificial radioisotopes.

Gamma-gamma logging

Gamma-gamma logs, also called density logs, are records of the radiation received at a detector from a gamma source in a probe, after it is attenuated and scattered in the borehole and surrounding rocks. The logs can be calibrated in terms of bulk density under the proper conditions and converted to porosity if grain and fluid density are known. Gamma-gamma logs are extensively used and readily available in the petroleum industry, but they are used much less for ground-water applications.

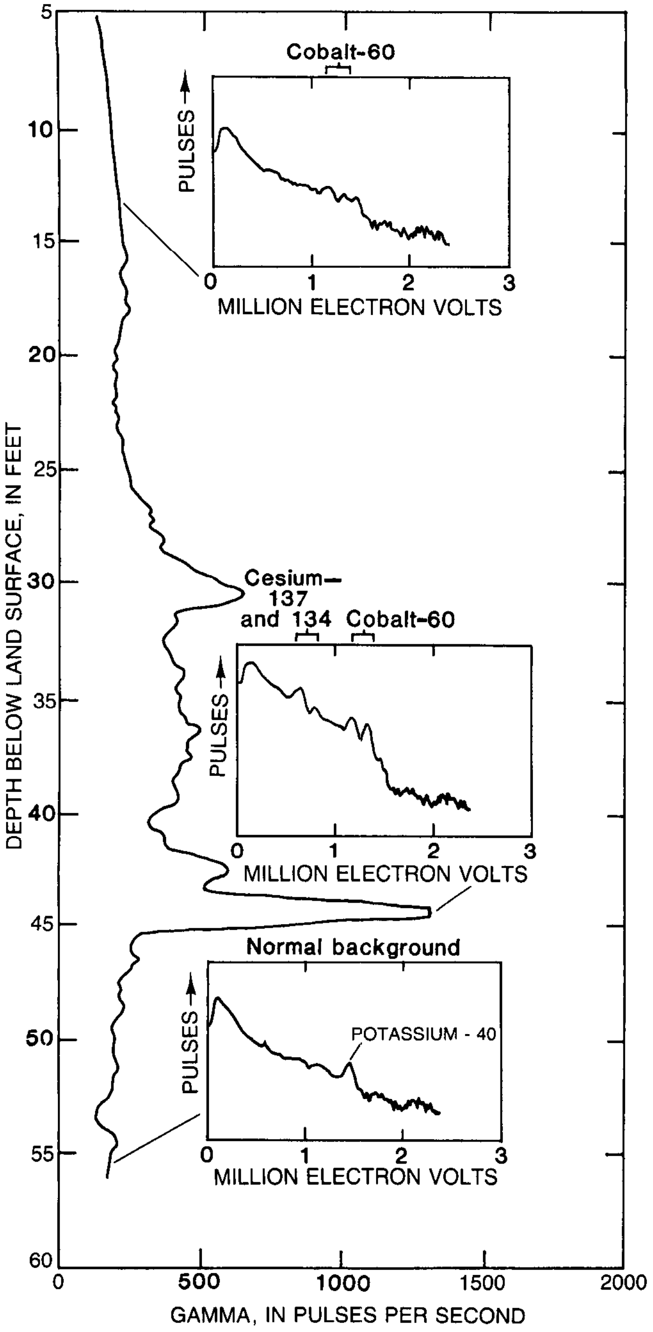


Figure 55.—Gamma log and gamma spectra at three depths, Maxey Flats, Ky. (Keys, Senftle, and Tanner, 1979).

Principles

Gamma-gamma probes contain a source of gamma radiation, usually cesium-137 in newer probes, and one or more gamma detectors. Cesium-137 has a principal energy peak at 0.66 MeV. Cobalt-60 has been used in the past, but it has greater energy, which increases the effect of elemental composition, and a much shorter half-life, which necessitates frequent correction and source replacement. A recent study of gamma-gamma logging in ore deposits indicates that a cobalt-60 source will provide density measurements of common rocks that are virtually independent of their chemical composition (Borsaru and others, 1984). The detectors in a gamma-gamma probe are shielded from direct radiation from the source by heavy metal, commonly lead or a tungsten alloy. Modern gamma-gamma probes are decentralized and side collimated. The two parts of the probe shown in figure 56 screw together, with the source and detectors at the bottom. Side collimation with heavy metal tends to focus the radiation from the source and to limit the detected radiation to that part of the wall of the borehole that is in contact with the source and detectors. The decentralizing caliper arm also provides a log of hole diameter. In some probes, the source and detectors are mounted in a decentralized skid on an arm. The modern probes are called borehole compensated or borehole corrected, but logs made with these probes still display some borehole effects. Older probes used a single detector, and some were not side collimated, so borehole effects were greater under most conditions.

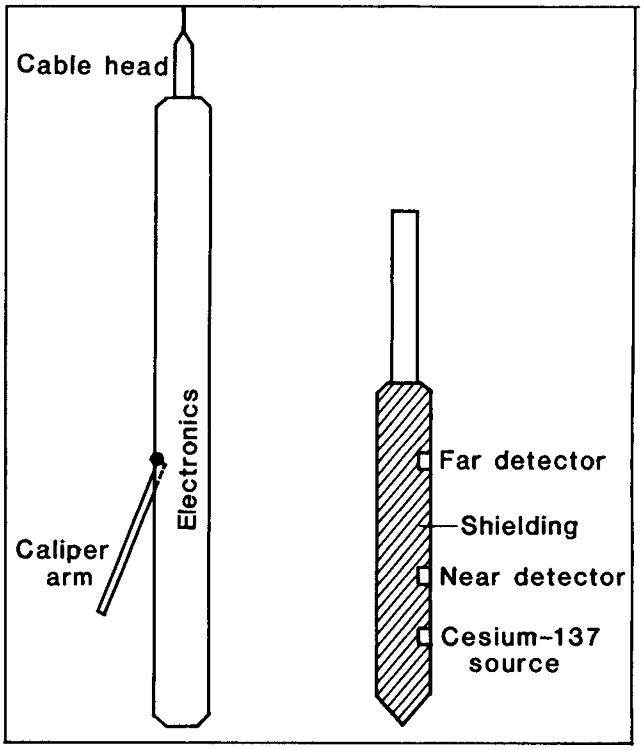


Figure 56.—Probe for making compensated gamma-gamma logs.

Gamma-gamma logging is based on the principle that the attenuation of gamma radiation as it passes through a borehole and surrounding rocks is proportional to the bulk density of those rocks. Gamma rays

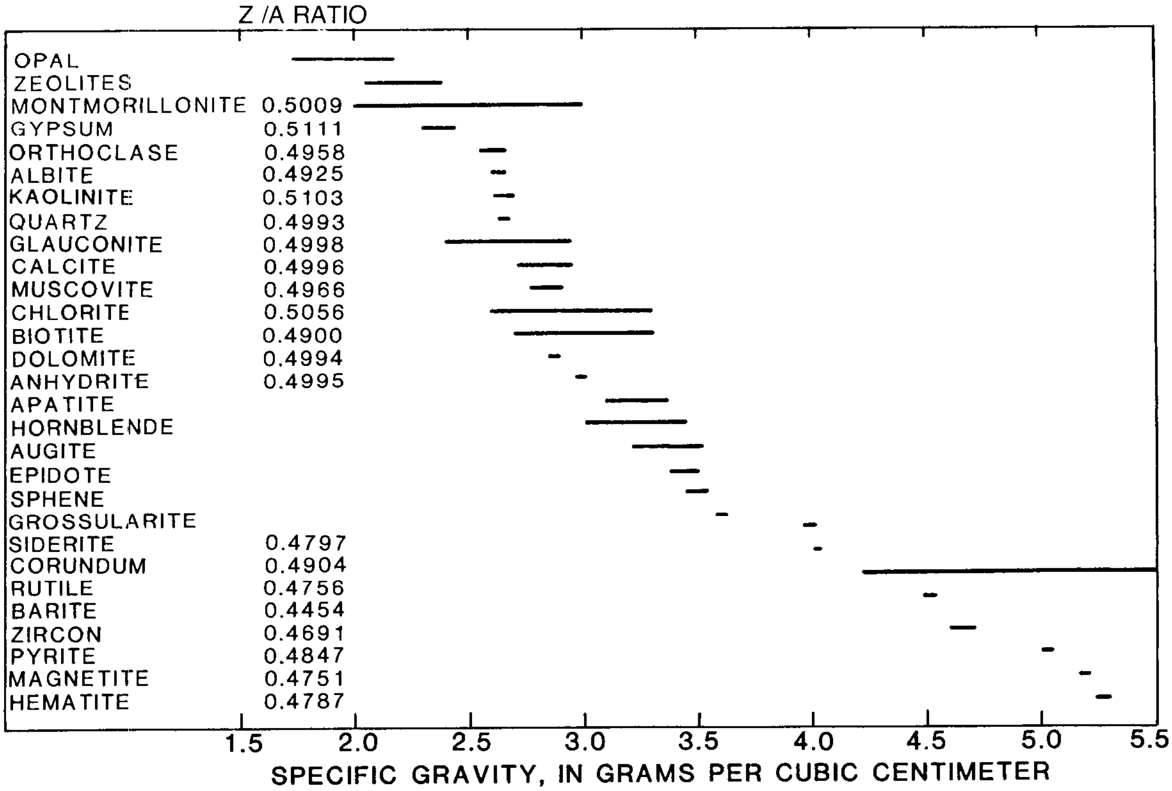


Figure 57.—Specific gravity and Z/A ratio for some common minerals (no value indicates Z/A ratio not available).

or photons react with matter by three processes: Compton scattering, photoelectric absorption, and pair production. Only Compton scattering is not principally dependent on the elemental composition of the matter through which the radiation passes. Compton scattering is the main process in gamma-gamma logging, because pair production cannot take place at energies of less than 1.02 MeV, and because the probe shell attenuates the low-energy radiation from photoelectric processes.

If a probe detects only radiation resulting from Compton scattering, the count rate will be inversely proportional to the electron density of the material through which the radiation passes. Electron density is approximately proportional to bulk density for most materials that are logged. A Z/A correction must be applied for any minerals that do not have the same ratio of atomic number to atomic mass as the calibration environment (Tittman and Wahl, 1965). Salt and gypsum are two common minerals that require such a correction. A plot of specific gravity, or density, and Z/A ratios for some common minerals is given in figure 57.

Calibration and standardization

Like other logging systems, calibration of gamma-gamma response is best done in pits designed for the purpose. Calibration can be done in porosity pits such as the American Petroleum Institute's neutron pit in Houston, Tex., or in pits maintained by commercial service companies. A set of bulk-density pits is available for free use by anyone at the Denver Federal Center (see table 3). Core also can be used, but precautions should be taken to avoid using data from any intervals of a borehole that deviate from the uniform borehole size because of the substantial effect of rugosity on the log.

Onsite standardization of probe response usually is done with large blocks of aluminum and magnesium that are machined with a groove that tightly fits the source and detector section of the probe. Aluminum has a density of 2.7 g/cm^3, and magnesium has a density of 1.71 g/cm^3; these densities are corrected for the Z/A ratio used to calibrate the probe. These blocks can be used to develop a calibration plot, as explained by Head and Barnett (1980); however, calibration in a pit is likely to be more accurate. The blocks must be large enough that effects of the environment are minimized; they also should be located off the ground and away from a logging truck that may contain radioactive sources. Probe standardization should be done frequently during calibration and logging operations. Onsite standardization of probe response also can be done with a radioactive source; however, this technique is not as useful, because it tests only the detectors, and not the complete system as configured for logging.

A "spine and ribs" calibration plot for a dual-detector gamma-gamma probe is given in figure 58. The procedures for developing such a plot have been explained in detail by Scott (1977). In figure 58, the X and Y scales are shown in pulses per second; however, they also could have been in grams per cubic centimeter, had the density response of each of the detectors been calibrated. Stand-off error is caused when a side-collimated, decentralized probe or skid is separated from the borehole wall by mud cake or wall roughness. Points along the ribs to the right of the spine represent stand-off error, which may be caused by borehole rugosity or low-density mud cake; points along the ribs to the left of the spine may be caused by high-density mud. After the shape of the ribs has been determined by calibrating a probe, the spine-and-ribs plot can be used to obtain density corrected for stand-off even though the separation between logging tool and borehole wall may be unknown. This is done by moving from a measured value of long-spaced versus short-spaced count rate along a rib to the correct density on the spine. According to Scott (1977), stand-off errors of 0.4 in or more can be corrected accurately.

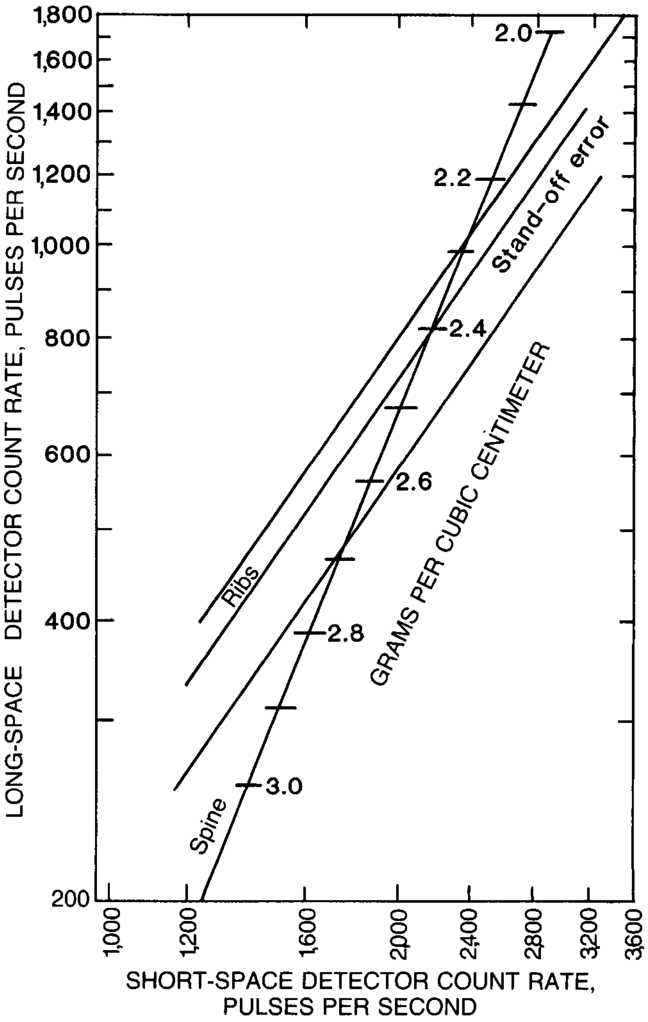


Figure 58.—Calibration plot for a dual-detector gamma-gamma probe. "Spine and ribs plot" permits correction for stand-off error.

Volume of investigation

The volume of investigation of a gamma-gamma probe probably has an average radius of 5 to 6 in; 90 percent of the pulses recorded originate from within this distance. However, the volume of investigation is a function of many factors. The density of the material being logged, and of any casing, cement, or mud through which the radiation must pass, has a substantial effect on the distance gamma photons will travel before being stopped. Within limits, the greater the spacing between source and detector, the larger the volume of investigation. This is the basis for using detectors at two different spacings. The closer detector is more affected by borehole parameters than the farther detector. In porous rocks, such as tuff, a greater than normal spacing must be used, and this increases the volume of investigation.

Experiments have been made with gamma-gamma transmittance logging to increase the volume of investigation and decrease borehole effects (Brown and Keys, 1985). The technique is based on moving synchronously, at the same depth, a source in one borehole and a detector in another borehole located a few feet away. Using a cobalt-60 source, changes in moisture content and porosity were detected between two boreholes located 4 ft apart. For most materials, a borehole spacing of 2 ft probably is better. Gamma-gamma transmittance logs are little affected by the borehole because it is a small part of the material traversed by the radiation. The technique is severely limited by the difficulty in maintaining a constant distance between boreholes. Unless the distance is known accurately, bulk density cannot be calculated from gamma-gamma transmittance logs; however, changes in bulk density and moisture content can be detected.

Extraneous effects

Gamma-gamma logs demonstrate significant effects from borehole-diameter changes, and from casing, cement, mud cake, and probe stand-off. These effects are reflected on borehole-compensated logs, but they are smaller in magnitude than on single-detector logs. The effect of borehole-diameter differences on the single-detector gamma-gamma logs that have been most commonly applied to ground-water investiga-

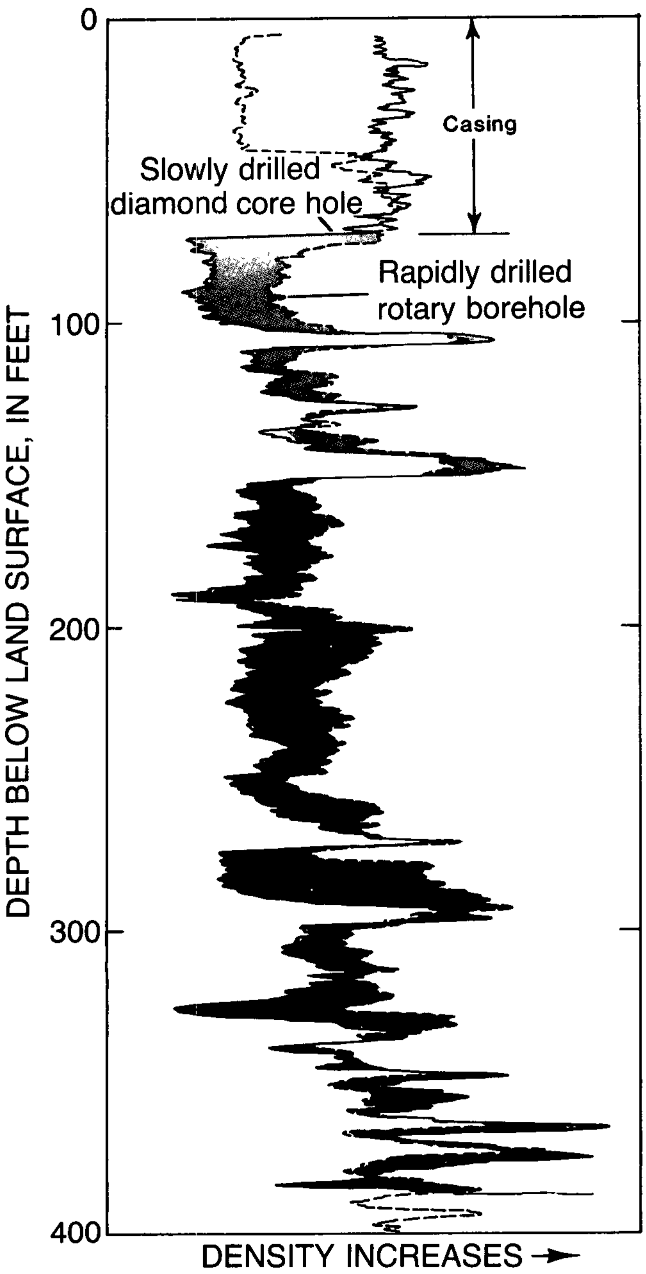


Figure 59.—Effect of drilling technique on gamma-gamma logs. (Note that the boreholes are close together in an area of persistent lithology.)

tions in the past is illustrated in figure 59. The two boreholes shown in the figure were drilled close together in an area where lithology is persistent for long lateral distances. The log on the left was made in a core hole that was drilled slowly and for which a large volume of drilling fluid was circulated to maximize core recovery. The log on the right was made in an uncored borehole that was drilled rapidly by rotary methods to minimize borehole-diameter changes. The caliper logs of these two boreholes, shown in figure 20, demonstrate that the differences between the two gamma-gamma logs shown by shading are from differences in borehole diameter. The larger diameter washed-out intervals in the slowly drilled core hole are indicated as having a smaller bulk density or a larger porosity than the same rocks in the adjacent borehole. Borehole-rugosity effects usually can be recognized by a detailed comparison of a gamma-gamma log with a high-resolution caliper log. When sharp peaks on a caliper log, which indicate borehole rugosity, match sharp negative deflections on a gamma-gamma log, the deflections most likely are the result of borehole-diameter changes. Borsaru and others (1984) have suggested that the use of a cobalt-60 source and a correction factor derived from the count rate in high-energy spectral windows can provide a measurement of density that is not sensitive to borehole diameter.

Casing, cement, and gravel pack all introduce errors large enough that quantitative interpretation of gamma-gamma logs made through these materials is questionable, unless the thickness is constant and core is available for calibration. The effect of borehole construction on gamma-gamma logs can be used to locate the tops of cemented zones, gravel-pack outside the casing, or one string of casing outside another. If a gamma-gamma log is run in drill stem or screw-coupled casing, the collars or threaded joints generally will be indicated as sharp deflections on the log.

Errors also will be produced on gamma-gamma logs by background radiation in rocks penetrated by the borehole if the radiation is greater than the standard error of the measured count rate. The background radiation can be determined by running the probe with no radioactive source installed. Substantial background radiation is not a common problem in groundwater investigations; when present, it can be corrected by using the sensitivity-corrected difference between the count rates from the two detectors (Scott, 1977).

Interpretation and applications

Properly calibrated gamma-gamma logs can be used to distinguish lithologic units, and to determine well construction as well as bulk density, porosity, and moisture content. Close source-detector spacing or measurement of the high-energy part of the spectrum will provide borehole-diameter information.

The chief use of gamma-gamma logs has been for determining bulk density, which can be converted to porosity. Although commercial gamma-gamma logs generally have a scale indicating porosity, the log response is related directly to electron density, which may be related to bulk density by calibration and correction for Z/A errors. The accuracy of bulk-density determinations with these logs has been reported by various authors to be from 0.03 to 0.05 g/cm^3. The best results with gamma-gamma logs are obtained in rocks of minimal bulk density or substantial porosity. This contrasts with neutron logs, which give the best results in rocks of substantial bulk density or minimal porosity.

Gamma-gamma logs conventionally are recorded with bulk density increasing to the right, which means that porosity increases to the left. Recording has been done in this manner because porosity increases to the left on neutron and acoustic-velocity logs. Most equipment used for water-well logging records count rate, which by convention increases from left to right on the analog record. If a gamma-gamma log is run with this equipment, porosity will increase to the right, rather than to the left. This reversal from convention in the petroleum industry has caused much confusion in interpreting the logs; recording all gamma-gamma logs with count rate increasing to the left will avoid the confusion.

The following equation is used to calculate porosity from bulk-density logs:

Porosity=
(Grain density−Bulk density)/(Grain density−Fluid density)

Bulk density can be derived from a calibrated and corrected gamma-gamma log. Fluid density is 1 g/cm^3 for most ground-water applications where the rock is saturated with freshwater, but it may be as much as 1.1 g/cm^3 in rocks saturated with brine. Grain or mineral density can be obtained from most mineralogy texts. This density is 2.65 g/cm^3 for quartz; 2.71 g/cm^3 commonly is used for limestone, and 2.87 g/cm^3 commonly is used for dolomite. On most large service-company trucks, the gamma-gamma system is programmed to solve this equation in real time and produce a log of porosity. A plot of porosity from laboratory analyses of core samples versus porosity from a compensated gamma-gamma log is shown in figure 60. The scatter of points for this data set is the result of several factors. A density value for limestone matrix was used in the porosity equation, although many of the rocks penetrated by this test well were dolomite. Secondary porosity is substantial in some intervals of the test well; usually it is not represented correctly by core samples. Some of the zones of secondary porosity are shown, by a high-resolution caliper log, to be rough and larger than bit size; these zones may introduce a stand-off error.

Another important factor in attempting to relate core analyses to logs is the likelihood of depth discrepancies between the two sets of data. A basic consideration in relating any set of core analyses to equivalent logs is the large difference in the volume of material investigated. Unless the rock is homogeneous, a large number of small core samples will be needed to represent correctly the much larger volume of rock sampled by a log.

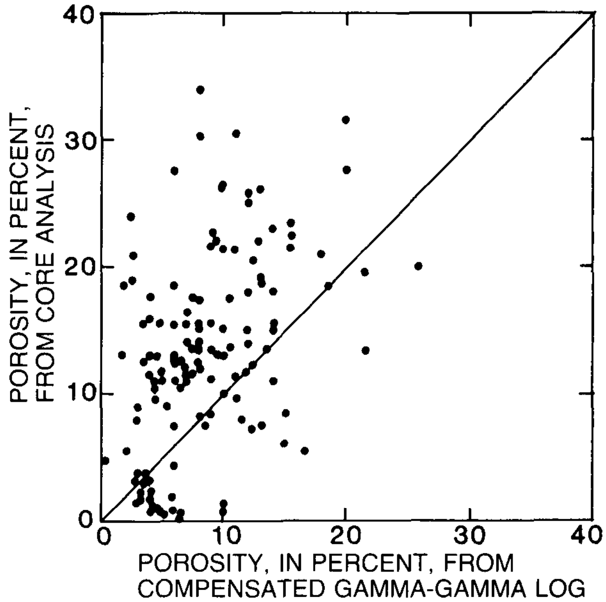


Figure 60.—Porosity from core analysis versus porosity from a compensated gamma-gamma log, Madison Limestone test well 1, Wyoming.

Because moisture content affects the bulk density of rocks, gamma-gamma logs can be used to record changes in moisture above the water table. In most cases, a neutron-logging system is preferred for this purpose, because errors from extraneous effects usually are smaller. If gamma-gamma logs are run before and after drawdown during a pumping test, they can be used to calculate specific yield (Davis, 1967).

Gamma-gamma logs can be used to locate cavities or unfilled annular space behind casing and to locate the top of cement through casing. A comparison of logs made before and after cementing will provide the most accurate location of the top of the cement.

Neutron logging

In neutron logging, the probe contains a source of neutrons, and detectors provide a record of the neutron interactions that occur in the vicinity of the borehole. Most of these neutron interactions are related to the quantity of hydrogen present; in ground-water environments, the quantity of hydrogen is largely a function of the water content of the rocks penetrated by the borehole. Neutron logs are used extensively in the petroleum industry to measure porosity; they also are being used increasingly in water-resources investigations because they can be used to determine porosity for a considerable range of borehole conditions and rock types. Two different neutron-logging techniques are used in ground-water studies: (1) neutron probes with a large source and long spacing are used for measuring saturated porosity; and (2) probes with a small source and short spacing are used for measuring moisture content in the unsaturated zone. Neutron activation, neutron lifetime, and nuclear-magnetic resonance are discussed in a separate section of this manual because they are relatively new and are not yet readily available or commonly applied.

Principles

Neutron probes contain a source that emits high-energy neutrons; some neutron sources also emit gamma radiation. Most isotopic-neutron sources are made from a mixture of beryllium and an alpha-emitting radioisotope encapsulated in a double-wall, welded, steel container so that the alpha particles do not escape. When bombarded with alpha particles, the beryllium emits large numbers of neutrons with an energy of a few million electronvolts. The most common neutron source is a mixture of beryllium and americium, which is used in sizes that range from about 3 to 25 Ci in porosity tools; moisture probes may use a source as small as 100 mCi. Americium-241 has a half-life of 458 years and an average neutron energy of 4.5 MeV. Mixtures of beryllium and radium, and of beryllium and plutonium, still may be used in some older probes. A disadvantage of radium is that it emits substantial gamma radiation; plutonium sources must be large because the isotope has a relatively low specific radioactivity. Californium-252 emits large numbers of neutrons spontaneously, so a source emitting a large neutron flux may be physically small. It has been used experimentally for neutron and neutron-activation logging (Keys and Boulogne, 1969). The 50-mCi source used in those tests emitted 2.1×10^8 neutrons per second, whereas a 3-Ci americium-beryllium source typically used for logging water wells emits 8.62×10^6 neutrons per second. Californium-252 has the disadvantage of having a half-life of only 2½ years. If neutron sources are stored near sodium-iodide crystals, which are commonly used in gamma and gamma-gamma probes, the neutron sources will activate the sodium, and the crystals will become temporarily radioactive.

Neutron-porosity logs are of three general types: neutron-epithermal neutron, neutron-thermal neutron, and neutron-gamma. Three types of detectors typically are used in neutron probes: lithium-iodide crystals, helium-3 tubes, and sodium-iodide crystals. Sodium-iodide crystals detect gamma radiation as well as neutrons. Detectors of the other two types can be designed to detect mostly epithermal neutrons; these neutrons provide logs relatively free of errors resulting from the chemical composition of the rocks and contained fluids. Cadmium foil can be used to shield detectors from thermal neutrons. Neutron logs, based on the detection of thermal neutrons or gamma rays, may be affected markedly by the chemical composition of the material traversed by the neutrons. Thermal-neutron probes are used by some small loggers because they have the advantage of producing a larger count rate, so that a smaller source can be used. A probe has been described that uses two pairs of detectors—thermal and epithermal (Davis and others, 1981). Because the thermal neutrons are affected by chemical composition, the difference between the two pairs of detectors can indicate clay content. Two or more detectors are used in modern neutron probes, which may be collimated and decentralized. The ratio of the near to the far detector provides logs that are less affected by borehole parameters than are single-detector logs. A schematic drawing of a compensated epithermal-neutron probe developed and tested by the U.S. Geological Survey is given in figure 61. For this probe, porosity is related to the ratio of the count rate

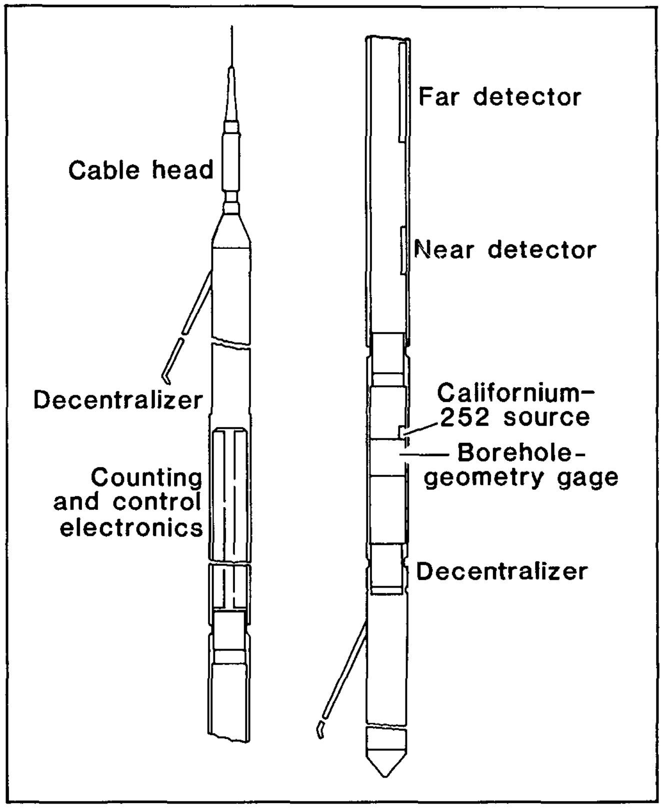


Figure 61.—Probe for making compensated neutron-porosity logs.

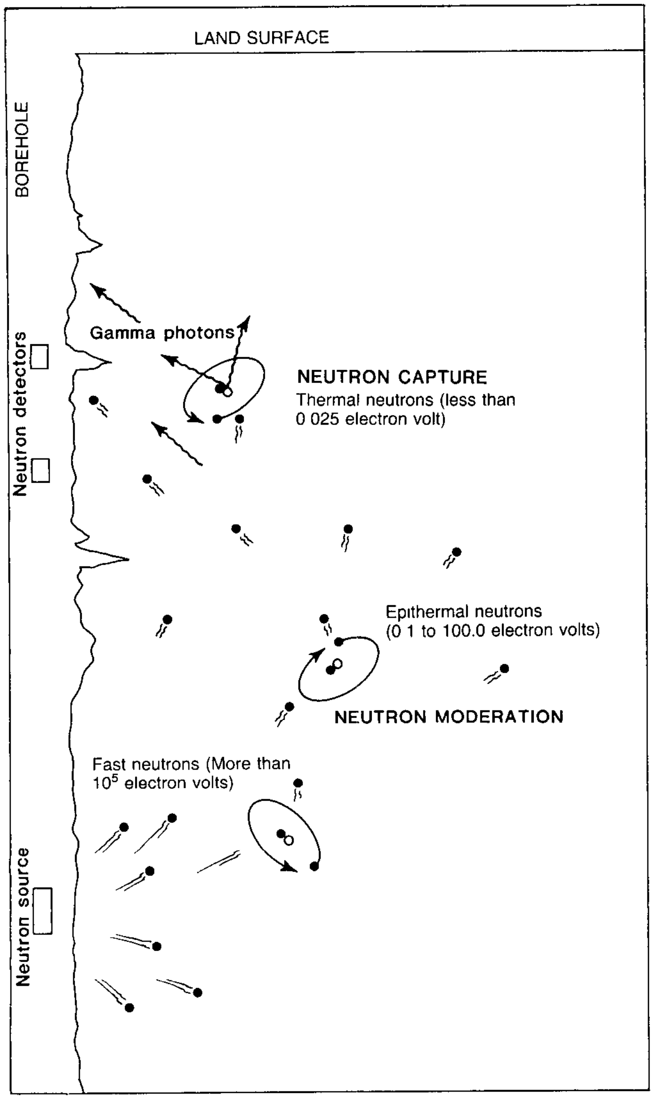


Figure 62.—Neutron processes, from source to detectors, through rocks surrounding a borehole.

from the near detector to the count rate from the far detector; a caliper arm and additional detectors, located in the section labeled "borehole geometry gage," provide data to make corrections for borehole diameter and probe position.

The flux of neutrons around a source can be visualized as a cloud of varying neutron density; detectors are located at various distances from the source within the cloud. Fast neutrons emitted by a source undergo three basic types of reactions with matter in and adjacent to the borehole as they lose energy and ultimately are captured: inelastic scatter, elastic scatter, and absorption or capture. The loss of neutron energy is called moderation, and the elements that cause that loss are called moderators. A diagrammatic representation of this process is shown in figure 62. Inelastic scattering can take place only with fast or energetic neutrons immediately after they have been emitted by a source; it is not an important factor in well logging. When a neutron undergoes inelastic scattering off the nucleus of an atom near the source, that nucleus is left in an excited state and emits gamma radiation as it decays back to a stable state. When the neutron energy decreases to less than the threshold for inelastic scatter, that process no longer can take place and elastic scatter becomes the important process.

In elastic scatter, the mass of the scattering element controls the loss of energy by the neutron. Light elements are most effective in moderating neutrons, whereas heavy elements have little effect on neutron velocity or energy. A comparison of the neutron response of several common elements is presented in table 4. Hydrogen is the element most effective in moderating neutrons because it has the same mass as a neutron. An analogy can be made using a Ping-Pong ball and a billiard ball. The Ping-Pong ball may lose little energy in a direct collision with a billiard ball, but it may lose all of its energy and stop after a direct collision with another Ping-Pong ball. The probability or cross section for elastic scatter with hydrogen is considerable and, on the average, neutrons lose one-half their energy in each scatter. By this process they are slowed—first to epithermal energies of 0.1 to 100 eV, and then to thermal energies of less than 0.025 eV. Because hydrogen is the most effective moderating element, the cloud of epithermal and thermal neutrons occurs closer to the source in rocks having a large hydrogen (or water) content than in rocks having a small hydrogen (or water) content. Neutron capture takes place along the outer margin of this cloud. The location of the capture margin is more a function of the distance the neutrons take to slow down to thermal energy than the distance they diffuse after they are thermalized.

Although a few neutron-absorption or neutron-capture reactions may take place at higher energies, most take place at thermal energies. When a thermal neutron is captured by a nucleus, the nucleus becomes excited and instantly emits capture gamma radiation, which has an energy characteristic of the capturing element. Cross sections for thermal-neutron capture are dependent on the elements involved; for example, chlorine is much more likely to capture a neutron than is oxygen.

The processes described result in an inverse relation between the number of epithermal neutrons, thermal neutrons, and capture gamma photons and the hydrogen content of the rocks at a source-to-detector spacing greater than about 12 in. In many rocks, the hydrogen content or index is a function of

Table 4.—Comparison of the neutron response of some common elements for a neutron with an initial energy of 2 million electronvolts

[Modified after Wood and others, 1974]

Element	Average number of collisions per neutron	Maximum energy loss per collision (percent)	Atomic weight	Atomic number
Calcium	371	8	40.1	20
Chlorine	318	10	35.5	17
Silicon	261	12	28.1	14
Oxygen	150	21	16.0	8
Carbon	115	28	12.0	6
Hydrogen	18	100	1.0	1

the volume of water in the pore spaces; this relation is affected by the chemical composition of the water and by the presence of water of crystallization in some minerals and bound water in shale. If detectors are located closer than 11.8 in from the source, as in moisture probes, the number of moderated and captured neutrons increases with increasing hydrogen content because the neutrons are not able to travel as far. In practice, spacing for moisture probes usually is much less than the crossover distance of 11.8 in. Typical neutron processes for a long-spaced, dual-detector porosity probe are illustrated in figure 62. As the hydrogen index in the materials between the source and the detectors increases, fewer slowed neutrons will reach the vicinity of the detectors and be detected.

Calibration and standardization

Calibration of all neutron-logging systems used in the petroleum industry is based on the American Petroleum Institute's calibration pit in Houston, Tex. The pit contains three sets of six quarried marble and limestone blocks that have an average porosity of 1.884, 19.23, and 26.63 percent. These values have been rounded by the American Petroleum Institute to 1.9, 19, and 26 percent, and the 19-percent set of blocks has been assigned the value of 1,000 API neutron units (Belknap and others, 1959). Individual blocks measure 5 ft across the octagonal flats and are 1 ft thick, and the drill hole is 7⅞ inches in diameter. A plot of the calibration values for the U.S. Geological Survey's experimental compensated neutron probe is given in figure 63. Values for near-detector/far-detector ratios are plotted from the digitized data. Ratios are used because they provide some correction for borehole effects. Note the errors from the effect of the adjacent blocks at the top and bottom of each porosity interval. Two calibration curves calculated for the compensated neutron probe from the data collected at the API calibration pit are shown in figure 64. The equation for the dashed curve seems to provide a slightly better fit to the data than the equation for the straight line. The greater scatter of data for the larger values of porosity may be caused in part by the smaller count rate, which increases the statistical error.

Although the API pit is the accepted primary standard, it is valid only for marble and limestone. Therefore, most large logging companies maintain their own calibration facilities for other rock types, such as dolomite and sandstone. Careful evaluation of laboratory analyses of core samples may result in valid calibration, but scatter of data points is to be expected. If information on lithology is available, it may be possible to do calibration onsite, as explained by MacCary (1980). An example of this practical method is given in figure 65; shale was estimated to have a porosity of 40 percent, and anhydrite was estimated to have a porosity of 2 percent, which enabled the placement of a logarithmic scale on the neutron log. A logarithmic scale can be fitted on an angle between two known porosity values; then the appropriate scale values can be extended parallel to the vertical grid lines to create a new horizontal scale.

Regardless of how primary calibration is done, onsite standardization should be done at the time of calibration and during logging operations. The most practical field standards permit the checking of probe response with the source installed in a reproducible environment that has a substantial hydrogen content. A plastic sleeve may be used, but it should be large enough to cover both source and detectors and thick enough to decrease outside effects. If a plastic sleeve is used, different values can be simulated by positioning the sleeve along the probe axis. A better approach is to use a tank that may be filled with water for standardization. The probe is locked in a fixed vertical position in the tank, and a sleeve, sealed to exclude water, is moved to different positions along the probe axis. The sleeve displaces water away from the probe, simulating different porosity values as it is moved to different vertical positions.

Factory-calibration data generally are provided with moisture meters; however, these should always be checked. Plastic sleeves also may be provided that are labeled with their equivalent moisture values.

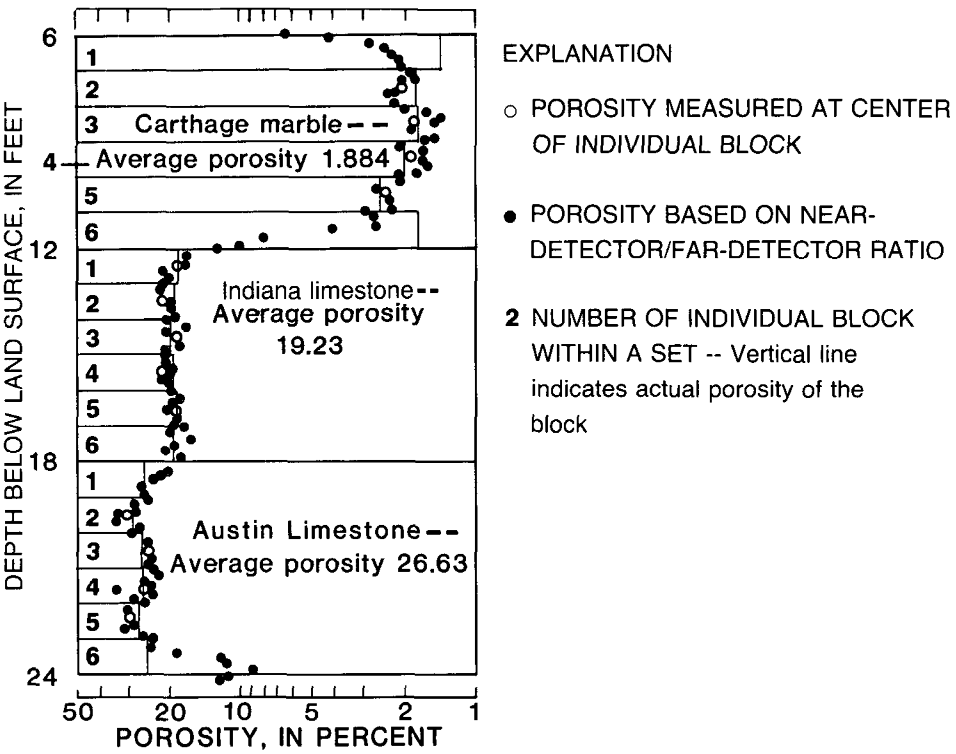


Figure 63.—Calibration data obtained with a compensated neutron-porosity probe in the American Petroleum Institute's calibration pit.

Checking the validity of factory calibration and standardization data can be done in a properly constructed and cored borehole. The core samples should be sealed as soon as they are collected and weighed immediately so that corrections for possible moisture loss can be made. Borehole construction for moisture logging is discussed in the section on extraneous effects.

Volume of investigation

The volume of investigation of a neutron probe is related to the content of hydrogen or other strong neutron absorbers in the material surrounding the probe, the spacing between the source and the detector, and the energy of the neutrons. Sherman and Locke (1975) reported the results of a study of the radius of investigation of various types of neutron and gamma-gamma probes in sand having a saturated porosity of 35 percent. Their experimental data and theoretical calculations agreed quite well. Three different types of neutron probes received 90 percent of the recorded signal within 6.7, 9.3, and 10.3 in of the borehole wall. In contrast, a gamma-gamma probe had a measured radius of investigation of 5.0 in. They also reported that a 4-in increase in spacing was needed on the neutron tools to increase the radius investigated by 1 in. Increased hydrogen content will decrease the radius of investigation. Under some conditions, an epithermal-neutron probe will provide data on rock farther from the borehole than a thermal-neutron probe. Volume of investigation can be increased substantially, and borehole effects can be decreased, by using neutron-transmittance techniques.

Increasing the source-to-detector spacing increases the volume of rock investigated in the vertical as well as the horizontal direction. This increased volume of investigation has a marked effect on thin-bed resolution, as demonstrated in figure 66. The hypothetical volume of investigation is shown by shading in the figure. Note that the size and shape of this volume are shown to change as a function of porosity, when the probe is moved up the borehole. The log gives only an approximately correct value for porosity and thickness when the volume of investigation is entirely within the bed being logged. Thus, in figure 66, the upper thin limestone bed with 3.3 percent porosity is indicated by the log to have a much greater porosity and greater apparent thickness than the lower limestone bed, which also has a porosity of 3.3 percent. The usual technique for determining bed thickness from any type of nuclear log is to make the measurement at one-half the maximum amplitude of the deflection that represents that bed, as shown in the figure. Although this technique may not be the best under all conditions, it is applicable under most conditions for

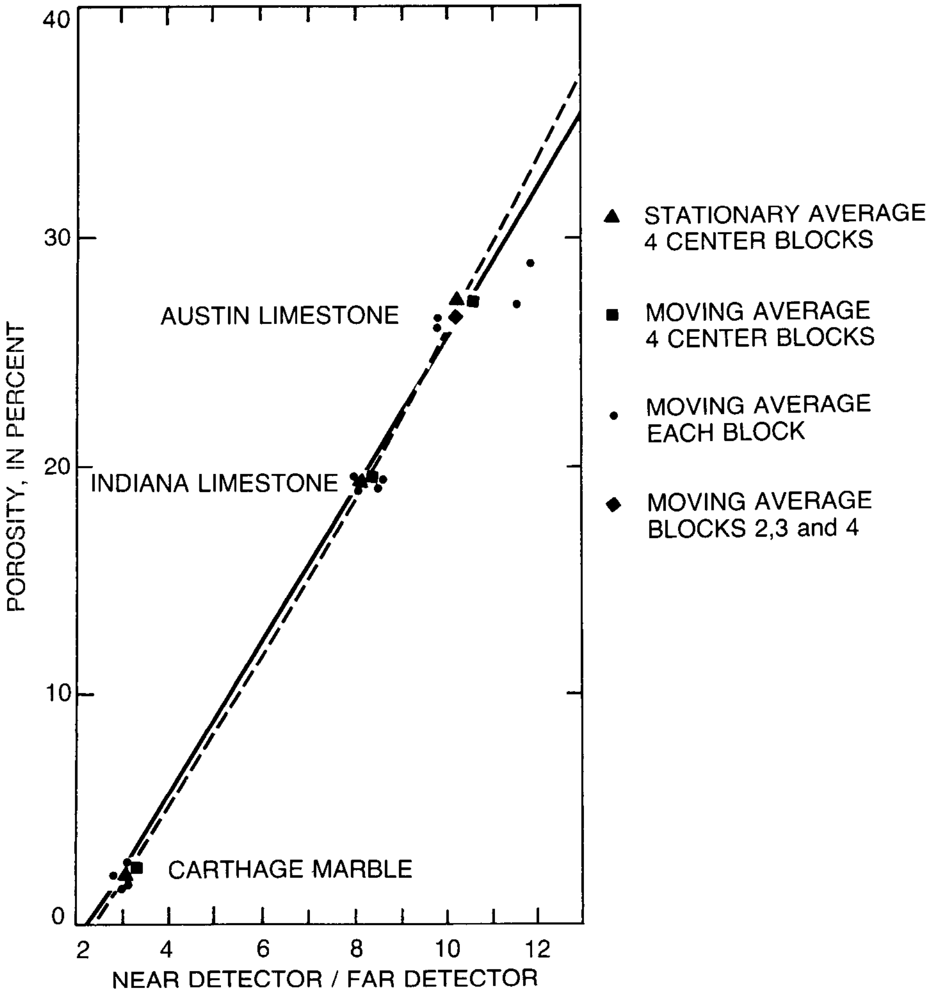


Figure 64.—Calibration curves for a compensated neutron-porosity probe based on data from the American Petroleum Institute's calibration pit. A straight line and a dashed curve have been calculated to fit the data.

beds that are thicker than the vertical dimension of the volume of investigation. In figure 66, the apparent bed thickness derived from the one-half-amplitude technique is equal to the true bed thickness for the lower limestone bed that has a porosity of 3.3 percent, but not for the thinner upper limestone bed.

Extraneous effects

Neutron logs are affected by many of the same borehole parameters that affect gamma-gamma logs, although usually to a lesser degree. These extraneous effects include variations in borehole diameter, thickness of mud cake or stand-off, salinity of the borehole and interstitial fluids, mud weight, thickness of casing and cement, temperature and pressure, and elemental composition of the rock matrix. Matrix effects are evaluated during log interpretation and can be analyzed by cross-plotting techniques, as demonstrated in figure 15. Corrections for all of these extraneous effects are different for each type of neutron probe; they may be calculated theoretically, but they should be substantiated by measurements in models.

Correction factors determined both theoretically and experimentally for compensated neutron probes, used by two different service companies, have been presented by Arnold and Smith (1981) and Ellis and others (1981). Correction factors are available in manuals provided by logging-service companies, but they may not be available from manufacturers of smaller loggers, which commonly are used for water-well logging. When data for correction for extraneous effects are not available, they can be determined experimentally, or depth intervals where conditions are likely to cause errors should be eliminated from quantitative analysis. For example, a plot of porosity measurements of cores versus neutron-log response for a well completed in the Madison limestone had widely scattered points; after elimination of all depth

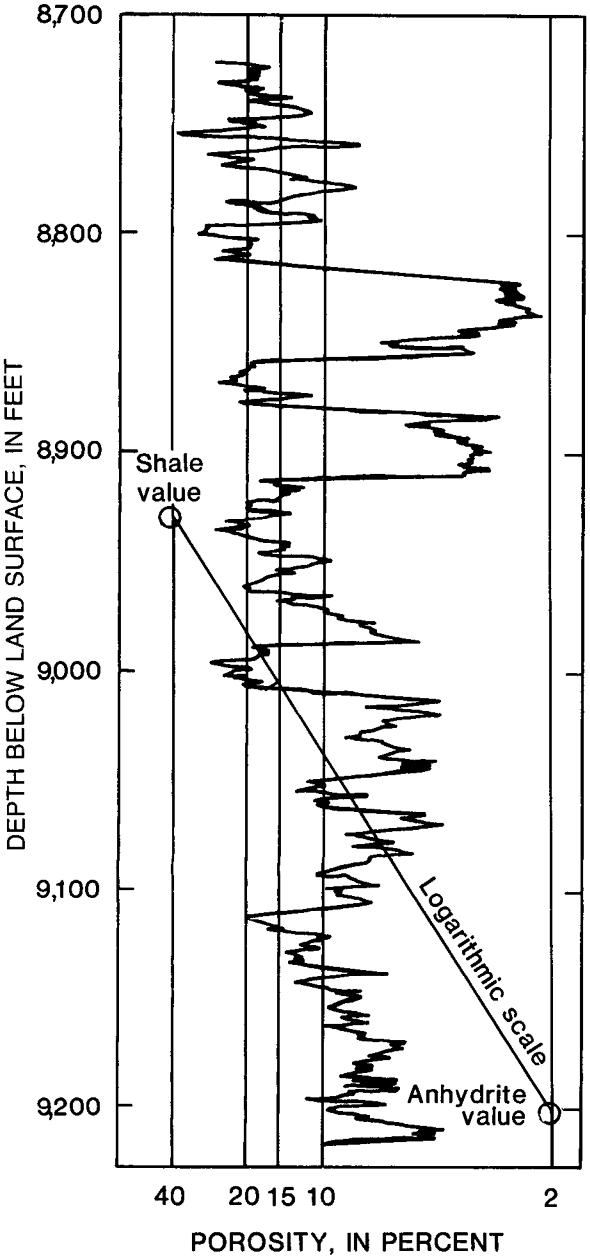


Figure 65.—Neutron log of the Red River Formation, Custer County, Mont., showing method for onsite calibration using estimated values of porosity for shale and anhydrite (modified from MacCary, 1980).

intervals where the gamma log exceeded a value likely to indicate the presence of shale, and all intervals where the caliper log indicated a borehole diameter 0.4 in greater than bit size, the relation between core analyses and neutron-log response was much improved. Shale and clay cause errors in the measurement of porosity because they usually contain bound water, and a neutron-logging system is not capable of distinguishing the difference between hydrogen in bound water and hydrogen in free water in the pore spaces. Some scatter is to be expected in core versus log plots, even if all extraneous effects are removed, because of the large difference in the volume of material sampled by the neutron probe and analyses of core and the likelihood of some discrepancy between depths on a log and core depths.

Casing does not cause a major shift on most neutron logs, as it typically does on gamma-gamma logs. Neutron logs made through drill stem do not show the location of collars, as gamma-gamma logs do. The small difference between a neutron log of an uncased augered borehole and a neutron log of a borehole about 2 ft away that was cased with 2-in steel pipe is shown in figure 67. Laboratory analyses for moisture content are plotted on the logs to demonstrate that both logs adequately represent the distribution of moisture. Although the common belief is that neutron logs cannot be made through plastic casing, that casing is no different from an annular space filled with water. Plastic pipe of constant thickness merely causes a shift in log response similar to, but of lesser magnitude than, that caused by the water level in a small-diameter borehole. Some of the differences between the two logs in figure 67 may be the result of differences in the diameters of the two boreholes.

The major effect on neutron logs caused by changes in thickness or lack of backfill in the annular space is shown in figure 68. This effect is analogous to the hole-diameter effect on neutron logs. The log on the right was made after 2-in pipe was installed in borehole S-3 and the annulus was backfilled. The major anomaly between a depth of 37 ft and about 90 ft was caused by nonuniform backfill. The annulus probably was not filled for much of this interval. The neutron-transmittance log between boreholes S-3 and S-11 is little different from the log of borehole S-3 before it was cased, and it does not indicate the absence of backfill. The backfill was removed with a hollow-stem auger and replaced by reversing the auger. After this procedure, a normal log was obtained for borehole S-3. Neutron-transmittance logs have been made through moist sand and gravel between boreholes as much as 4 ft apart, but the technique is limited by the difficulty of maintaining a constant distance between the boreholes.

The extraneous effects caused by borehole construction are much greater for neutron-moisture logs than for neutron-porosity logs, such as those in figures 67 and 68. The short spacing used in moisture probes decreases the volume of investigation so that borehole effects are increased. For this reason, boreholes to be logged with a moisture probe should be drilled as small as possible; the annular space between casing and borehole wall also should be as small as possible,

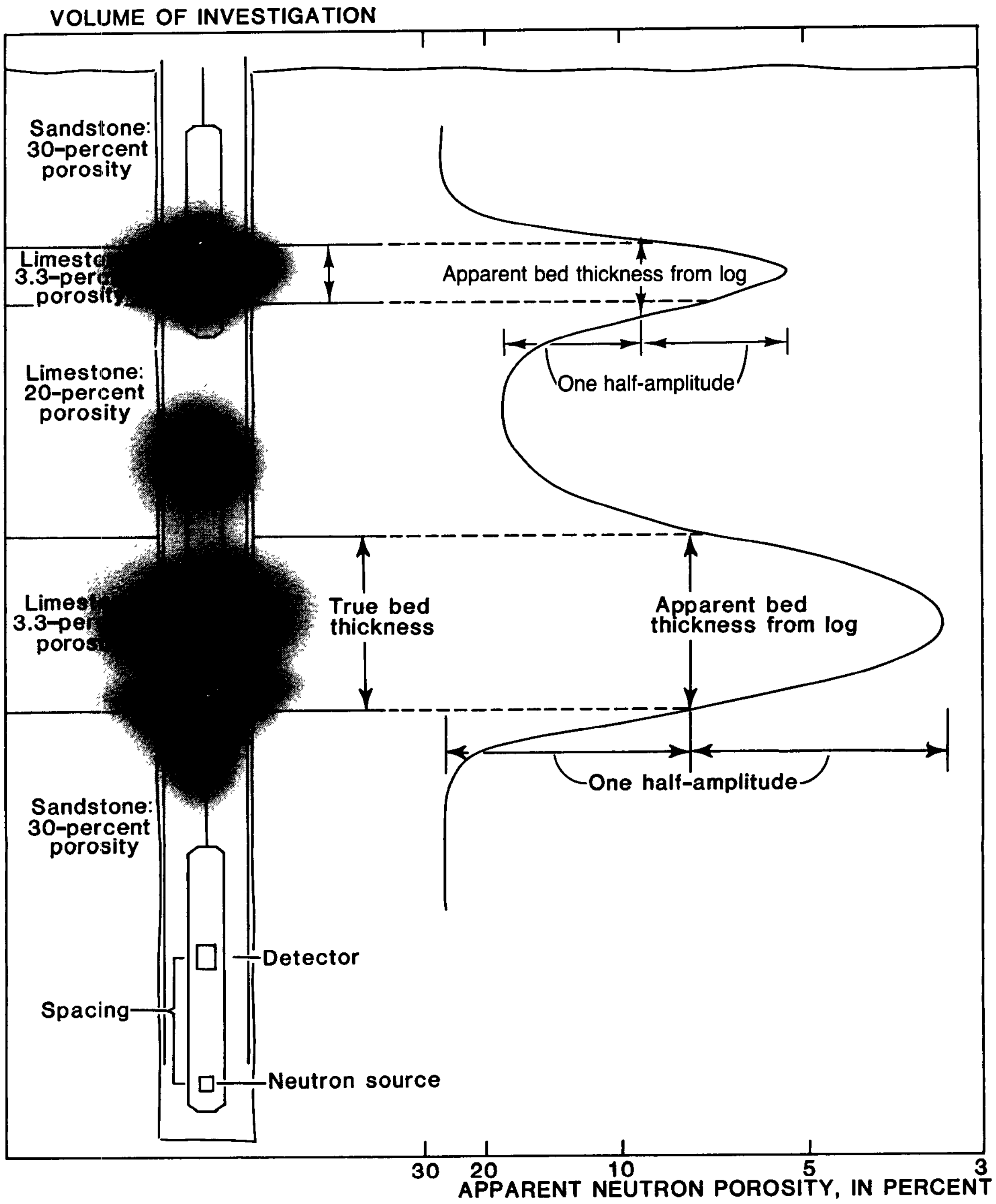


Figure 66.—Theoretical response of a neutron probe to changes in porosity and bed thickness. The shaded areas represent the volume of investigation at different probe positions.

and the probe should fit the casing tightly. Methods for installing access tubes for moisture probes have been evaluated by Teasdale and Johnson (1970).

The presence of saltwater does not affect the response of epithermal-neutron probes because the chloride is not detected directly; however, in brine, some of the hydrogen has been replaced by salt. A saturated brine of 250,000 mg/L will have a hydrogen density about 90 percent that of freshwater, so the effect will be to decrease the apparent porosity on a neutron log. Interfaces in the fluid column from changes in quality, such as an interface between mud and water, may cause a slight shift in a neutron log; however, the largest shift will be caused by the water

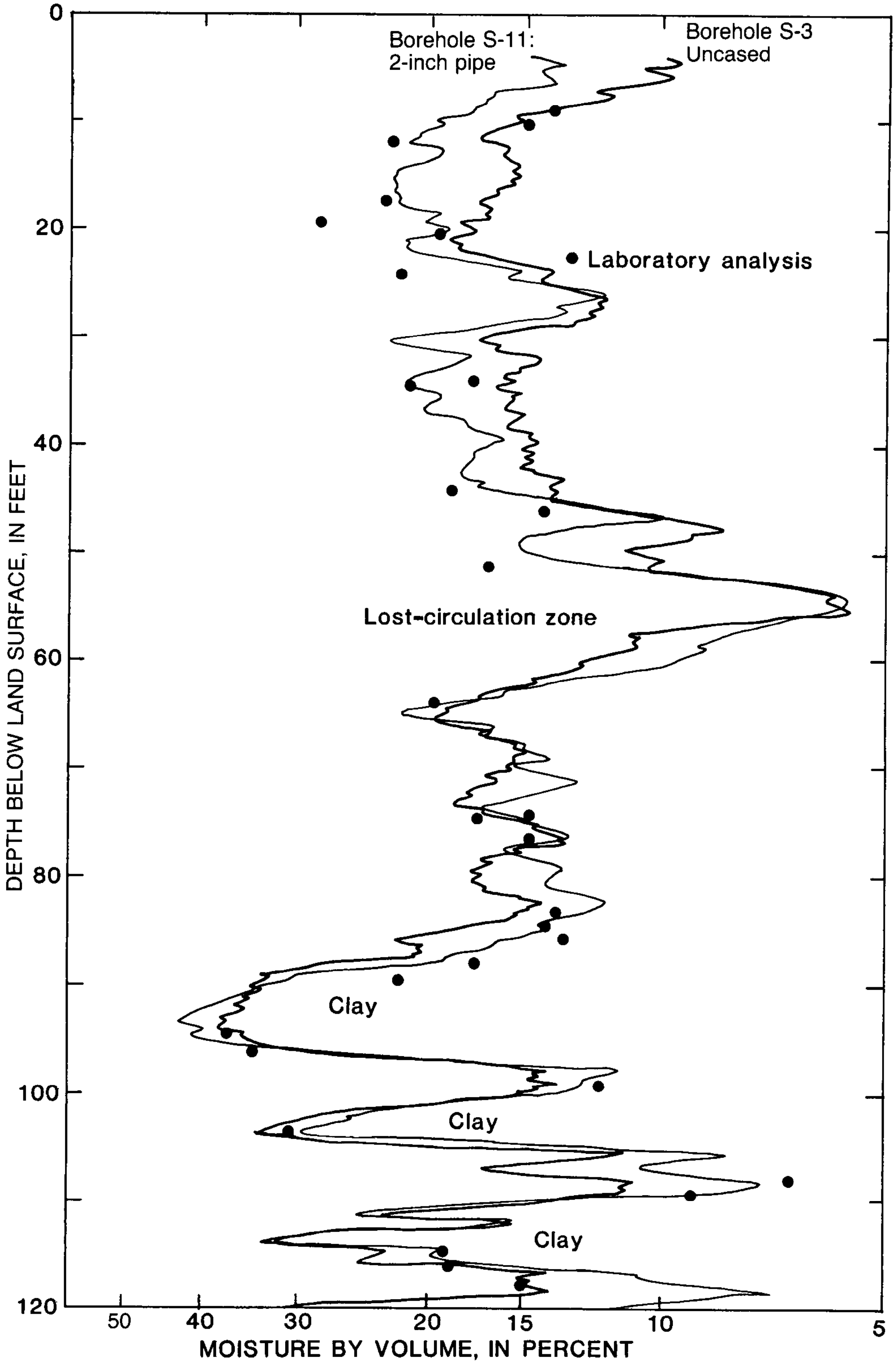


Figure 67.—Moisture content from core analyses compared with neutron logs in cased and uncased boreholes, Lubbock, Tex.

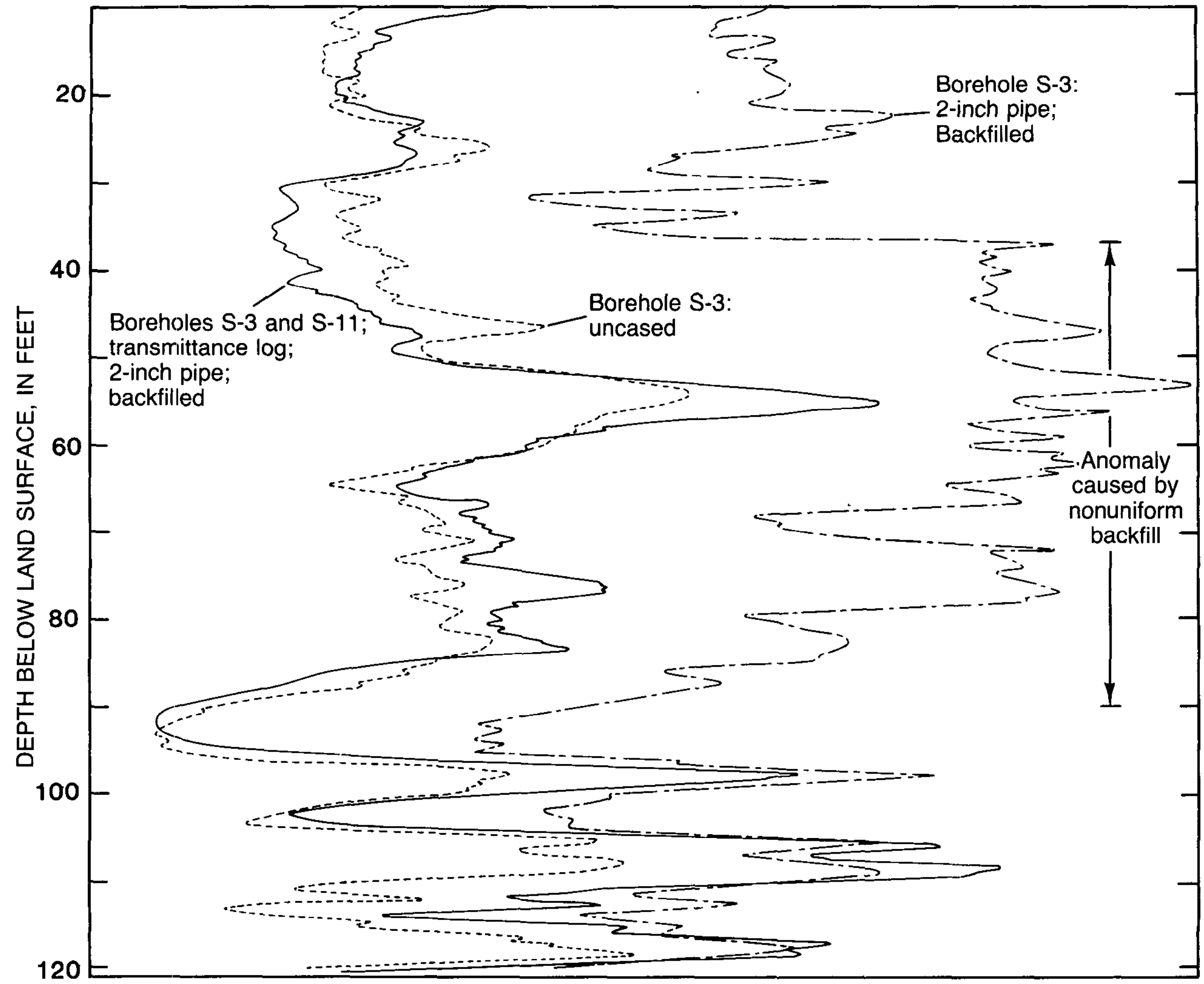


Figure 68.—Neutron-transmittance log between boreholes S-3 and S-11 compared with single-borehole neutron logs of borehole S-3, cased and uncased, Lubbock, Tex.

level. Fluid levels behind casing can be detected by a shift on a neutron log.

Interpretation and applications

Although neutron logs have been used primarily to determine porosity and moisture content, they have also been used frequently to determine lithology. Like gamma logs, they can be used for lithologic and stratigraphic correlation for a considerable range of borehole conditions. The way a neutron log cross-plotted with an acoustic-velocity log, or with a gamma-gamma log, can be used to determine lithology and corrected porosity is shown in figure 11. Driller's logs and neutron logs for two water wells drilled several hundred feet apart in glacial sediments at Anchorage, Alaska, are shown in figure 69. These sediments are very difficult to identify or correlate from either drill cuttings or logs. In this example, there appears to be no correlation of lithologic units based on the driller's logs; in contrast, the neutron logs indicate that correlation is good, except for the anomaly in well 111A in the depth interval from 155 to 175 ft. These wells have large diameters, were drilled with a cable-tool rig, and are cased, so the anomaly in well 111A probably was caused by borehole enlargement.

The typical responses of a neutron log to a hypothetical sequence of sedimentary rocks, and to borehole-diameter changes (as identified by the caliper log), are illustrated in figure 70. Note that both coal and gypsum cause large deflections to the left, indicating substantial porosity even though both probably have a relatively small porosity. Coal is a hydrocarbon containing abundant hydrogen that is not in the form of water, and gypsum contains water of crystallization. Each of these rocks may be more

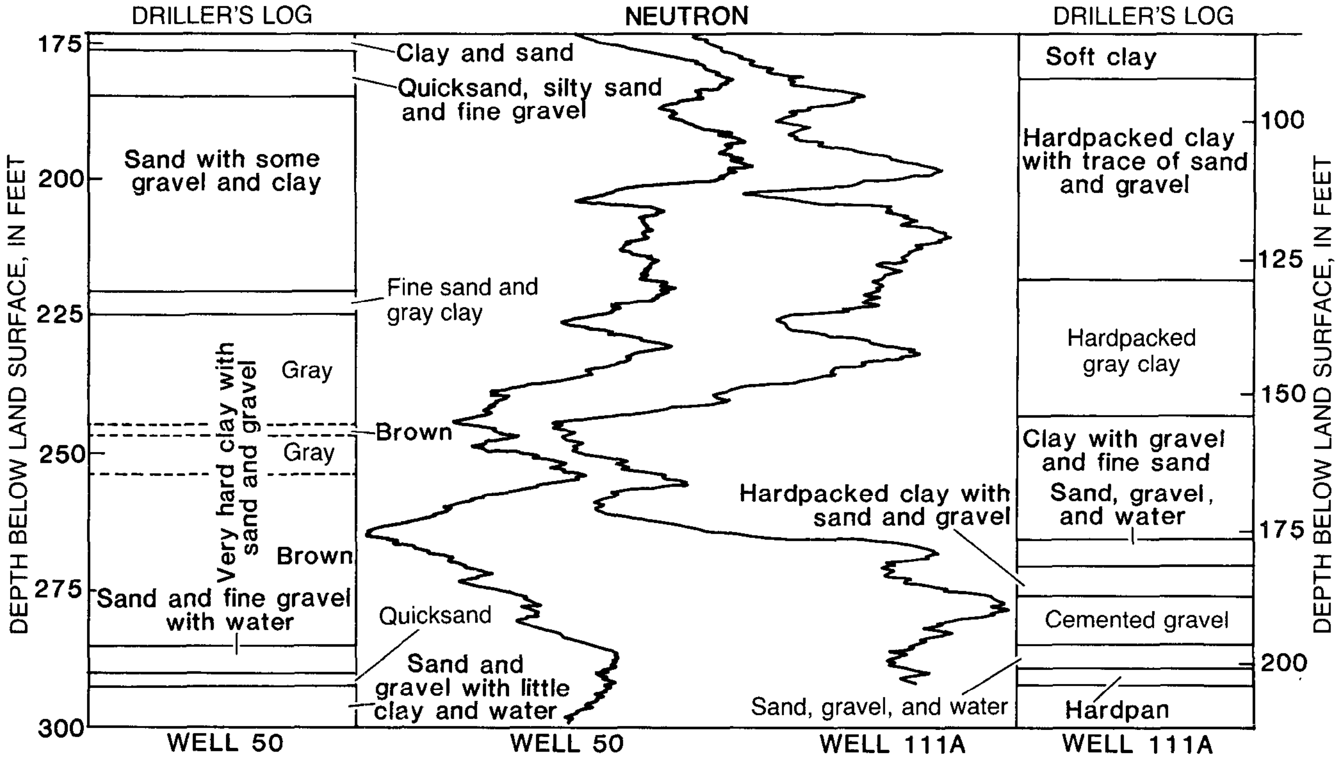


Figure 69.—Driller's logs and neutron logs of two closely spaced water wells completed in glacial sediments, Anchorage, Alaska.

diagnostically identified by the use of other logs in combination with neutron logs. Resistivity and neutron logs of most rocks will be similar because of the relation between saturated porosity and resistivity. Deflections marking both coal and gypsum are in opposite directions on resistivity logs and neutron logs. In general, shale or clay will be indicated by anomalously large apparent porosity, because of bound water. They generally can be recognized by use of a gamma log. The neutron log in figure 70 shows a gradual decrease in apparent porosity with depth, with the average porosity of limestone and granite being minimal. The sharp deflections on the caliper log in the limestone and arkose were caused by solution openings and fractures that produced negative deflections on the neutron log. Part of this response indicating large porosity may have resulted from borehole-diameter increase caused by fractures and solution openings; another part of the response may have resulted from an increase in porosity in the undisturbed rock. No effect is shown on the hypothetical compensated neutron log at the change from 8- to 6-in bit size, or at the change from freshwater to saline water. However, a shift is apparent at the bottom of the surface casing, because both the borehole and the casing are larger in diameter above this depth, and the lithology changes at the same depth. The borehole enlargement at the bottom of the surface casing is typical; however, it may not be shown clearly on the neutron log, because it has shifted as a result of the lithologic changes that occur at this depth.

A relation between neutron-log response and clay content resulting from alteration in crystalline rocks is shown in figure 71. In general, such rocks have a primary porosity of less than 1 percent, and apparent increases in porosity within one rock type generally are the result of fractures or alteration to clay. Typical responses of a neutron log and several other types of logs to different types of igneous rocks are shown in figure 8.

The responses of neutron logs to porosity and moisture content, described in detail earlier in this section, are summarized here. Neutron logs do not measure porosity or moisture directly. They must be calibrated for these characteristics and corrected for extraneous effects. Logs made with a neutron-porosity probe with long spacing and a large source will demonstrate a decrease in count rate with an increase in hydrogen content, whereas logs made with a neutron-moisture probe with short spacing and a small source will indicate an increase in count rate with an increase in hydrogen content.

Neutron logs can be used to determine the specific yield of unconfined aquifers (Meyer, 1962). A neutron

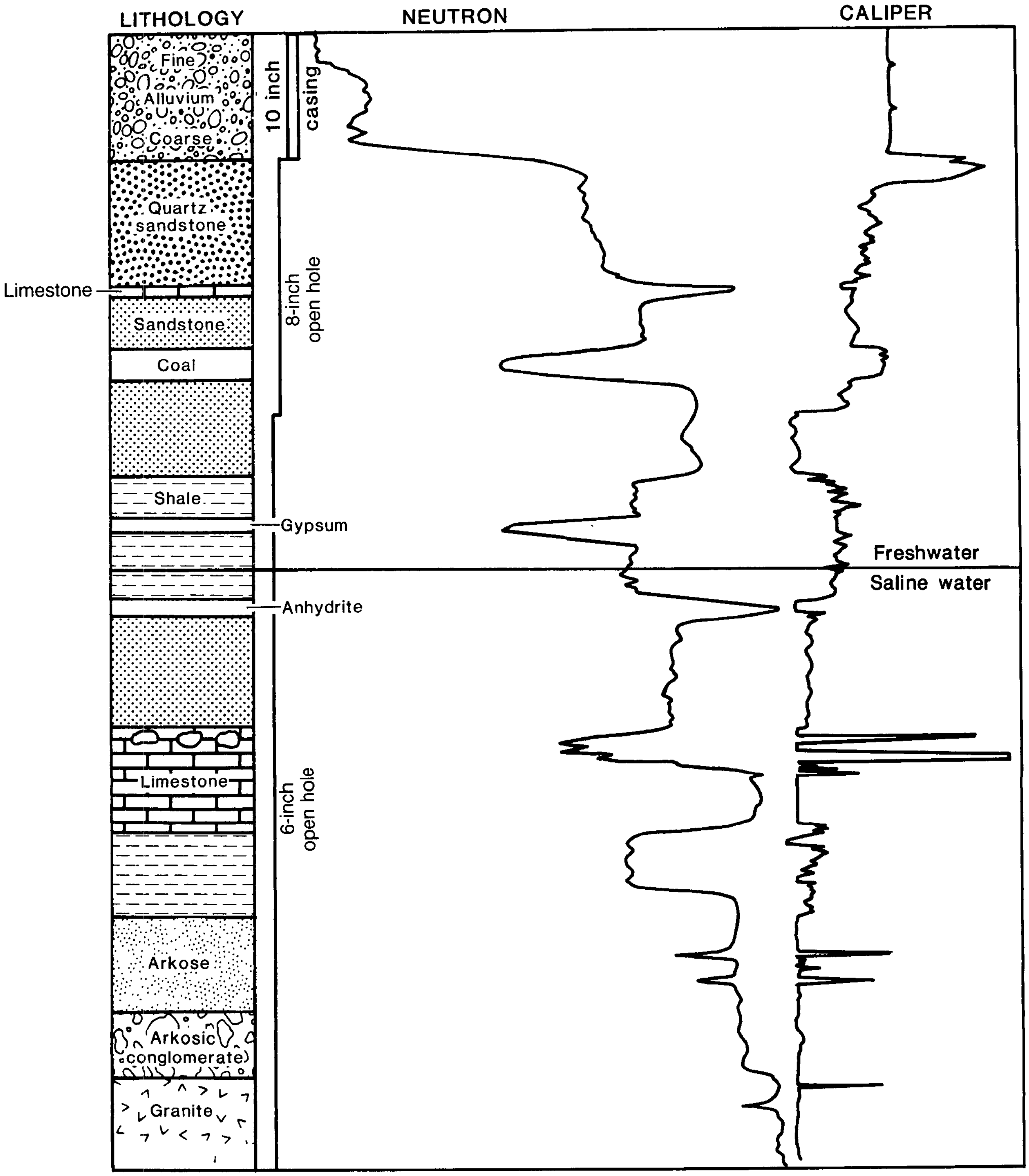


Figure 70.—Typical responses of neutron and caliper logs to a sequence of sedimentary rocks.

probe is used to measure the moisture content of saturated material before and after it is drained by a pumping test. Meyer (1962) reported that specific yields measured with a neutron probe were similar to those calculated by conventional equations based on drawdown data.

Neutron logs also can be used to locate depth intervals where porosity may have increased from

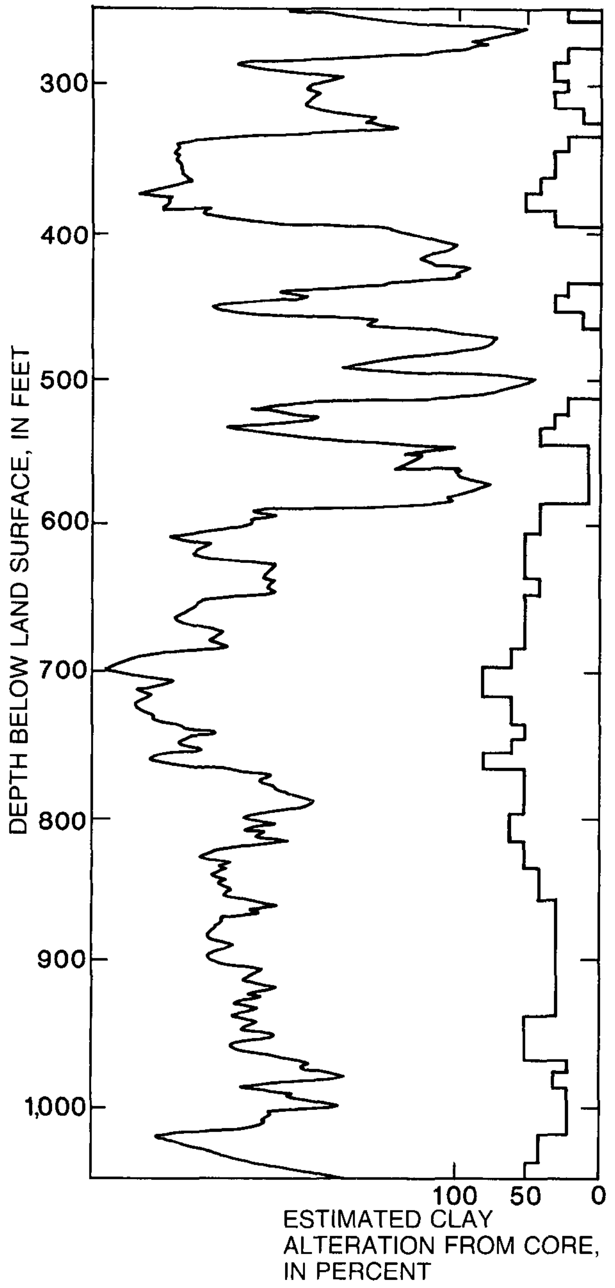


Figure 71.—Relation between a neutron log and the estimated clay content of core from a borehole penetrating crystalline rocks. Apparent porosity increases to the left.

development of a well or decreased from plugging during artificial recharge. Substantial changes in packing or porosity caused by development in the annular space behind casing or screen may be detected. Small changes may not be detectable when porosity is substantial because of the compressed log response in this range. Neutron logs are most suitable for detecting small changes in porosity when porosity is minimal; gamma-gamma logs are more sensitive to small changes in porosity when porosity is large.

Other nuclear-logging techniques

Several nonstandard nuclear-logging techniques have potential for wide application in ground-water hydrology. Neutron-activation logging and neutron-lifetime logging use a neutron source; nuclear-magnetic-resonance logging measures a characteristic of the nuclei of hydrogen atoms.

Neutron-activation logging

Neutron-activation logging has potential for application in studies of ground-water quality, because this technique permits remote identification of elements present in the borehole fluid and in adjacent rocks under a wide variety of borehole conditions. Neutron-activation logs are available from several commercial service companies; these logs have been used to provide more diagnostic data on lithology and to measure flow behind casing. The basic nuclear reactions are described in the section on the fundamentals of nuclear geophysics, but further explanation is needed here. For a complete description of the principles, consult publications by Caldwell and others (1966) and Owen (1966).

Gamma photons produced by neutron reactions may be classified as prompt, capture, and activation; these photons have energies that permit identification of the target nuclei. Prompt gamma photons result from inelastic scattering of fast neutrons; they are present only during neutron irradiation. Capture gamma photons are emitted immediately after a neutron is incorporated in a nucleus. The emission of activation gamma radiation begins with neutron irradiation; radiation then decreases as a function of the half-life of the newly produced radioisotope after the neutron flux is terminated. Neutron activation produces radioisotopes from stable isotopes; the parent or stable isotope can be identified by the energy of the gamma radiation emitted and its half-life.

The gamma activity that may be produced by neutron irradiation is related to the neutron flux and to the nuclear characteristics of the parent and daughter nuclides. Saturation is the maximum gamma activity that can be produced in a sample by a given neutron flux. When the irradiation time is equal to five times the half-life of the daughter isotope, an activity of 96.8 percent of saturation will be produced. The characteristics of some common stable isotopes that are readily activated by thermal-neutron capture are summarized in table 5.

The data in table 5 indicate that the radioactivity produced by activation is quite variable and that a

Table 5.—Activation data for some common isotopes

[Based on normal nuclide abundance, a flux of neutrons of 10^8 per square centimeter per second, and a 10-percent counting efficiency. Min, minute; h, hour; MeV, million electronvolts. Modified after Senftle and Hoyte (1966), with additional data from Goldman and Stehn (1961)]

Parent isotope	Daughter isotope	Counts per second per gram after 2-min irradiation	Half-life	Energy of major gamma peaks (MeV)
Aluminum-27	Aluminum-28	2.7×10^4	2.3 min	1.78
Chlorine-37	Chlorine-38	8.1×10^2	37.5 min	2.16,1.63
Potassium-41	Potassium-42	1.9×10^2	12.4 h	1.53
Magnesium-26	Magnesium-27	3.1×10^2	9.5 min	0.85,1.02
Manganese-55	Manganese-56	1.2×10^4	2.58h	0.84,1.81,2.13
Sodium-23	Sodium-24	2.1×10^2	15.0 h	1.37,2.75
Silicon-30	Silicon-31	5.9	2.6 h	1.26

relatively large neutron source is needed to keep activation times within practical limits. Neutron sources commonly used for water-well logging have a neutron flux that is two orders of magnitude smaller than the neutron flux mentioned in table 5. Although a typical 3-Ci americium-beryllium source can be used for neutron activation, long irradiation times are necessary. For example, if such a neutron source is left suspended in a well for a number of hours, or in a large container filled with a concentrated sodium-chloride solution overnight, the radiation from sodium-24 will be detectable with a gamma probe but the maximum activity will not be detected until after more than 75 hours of activation. The U.S. Geological Survey has explored the possibility of using 3-Ci neutron sources to activate iodides and bromides for ground-water tracers; detection of small concentrations was not possible with the small source.

A 1-Ci source of californium-252 emits, by spontaneous fission, 300 times the neutrons of any other 1-Ci radioisotope source. This source has additional advantages for well logging—small physical size and minimal gamma and heat emission; however, it also has the disadvantage of a short half-life. The first experimental well logging with californium-252 was done by personnel of the U.S. Geological Survey (Keys and Boulogne, 1969). Some of the gamma spectra produced by neutron activation in a well using a 50-mCi source of californium-252 are shown in figure 72. Note that a substantial difference occurred in the sodium-24 detected by activation at depths of 595 and 995 ft. The significant peak from aluminum-28 at a depth of 534 ft indicates that it could be produced by activation on a continuous basis while logging slowly. With 5.5 ft of spacing between the source at the bottom of the probe and the detector above it, no radiation from the source was reaching the detector. Logging down at a speed of about 5 ft/min produced a continuous neutron-activation log that was mostly related to the concentration of aluminum. Most clays are hydrous-aluminum silicates; therefore, the continuous neutron-activation log has the potential for providing additional information on clay content. Logging upward with the same probe configuration produced a standard gamma log. Neutron-porosity logs made with this large source and longer than normal spacing were superior to commercial neutron logs made in the same well; because of the larger volume of investigation, the U.S. Geological Survey logs recorded much less borehole-diameter effect.

Neutron-activation logging in boreholes also is done using an electronic neutron generator that emits pulses of neutrons with an energy of 14.2 MeV. A neutron generator accelerates deuterium ions into a tritium target to produce high-energy neutrons; the generator has the advantage that no radioactivity is emitted when it is turned off. Using a neutron generator, which is pulsed many thousands of times per second, and a synchronously gated detector, short-lived gamma radiation from prompt and capture reactions can be detected. Either sodium-iodide or solid-state detectors can be used for measuring the gamma radiation from activation; the pulses are input to a multichannel analyzer, as in spectral-gamma logging. One commercially available neutron-activation log can provide the ratios of carbon to oxygen and silicon to calcium (Lawrence, 1979). These data can be interpreted in terms of lithology and in situ hydrocarbons. A neutron generator also is potentially useful for activating oxygen in water flowing behind casing so that flow rates can be measured.

If a daughter nuclide can be identified, its concentration can be determined from measurements of the gamma activity from the daughter nuclide. Quantitative neutron-activation analysis in wells is not likely to be as accurate as laboratory analysis using the same technique because of the complex and varying geometric relations between source, detector, and distribution of isotopes.

Neutron-activation analysis is complex but potentially useful in ground-water hydrology. The logging parameters, such as type and output of source, type of

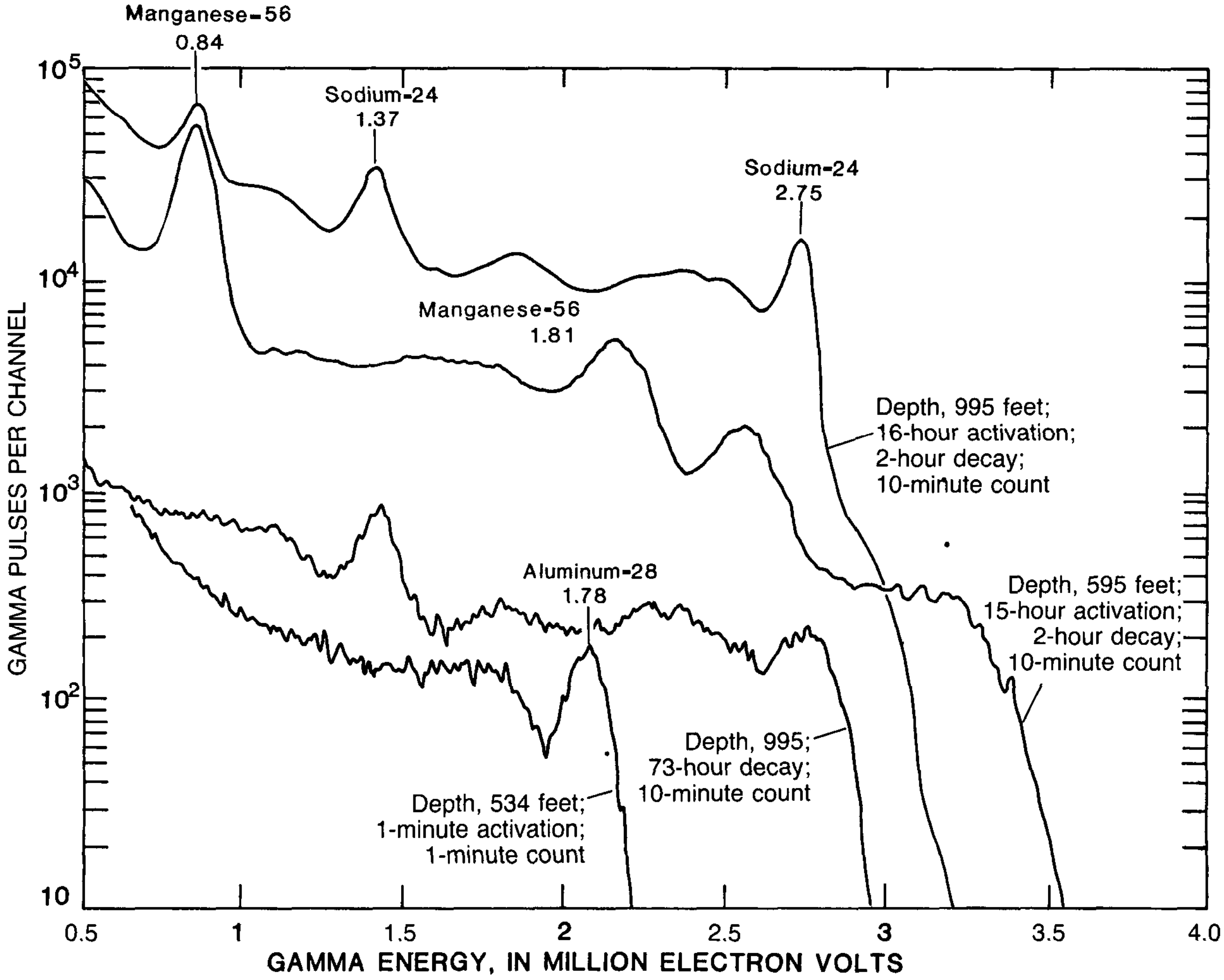


Figure 72.—Gamma spectra produced by neutron activation in a well using a 50-millicurie source of californium-252, near Aiken, S.C.

detector and irradiation, and delay or gating times, are based on an analysis of the isotopes sought and the presence of interfering elements.

Neutron-lifetime logging

Neutron-lifetime or pulsed neutron-decay logs are produced using a pulsed-neutron generator and a synchronously gated neutron detector to measure the rate of decrease of neutron population near the borehole as neutrons are thermalized and captured. The rate of neutron decay is greatly affected by the chlorine concentration; therefore, the log provides a measurement of salinity and porosity, similar to resistivity logs (Helander, 1983). Neutron-lifetime logs have a significant advantage over standard neutron logs because the measuring gate can be delayed long enough that borehole effects are greatly decreased. Neutron-lifetime logs can provide useful data through casing and cement. Usually the count rate from each of two time gates is recorded continuously, and a third curve may be calibrated in terms of capture cross section or capture units. The total capture cross section is a function of the cross sections of the individual elements, and it can be related to porosity and salinity. If another type of log calibrated in terms of porosity is available for comparison, neutron-lifetime logs can be interpreted in terms of salinity. The logs are used in the petroleum industry to measure water saturation and to distinguish among oil, gas, and saltwater in cased wells. To date, applications in ground-water studies have been limited.

Nuclear-magnetic-resonance logging

Nuclear-magnetic-resonance (NMR) logging or nuclear-magnetic logging (NML) has been studied for three decades, but it still is not widely used for petroleum applications and is relatively unknown in ground-water studies. Based on theory, it is a useful method for ground-water studies because a measurement can be obtained of the quantity of water that is free to move into a borehole from the rocks penetrated. At least one type of probe is available commercially. Tests are needed to determine the relation of the log to such important ground-water parameters as specific yield and permeability.

Several types of NMR logging systems exist; their basic principles are similar (Brown and Neuman, 1982; Jackson, 1984). The NMR uses a pulsed direct-current, polarizing field to align a fraction of the nuclei of hydrogen atoms (protons) with an induced magnetic field. The signal that is recorded on the log is produced by the precession of the magnetic fields of protons about the Earth's magnetic field after the polarizing signal is shut off. The proton relaxation time is short for fluids in solids or bound to surfaces, but is much longer for fluids free to move in pore spaces. The logs are calibrated in terms of the free-fluid index, which has been related to both porosity and permeability in some studies (Loren, 1972).

Use of NMR probes is limited by borehole conditions. One commercial probe has a coil 5.9 inches in diameter, so it seldom is used in boreholes less than 7 inches in diameter, and calibration is questionable in boreholes larger than 12.5 inches in diameter. The volume of investigation is relatively small; three-fourths of the signal originates from within one borehole radius of the probe. Because the borehole is filled with fluid that will be recorded as 100-percent porosity, it usually is necessary to add magnetite powder to the drilling mud to eliminate the borehole contribution to the log. A new (1984) NMR probe has been developed and successfully tested in the American Petroleum Institute calibration pit (Jackson, 1984). This new probe produces an NMR signal from a doughnut-shaped region in the rock and eliminates the borehole signal. In addition to providing porosity and saturation data, computer deconvolution of relaxation time measured by this probe yielded a measurement of pore-size distribution.

Test 3.—NUCLEAR LOGGING

1. A government license is required in order to make which of the following logs?
    a. Neutron.
    b. Gamma.
    c. Gamma gamma.
    d. Gamma spectrometry.
2. Neutrons are effectively shielded or absorbed by
    a. Paraffin.
    b. Lead.
    c. Plastic.
    d. Water.
3. Standard gamma logs
    a. Measure the quantity of clay in rocks.
    b. Provide information through casing.
    c. Distinguish among uranium, thorium, and potassium.
    d. Can be related to variations in permeability in some sediments.
4. The time constant
    a. Can be decreased in rocks having substantial radioactivity.
    b. Is the time for the signal (voltage) to increase to 63 percent of the voltage applied.
    c. Is an important factor in determining logging speed.
    d. Should be carefully selected for digitized logs.
5. Compensated neutron and gamma-gamma probes
    a. Eliminate the effect of borehole-diameter changes.
    b. Contain two detectors at different spacings.
    c. May provide more accurate data than uncompensated probes.
    d. Are side collimated.
6. Gamma-gamma logs may have substantial errors caused by
    a. Z/A ratio.
    b. Mud cake.
    c. Hydrogen content.
    d. Borehole diameter.
7. Neutron logs can be related to
    a. Moisture content.
    b. Effective porosity.
    c. Hydrogen content.
    d. Total porosity.
8. Which error(s) can be caused by running nuclear logs too fast?
    a. Decreased log response.
    b. Incorrectly located lithologic contacts.
    c. Inadequate resolution of thin beds.
    d. Incorrect porosity values from neutron and gamma-gamma logs.
9. Which nuclear particles or photons can be detected in well logging?
    a. Activation gamma photons.
    b. Beta particles.
    c. Alpha particles.
    d. Protons.
10. Neutron logs probably would be more useful than gamma-gamma logs under which of the following conditions?
    a. Large rock porosity.
    b. Small rock porosity.
    c. Steel casing in the borehole.
    d. Large rock bulk density.

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

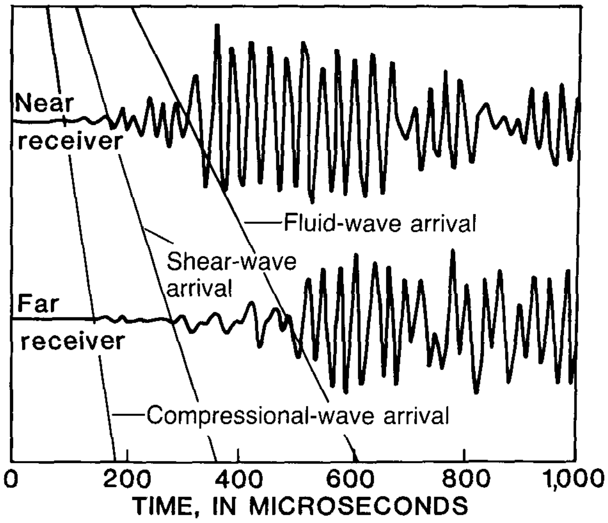


Figure 73.—Acoustic wave forms for a two-receiver system and arrival times of compressional, shear, and fluid waves (modified from Paillet and White, 1982).

Acoustic Logging

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

Acoustic-velocity logging

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

Principles and instrumentation

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

Acoustic energy transmitted in borehole fluid and adjacent rocks is divided into several components; the most important for this discussion are compressional waves and shear waves. Standard acoustic-velocity logs are based on the time the compressional wave arrives at the receivers. Compressional and shear waves at near and far receivers, along with the fluid waves that are transmitted through the borehole fluid, are shown in figure 73 (Paillet and White, 1982). The optimum frequency range for excitation of compressional and shear waves depends in a complicated