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

Chapter E2

BOREHOLE GEOPHYSICS APPLIED TO GROUND-WATER INVESTIGATIONS

By W. Scott Keys

Book 2

COLLECTION OF ENVIRONMENTAL DATA

U.S. DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, Jr., *Secretary*

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PREFACE

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

The unit of publication, the chapter, is limited to a narrow field of subject matter. This format permits flexibility in revision and publication as the need arises. "Borehole geophysics applied to ground-water investigations" is the second chapter to be published under Section E of Book 2.

Reference to trade names, commercial products, manufacturers, or distributors in this manual constitutes neither endorsement by the U.S. Geological Survey nor recommendation for use.

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TWRI 1–D1. Water temperature—influential factors, field measurement, and data presentation, by H.H. Stevens, Jr., J.F. Ficke, and G.F. Smoot. 1975. 65 pages.

TWRI 1–D2. Guidelines for collection and field analysis of ground-water samples for selected unstable constituents, by W.W. Wood. 1976. 24 pages.

TWRI 2–D1. Application of surface geophysics to ground-water investigations, by A.A.R. Zohdy, G.P. Eaton, and D.R. Mabey. 1974. 116 pages.

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TWRI 2–E1. Application of borehole geophysics to water-resources investigations, by W.S. Keys and L.M. MacCary. 1971. 126 pages.

TWRI 2–E2. Borehole geophysics applied to ground-water investigations, by W. Scott Keys. 1990. 150 pages.

TWRI 2–F1. Application of drilling, coring, and sampling techniques to test holes and wells, by Eugene Shuter and Warren E. Teasdale. 1989. 97 pages.

TWRI 3–A1. General field and office procedures for indirect discharge measurements, by M.A. Benson and Tate Dalrymple. 1967. 30 pages.

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TWRI 3–A6. General procedure for gaging streams, by R.W. Carter and Jacob Davidian. 1968. 13 pages.

TWRI 3–A7. Stage measurements at gaging stations, by T.J. Buchanan and W.P. Somers. 1968. 28 pages.

TWRI 3–A8. Discharge measurements at gaging stations, by T.J. Buchanan and W.P. Somers. 1969. 65 pages.

TWRI 3–A9.[1] Measurement of time of travel in streams by dye tracing, by F.A. Kilpatrick and J.F. Wilson, Jr. 1989. 27 pages.

TWRI 3–A10. Discharge ratings at gaging stations, by E.J. Kennedy. 1984. 59 pages.

TWRI 3–A11. Measurement of discharge by moving-boat method, by G.F. Smoot and C.E. Novak. 1969. 22 pages.

TWRI 3–A12. Fluorometric procedures for dye tracing, Revised, by J.F. Wilson, Jr., E.D. Cobb, and F.A. Kilpatrick. 1986. 41 pages.

TWRI 3–A13. Computation of continuous records of streamflow, by E.J. Kennedy. 1983. 53 pages.

TWRI 3–A14. Use of flumes in measuring discharge, by F.A. Kilpatrick, and V.R. Schneider. 1983. 46 pages.

TWRI 3–A15. Computation of water-surface profiles in open channels, by Jacob Davidian. 1984. 48 pages.

TWRI 3–A16. Measurement of discharge using tracers, by F.A. Kilpatrick and E.D. Cobb. 1985. 52 pages.

TWRI 3–A17. Acoustic velocity meter systems, by Antonius Laenen. 1985. 38 pages.

TWRI 3–A18. Determination of stream reaeration coefficients by use of tracers, by F.A. Kilpatrick, R.E. Rathbun, N. Yotsukura, G.W. Parker, and L.L. DeLong. 1989. 52 pages.

TWRI 3–A19. Levels at streamflow gaging stations, by E.J. Kennedy. 1990. 31 pages.

TWRI 3–B1. Aquifer-test design, observation, and data analysis, by R.W. Stallman. 1971. 26 pages.

TWRI 3–B2.[2] Introduction to ground-water hydraulics, a programmed text for self-instruction, by G.D. Bennett. 1976. 172 pages.

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[1]This manual is a revision of "Measurement of Time of Travel and Dispersion in Streams by Dye Tracing," by E.F. Hubbard, F.A. Kilpatrick, L.A. Martens, and J.F. Wilson, Jr., Book 3, Chapter A9, published in 1982.

[2]Spanish translation also available.

TWRI 3–B3. Type curves for selected problems of flow to wells in confined aquifers, by J.E. Reed. 1980. 106 pages.
TWRI 3–B4. Regression modeling of ground-water flow, by Richard L. Cooley and Richard L. Naff. 1990. 232 pages.
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TWRI 3–C2. Field methods of measurement of fluvial sediment, by H.P. Guy and V.W. Norman. 1970. 59 pages.
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TWRI 4–B3. Regional analyses of streamflow characteristics, by H.C. Riggs. 1973. 15 pages.
TWRI 4–D1. Computation of rate and volume of stream depletion by wells, by C.T. Jenkins. 1970. 17 pages.
TWRI 5–A1. Methods for determination of inorganic substances in water and fluvial sediments, by Marvin J. Fishman and Linda C. Friedman, editors. 1989. 545 pages.
TWRI 5–A2. Determination of minor elements in water by emission spectroscopy, by P.R. Barnett and E.C. Mallory, Jr. 1971. 31 pages.
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TWRI 5–A4.[2] Methods for collection and analysis of aquatic biological and microbiological samples, by L.J. Britton and P.E. Greeson, editors. 1989. 363 pages.
TWRI 5–A5. Methods for determination of radioactive substances in water and fluvial sediments, by L.L. Thatcher, V.J. Janzer, and K.W. Edwards. 1977. 95 pages.
TWRI 5–A6. Quality assurance practices for the chemical and biological analyses of water and fluvial sediments, by L.C. Friedman and D.E. Erdmann. 1982. 181 pages.
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TWRI 6–A1. A modular three-dimensional finite-difference ground-water flow model, by Michael G. McDonald and Arlen W. Harbaugh. 1988. 586 pages.
TWRI 7–C1. Finite difference model for aquifer simulation in two dimensions with results of numerical experiments, by P.C. Trescott, G.F. Pinder, and S.P. Larson. 1976. 116 pages.
TWRI 7–C2. Computer model of two-dimensional solute transport and dispersion in ground water, by L.F. Konikow and J.D. Bredehoeft. 1978. 90 pages.
TWRI 7–C3. A model for simulation of flow in singular and interconnected channels, by R.W. Schaffranek, R.A. Baltzer, and D.E. Goldberg. 1981. 110 pages.
TWRI 8–A1. Methods of measuring water levels in deep wells, by M.S. Garber and F.C. Koopman. 1968. 23 pages.
TWRI 8–A2. Installation and service manual for U.S. Geological Survey monometers, by J.D. Craig. 1983. 57 pages.
TWRI 8–B2. Calibration and maintenance of vertical-axis type current meters, by G.F. Smoot and C.E. Novak. 1968. 15 pages.

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[1]This manual is a revision of TWRI 5–A3, "Methods of Analysis of Organic Substances in Water," by Donald F. Goerlitz and Eugene Brown, published in 1972.

[2]This manual supersedes TWRI 5–A4, "Methods for collection and analysis of aquatic biological and microbiological samples," edited by P.E. Greeson and others, published in 1977.

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METRIC CONVERSION FACTORS

The inch-pound units used in this report can be converted to metric units by use of the following conversion factors:

Multiply	*By*	*To obtain*
gallon	3.785	liter
gallon per minute (gal/min)	0.06309	liter per second
foot (ft)	0.3048	meter
inch (in)	25.40	millimeter
mile (mi)	1.609	kilometer
pound	0.4536	kilogram
pound per square inch (lb/in^2)	6.895	kilopascal

To convert degrees Fahrenheit (°F) to degrees Celsius (°C), use the following formula:

$$°C=(°F-32)/1.8.$$

To convert degrees Celsius (°C) to degrees Fahrenheit (°F), use the following formula:

$$°F=1.8\ °C+32.$$

The following terms and abbreviations also are used in this report:

revolutions per second (r/s)
foot per second (ft/s)
foot per minute (ft/min)
foot per inch (ft/in)
second per foot (s/ft)
square meter (m^2)
cubic meter (m^3)
microsecond per foot (μs/ft)
gram per cubic centimeter (g/cm^3)
milliliter (mL)
milligram per liter (mg/L)
ohm-meters (ohm-m)
ohms per inch (ohm/in)
microsiemens per centimeter at 25 degrees Celsius (μS/cm)
micromhos per centimeter (μmho/cm)
electronvolt (eV)
thousand electronvolts (keV)
million electronvolts (MeV)
parts per million (ppm)
pulse per second (p/s)
second (s)
volt (V)
ampere (A)
kilohertz (kHz)
curie (Ci)
millicurie (mCi)

GLOSSARY OF COMMON WELL-LOGGING TERMS USED IN THIS MANUAL

Acoustic log.—A record of changes in the character of sound waves as they are transmitted through liquid-filled rock; transit time (*t*) is the characteristic most commonly measured, but amplitude and the full acoustic-wave form also are recorded. Also called a sonic log.

Acoustic-televiewer (ATV) log.—A record of the amplitude of high-frequency acoustic pulses reflected by the borehole wall; provides information on location and orientation of bedding, fractures, and cavities; compare with optical image produced by the borehole television.

Acoustic wave.—A sound wave transmitted through material by elastic deformation.

Activation log.—A record of radiation from radionuclides that are produced in the vicinity of a well by irradiation with neutrons; short-half-life radioisotopes usually are identified by the energy of their gamma radiation or by their decay time. Also called a neutron-activation log.

A electrode.—One of the current-emitting electrodes of a resistivity-logging system, labeled A; the current-return electrode is labeled the B electrode.

AM spacing.—The distance between the current-emitting electrode (A electrode) and the potential electrode (M electrode) in a normal-resistivity-logging system.

Alpha particle.—The nucleus of a helium atom emitted during the decay of some radioisotopes; not measured by well logging because of very low penetrating ability.

Analog recording.—A recording in which data are represented as a continuous record of physical variables rather than discrete values, as in digital recording.

Annulus.—General designation for annular space, such as the space between the drill pipe or casing and the borehole wall or the transition interval between the invaded zone and the unaltered formation.

API unit.—A unit used in the American Petroleum Institute (API) test pits for calibrating neutron and gamma logs. The API neutron unit is 1/1,000 of the difference between electrical zero and the logged value opposite the Indiana limestone in the calibration pit, which has an average porosity of 19 percent. The API gamma unit is 1/200 of the deflection between intervals of high and low radioactivity in the calibration pit.

Apparent resistivity (*Ra*).—Resistivity on a log that deviates from the true value because of the effects of the borehole or the invaded zone, or other extraneous effects; the term "apparent" also is used for other logs that might need correction to provide true values.

Armor.—Layers of steel wire (usually two layers) wrapped on the outside of most logging cable, to serve as a strength member and to protect the inner conductors.

Arrow plot.—A depth plot of data from a dipmeter log that shows the direction of dip of planar features or the drift of the hole.

Atomic number.—The number of protons in the nucleus of an atom; equals the number of electrons in a neutral atom.

Atomic weight.—The total number of protons and neutrons in the nucleus of an atom.

Attenuation.—The decrease in amplitude of a form of energy when it is propagated through a medium.

Azimuth.—The compass direction measured from magnetic north in a clockwise direction.

Background radiation.—The radioactivity at the land surface or in a well, in addition to the source of radioactivity that is being measured; surface background comes from natural radioisotopes in rocks and from cosmic radiation.

Back-up curve.—A curve on the analog record that displays log data on a new scale when deflections on the main curve exceed the width of the paper; usually displayed with a different pattern or color.

Baseline shift.—A shift in the average response of a log as a result of a change in hole conditions or lithology; also, manual rebasing or repositioning of the pen to prevent a log from going off scale.

Beta particle.—An electron or positron emitted from a nucleus during beta decay; capable of penetrating only a few millimeters of rock.

Bond index.—An index based on interpretation of a cement-bond log; the ratio of acoustic attenuation in a depth interval of interest to attenuation in a well-cemented interval.

Borehole-compensated.—A descriptive term applied to probes designed to reduce the extraneous effects of the borehole and of probe position.

Borehole gravimeter.—A gravimeter designed for well logging; provides information on the bulk density of materials distant from the borehole.

Borehole television.—A downhole television camera. *See* **Acoustic-televiewer log.**

Bottom-hole temperature (BHT).—The temperature at the bottom of the hole, usually measured with maximum recording thermometers attached to a logging probe but sometimes inferred from other data and thus hypothetical.

Bridle.—The flexible, insulated cable on which some of the electrodes are mounted for multielectrode resistivity logging; also, a short, readily disconnected length of cable that contains the cable head and fishing bell.

Bulk density.—The mass of material per unit volume; in logging, the density, in grams per cubic centimeter, of the rock in which the pore volume is filled with fluid.

Calibration.—Determination of the log values that correspond to environmental units, such as porosity or bulk density; usually carried out in pits or by comparison with laboratory analyses of core.

Caliper log.—A continuous record of hole diameter, usually made with a mechanical probe having one to six arms.

Capture cross section.—The effective area within which a neutron must pass to be captured by the nucleus of an atom.

Casing-collar locator (CCL).—An electromagnetic device usually run with other logs to record the location of collars or other changes in casing or pipe.

Cementation factor (*m*).—The cementation exponent in Archie's (1942) equation relating formation-resistivity factor and porosity; this constant is related to many aspects of pore and grain geometry that affect permeability.

Cement-bond log.—An acoustic-amplitude log used to determine the location of cement behind casing and, under some conditions, the quality of the bonding to casing and rock.

Centralizer.—A device designed to maintain a probe in the center of a borehole.

Circulation.—The flow of fluid during the drilling process; flow usually is down the drill pipe and up the annulus to the surface.

Collimation.—The shielding technique for confining radiation, such as gamma photons, to form a beam.

Compressional wave.—Acoustic wave propagated in the same direction as particle displacement. Compressional waves are faster than shear waves and are used for measuring acoustic velocity or transit time. Also called a dilatational wave or a P wave. *Compare* **Shear wave.**

Compton scattering.—The inelastic scattering of gamma photons by orbital electrons; related to electron density, and a significant process in gamma-gamma (density) logging.

Correlation.—Determination of the position of stratigraphically equivalent rock units in different wells, often done by matching the character of geophysical logs; also, the matching of variables, such as log response and core analyses.

Cross plot.—A term used in log analysis for a plot of one parameter versus another, usually two different types of logs.

Curie.—The quantity of any radionuclide that produces 3.70×10^{10} disintegrations per second.

Cycle skip.—In acoustic-velocity logging, erroneous sharp deflections on a log and incorrect transit times that result when only one of a pair of receivers is triggered by an arriving wave.

Dead time.—In nuclear logging, the amount of time required for the system to be ready to count the next pulse. Pulses occurring during dead time are not counted.

Decay.—In nuclear physics, the process of disintegration of an unstable radioisotope by the spontaneous emission of charged particles or photons.

Decentralize.—To force a logging probe against one side of the drill hole.

Density log.—The log that results when gamma photons emitted from a radioactive source in the probe are backscattered to a detector; the backscattering is related to the bulk density of the material around the probe. Also called a gamma-gamma log.

Departure curves.—Graphs that show the correction that may be made to logs to correct for some extraneous effects, such as hole diameter, bed thickness, and temperature.

Depth reference or datum.—The zero reference for logs of a well; the kelly bushing may be used if the rig is still on the well; ground level or top of casing frequently is used.

Depth of invasion.—The radial distance from the wall of the hole to the radial location of the interface between formations invaded by mud filtrate and uninvaded formations.

Depth of investigation.—*See* **Volume of investigation.** Also called radius or diameter of investigation.

Detector.—A sensor of any kind used to detect a form of energy; usually refers to nuclear detectors, such as scintillation crystals.

Deviation.—The departure between the drill hole or probe axis and the vertical, in degrees.

Differential log.—A log that records the rate of change of some logged value as a function of depth; sensitive to very small changes in absolute value.

Digital log.—A log recorded as a series of discrete numerical values (*compare* **Analog recording**).

Dipmeter.—A multielectrode contact-resistivity probe that provides data from which the strike and dip of bedding can be determined.

Directional survey.—A log that provides data on the azimuth and on deviation of a borehole from the vertical.

Disequilibrium.—State that occurs when population of daughter isotopes in a decay chain are not present in concentrations that would be achieved in the long-term absence of isotope mobility; the total radioactivity measured may not correctly indicate the quantity of radioisotopes present if all isotopes in the decay series are not present in equilibrium proportions.

Dual induction log.—An induction log with two conductivity curves having different volumes of investigation; usually run with a shallow focused-resistivity device.

Dual laterolog.—A focused-resistivity log with both shallow and deep investigation which results from simultaneous measurements with different volumes of investigation; usually gamma, spontaneous-potential, and microfocused logs are run simultaneously with the dual laterolog.

Effective porosity.—Interconnected pore space that contributes to permeability.

Electric log.—Generic term usually referring to a resistivity log that consists of long-normal, short-normal, lateral, and spontaneous-potential curves; also refers to other types of resistivity logs.

Electromagnetic casing-inspection log.—A record of the thickness of the casing wall made by measuring effects of eddy currents on a magnetic field.

Electronvolt (eV).—The energy acquired by an electron passing through a potential difference of 1 volt; used for measuring the energy of nuclear radiation and particles, usually expressed as million electronvolts (MeV).

Epithermal neutron.—A fast neutron that has been slowed by moderation to an energy level just above thermal equilibrium, making it available for capture; most modern neutron probes measure epithermal neutrons because they are less affected by chemical composition than thermal neutrons.

Field print.—A copy of a log obtained at the time of logging that has not been edited or corrected.

First reading.—The depth at which logging began at the bottom of the hole.

Fish.—An object lost in a well, such as a logging probe. The operation designed to recover the lost object is called fishing; a device at the top of a probe designed for ease of connection to an overshot device sometimes is called a fishing bell.

Flowmeter.—A logging device designed to measure the rate, and usually the direction, of fluid movement in a well; most flowmeters are designed to measure vertical flow.

Fluid sampler.—An electronically controlled device that can be run on a logging cable to collect water samples at selected depths in a well.

Flushed zone.—The zone in a borehole wall behind the mud cake that is considered to have had all mobile native fluids flushed from it.

Focused log.—A resistivity log that employs electrodes designed to focus the current into a sheet; provides greater penetration and greater vertical resolution than an unfocused log.

Formation.—In well-logging literature in a general sense, all material penetrated by a drill hole without regard to its lithology or structure; in a stratigraphic sense, a named body of rock strata having unifying lithologic features.

Formation-resistivity factor (*F*).—The ratio of the electrical resistivity of a rock 100 percent saturated with water (Ro) to the resistivity of the water with which it is saturated (Rw): $F=Ro/Rw$.

Formation tester.—A wire-line device that can be used to recover fluid samples from rocks penetrated by a borehole and to record flowing and shut-in pressure versus time.

Free-fluid index.—Measurement by a nuclear-magnetic log that indicates the amount of fluid (containing hydrogen) that is free to move.

Gamma log.—A log of the natural radioactivity of the rocks penetrated by a drill hole; also will detect gamma-emitting artificial radioisotopes (*see* **Spectral-gamma log**). Also called a gamma-ray log or a natural-gamma log.

Gamma ray.—A photon having neither mass nor electrical charge that is emitted by the nucleus of an atom; measured in gamma logging, and output from a source used in gamma-gamma logging.

Gradiomanometer.—A probe used to measure the average density of fluid in a 2-ft interval of a well bore.

Grain density.—The density of a unit volume of rock matrix at zero porosity, in grams per cubic centimeter. Also called matrix density.

Ground electrode.—A surface electrode used for spontaneous-potential and resistivity logging.

Guard log.—A type of focused-resistivity log that derives its name from guard electrodes that are designed to focus the flow of current.

Half-life.—The time required for a radioisotope to lose half its radioactivity from decay.

Half-value thickness.—The thickness of a material that reduces the radioactivity to half the initial value.

Hydrogen index.—The ratio of the number of hydrogen atoms per unit volume of a material to the number in pure water at 75 °F.

Induced polarization.—A surface and logging method based on measurement of the decay of voltage in the ground after excitation by a current pulse.

Induction logging.—A method for measuring resistivity or conductivity that uses an electromagnetic technique to induce eddy currents in the rocks around a borehole; can be used in nonconductive borehole fluids, and can make measurements through nonconductive casing.

Interval transit time (*t*).—The time required for a compressional acoustic wave to travel a unit distance; usually measured by acoustic or sonic logs, in microseconds per foot, and is the reciprocal of velocity.

Invaded zone.—The annular interval of material around a drill hole where drilling fluid has replaced all or part of the native interstitial fluids.

Isotopes.—Atoms of the same element that have the same atomic number but a different mass number; unstable isotopes are radioactive and decay to become stable isotopes.

Kelly bushing (KB).—The bushing on the derrick floor that transmits rotary motion to the drill pipe; most logs of oil wells are referenced to the kelly bushing, which may be many feet above ground level.

Lag.—The distance a nuclear logging probe moves during one time constant.

Last reading.—The depth of the shallowest value recorded on a log.

Lateral logging.—A multielectrode resistivity-logging technique that has a much greater radius of investigation than the normal techniques but requires thick beds and produces an unsymmmetrical curve.

Laterologging.—A focused-resistivity logging technique designed to achieve greater penetration into the formation; *see also* **Guard log**.

Long-normal log.—A resistivity log with AM spacing (the distance between the A and M electrodes) usually 64 in; *see* **Normal log.**

Lubricator.—A hydraulic-packing device through which the cable passes that permits logging of wells under pressure; the lubricator may be screwed to the casing or valve at the well head.

Mark.—A magnetic marker or metallic shim on a logging cable, used for depth control; also an arbitrary probe reference for sweep on acoustic-televiewer logs.

Matrix.—The solid framework of rock or mineral grains that surrounds pore spaces.

M electrode.—The potential electrode nearest the A electrode in a resistivity device (*compare* **N electrode**).

Mho.—A unit of electrical conductance that is the reciprocal of ohm; siemens.

Microresistivity log.—One of a group of short-spaced resistivity logs that are used to measure the mud cake and invaded zone.

Monitor curve.—A curve on a well log that is related to probe performance or stability.

Mud cake.—The layer of mud particles that builds up on the wall of a rotary-drilled hole as mud filtrate is lost to the formation. Also called filter cake.

Mud filtrate.—The liquid effluent of drilling mud that penetrates the wall of a hole.

Mud logging.—Analysis of circulated drilling mud for hydrocarbons, lithology, salinity, viscosity, and so forth.

N electrode.—The potential electrode distant from the A electrode in a resistivity device (*compare* **M electrode**).

Neutron.—An elementary particle of the nucleus of an atom that has the same mass as a proton (1) but no charge; a neutron source is required to make neutron logs.

Neutron generator.—A high-voltage electromagnetic device that can be controlled to emit neutrons only when it is turned on, contrasted with an isotopic source that emits neutrons at all times.

Neutron-lifetime log.—A log that measures the lifetime of the neutron population emitted by a pulsed-neutron generator and can be related to porosity, salinity, and clay content. Also called a pulsed-neutron or thermal-decay time log.

Neutron log.—A log that measures neutrons from an isotopic source at one or several detectors after they migrate through material in, and adjacent to, the borehole; log response results primarily from hydrogen content, but it can be related to saturated porosity and moisture content.

Noise.—A spurious or erratic log response not related to the property being logged; sonic noise logs use an acoustic receiver to detect sound caused by rapid fluid movement in a hole.

Normal log.—A quantitative-resistivity log, made with four electrodes, that employs spacings between the A and M electrodes of 4 to 64 in to investigate different volumes of material around a borehole; *see* **Long-normal log** and **Short-normal log**.

Nuclear log.— A well log using nuclear reactions to measure either response to radiation from sources in the probe or natural radioactivity present in the rocks.

Nuclear-magnetic logging.—A procedure in which protons (hydrogen nuclei) are aligned with an impressed magnetic field that is turned off, and the radiation produced by the precession of their magnetic fields about the Earth's magnetic field is measured; the measured intensity of this precession at a specified time after the impressed field is turned off is logged as free-fluid index, which is related to hydrogen in fluids that are free to move. Also called a nuclear-magnetic-resonance, or NMR, log.

Ohm.—The unit of electrical resistance through which 1 ampere of current will flow when the potential difference is 1 volt.

Ohm-meter.—The resistivity of 1 cubic meter of material, which has a resistance of 1 ohm when electrical current flows between opposite faces; the standard unit of measurement for resistivity logs.

Open hole.—The uncased intervals of a drill hole.

Photoclinometer.—A logging device that photographically records the azimuth and the deviation of a well at preselected depths.

Porosity.—The ratio of the void volume of a porous rock to the total volume, usually expressed as a percentage.

Probe.—A downhole well-logging instrument package. Also called a sonde or a tool.

Production log.—A log run in a petroleum production or injection well; small-diameter probes are used to make logs mostly related to fluid movement.

Proton.—The nucleus of a hydrogen atom; a positively charged nuclear particle having a mass of 1; *see* **Neutron.**

Pulsed neutron log.—Any log made with a pulsed neutron source.

Pulse-height analyzer.—An electronic device used to sort and record radiation pulses as a function of their energy; used for gamma-spectral logging and activation logging.

Radioactivity.—The energy emitted as particles or rays during the decay of an unstable isotope or nuclide to another unstable isotope or a stable isotope.

Repeat section.—A short interval of log that is run a second time to establish repeatability and stability.

Resistivity log.—Any of a large group of logs that are designed to make quantitative measurements of the specific resistance of a material to the flow of electric current; calibrated in ohm-meters.

Reversal.—A typical distortion of normal-resistivity logs opposite beds that are thinner than the AM spacing (the space between the A and M electrodes); the effect is an apparent decrease in resistivity in the center of a resistive unit.

Rugosity.—The irregularity or roughness of the wall of a borehole.

Saturation.—The percentage of the pore space occupied by a fluid, usually water in hydrologic applications.

Scintillation detector.—An efficient detector used in nuclear-logging equipment; ionizing radiation causes flashes of light that are sensed by a photomultiplier tube and converted to pulses of electric current.

Secondary porosity.—The porosity developed in a rock after its deposition as a result of fracturing or solution; usually not uniformly distributed.

Sensitivity.—The amplitude of deflection of a log in response to a standard-input signal. Also called span.

Shale baseline.—A line drawn through spontaneous-potential log deflections that represent shale; a similar technique can be used on gamma logs and can represent the average log response of sand or other lithologies.

Shear wave.—An acoustic wave propagated at right angles to the direction of particle vibration. Also called an S wave. *Compare* **Compressional wave.**

Short-normal log.—One of a group of normal-resistivity logs usually with AM spacing (the distance between the A and M electrodes) of 16 in or less; *see* **Normal log.**

Sidewall.—A term describing a logging device with sensors mounted on a pad or skid that is forced into contact with a borehole wall.

Signal.—The desired portion of the response of a logging device, contrasted with the unwanted noise.

Single-point-resistance log.—A log of resistance measured by a single-electrode device; cannot be used quantitatively.

Spacing.—The distance between sources or transmitters and detectors or receivers on a logging probe.

Spectral-gamma log.—A log of gamma radiation as a function of its energy; permits identification of the radioisotopes present.

Spike.—A sharp deflection on a log, usually the result of a spurious signal or noise.

Spine-and-ribs plot.—A plot of long-spaced detector output versus short-spaced detector output for a dual-detector gamma-gamma probe; permits correction for some extraneous effects.

Spinner survey.—A log of fluid velocity made with an impeller flowmeter.

Spontaneous-potential log.—A log of the difference in DC voltage between an electrode in a well and an electrode at the surface; most of the voltage results from electrochemical potentials that develop between dissimilar borehole and formation fluids.

Stand-off.—The distance between a probe and the wall of a borehole.

Survey.—An oil-industry term for the performance or result of a well-logging operation.

Temperature log.—A log of the temperature of the fluids in a borehole; a differential-temperature log records the rate of change in temperature with depth and is sensitive to very small changes.

Thermal neutron.—A neutron that is in equilibrium with the surrounding medium such that it will not change energy (average 0.025 eV) until it is captured.

Time constant.—The time, in seconds, required for a varying signal to record 63 percent of the change that actually occurred from one signal level to another.

Tracer log.—A log made for the purpose of measuring fluid movement in a well by means of following a tracer injected into the well bore; tracers can be radioactive or chemical. Also called a tracejector log.

Track.—The areas in the American Petroleum Institute log grid that are standard for most large well-logging companies; track 1 is to the left of the depth column, and tracks 2 and 3 are to the right of the depth column, but are not separated.

Transducer.—Any device that converts an input signal to an output signal of a different form; can be a transmitter or receiver in a logging probe.

Ultra-long-spaced electric log.—A modified long-normal device with an AM spacing (the distance between the A and M electrodes) of as much as 1,000 ft; can be used to locate anomalies quite distant from a borehole.

Variable-density log.—A log of the acoustic wave train that is recorded photographically, so that variations in darkness are related to the relative amplitude of the waves. Also called a three-dimensional log.

Volume of investigation.—The volume of borehole fluid, and invaded and uninvaded formation surrounding the geophysical logging probe which determines 90 percent of the measurement obtained from the probe; the radius of this volume generally depends on both probe configuration and the properties of the formation and fluids.

Z/A effect.—An effect on the relation between the response of gamma-gamma logs and bulk density based on the ratio of the atomic number (Z) to the atomic weight (A) of elements in the formation.

BOREHOLE GEOPHYSICS APPLIED TO GROUND-WATER INVESTIGATIONS

By W. Scott Keys

Abstract

The purpose of this manual is to provide hydrologists, geologists, and others who have the necessary background in hydrogeology with the basic information needed to apply the most useful borehole-geophysical-logging techniques to the solution of problems in ground-water hydrology. Geophysical logs can provide information on the construction of wells and on the character of the rocks and fluids penetrated by those wells, as well as on changes in the character of these factors over time. The response of well logs is caused by petrophysical factors, by the quality, temperature, and pressure of interstitial fluids, and by ground-water flow. Qualitative and quantitative analysis of analog records and computer analysis of digitized logs are used to derive geohydrologic information. This information can then be extrapolated vertically within a well and laterally to other wells using logs.

The physical principles by which the mechanical and electronic components of a logging system measure properties of rocks, fluids, and wells, as well as the principles of measurement, must be understood if geophysical logs are to be interpreted correctly. Planning a logging operation involves selecting the equipment and the logs most likely to provide the needed information. Information on well construction and geohydrology is needed to guide this selection. Quality control of logs is an important responsibility of both the equipment operator and the log analyst and requires both calibration and well-site standardization of equipment.

Logging techniques that are widely used in ground-water hydrology or that have significant potential for application to this field include spontaneous potential, resistance, resistivity, gamma, gamma spectrometry, gamma-gamma, neutron, acoustic velocity, acoustic televiewer, caliper, and fluid temperature, conductivity, and flow. The following topics are discussed for each of these techniques: principles and instrumentation, calibration and standardization, volume of investigation, extraneous effects, and interpretation and applications.

Introduction

Purpose and scope

Borehole geophysics, as defined in this manual, is the science of recording and analyzing continuous or point measurements of physical properties made in wells or test holes. The chief purpose of this manual is to serve as a comprehensive source of information on how to make and record geophysical logs for ground-water investigations, and therefore ensure that all hydrologic information contained in the logs is made available. It is also intended to update the version published in 1971 (Keys and MacCary, 1971). This updating is done by emphasizing techniques that have changed most since 1971. Additional emphasis is placed on newer logs, such as the acoustic televiewer, that have become widely used since 1971; some text and figures describing older techniques that appeared in the earlier version have been omitted. Newer applications of borehole geophysics, to such problems as waste disposal and geothermal energy, are emphasized because of their increased importance during the past 19 years. Interest in these applications, as well as in applications to the prediction of earthquakes and volcanism, has increased the need for log analysis in igneous and metamorphic rocks. These rocks, which have been of little importance to ground-water hydrologists until recently, are discussed in greater detail in this manual. The emphasis in this manual is on the principles of borehole geophysics and their application to ground-water investigations, rather than on how to operate a specific logger, or how to make hole-diameter corrections on a specific type of gamma-gamma log made by a commercial service company.

Most of the literature on borehole geophysics is directed toward petroleum applications, which can be quite different from ground-water applications. Log analysis for petroleum stresses the determination of hydrocarbons in pore space, normally expressed as water saturation (Sw), in the presence of two immiscible fluids, and the relative permeability to these fluids; this is a rare situation in ground-water investigations. Water encountered in oil-well logging usually is saline; most of the equations developed for analysis of electric logs under these conditions do not apply to fresh water.

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No manual or book can answer all possible questions on borehole geophysics, and length limitations preclude describing some subjects here. For example, specifications and calibration data are so variable among logging tools of the same type that space does not permit inclusion of that type of information; manuals provided by manufacturers or logging-service companies can be consulted for that type of information.

The glossary at the front of this manual includes only those terms used in the text. A more complete glossary has been published by the Society of Professional Well Log Analysts (1975). Terms and abbreviations differ among commercial service companies. This terminology problem is compounded by the fact that the same type of log may be given a different name by each of the major logging-service companies.

The list of references included herein is far from complete; only the most important are included. A more complete bibliography related to ground-water applications of borehole geophysics has been published by Taylor and Dey (1985).

Background

Most texts on borehole geophysics credit the Schlumberger brothers for developing the first geophysical logs, in France in 1927. They made the first resistivity logs by manually plotting the deflections of a galvanometer that responded to resistivity of rocks and interstitial fluids (Schlumberger and Schlumberger, 1929). In 1931, Schlumberger engineers recorded natural electrical potentials caused by differences in the lithology penetrated by wells. The existence of these potentials was known as early as 1830. A log of these spontaneous potentials was called a porosity log at that time.

In the United States, the first geophysical well logs probably were plotted from temperature measurements made by Hallock (1897), although Lord Kelvin made downhole temperature measurements in 1869 (Van Orstrand, 1918). C.E. Van Orstrand (1918) of the U.S. Geological Survey described downhole temperature-logging equipment with a resolution of 0.01 °C, which he used to plot "depth-temperature curves." Van Orstrand also worked with personnel of the Carnegie Institute in Washington, D.C., who made temperature measurements with similar equipment prior to 1916 (Johnston and Adams, 1916). The winch that was used to log to depths of as much as 7,000 ft and the related surface equipment are shown in figures 1 and 2. The cable was not unlike that used today, with a strength member and two separate insulated conductors. This logging equipment was probably the first used by the U.S. Geological Survey,

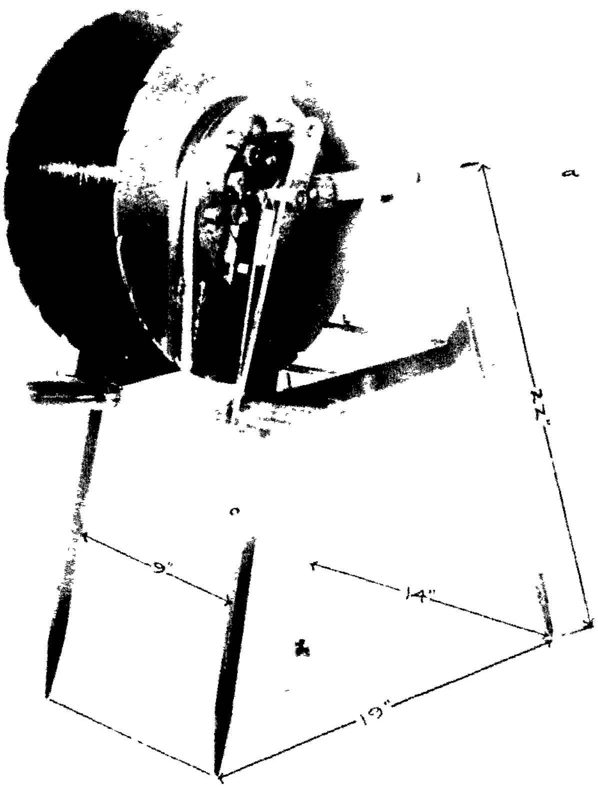


Figure 1.—Hand-cranked winch and cable used by the U.S. Geological Survey to make temperature logs prior to 1918 (from Van Orstrand, 1918).

and among the earliest used anywhere. An example of one of Van Orstrand's "depth-temperature curves" is shown in figure 3; he attributed the anomalies to water, gas, and oil. He also speculated that such temperature curves might "...afford a means of determining the relative water content of rocks in situ." Temperature logs can sometimes be used to locate permeable zones intersected by water wells.

At present (1985), geophysical well logs are run in every exploration or production well drilled for oil anywhere in the world. Because the value of the product justified the expense, almost all of the advances in borehole geophysics have been made for oil-well logging. As a consequence, most of the literature on the field is related to petroleum. Both the use and the development of borehole geophysics in ground-water hydrology lag substantially behind the petroleum industry; however, the gap has narrowed over the past 15 years.

The first comprehensive report pertaining to the use of subsurface geophysical methods in ground-water hydrology was written by Jones and Skibitzke (1956). The first U.S. Geological Survey logger for the

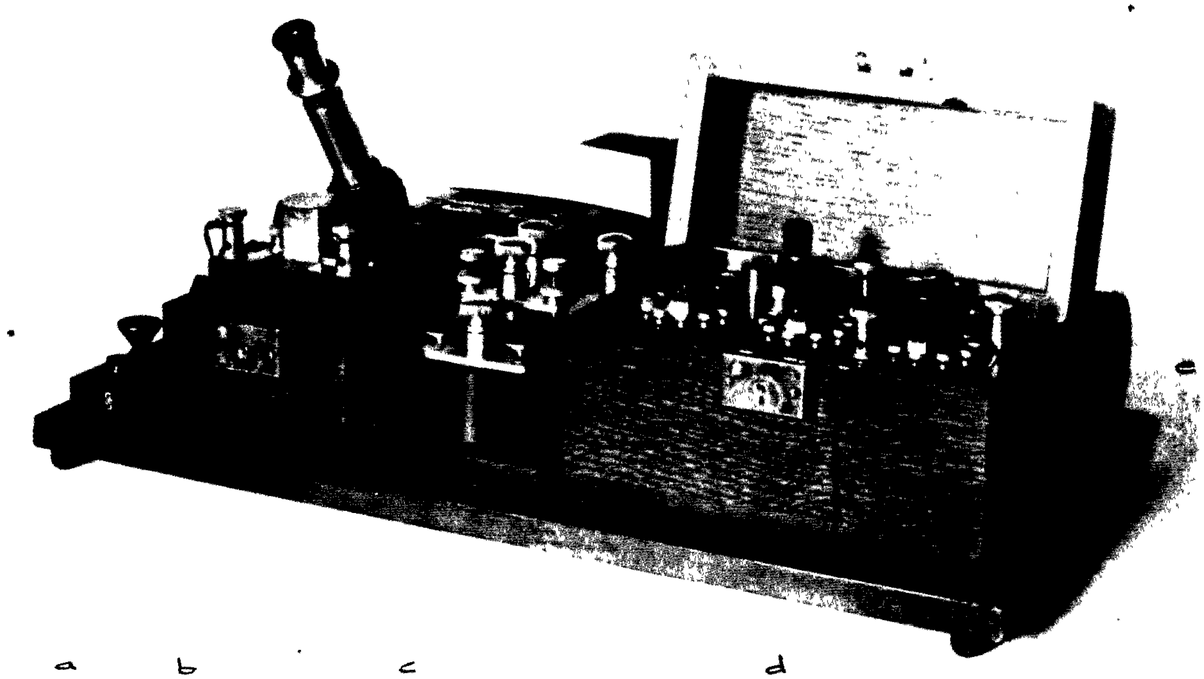


Figure 2.—Wheatstone-bridge system used to make depth-temperature curves or logs with a resolution of 0.01 degree Celsius (from Van Orstrand, 1918).

study of ground water was purchased by P.H. Jones in 1946 for $499. Two views of that early "Widco" logger, built by Hubert Guyod, are shown in figures 4 and 5. The logger was modified with the addition of a gamma panel above the recorder. It probably was also modified by changing the curvilinear recorder first used to a rectilinear recorder. The Widco Company, which no longer exists, was started by Hubert Guyod and produced all the early small loggers used in ground-water hydrology. Guyod also did considerable research on log analysis and published early reports that were useful for ground-water applications (Guyod, 1952, 1966; Guyod and Pranglin, 1959).

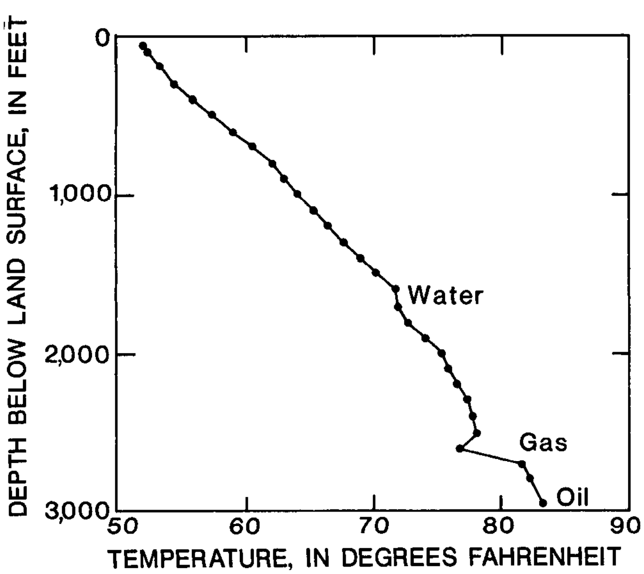


Figure 3.—Depth-temperature curve and interpretation (modified from Van Orstrand, 1918).

How to use this manual

This manual is organized into introductory sections on the principles of borehole geophysics followed by sections describing each of the types of geophysical logs that have important application to ground-water hydrology. To select the logs needed to solve a specific problem, the reader should refer to the sections on log analysis, petrophysics, and ground-water flow. Explanation of how to select the types of logs that will provide, from the wells available, the information needed for the rocks and fluids penetrated is, in fact, one of the most important purposes of this manual. The section on planning a logging program should be reviewed early in a project, preferably before drilling is started. Sections on specific types of logs should be studied after the logs to be used have been selected. The glossary may be helpful in early stages of a study. If preliminary information indicates that a certain type of log may be applicable, then the subsections on

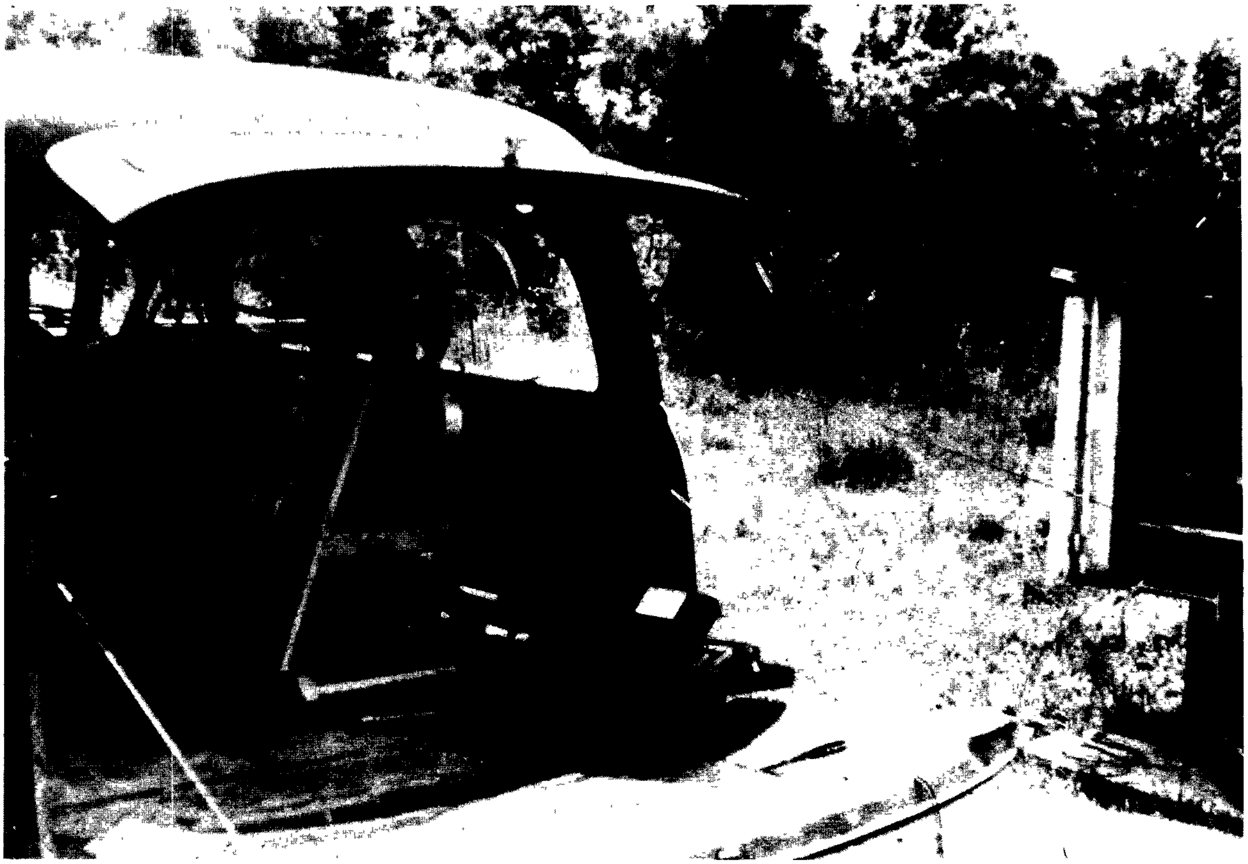


Figure 4.—First geophysical well logger for water-resources investigations bought by the U.S. Geological Survey in 1946.

interpretation, applications, and extraneous effects for that type of log should be reviewed. Finally, when the decision has been made to use or interpret a specific suite of logs, the sections on those logs should be studied thoroughly. References mentioned in each section may be consulted for more complete information on a subject. Descriptions of instrumentation or calibration may be reviewed, even though the reader does not plan to participate in making the logs, because equipment and procedures must be understood if the logs are to be interpreted correctly. Multiple-choice tests on related types of logs at the end of some sections, or groups of sections, may help the reader determine whether significant points are understood; test answers are given at the end of the manual.

Why log?

The most important objective of borehole geophysics is to obtain more information from a well than can be obtained from drilling, sampling, and testing. Drilling any kind of a test hole or well is an expensive procedure. The test hole or well provides access to the ground-water system at one point; therefore, each test hole or well provides a valuable opportunity to obtain vertical profiles or records of many kinds of data. The cost-benefit ratio for recording geophysical logs usually is quite favorable. That is why all oil wells drilled anywhere in the world are logged. Although the unit costs for drilling most water wells are less than those for drilling oil wells and the value of the product usually is less, the cost of logging usually also is less.

Geophysical logs provide continuous analog or digital records that can be interpreted to provide an understanding of the physical properties of the rock matrix, the contained fluids, and the construction of the well. Logs can be interpreted in terms of the lithology, thickness, and continuity of aquifers and confining beds; the permeability, porosity, bulk density, resistivity, moisture content, and specific yield of aquifers and confining beds; and the source, movement, and chemical and physical characteristics of ground water. These data are objective, repeatable over a long period of time, and comparable, even

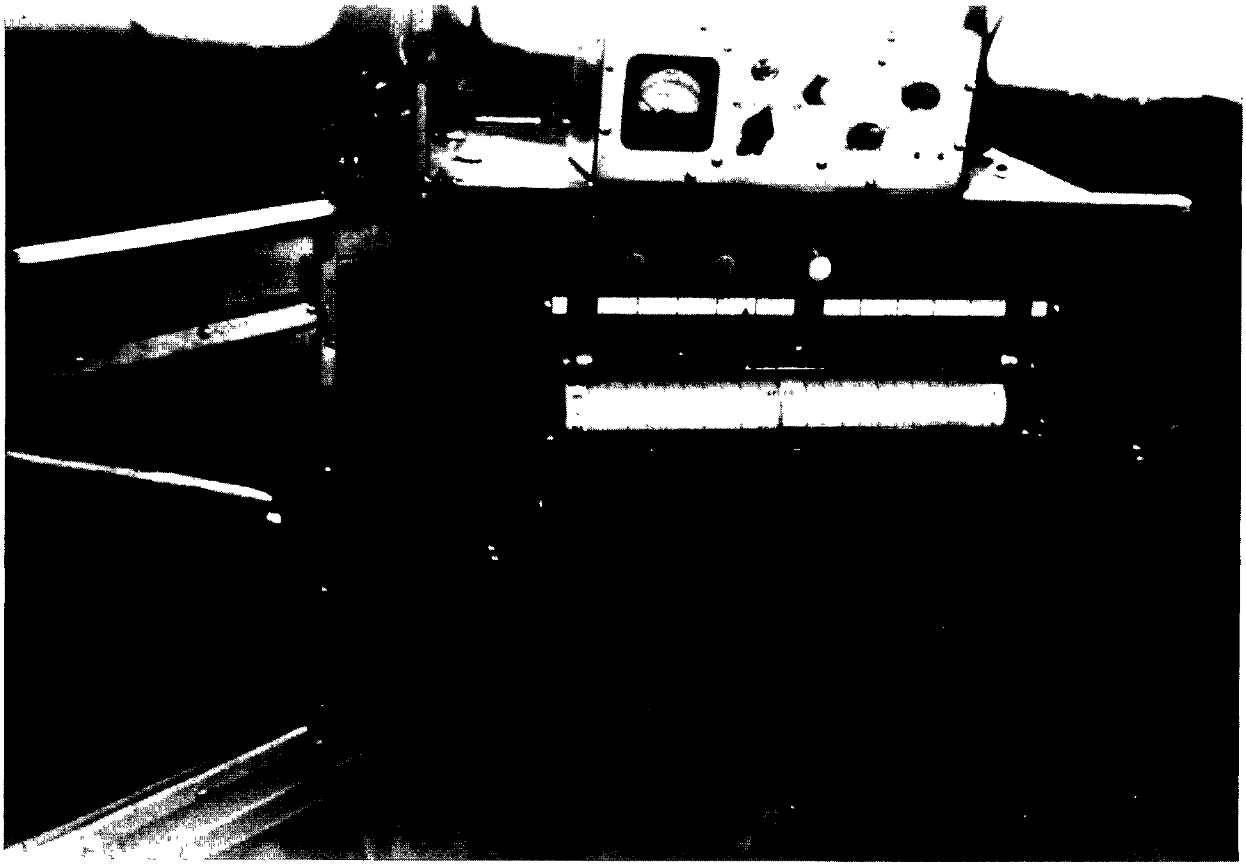


Figure 5.—Recorder and controls on 1946 logger. Single-point-resistance and spontaneous-potential logs were run with controls on the recorder. Gamma panel was added later.

though gathered with different equipment. Repeatability and comparability provide the basis for measuring changes in a ground-water system over time. Changes in the aquifer matrix, such as in porosity, or changes in water quality, such as in salinity or temperature, may be identified. Thus, logs can be used to establish predevelopment characteristics of an aquifer so that future logging can identify changes that may have occurred. Now that computers are being used for log analysis, logs that are digitized at the well site or later in an office can be rapidly corrected, collated, and analyzed. Digitized logs can be transmitted by telephone; a number of comprehensive computer programs are available for interactive analysis of data.

Geophysical logs for most oil wells and for some water wells, in analog or digital format, can be purchased from a number of private companies. Copies of logs can also be obtained from various Federal and State agencies. Logs of old wells are a valuable source of data when studying a new area.

Some geophysical logs measure the properties of a volume of rock many times larger than the core or cuttings that have been extracted from the hole. Some probes record data from rock beyond the rock disturbed by the drilling process. Laboratory analysis of samples provides data from small volumes of rock, whereas logs usually provide continuous data and can be analyzed immediately at the well site to guide completion or testing procedures. Unlike descriptive logs written by a driller or geologist, which are limited by their author's experience and purpose and are subjective, geophysical logs later may provide information on some characteristic not required at the time of logging. Serendipity of this type (from analysis of old well logs) has resulted in discovery of uranium, phosphate, and potash.

Data from geophysical logs are useful in the development of digital models of aquifers and in the design of ground-water supply, recharge, and disposal systems. A log analyst who has the necessary background data on the area being studied can provide usable first approximations of the hydraulic properties needed for these purposes. Stratigraphic correlation is a common use of geophysical logs; logs also permit lateral extrapolation of quantitative data from test or core holes. Using logs, a measured value at a point in a water well can be extrapolated in three dimensions, thereby increasing its value greatly.

Many techniques used in surface geophysics are similar to techniques in borehole geophysics, and the two are considered together when a comprehensive ground-water investigation is planned. Most surface geophysical surveys cannot be uniquely interpreted; geophysical logs, such as acoustic-velocity and resistivity logs, can provide detailed profiles of data that are useful in interpreting surface surveys, such as seismic and resistivity surveys.

Limitations of logging

Geophysical logging cannot replace sampling completely, because some sample data are needed for each study area to aid in log analysis. A log analyst cannot evaluate a suite of logs properly without some information about the local geology. Logs do not have a unique response; for example, gamma-log anomalies from shale are indistinguishable from anomalies from granite. No absolute rules for log interpretation exist. To maximize results from logs, at least one core hole may be drilled in each depositional basin or unique aquifer system. If coring the entire interval of interest is too expensive, intervals for coring and laboratory analysis can be selected on the basis of geophysical logs obtained from a nearby hole. Laboratory analysis of core is essential either for direct calibration of logs or for checking calibration done by other means. Because of the effect of chemical composition of the rock matrix, calibration of logs made in one rock type may not be valid in other rock types. Even subtle changes in the rock matrix can produce large changes in log response.

In spite of the existence of many equations for log interpretation and of charts that provide values such as porosity, log analysis still is affected by many variables that are not completely understood. Most log analysis is guided by empirical rules developed from oil-field data. Such rules may not be applicable to, or may introduce errors when applied to, aquifers. Correct interpretation of logs is based on a thorough understanding of the principles of each technique. For this reason, interpretation of logs in the petroleum industry is done largely by professional log analysts. Because few professional log analysts are working in ground water, and because the cost usually is not justified, interpretation of logs for ground-water applications usually is done by less experienced people, and errors may be more common than in the petroleum industry. In addition, neither the experience nor the scientific literature available for ground-water applications is comparable to that available for petroleum applications.

Although this manual will answer basic questions regarding the application of borehole geophysics to ground-water hydrology and will serve as a reference for experienced analysts, it is not a substitute for on-the-job training and formal courses. Training is needed by equipment operators as well as analysts; the quality of logs made in water wells generally is not comparable to the quality of logs made in oil wells. Standards for log headings (explained in a later section) and log calibration are well established for the petroleum industry but are lacking for ground-water investigations. Even when commercial oil-well-logging services are used, scales and logging speed may not be correct for ground-water applications unless a geologist or hydrologist works with the logging-service personnel and knows what to ask for. Control of the quality of water-well logs has been a major limitation to appropriate application in the past; hence, the subject is discussed in some detail in this manual.

The cost of geophysical logs usually is cited as a reason for their limited use in ground-water investigations. The cost of logging can be decreased markedly by making only those logs that offer the best possibility of providing the answers sought. Further decreases in cost can be achieved by logging only those wells that are located and constructed so as to maximize results from logging, and by using logging equipment no larger and no more sophisticated than the level required by the specific study. In contrast, more money needs to be spent on log analysis. More time may be needed to thoroughly analyze a suite of logs than to make the logs; too often this time is not budgeted when a study is planned.

To be of maximum benefit, a logging program must be well planned. A sequence of steps that will improve the cost-benefit ratio follows:

1. Plan the logging program on the basis of the information needed and the boreholes that will be available.
2. Drill and complete test holes and wells to optimize results from sampling, testing, and logging.
3. Collect representative water and core or cuttings samples at depths where significant changes in water quality or lithology take place, using logs as a guide if possible.
4. Control the quality of logs recorded by complete labeling, calibrating, and standardizing.
5. Interpret logs as a suite, based on a thorough understanding of the principles, while considering all available background data for the area.

Analysis of Logs

The qualitative and quantitative analysis of geophysical logs in the petroleum industry usually is done by specialists called log analysts. Because of the complexity and scope of borehole geophysics, few, if any, of these specialists are knowledgeable about all logging techniques in all geologic environments, and even fewer are knowledgeable about hydrologic applications. In recent years, computer techniques have dominated log analyses; however, this development has not changed the basic requirements for obtaining the most information possible from logs. First, background information about each new geohydrologic environment where logs are to be used is essential. The quantity and kind of background data needed are functions of the objectives of the study. Second, the suite of logs to be made must be based not only on study objectives, but also on knowledge of the synergistic nature of logs. Two logs may provide answers that would not be obtainable from either log analyzed separately, and each additional log may add much more to a total understanding of the system. Third, logs must be selected, made, and analyzed on the basis of a thorough understanding of the principles of each log, even if the final results are generated by a computer.

Most logs obtained for ground-water applications are interpreted by the geologist or hydrologist in charge of the study, because the services of a professional log analyst cannot be justified economically. Only the largest ground-water organizations have professional log analysts on their staffs. The geoscientist expert in the area of study can do an excellent job of log analysis if he or she understands the basic principles of the logs used. One of the purposes of this manual is to provide some of the necessary information to permit nonexperts to use borehole geophysics effectively.

Qualitative log analysis

The first uses of logs were for identification and lateral correlation of rock and fluid types and for selection of likely producing intervals for well completion; these uses are still vital today in both ground-water and petroleum studies. Qualitative log analysis is based mostly on knowledge of local geology and hydrology, rather than on log-response charts or computer plots. Examination of outcrops, core, and cuttings, coupled with an understanding of log response, will permit identification and correlation of known aquifers and confining beds. Where the aquifers have not been identified previously, various kinds of flow logs, obtained under pumping or injection conditions, will assist in locating and characterizing the aquifers and confining beds. Even for qualitative log analysis, hole conditions must be known, because they can alter log response markedly. Qualitative log analysis is usually an early step in quantitative analysis; matrix parameters must be understood before proceeding with quantitative analysis.

Because geophysical logs do not have unique responses, lithologic interpretation of logs must be checked against data from other sources. This also is true of stratigraphic correlation, because gross errors can be made by just "matching the wiggles." Even within one depositional basin, the response of one type of log may shift, because of lateral facies changes. For example, the feldspar content of a sandstone may increase toward a granitic source area, and this probably would cause an increase in the radioactivity measured by gamma logs. This measurement might be interpreted mistakenly as an increase in clay content, unless other logs or data were available. For this reason, the synergism of composite-log interpretation is stressed in this manual. Logs are interpreted as an assemblage of data, not singly, to increase the accuracy of analysis. Stratigraphic correlation, using acoustic-televiewer, caliper, gamma, neutron, and gamma-gamma logs, is shown in figure 6. The two drill holes are located 1,175 ft apart in Illinois; they penetrate dolomite of the Silurian Niagaran Series. The correlation of individual beds and intervals of solution between the two boreholes is apparent, even though the logs were not recorded at the same horizontal scale or gain. Correlation by matching log character can be done without understanding the response to lithology, but this approach also can lead to erroneous results. In figure 6, anomalies on the caliper logs represent solution openings, probably along bedding planes because one interval correlates between the boreholes. The excellent correlation on the gamma logs probably is due to shaly units that are more radioactive than dolomite. Changes in responses on the neutron and gamma-gamma logs probably represent dolomitic beds of different porosity that are relatively consistent in the area of these drill holes.

The effectiveness of qualitative interpretation usually improves with an increase in the number of wells that are logged in an area and in the quantity of core data that is available. A gradual change in log response across a depositional basin may indicate a facies change. One anomalous log caused by unusual hole conditions may be identifiable when compared with a number of logs that show consistent responses; such errors are not likely to repeat. Continuous core, or a large number of core samples from one test hole, is more useful than a few nonrepresentative samples from throughout the section. If continuous coring of one hole cannot be funded, then logs of a nearby hole can be used to select representative intervals for coring. This subject is discussed in more detail in the section on log calibration. Although an increase in the

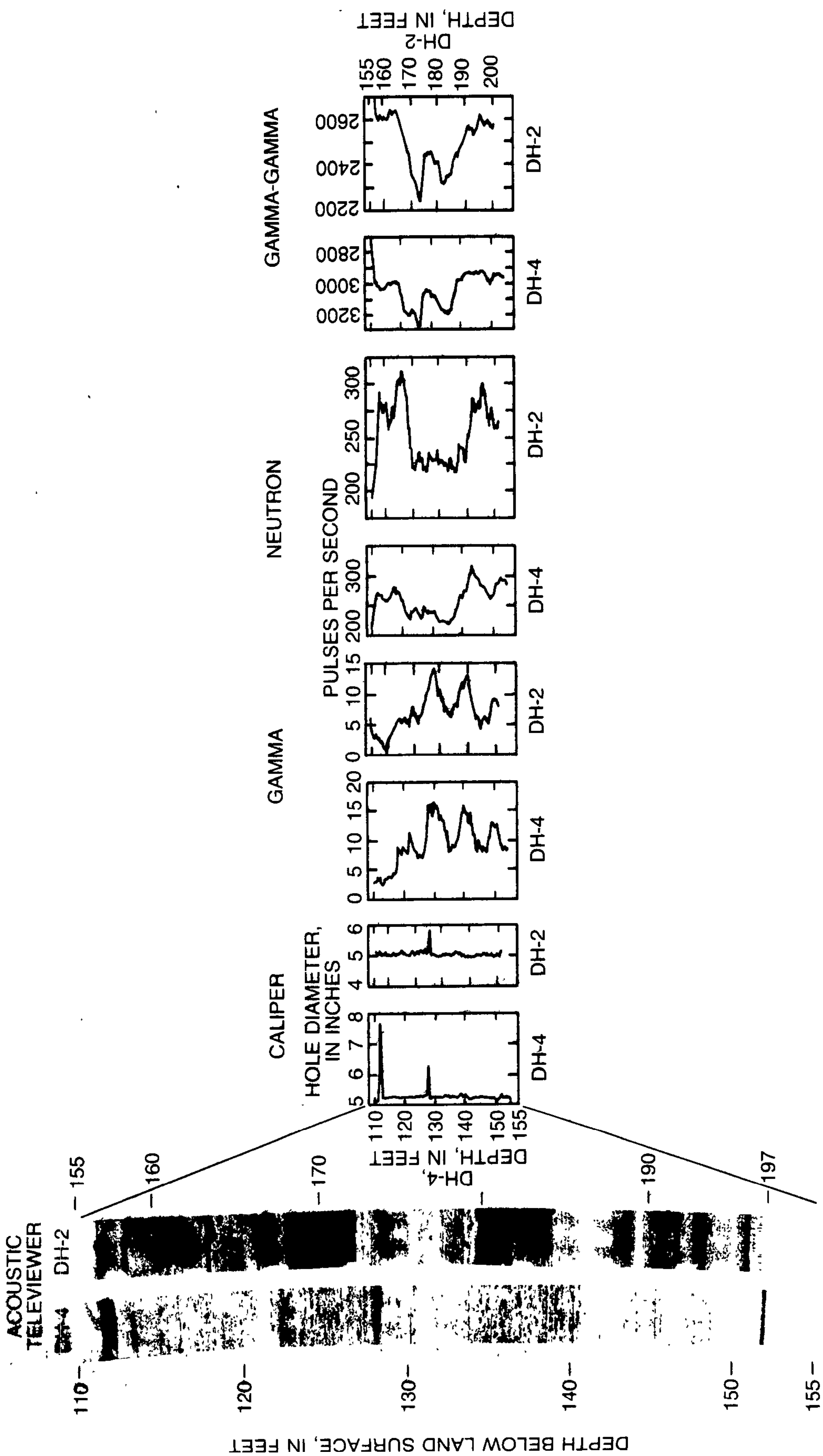


Figure 6.—Correlation of lithologic units between two drill holes, based on acoustic-televiewer, caliper, gamma, neutron, and gamma-gamma logs, Cook County, Ill. (modified from Nicholas and Healy, 1988).

number of different types of logs run may improve the accuracy of interpretation and the variety of results, the logs should be selected carefully. Too often logs are run that are not appropriate for the environment or for the information desired.

Quantitative log analysis

Obtaining quantitative data on aquifer or water characteristics is an important objective of many ground-water logging programs; however, the steps that will ensure reasonable accuracy of the data often are not followed. For example, the scales on logs in environmental units, such as percent porosity or bulk density, in grams per cubic centimeter, must be checked. Further, even if the procedures described in the sections on log calibration and standardization are followed carefully, corroborating data for the particular rocks and wells logged are needed. Repeatability can be checked by logging selected depth intervals a second time; equipment drift is indicated by changes in response as a function of time or temperature. Because of the matrix effect, calibration for one rock type may not ensure accurate scales for another rock type. For this reason, if the rocks being logged are not the same as those in which the equipment was calibrated, core analyses are needed to check values on the logs. Before any log data are used quantitatively, they must be checked for extraneous effects, such as borehole diameter or bed thickness. Data are of questionable value if they were obtained from depth intervals where borehole diameter is considerably greater than bit size, or from intervals where bed thickness is equal to, or less than, the vertical dimension of the volume of investigation for the probe.

Both vertical and horizontal scales on logs should be selected on the basis of requirements for resolution and accuracy of the data to be obtained. Most commercial logs are recorded on a vertical scale of 20 or 50 ft/in; this scale is not adequate for the detail required in many ground-water studies, in which the wells may be only a few hundred feet deep. Similarly, the horizontal scales on many commercial-service-company logs are compressed, to avoid off-scale deflections; some logs also may be run too fast for the accuracy required. These factors are discussed in the section on quality control of logs.

Few logs measure the quantity shown on the horizontal scale directly; for example, the neutron log does not measure porosity, but responds chiefly to hydrogen content. The difference between porosity and hydrogen content can lead to a large porosity error where bound water or hydrocarbons are present. Thus, knowledge of the principles of log-measuring systems is necessary for accurate quantitative analysis of logs.

Synergistic log analysis

Multiple-log analysis takes advantage of the synergistic nature of many logs; usually much more can be learned from a suite of logs than from several logs analyzed individually. For example, gypsum can be distinguished from anhydrite by interpretation of gamma and neutron logs together. Both rocks contain small concentrations of radioactive elements, so a gamma log indicates minimal radioactivity for both rocks. However, gypsum contains substantial water of crystallization, so it appears relatively porous on a neutron log. In contrast, anhydrite contains little, if any, water of crystallization, so it appears relatively nonporous on a neutron log. Both minerals will be logged as high resistivity. This response, as well as typical responses of a suite of logs in a section of sedimentary rocks, is shown in figure 7.

The logs in figure 7 are hypothetical; it is difficult to find a complete suite of logs from one well that includes the diverse lithologic section shown. The log responses shown are typical for the rock types represented, but they do not represent unique signatures for those rock types. For example, coal and limestone are shown on the gamma log as having little radioactivity, although in some areas lignite and limestone are uraniferous and, therefore, are quite radioactive. Coal and limestone that lack solution openings can be distinguished by neutron and resistivity logs, which have similar responses in most rock types. Although both rock types have a relatively high resistivity, coal is logged on neutron logs as having relatively high porosity (negative deflection) because of its hydrocarbon content. Thus, neutron and resistivity logs usually show reversed responses in coal beds. Note that the caliper and single-point-resistance logs indicate the reason for the cycle skips on the acoustic-velocity log—solution openings and fractures. Extraneous effects, such as the major shift in the single-point-resistance log caused by a change in fluid salinity in the rocks, and reversals in response of the long normal-resistivity log caused by bed-thickness effects, are shown in figure 7. It is assumed that the fluid in the lower part of the borehole is saline; this salinity causes the spontaneous-potential log to be featureless and decreases response of the resistance and resistivity logs in this part of the borehole. Portions of this figure are included and described in more detail in the sections on specific types of logs. The hypothetical responses of these logs to a wide range of lithologies may be typical of one depositional basin but not of another. Log response must be learned for each new study area, where it usually becomes a recognizable signature.

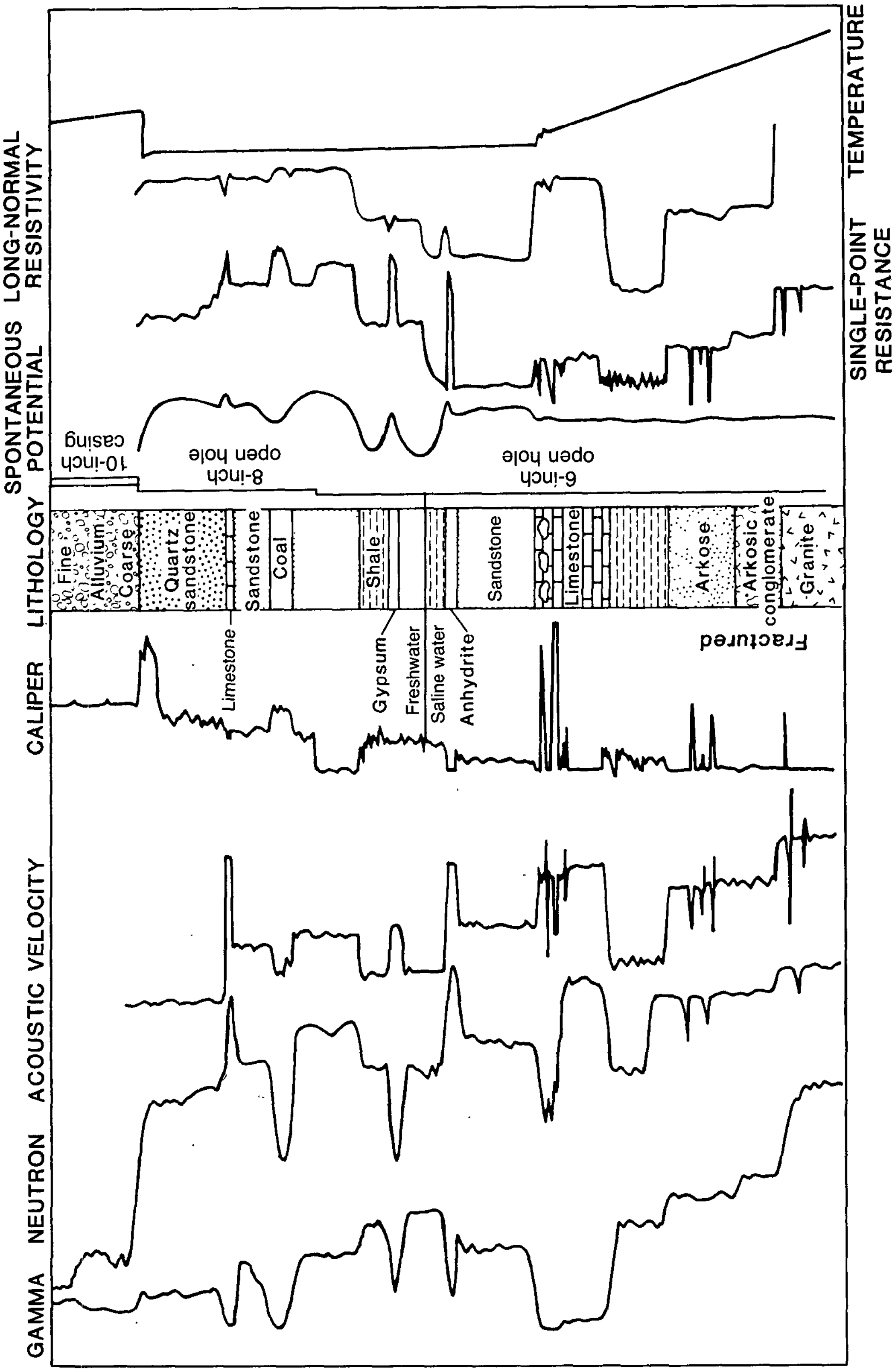


Figure 7.—Typical responses of a suite of hypothetical geophysical well logs to a sequence of sedimentary rocks. The measurement units for all logs except the neutron and acoustic velocity increase to the right.

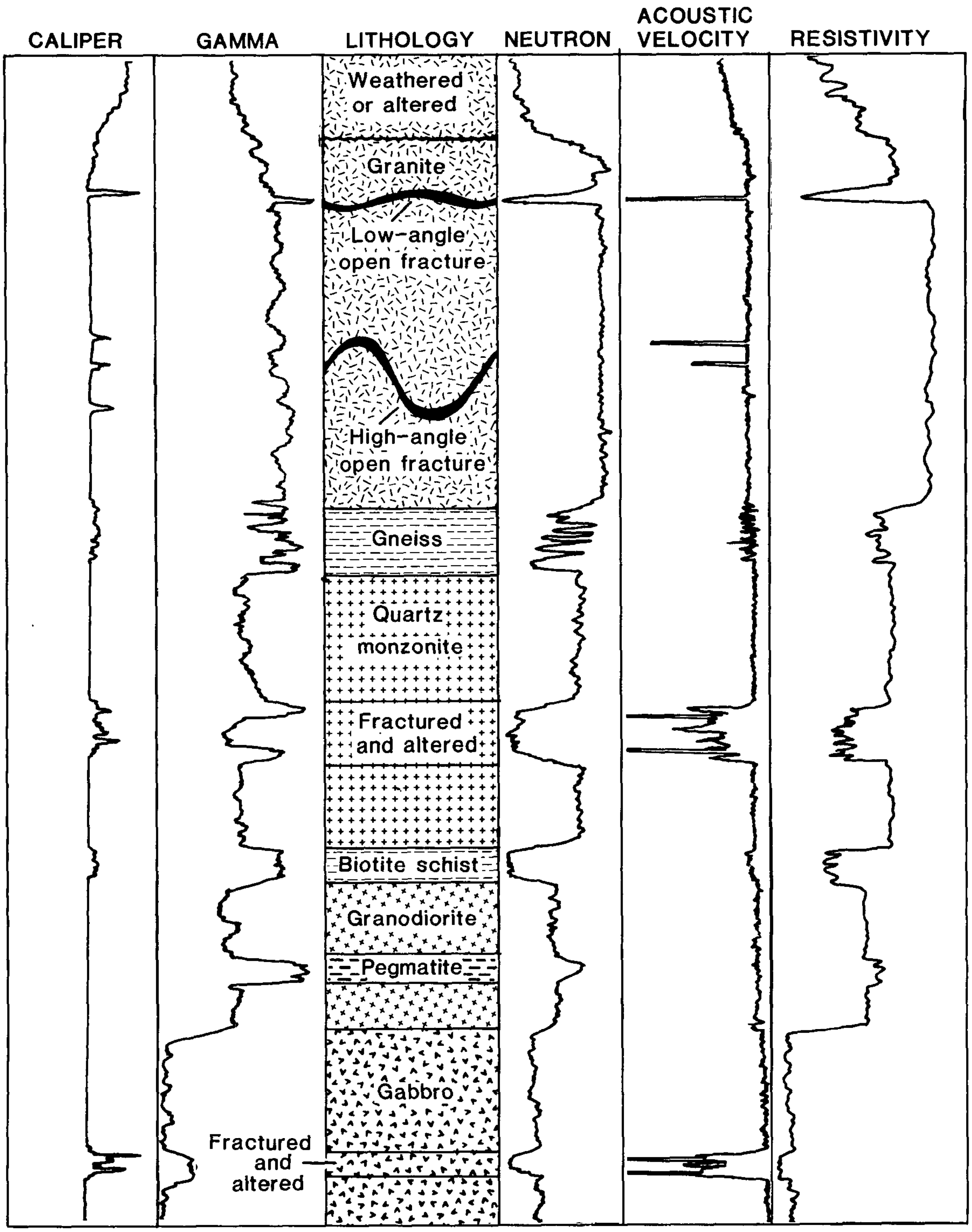


Figure 8.—Typical responses of hypothetical caliper, gamma, neutron, acoustic-velocity, and resistivity logs to various altered and fractured crystalline rocks. Porosity increases to the left on the neutron and acoustic-velocity logs; scales increase to the right on the other logs.

The typical responses of some logs to various types of altered and fractured igneous and metamorphic rocks are shown in figure 8. Data on log response in crystalline rocks have been few until the recent expansion of exploration for geothermal energy and for potential repositories for radioactive waste. The logs in figure 8 reflect a summary of some of the experience gained in those programs by the U.S. Geological

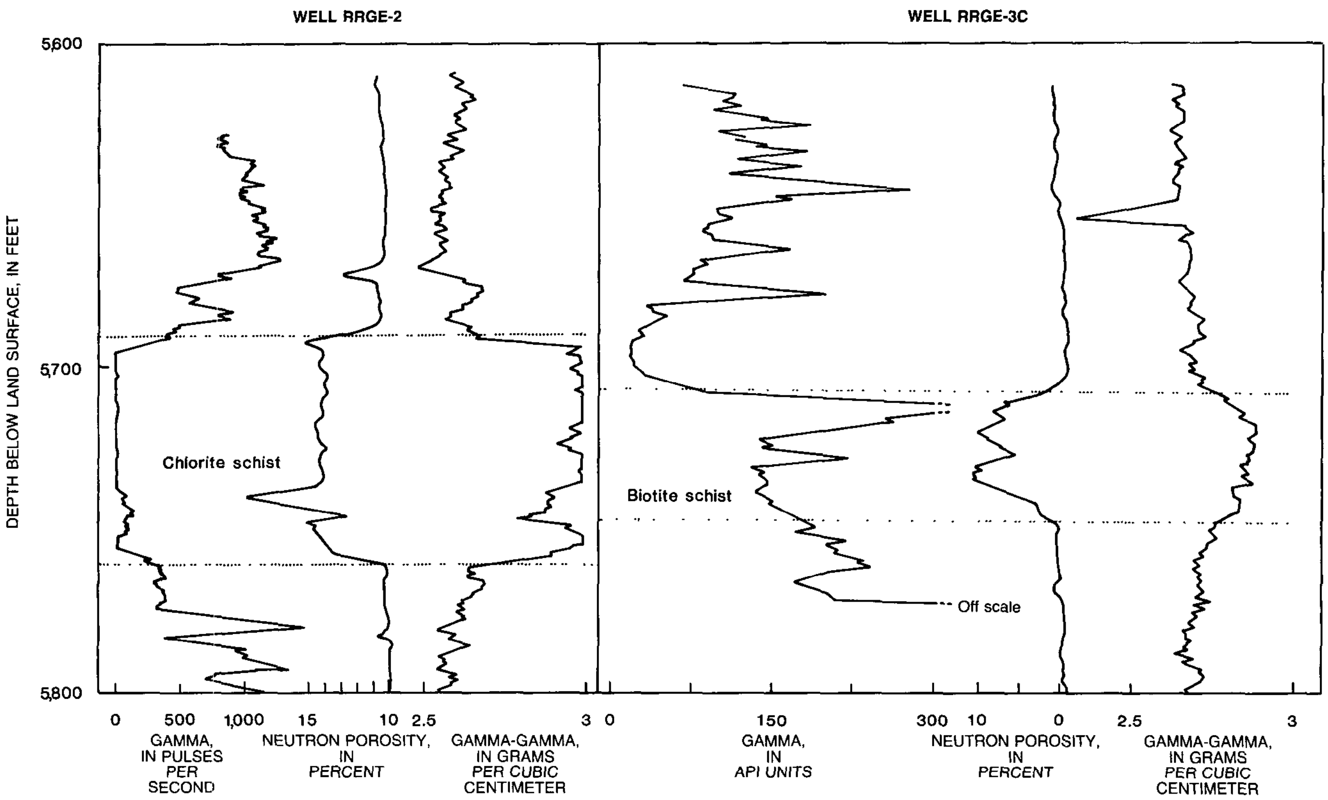


Figure 9.—Gamma, neutron, and gamma-gamma logs for two wells in the Raft River geothermal reservoir, Idaho.

Survey. Synergistic log analysis is just as useful in crystalline rocks as in sedimentary rocks. An example of the use of gamma, neutron, and gamma-gamma logs to distinguish chlorite schist from biotite schist in the Raft River geothermal reservoir, Idaho, is shown in figure 9. The schists are marked by an anomalously large porosity, based on the neutron logs, and by a marked increase in density, based on the gamma-gamma logs. This difference is caused by the large content of bound water or water of crystallization in the mica minerals. Radioactivity of the chlorite schist was decreased substantially during the process of hydrothermal alteration from biotite. Leaching of potassium, and possibly of uranium, during alteration caused the decrease in radioactivity, which allowed the two types of schist to be distinguished by use of gamma logs.

The technique of studying the different types of logs as a group, rather than one at a time, is an important one to develop. For this purpose, the logs for one well are placed side by side after the appropriate corrections for depth errors have been made. Locating logs that show similar responses, such as neutron and resistivity, side by side makes depth errors and differences in response easier to identify. Plotting any core data or lithologic descriptions on the same vertical scale as the logs is helpful, but these data usually will require vertical displacement with respect to the logs because the depth datum may be different by as much as 20 ft. A few correlation lines drawn across a suite of logs at major anomalies also are helpful.

Examining a suite of logs from a few feet away is good practice. From that distance, detail becomes less important, and significant trends and shifts in response become more obvious. Replotting logs at different vertical or horizontal scales, using a computer, may bring out features not previously obvious. A suite of logs should be examined for similarities and differences, and explanations should be sought for a log response that departs from that anticipated on the basis of available background data. When searching for explanations for anomalous log response, one should first examine the caliper log to determine if borehole-diameter increase is a reason. Well-construction information also may explain an anomalous response, as may information on the mineral or chemical composition of the rock. The results of synergistic log analysis depend on the information available from other sources and on a complete understanding of what the various logs respond to.

Computer analysis of logs

During the last few years, computer analysis of geophysical well logs has become widely used in the petroleum industry, but it is seldom applied in ground-water hydrology. If done properly, computer analysis of logs can provide many additional data for ground-water studies. The large quantity of data represented by a suite of well logs cannot easily be collated or condensed in the human mind so that all interrelations can be isolated and used. Computer analysis makes this possible. All major commercial well-logging service companies offer digitized logs and computer interpretation; some offer real-time interpretation at the well site. Several programs are available for purchase that will run on minicomputers and microcomputers having sufficient memory, data storage, and graphics capability. Numerous log-analysis programs also have been written for programmable pocket calculators. In addition to the logging-service companies, several other companies will process logs with their computer-analysis packages. Logs that have not been digitized onsite can be sent out for commercial digitizing. Computer-analysis programs have been developed in Government agencies such as the U.S. Geological Survey (Merkel and others, 1976; Scott, 1977).

Recent improvements in and decreases in the cost of microcomputers and personal computers make them suitable for log analysis and economically justified for ground-water applications (Keys, 1986). Geophysical logs can be transmitted by telephone from a logging truck or another computer to a personal computer equipped with a modem, and can be analyzed and plotted using a spreadsheet program. Although the spreadsheet was not designed for log analysis, a few hours with the program manual and computer will allow someone who understands logs to manipulate the data and plot results similar to those available from commercial organizations at a fraction of the cost.

Computer analysis of logs offers a number of advantages compared with other methods used in the past: (1) a large mass of data can be collated and displayed; (2) logs can be corrected and replotted; (3) scales can be changed; (4) smoothing and filtering operations can be conducted; (5) cross plots can be made between different kinds of logs, and between logs and core data; and (6) calibration curves, correlation functions, and ratios, as well as cross-section and thickness maps, can be plotted. Finally, these results can be plotted as publication-quality figures at a cost less than that required for professional drafting. Although all of these manipulations can be done manually, the large quantity of data available from a suite of logs, or from the logs of all wells penetrating an aquifer system, is ideally suited for computer analysis.

The disadvantages of computer analysis are several. First, the cost may be excessive, particularly for a small quantity of data. Further, the complexity of the approach may lead to overestimation of the value of the answers it provides. This is particularly dangerous because most of the algorithms developed commercially for log analysis are for petroleum applications and may require modification for ground-water applications. An understanding of log analysis is necessary before computer interpretation is attempted. Finally, the computer-plotted data are no better than the original log data; if the logs are improperly recorded or calibrated, the computer output may be useless until corrections are made.

Digitizing logs

Geophysical logs may be digitized at the well site while they are being recorded in analog format, or subsequently from the analog record. Onsite digitizing is more accurate and less expensive; with computers now on some logging trucks, the data can be processed in real time. Onsite digitizing also provides backup for recovery of data that are lost on the analog recorder because of incorrect selection of scales. Off-scale deflections lost from the analog recorder will be available from the digital record, if it is made correctly. Some systems permit immediate playback of the digital record to the analog recorder with adjustment of both horizontal and vertical scales. The equipment for onsite digitizing is described in more detail in the section on logging equipment. In most systems, the signal from a logging probe is transmitted simultaneously to an analog recorder and through either an analog-to-digital converter or a digital ratemeter to a magnetic-tape recorder or to a disk. Sample interval and sample time must be correctly selected for onsite digitizing of logs. Digital sample time is important to the proper recording of all nuclear logs; it is discussed in the section on nuclear logging.

The digital data may be printed or plotted while the log is being run, but the analog record also is needed because watching a log develop on a chart-type recorder is one of the best ways to avoid major errors in logging and to optimize probe and data configuration. The analog record may show more detail than the digital record because of sample interval or the elimination of the step function present in many plots of digital data. Information on the digital record always is listed in the log heading of the analog chart. This information includes the label on the recording medium, file number, sample interval and time, depth interval recorded, and any calibration information pertinent to the digital record.

Although office digitizing of analog records is expensive and time consuming, no other choice may exist for old logs. Desk-top curve-following digitizers probably are available in most offices that have a computer. Because of the training needed to digitize logs, particularly multicurve commercial logs, correctly, better and less expensive results usually are obtained from a company that specializes in digitizing geophysical logs. Such companies are located in major oil-exploration centers. When logs are digitized commercially, certain specifications or instructions must be provided to the company along with the purchase order, such as recording medium, format and bits per inch, sample interval, depth shifts, editing required, and plots of the data that can be used to check accuracy of digitizing.

Correcting and calibrating logs

The computer is ideally suited for correcting logs and plotting them with calibrated scales. Depth correction is required on most logs, and it can be done at the same time the computer is being used to make the first plot of digitized data. Most depth errors are the result of operator error or use of a different depth reference at different times; however, other errors resulting from a stretched cable or a sticking probe, and errors in the cable measuring system, also occur. The most common correction needed is a consistent depth shift for the entire log to make it correlate with other logs of the same well or with core data. A technique for computer correlation of log and core data has been described by Jeffries (1966). Sometimes the logs in a suite require some shifting to agree with a preselected datum. If depth errors vary as a function of depth because of cable stretch, these errors can be corrected using the equation for the particular cable used. Sudden changes in depth may occur randomly in the log because of a sticking probe or because of changes in the depth reading, which are made manually by the operator when a magnetic cable marker is detected. These types of errors are best avoided, but should be noted on the log when they occur. Different corrections for specific depth intervals will produce either overlap or missing data sections that will require editing.

Data from probe calibration can be used to convert a log to the appropriate environmental units. For example, most neutron logs are recorded in pulses per second, which can be converted to porosity if necessary calibration and standardization data are available. It is better to record unprocessed log data, such as pulses per second, and calibration data for later conversion to environmental units, such as porosity, because it is easier to correct unprocessed data for errors.

Changing the vertical and horizontal scales of logs independently was almost impossible before computer processing became available; now replotting to produce scales best suited for the intended purpose is a simple matter. Correcting for nonlinear response and changing from a linear to a logarithmic scale also are relatively simple procedures. Most probes produce a pulse frequency or a voltage that can be related to the desired rock or fluid property by an equation. For example, many of the temperature probes used by the U.S. Geological Survey use a thermistor, which is stable and responds rapidly but is nonlinear. After careful calibration across the temperature range of use, the response equation for each probe can be calculated to replot the temperature log. The original field prints of logs, both analog and digital, have scales in pulses per second and are nonlinear with respect to temperature. The final computer plot will have a linear scale in temperature. Logs also can be plotted at several different scales to keep the full data range on the paper and, at the same time, to resolve small but significant changes.

Plotting data from logs

Probably the most important technique available for log analysis today (1985) is the computer plotting of data obtained from logs against data from other logs, core analyses, or tests. The most frequently used technique is cross plotting, which compares the response of two different logs. An idealized cross plot of log A versus log B in a three-mineral-component system is given in figure 10 (MacCary, 1978). If log A

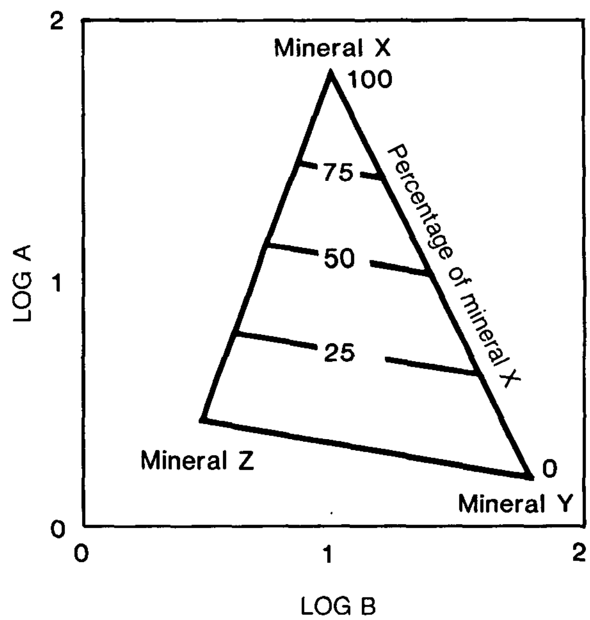


Figure 10.—Format of cross plot of two logs with three mineral matrices (modified from MacCary, 1978).

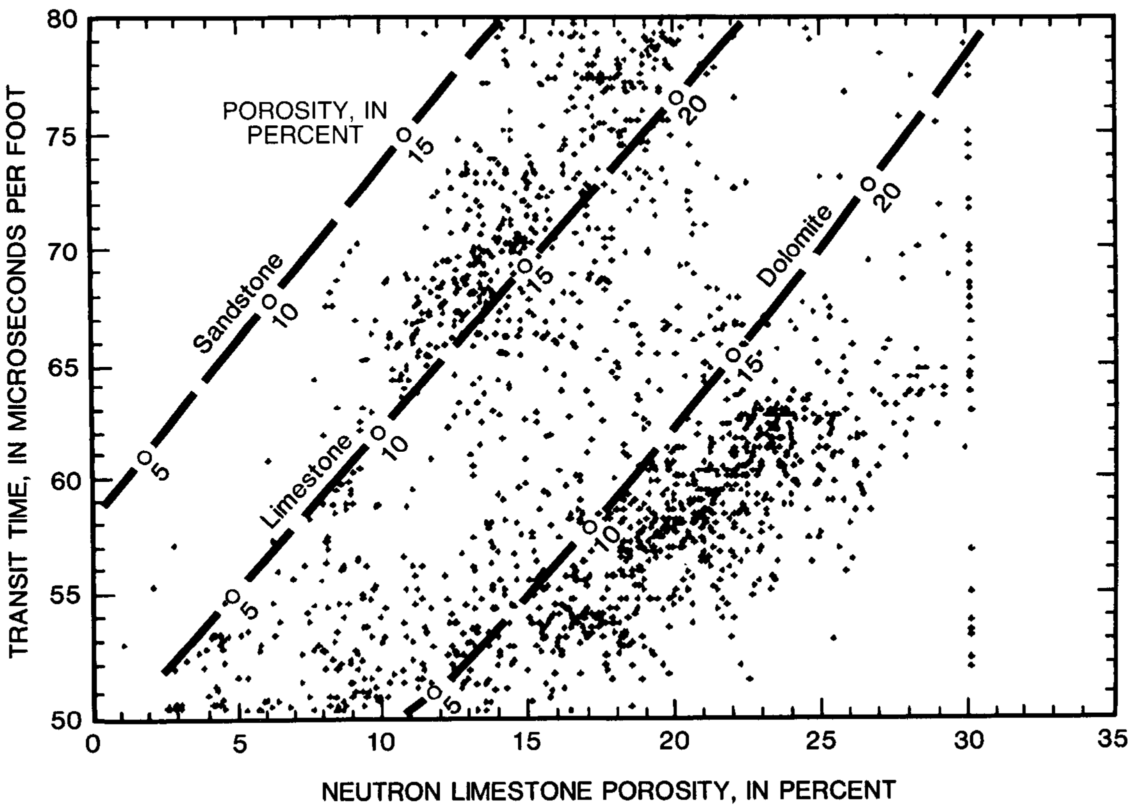


Figure 11.—Acoustic transit time versus neutron porosity, Madison Limestone test well 1, Wyoming.

and log B have inverse responses to minerals X and Y, a plot of A versus B will yield the line from 100 percent of mineral X to 100 percent of mineral Y. The percentage of the two minerals can be measured along a linear scale from X to Y. If a third mineral is added, as in figure 10, the relative content of the three minerals can be determined uniquely from the cross plot. If a fourth mineral is added, the solution is indeterminate, unless a third kind of log is added. Usually more than three minerals are present, even if only in trace quantities, so some scatter of data points will be produced. For a more complete description of cross plots, see MacCary (1978).

A cross plot of transit time from an acoustic-velocity log versus porosity from a neutron log, calibrated for limestone, is given in figure 11. The data were plotted from digitized commercial logs of Madison Limestone test well 1 (named for the Mississippian Madison Limestone) drilled by the U.S. Geological Survey in Wyoming. The calibration lines labeled sandstone, limestone, and dolomite were obtained from a plot in a book of log-interpretation charts provided by the company that did the logging for the survey. Such chart books are available at no charge from all major commercial well-logging service companies. The appropriate chart for the specific probes used to make the logs must be selected. When the cross plot is entered with the values from corresponding depths for the acoustic-velocity and neutron logs, the approximate lithology and the porosity corrected for matrix or mineral response can be read. Obviously, the logs must be depth corrected to the same datum before such plots can be made. Similar porosity values on the calibration lines for the three rocks may be connected with lines to facilitate interpolating porosities. The line of data points at 30-percent neutron porosity indicates that the log was limiting at this value, and that some porosity values probably are greater than 30 percent, although they may be caused by solution openings. These two logs indicate that two major rock types are in the interval plotted: limestone and dolomite. The group of points to the right of the dolomite line indicates secondary porosity in the dolomite. Unfortunately, all petroleum-oriented interpretation charts are based on only the three rock types shown, with the occasional addition of anhydrite.

A plot of bulk density from a gamma-gamma log versus a neutron log for the same well is given in figure 12. The plot clearly shows that the neutron log was artificially limited at 30-percent neutron porosity. Commercial logs commonly are limited at this value.

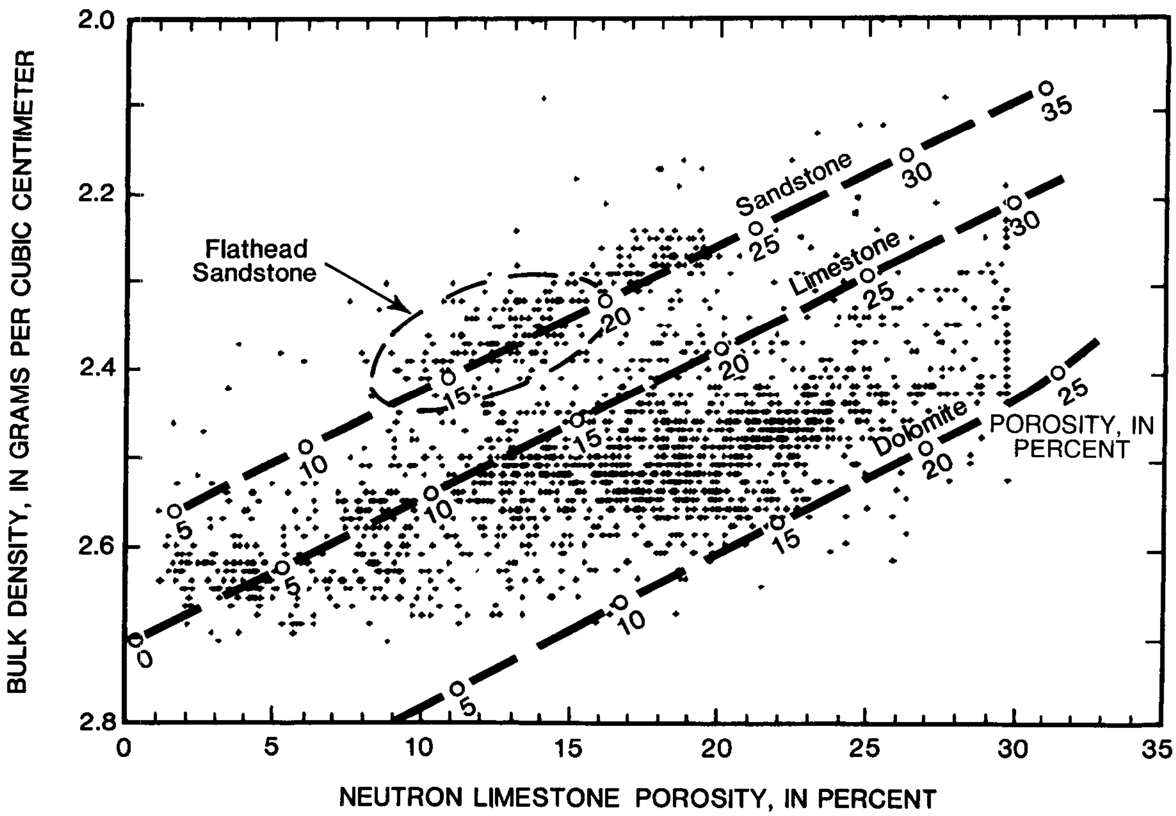


Figure 12.—Bulk density versus neutron porosity, Madison Limestone test well 1, Wyoming. The line of data points at 30-percent neutron porosity shows that the log was artificially limited at this value.

The plot also indicates that most of the rocks penetrated are limestone or dolomite; however, the presence of some sandstone is indicated. While the plot in figure 12 was being made, the group of points circled along the sandstone line were noted to occur within a continuous depth interval. A check of the lithologic log indicated that the Cambrian Flathead Sandstone was clearly defined on the cross plot.

Another kind of cross plot that can be made using a computer is illustrated in figure 13. The figure, modified from Head and Merkel (1977), shows a third log variable for an interval in the upper part of the Pennsylvanian and Permian Minnelusa Formation. The third variable plotted on the Z axis is a weighted function, from 1 to 10, of the gamma-log response. The presence of shale is indicated by Z-axis values greater than 8. The authors of the paper selected a shale-matrix point by examining trends in the third-variable plots. Matrix response for a log is the value for a pure matrix lithology at zero porosity. For example, in figure 13 the sandstone line intersects the 0-percent apparent neutron porosity line at 2.63 g/cm^3, which is similar to the grain density of quartz. Shale is not a pure matrix mineral and does not record a zero porosity.

Frequency plots appear similar to figure 13, but numerical values in the plot represent the frequency of occurrence of a pair of values from two logs rather than values from a third log. Where points are very numerous and overlapping, a frequency plot is easier to evaluate than a standard cross plot. The frequency of occurrence of values for each of the logs may be plotted along the axes.

Frequency-distribution plots or histograms are useful indications of the number of major rock types that are present, based on the response of a single log. They also may indicate abnormal log response by abrupt termination of data along either axis. A histogram of gamma-log response for a deep well near Raleigh, N.C., is shown in figure 14. The bimodal distribution probably indicates sandstone and conglomerate at count rates less than 1,500 p/s and clay or mudstone at count rates greater than 1,800 p/s. A histogram like this might indicate the cumulative thicknesses of rock types and whether contacts are distinct or gradational. This type of histogram has been used to calibrate old or incorrectly calibrated logs within a single formation and a limited area.

An example of the kind of final product that might result from the computer analysis of logs is given in

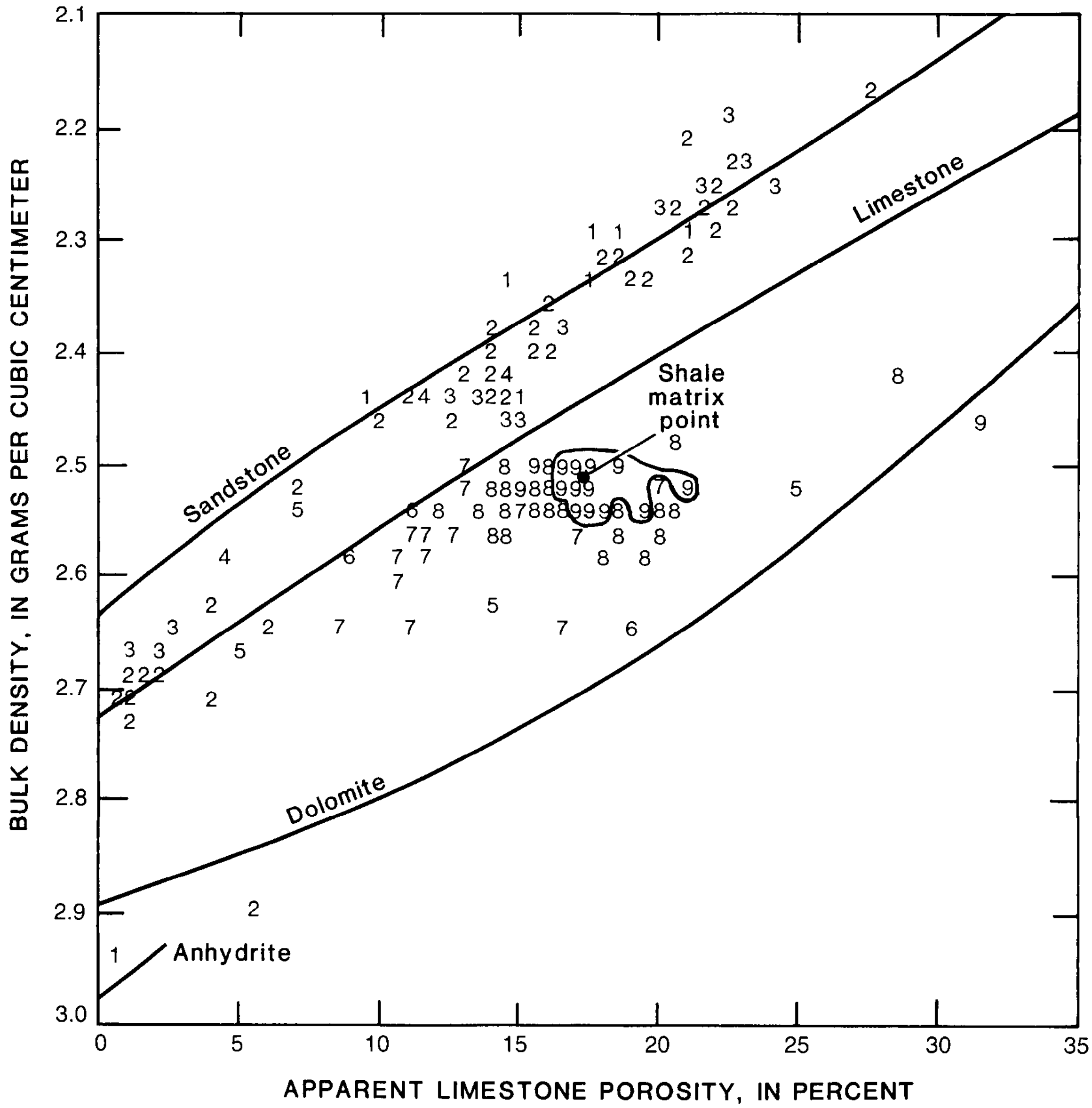


Figure 13.—Z-axis plot of gamma-log response versus gamma-gamma-log and neutron-log responses for the upper part of the Minnelusa Formation (modified from Head and Merkel, 1977). Numbers (1–9) represent a weighted function of the gamma-log response; values of 9 indicate the presence of shale.

figure 15. The plot is based on well logs of the Cretaceous Edwards Limestone near San Antonio, Tex.; the program was developed by Merkel and others (1976) of the U.S. Geological Survey. Porosity, dolomite, limestone, and sandstone as percentages of total rock mass are shown in figure 15. Bulk density, matrix density, and secondary porosity also are shown. The Edwards Limestone is most permeable in intervals that have the largest secondary porosity. Merkel and others (1976) also computed logs of thermal conductivity, heat flow, permeability, and apparent water resistivity. They used a linear-programming algorithm that allowed the analyst to weight the log data according to probable data quality, determined by examining logs and from cross plots. Many core analyses were available to calibrate the logs and to validate the final results.

Several computer programs for analysis of geophysical logs are available commercially, in addition to those used by the service companies for their own logs. These programs generally were written for petroleum-oriented applications, but some may be useful in ground-water hydrology. In any event, if computer-log analysis is used without knowing the basis for the algorithms, errors may result. The logs should be analyzed by a local hydrologist, on the basis

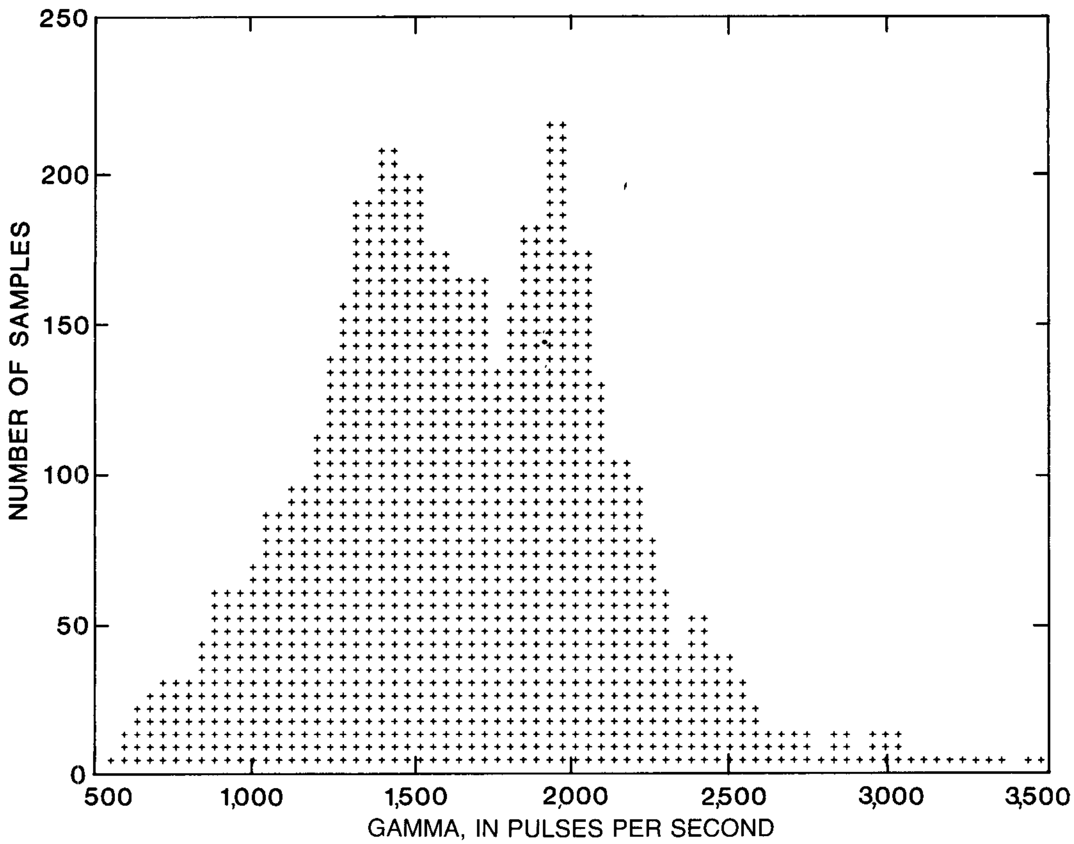


Figure 14.—Histogram of gamma-log response for a deep well near Raleigh, N.C.

of as complete knowledge of the study area as possible, rather than relying on "canned" computer analyses available from logging companies.

The validity of computer analyses must be evaluated in each geohydrologic environment. Many of the programs are limited because they are restricted to three rock types: limestone, dolomite, and sandstone. A correction for shale may be added by using gamma logs; igneous and metamorphic rocks are not considered. Water-saturation problems are a major part of commercial software packages for log analysis because of the importance of saturation in oil recovery. Almost all ground-water applications would involve sediments that are considered to be 100 percent saturated. Some companies use the term "index" when plotting such computer-calculated values as permeability and porosity. The term is used as a qualifier to indicate that neither true permeability nor porosity is being plotted. The log-interpretation equations used in computer analyses are mostly empirical, specific to the rocks commonly present in oil fields, and may not be applicable to a ground-water environment.

Petrophysics and Log Response

The responses of geophysical well logs are affected by several important factors: the rock matrix, the interstitial fluids, the borehole temperature, the construction of the well, and the fluids in the well. For most applications, responses to the first two factors are desired but generally are inseparable; the response resulting from the construction of the well usually is an extraneous or undesired response. Aspects of petrophysics that are most important in understanding log response are (1) the chemical composition of the rock or sediment, (2) the shape and size distribution of the grains or crystals, (3) the size, shape, continuity, and filling of the pore spaces, and (4) primary or secondary structures such as bedding and fractures. Well logging for physical properties has been discussed in much greater detail by Hearst and Nelson (1985).

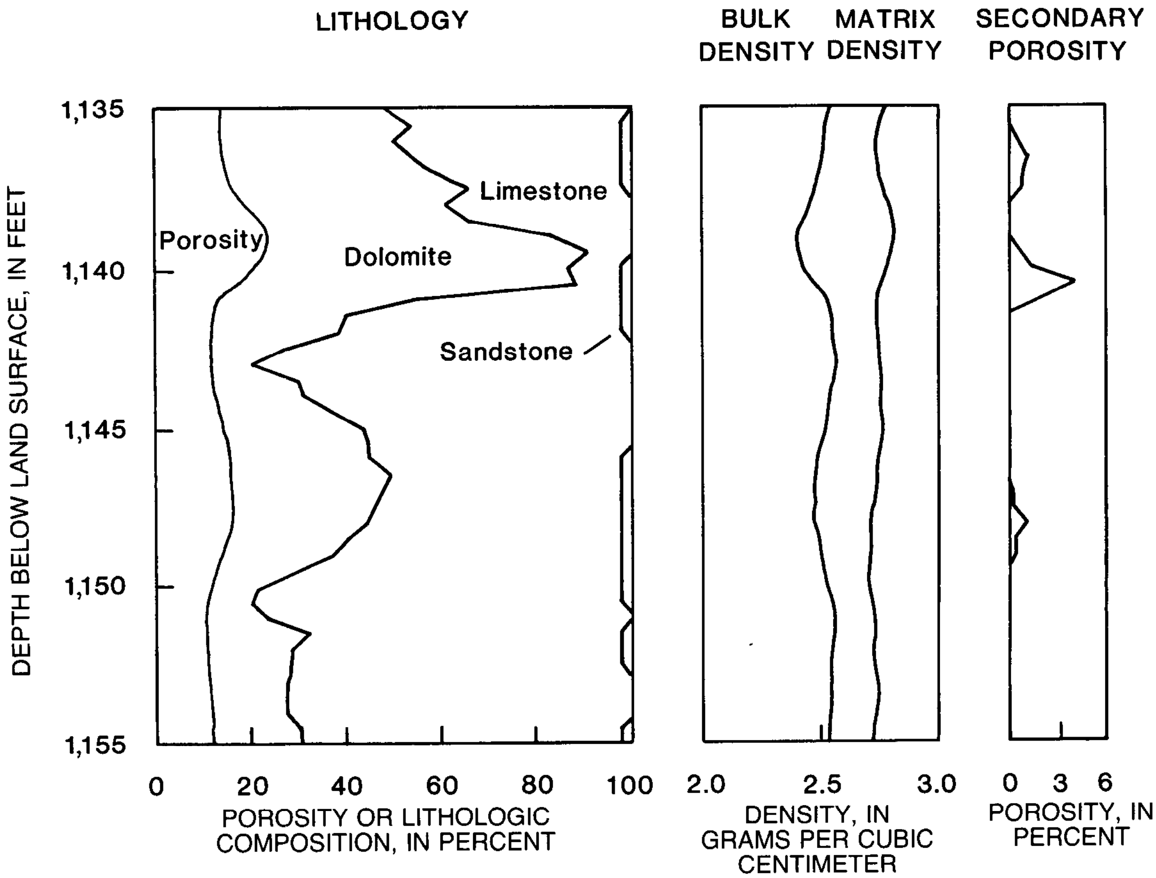


Figure 15.—Computer plots showing lithology, bulk density, matrix density, and secondary porosity based on geophysical logs of the Edwards Limestone near San Antonio, Tex. (from Merkel and others, 1976).

Mineral composition

The chemical composition of either crystals or detrital grains in a rock matrix or unconsolidated sediment has a substantial effect on the responses of nuclear and electric logs. Calibration of neutron and gamma-gamma logs should be done in pits or core holes where the chemical composition of the rock matrix is similar to that expected to be present during logging. Flow of most of the electric current that produces resistivity logs is through fluid-filled pore spaces rather than through rock matrix; however, electrically conductive minerals may have extraneous effects on the relation of current flow to porosity.

Because variations in mineralogy or chemical composition affect log response, semiquantitative laboratory analysis of selected core samples in a new study area is needed. When the minerals present are known, most standard texts on mineralogy can provide information on chemical composition and density. The "Handbook of Chemistry and Physics" (Weast and Astle, 1981) is useful for obtaining this type of information and some data on resistivity and nuclear characteristics. The physical, chemical, and nuclear characteristics of major rock-forming minerals that may affect log analysis are discussed in some handbooks on formation evaluation and books of log-interpretation charts available from major commercial logging-service companies. Addresses of these companies can be found in issues of the "Log Analyst," published by the Society of Professional Well Log Analysts, Houston, Tex.

Porosity

The porosity of rocks affects the response of many geophysical logs; neutron, gamma-gamma, and acoustic-velocity logs commonly are incorrectly called porosity logs. The various electric logs also respond to porosity. Different types of logs respond to total, effective, and primary or secondary porosity in dissimilar ways. To understand the effect of different types of porosity on logs, the type of porosity being measured using core or interpreted from logs needs to be defined. Because the terminology varies somewhat

Table 1.—Response of logs to porosity

Log	Property measured	Response to total porosity	Response to secondary porosity	Response to effective porosity	Spurious matrix and fluid responses
Neutron.	Hydrogen content.	Best response to low-porosity rocks.	Does not distinguish from primary porosity.	Does not distinguish.	Bound water and other neutron absorbers. High salinity. Pores must be saturated.
Gamma-gamma.	Electron density.	Best response to high-porosity rocks.	Does not distinguish from primary porosity.	Does not distinguish.	Matrix composition. High salinity. Saturation error.
Acoustic velocity.	Average compressional-wave transit time.	Related only to total porosity, when it is primary and intergranular.	Does not respond to secondary porosity under most conditions.	Does not distinguish.	No signal in gas or air.
Resistivity.	Both resistivity and volume of fluid in interconnected pores.	No current flow through isolated pores.	Detects secondary pores, but is affected by shape.	Responds only to effective porosity.	Boundary effects (surface conduction), fluid chemistry.

among various groups working with logs, definitions are provided in this text and in the glossary that will be used throughout this manual. Porosity is defined as the ratio of the void volume of a porous medium to the total volume, expressed as a decimal fraction or a percentage. In well-logging literature, the term "porosity" commonly is used without definition and without the modifying terms "total" or "effective." When the term "porosity" is used without a modifier in this manual, it refers to total porosity, and it includes all pore spaces, whether they are interconnected or not. Effective porosity includes only those pores that are interconnected and, therefore, are effective in transmitting fluids and electrical current. Effective and total porosity are nearly the same in most detrital sedimentary rocks; however, in some carbonate and volcanic rocks, isolated pores are common. Primary porosity includes porosity developed during the final stages of sedimentation, or porosity present at the time of deposition; it usually is intergranular and relatively uniform. Secondary porosity develops after deposition and usually is present as nonuniform fractures or solution openings.

Because the type of porosity is so significant in log analysis, it is important to determine exactly how laboratory measurements are made and the type of porosity measured. Laboratory porosity measured using core may be the only practical way of calibrating some logs made in ground-water systems; core analyses are necessary to confirm the porosity scales on commercial logs. The common scatter of data illustrates one of the problems with core measurements; porosity usually varies greatly within a small volume, and, therefore, a few samples may not be statistically representative.

The responses of specific logs to various types of porosity are described in detail in the section on each log; however, a brief summary is appropriate here. The ways in which resistivity, gamma-gamma, neutron, acoustic-velocity, and resistivity logs respond to porosity are summarized in table 1. This table can be used as a first step in selecting logs appropriate to estimate porosity; however, more detailed study is needed before making a final decision. No log measures porosity directly, and the widely used term "porosity log" is misleading. Resistivity logs provide an estimate of effective porosity only when no conductive mineral grains are present. Because the flow of electrical current through pore spaces is affected by the shape of those pores and by the conductivity of pore fluids, resistivity logs may be in error when used to estimate porosity. Gamma-gamma and neutron logs may provide estimates of total porosity under the right conditions, when they are properly calibrated. Acoustic-velocity logs also may provide estimates of total porosity, but some kinds of secondary openings may not be detected.

The measurement of effective porosity is important in determining the volume of water present. Variations in porosity can be used under favorable conditions to estimate variations in hydraulic conductivity; however, in most rocks, porosity and permeability are not related quantitatively. A very small secondary porosity, present as fractures or solution openings, may transmit large volumes of water in crystalline or carbonate rocks. For this reason, and because crystalline rocks are being investigated as possible repositories for radioactive waste, interest in determining the distribution and character of fractures by geophysical logging has increased greatly during the last decade. Acoustic-logging techniques are proving to be particularly useful for this purpose.

Particle size, shape, and cementation

Particle-size distribution and the shape of smaller particles, such as grains, or larger particles, such as pebbles, have a substantial effect on the ability of porous media to transmit fluids and therefore affect the response of some logs. Although no log provides a direct measurement of particle size, many fine-grained detrital sediments are more radioactive than coarse-grained sediments in the same depositional basin.

Particle sizes of sedimentary rocks penetrated by wells range from clay particles to large boulders; these different sizes affect logs very differently. Minimal sorting and large rock fragments produce an inhomogeneous rock. Logs made in such a rock are less diagnostic than logs made in uniform sandstone or shale. Geophysical logs measure the average of some physical characteristic within the volume of material being investigated. As the particles increase in size, the volume measured also needs to increase if the log is to be statistically representative of the material surrounding the borehole.

Flat particles, such as clay, have minimal resistivity. They have a greater surface area for a given volume; thus, they have a greater surface conduction, which can introduce errors in measuring the resistivity of clay-rich sediments. Because clay-rich sediments introduce an error in deriving porosity from neutron logs, analysts in the petroleum industry commonly adjust logs for clay content by applying a "shaliness factor" derived from gamma logs. The error is mostly the result of the relatively large hydrogen content of clay rather than the shape of the particles.

Cementation of mineral grains affects log response and the flow of fluids through detrital sediments. No log responds specifically to cementing material, but the cementation factor, or exponent (m), is important in the relation among resistivity, formation-resistivity factor, and porosity.

Cementation of grains has a major effect on the propagation of acoustic energy in detrital sediments. Attenuation of the signal is substantial in slightly cemented sediments; acoustic-velocity logs usually cannot be made in these materials. Acoustic reflectivity also is minimal, so acoustic-televiewer logs are difficult to make in poorly consolidated sediments. In general, acoustic logging of unconsolidated sediments is not done, because an uncased borehole cannot be kept open without the use of heavy drilling muds.

Formation-resistivity factor

The formation-resistivity factor (F) is an important concept in borehole geophysics; the various relations of F to porosity and resistivity can be used to calculate porosity ϕ or water quality from geophysical logs. Archie (1942) defined F as the ratio of the electrical resistivity of a rock 100 percent saturated with water (Ro) to the resistivity of the water with which it is saturated (Rw); $F=Ro/Rw$. He also stated that F is related to porosity as $F=1/\phi^m$, where m is the cementation exponent, sometimes called the porosity exponent. Many modifications have been made to Archie's (1942) original concept; they have been summarized by Ransom (1984). The more widely used modified formation factor is stated $F=a/\phi^m$, where the coefficient a and the exponent m can be calculated independently and are related to rock characteristics.

The coefficient a usually is 1 when clean, shale-free rocks are being investigated, but it may be less than 1 when clay or other conductive minerals are being logged. The presence of conductive minerals decreases resistivity within an aquifer; a would be less than 1 as long as m remains constant. Methods also are in use in the petroleum industry that compensate directly for conductive clays; when these methods are used, a would be 1 (Waxman and Smits, 1968; Ransom, 1977).

The porosity exponent m usually varies from 1.3 to 2.8 when $a=1$. This exponent is related to some of the same pore-geometry factors that affect permeability, such as shape of pores or particles, ratio of surface area to volume of particles, cementation, compaction, and anisotropy. The occurrence of secondary porosity, such as an open fracture, will have as substantial an effect on m as it does on permeability. The value of F calculated from resistivity logs of fractured igneous or vugular carbonate rocks will give misleading results if it is used to estimate water quality. A consistent increase in both permeability and F with an increase in particle size has been demonstrated (Jones and Buford, 1951). Alger (1966) published both laboratory and resistivity-log data demonstrating an increase in F with an increase in particle size.

The value of F tends to be relatively consistent for a given aquifer within a single depositional environment. It can be determined from resistivity logs in wells where Rw is known from water samples or from logs that are properly calibrated for porosity. When determined in this way, F has been called the field-formation factor and has been used to map the distribution of ground-water salinity using only resistivity logs (Turcan, 1966).

Rock structure

Primary structural features, such as bedding, and secondary features, such as fractures and faults, can be detected indirectly by log response. Bedding planes can be inferred from logs only when they are contacts between lithologies having dissimilar physical properties. Lithologic changes usually produce inflections on logs; such inflections usually are the basis for stratigraphic correlation from one well to another. Unless the log inflection is very sharp, contacts usually are assumed to occur at one-half the inflection-amplitude difference between two rock types. Thin bedding planes, from a layer of laminated minerals, may not cause recognizable log response unless the logging device has sufficiently high resolution. Both thin, cyclic bedding and graded bedding can be recognized on logs under favorable conditions. Although stratigraphic correlation with logs usually is done by "matching the wiggles," correlation is likely to be more accurate when based on a knowledge of the causes of log response.

Fractures and faults may be recognized on logs if they are wide enough to be resolved by the device in use or if they are marked by changes in rock type or alteration. Many fractures are too thin for recognition by any logging devices except those having the highest resolution, such as the acoustic televiewer. Only the acoustic televiewer, borehole television, and the dipmeter provide data that can be interpreted in terms of the dip and strike of planar structures, such as bedding planes or fractures. The potential for error in the correlation of planar structures between boreholes should be recognized. One potential source of errors is produced by deviation of boreholes. All deep boreholes deviate from the vertical, unless very careful control of drilling procedures is maintained. Borehole-deviation logs should be obtained and corrections made before three-dimensional information on bedding or fractures is assumed to be valid. More information on this subject is included in the sections on borehole effects and acoustic-televiewer logging.

Knowledge of the location, orientation, and character of fractures is essential to understanding the flow of ground water in many crystalline rocks and hard sedimentary rocks. In crystalline rocks, almost all flow is through fractures, even though such rocks may have minimal porosity. Widespread logging of wells in crystalline rocks in recent years indicates that most of the flow may be through one or several discrete fractures, even though a large number may have been intersected by the borehole. The significance of a few conductive fractures to rock permeability has been demonstrated both in geothermal reservoirs and in the Canadian Shield (Keys and Sullivan, 1979; Keys, 1984).

Ground-Water Flow and Log Response

Measurements of the flow of ground water and its relation to permeability and specific yield are among the most important objectives of borehole geophysical logging in water-resources investigations. Although no log measures permeability directly, several kinds of logs indicate where water is moving into or out of a well. Also, the relative magnitude of the permeability of discrete depth intervals can be estimated from flowmeter logs. In addition, moisture content and specific yield can be measured with properly calibrated logging equipment under certain conditions.

Well hydraulics

The uncased or screened interval of many wells provides a short circuit for vertical flow if two or more permeable intervals with different hydraulic heads are intersected. Vertical flow commonly is detected when several hundred feet or more of uncased borehole are available for logging. Flow may be in either direction, or may be upward in one depth interval and downward in another depth interval in the same well. Convective movement within a well caused by thermal gradients is common; the interpretation problems caused by convective flow are discussed in the section on temperature logging.

Temperature logs, impeller-flowmeter logs, and tracer logs of various types can be used to measure vertical flow in wells. Temperature logs are most useful for locating intervals in which water flows into or out of a well. Impeller-flowmeter logs can be used in continuous logging mode to locate these intervals, or in stationary mode for more accurate measurements when velocity is sufficiently fast. Tracer logging is most useful when velocities are too slow for impeller flowmeters.

When velocity of flow is not sufficient for detection by available equipment, the aquifer system may be stressed by injecting water at the land surface or by pumping the well at a constant rate. Velocities measured in the cased interval can be used to calibrate the logging equipment. Water with temperature different from that of the ground water can be injected in one well, and its movement to other wells can be detected using temperature logs (Keys and Brown, 1978). The distribution of water of different salinities can be mapped using fluid-conductivity logs. Both temperature and fluid-conductivity logs will identify the more permeable intervals by locating the depths at which the anomalous water arrives. If permits can be obtained, a short-half-life gamma-emitting radioisotope, such as iodine-131, can be used for accurate measurement of vertical flow within a well or flow between wells.

Caliper logs are essential for quantitative interpretation of flow in wells because discharge is proportional to the cross-sectional area of the borehole. Using properly calibrated flow-measuring probes and correcting for hole diameter, the relative hydraulic conductivity of depth intervals within a well can be calculated.

Hydraulic conductivity and intrinsic permeability

No log measures hydraulic conductivity or intrinsic permeability directly, yet these measurements are essential to most ground-water studies. Hydraulic conductivity (*K*) is the quantity of water that will flow through a unit cross-section area of rock, per unit time, at a specified temperature under a unit hydraulic gradient and is, therefore, a function of both the properties of the rock and the water contained in the rock. Intrinsic permeability (*k*) is a measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient and is, therefore, a function only of the properties of the rock.

Computer-plotted logs available from some commercial service companies may have a scale labeled "permeability index." Although the units usually are millidarcies, the qualifier "index" is used as a disclaimer of accurate permeability measurement. Knowing how this index is calculated is important because the technique used may not be appropriate for aquifers that are 100 percent saturated with water, in contrast to the two-phase system (water and oil or gas), which is the basis for most log analysis in petroleum applications. Although *K* cannot be measured directly by borehole geophysics, a number of relations exist that permit its estimation from logs. The basic principles of these relations need to be understood as an aid in selecting and interpreting logs.

A popular misconception is that porosity and permeability are directly related. Although a general relation has been demonstrated in a limited number of geologic environments, the problems of establishing a clear relationship are many. A plot of porosity versus horizontal permeability, measured using core samples of replacement dolomites from a well completed in the Madison Limestone, is shown in figure 16 (Thayer, 1983). This plot is typical of the scatter usually obtained; permeability cannot be estimated from porosity values of less than 20 percent, yet most of the samples having a porosity greater than 20 percent also are more permeable than the less porous samples. This relation may pertain elsewhere in the Madison Limestone, but the possibility would have to be established by measurement. When secondary porosity, such as fractures or solution openings, contributes substantially to flow, no relation between porosity and *K* is detected. Other problems in trying to establish relations of this type are the potential for error in measuring *K* using core and the relatively small size of core samples; small samples are not representative if the rock is not homogeneous.

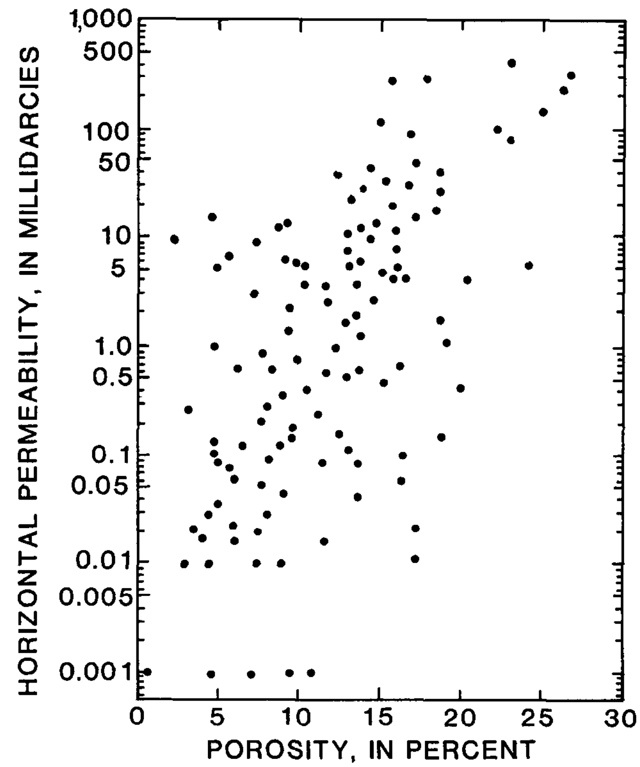


Figure 16.—Relation of porosity and horizontal permeability for replacement dolomites in the Madison Limestone (modified from Thayer, 1983).

A relation between the formation-resistivity factor and *K*, mentioned previously, and a relation to radioactivity from gamma logs are shown in figure 17, which is modified after Kwader (1982). The data are from a carbonate aquifer in Florida. Gamma logs usually indicate greater radioactivity in clay than in coarser sediments or in carbonates; any relation to *K* must be demonstrated by a statistically significant number of samples. This relation has been demonstrated in a number of depositional basins throughout the world.

Raiga-Clemenceau (1977) suggested a relation between intrinsic permeability and the cementation exponent in the porosity-formation-factor equation. Jones and Buford (1951) and Alger (1966) demonstrated that both *F* and *k* increase with grain size. Croft (1971) used Alger's (1966) plot of *k* versus *F* to determine *K* from resistivity logs; he found reasonable agreement with values obtained by other methods. Worthington (1977) showed that the relation between *F* and *k* may not be systematic because of surface conduction. Urish (1981) obtained a relation opposite to that suggested by Alger (1966) and Croft (1971) and

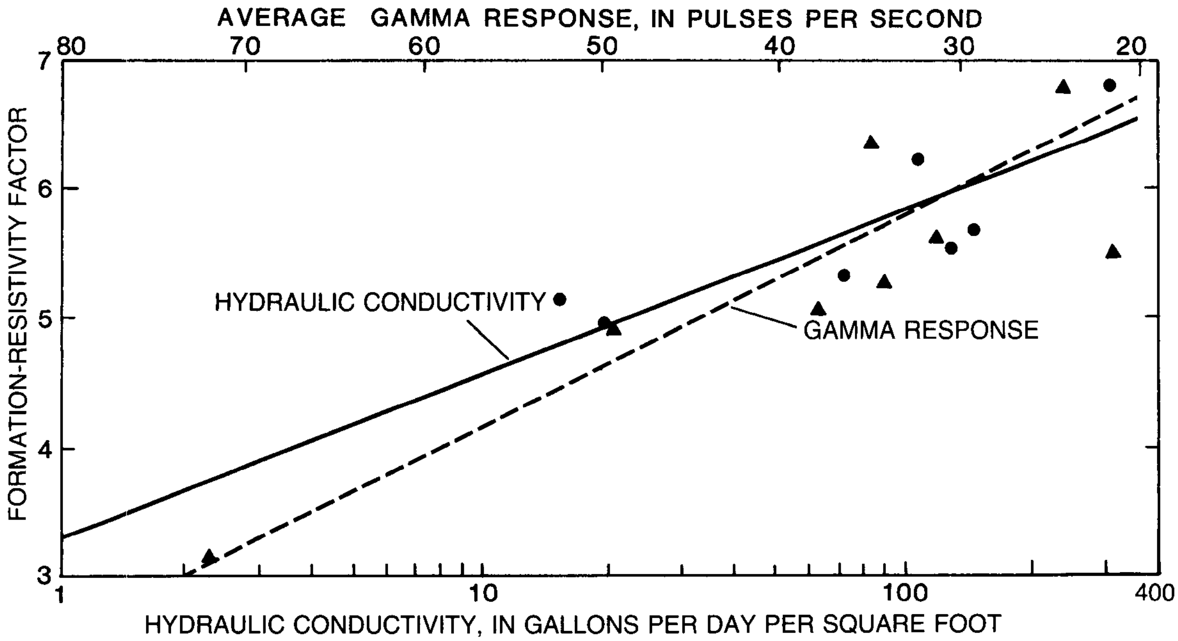


Figure 17.—Hydraulic conductivity and gamma response versus formation-resistivity factor for a limestone aquifer in Florida (modified from Kwader, 1982).

concluded that variations in porosity and matrix conduction limited the method to qualitative evaluation of *k*. The varying conclusions of these studies suggest that relations between the formation-resistivity factor and intrinsic permeability must be demonstrated for each aquifer before they can be used in a predictive sense.

Intrinsic permeability cannot be obtained directly from logs because it is related not only to the percent and kind of porosity (ϕ), but also to particle-size distribution, particle shape and orientation, and the type and distribution of cement. The Kozeny equation relates *k* and ϕ and other fundamental properties of porous media (Kozeny, 1927). The equation states that

$$k=\frac{\phi^3\times10^8}{2T^2S_v^{\,2}(1-\phi)^2} \qquad (1)$$

where

T =coefficient of tortuosity, and

S_v=specific surface of particles exposed per unit volume of matrix.

Specific surface is controlled by grain size. At a given porosity, smaller particle size will decrease *k*. The Kozeny equation indicates that a combination of logs that provide information on both effective porosity and particle size might allow estimation of *k*. Thus, the importance of applying several different logs to the problem of estimating hydraulic conductivity and other hydrologic characteristics is emphasized in this manual.

Specific yield and moisture content

Specific yield is the ratio of the volume of water that saturated rock will yield by gravity to its own volume (Meinzer, 1923). Specific yield plus specific retention equals effective porosity. Specific yield also is a function of particle-size distribution (Johnson, 1967). In general, maximum values of specific yield are associated with medium sand with uniform size distribution, and minimum values of specific yield are associated with clay and silt; therefore, under the right conditions the specific yield of aquifer materials can be estimated using geophysical logs.

Specific yield or storage coefficient of an unconfined aquifer can be determined by using neutron logs to measure the moisture remaining after gravity drainage is complete (Meyer, 1962). The moisture in the unsaturated zone is important because it is related to evapotranspiration and recharge. Neutron-moisture logging can be done on a periodic basis in order to record changes over time.

Interstitial Fluids and Log Response

Logs respond to the fluids contained in pore spaces as well as to the rock matrix, although separating the two effects is not always possible. Only those logging devices designed to measure the fluid column alone provide data unaffected by the matrix. Unfortunately, the fluid in the well bore is not always representative of the fluid in the adjacent rock mass. This problem affects all fluid-column logs, and it can be resolved only through an understanding of the flow within the well, and of the construction, drilling, and testing of the well. Vertical movement in the fluid column, including that caused by convection, displaces fluids away from their host rocks. Accurate information on well construction is essential for correct interpretation of the fluid profile. Knowledge of the character of the fluids injected, and of the time since drilling, circulation, pumping, or injection, will aid in determining when the fluid column might reach equilibrium and will provide measurements that are related to the surrounding rock mass. Under some conditions, many months might be necessary for the fluid column to reach equilibrium; in fact, it may never be possible to obtain representative information by logging the fluid column. McConnell (1985) reported that owing to invasion of freshwater aquifers by drilling fluids containing sodium, it may be necessary to pump seven or more pore volumes before the resistivity of the water is 90 percent of its true value.

Standard logging probes are available to measure fluid resistivity, which can be converted to conductivity, and simultaneously to measure temperature. Specific ion electrodes have been modified for well logging, and neutron-activation analysis has been done experimentally in wells, but neither of these techniques is routine or dependable at this time.

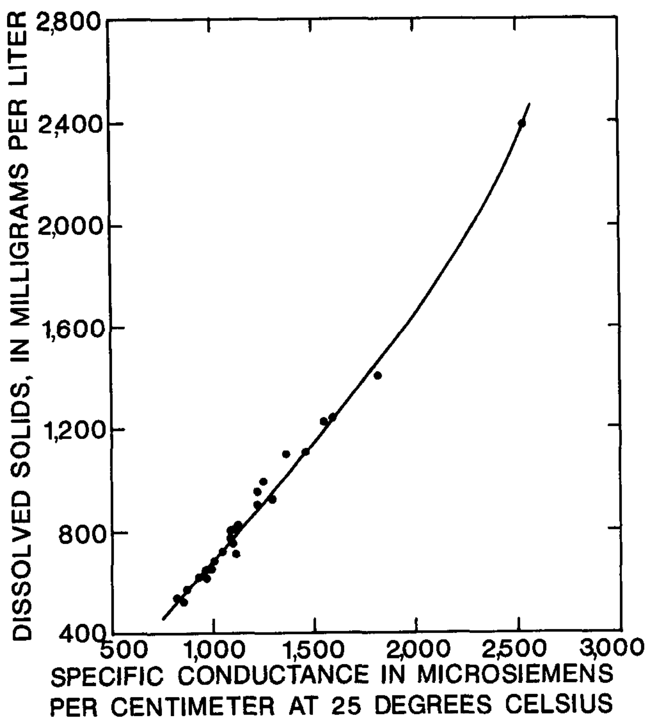


Figure 18.—Relation between specific conductance and dissolved solids in water from 25 wells completed in the Lockport Dolomite, Ohio (modified from MacCary, 1971).

Electrical conductivity

Measurement of the electrical conductivity of ground water provides data related to water quality. Most logging probes measure the resistivity of the fluid in the borehole directly, and the reciprocal is conductivity. Specific conductance can be calculated when temperature logs are available. When enough chemical analyses are available from one aquifer, the relation between specific conductance and dissolved-solids concentration can be established for that aquifer. A plot of the relation between specific conductance and dissolved solids in water from 25 wells completed in the Silurian Lockport Dolomite in Ohio is given in figure 18. Such a relation can be used to predict concentration of dissolved solids from conductivity logs.

The graph in figure 19 allows rapid conversion from resistivity to conductivity and to approximate sodium chloride (NaCl) concentration, in milligrams per liter, corrected for borehole temperature; the graph is extensively modified from one published by Schlumberger Well Surveying Corp. (Alger, 1966). Temperature scales are included in both degrees Celsius and degrees Fahrenheit because most commercial well-logging services still use Fahrenheit. Chloride concentrations, expressed in parts per million, are still in common use in the well-logging industry. Sodium chloride rarely is the only salt present, so correction needs to be made for the presence of other ions. The following multiplying factors can be used to convert to electrically equivalent sodium chloride concentrations: Ca^{+2}, 0.95; Mg^{+2}, 2.00; K^{+}, 1.00; SO_4^{-2}, 0.50; HCO_3^{-}, 0.27; and CO_3^{-2}, 1.26 (Lynch, 1962). For example, if the chemical composition of water from an aquifer is known, from chemical analyses of water samples, to be consistent, the approximate fluid resistivity or conductivity that would be obtained from logs can be estimated as follows:

1. Multiply the concentration of each ion, in milligrams per liter, by the factor given above and sum the results. This concentration, in milligrams per liter, is the electrically equivalent sodium chloride concentration.
2. Using the graph in figure 19, plot this concentration at the intersection of the appropriate diagonal line representing this concentration and the borehole temperature; read resistivity or conductivity at the bottom or top of the graph.

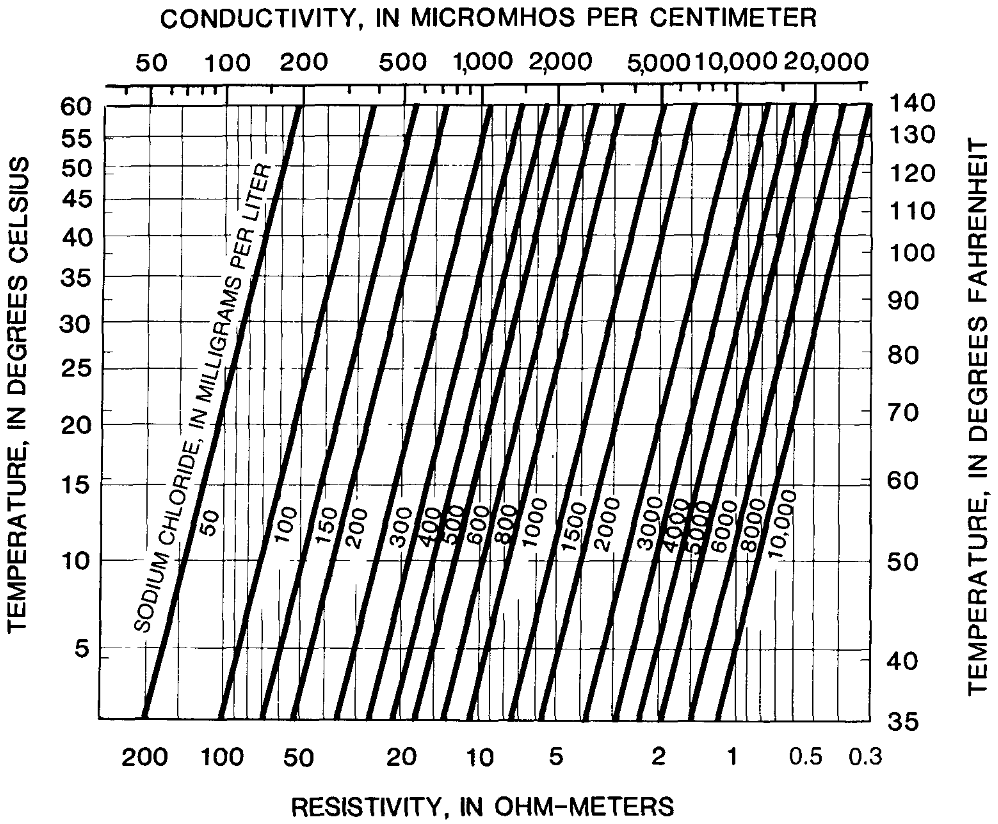


Figure 19.—Electrically equivalent sodium chloride solution plotted as a function of conductivity or resistivity and temperature (modified from Alger,1966).

Fluid-conductivity logs are important in the interpretation of other logs because the salinity of the fluid column can have extraneous effects on resistivity, gamma-gamma, and neutron logs. Although multiple-electrode resistivity logs are supposed to measure only the rock surrounding the borehole, very saline water or brine in the borehole may cause some electrical current to flow through the borehole fluid, producing an error on the log. A large salt concentration also decreases the concentration of hydrogen in borehole and interstitial fluids and increases the density of those fluids. These effects may cause errors on gamma-gamma and neutron logs.

Several problems with fluid-conductivity logging are discussed later. Some probes are improperly designed, so that logs made with them are affected by changes in resistivity outside the fluid column. Fluid-conductivity logs should be made at the beginning of the logging program, before the fluid column is disturbed; also, they should be made traversing down the borehole. Temperature logs should be made simultaneously, if possible. The flow system in the borehole must be understood if the conductivity data for the fluid column are to be interpreted correctly, and the effect of the drilling fluid must be recognized.

Temperature

Temperature logs of the borehole fluid have a number of important applications in ground-water hydrology. They are essential in the search for hot ground water that might be a source of geothermal energy. These logs can also be a guide to the source and movement of ground water and contaminants. Temperature data are needed to correct for the effect on ground-water flow of variation of viscosity with temperature. Water of a different temperature can be used as a ground-water tracer. Temperature data are needed to correct other logs, such as resistivity logs, and to provide evidence of unwanted temperature drift, characteristic of some probes. Temperature logs also can be used to locate cement behind casing by means of heat released by curing cement.

As with fluid conductivity, temperature should be logged down the hole and run first, simultaneously with conductivity, if possible. Although temperature logs can help explain the flow system in a well, corroborating logs are needed. Temperature-logging equipment is relatively simple and inexpensive, but much of the available equipment is inaccurate and lacks the sensitivity necessary for many ground-water applications.

Chemical Composition

Although a great need exists for a logging probe that will provide accurate data on the chemical composition of ground water, no such probe is available at this time (1985). Specific-ion electrodes, widely used in the laboratory, have been modified experimentally for well logging, but they have not become commercially available for operation on standard logging cable. Research on neutron activation in boreholes has been in progress for a number of years, but the effort has not produced a simple, inexpensive system that yields unambiguous chemical analyses of ground water. At present, the best method for obtaining chemical analyses of ground water is to use one of several types of remotely controlled water samplers that are available for operation on any type of geophysical logger. Logs of fluid conductivity, temperature, and vertical flow can be used to select depths for water samples and to extrapolate analytical data vertically.

Borehole Effects

The manner in which a test hole or well is drilled, completed, and tested has a marked effect on geophysical logs made in that test hole well. One of the objectives of logging is to obtain measurements of physical properties of undisturbed rocks which can be converted to approximate values of such rock properties as porosity, bulk density, acoustic velocity, and resistivity. However, the drilling process disturbs the rock near the borehole to varying degrees. Although a number of different types of logging probes have been developed that are called "borehole compensated" or "borehole corrected," all probes are affected by the borehole to some degree. Borehole effects on geophysical logs can be categorized as effects produced by (1) drilling fluids, (2) borehole diameter, and (3) well-construction techniques. All three types of effects can be controlled to produce better logs, if that is a priority objective. In some situations, it may be cost effective to drill two boreholes close together—one designed to optimize logging and the other cored in the depth intervals indicated by those logs. Even if drilling and completion techniques are beyond the control of the hydrologist, the effect on log response can be decreased by careful selection of probes. An understanding of borehole effects will decrease errors in log analysis. Specific effects are discussed in the sections on each type of log.

Drilling fluids

Although cable-tool and air-rotary methods are used occasionally, most drilling today (1985) for ground-water purposes is done by mud rotary methods, with some augering used for shallow test holes. Fluid is circulated in the borehole during rotary drilling for the following reasons: to suspend and remove cuttings, to support the wall of the borehole, to cool and lubricate the bit and drill pipe, and to seal the wall of the borehole to decrease fluid loss. The fluid in the borehole also serves as the coupling medium for electrical and acoustic logging. The hydrostatic pressure of the fluid column is an important factor in preventing caving of unconsolidated materials. This same pressure can cause invasion of an aquifer by the mud filtrate and the development of a mud cake on the wall of the borehole. The pressure in the fluid column forces the water in the mud (mud filtrate) into permeable rock. The mud cake may decrease the permeability of the aquifer adjacent to the well and, thus, change results obtained from various flow-logging devices. The thickness of the mud cake varies with the permeability and porosity of the rocks adjacent to the well. In oil wells, the mud cake is commonly thinner on more porous rocks than on less porous rocks. In contrast, in water wells, the thickest mud cake often is present on more porous aquifers. Some of this difference in mud-cake thickness and distribution may be the result of the carefully controlled drilling mud program used in most oil wells. Geophysical logs can be used to measure the effectiveness of well-development techniques designed to remove drilling fluids and increase permeability adjacent to the well. Periodic neutron logs may detect changes in porosity; periodic flow logs may determine changes in source and quantity of water during pumping or injection. Gamma-gamma transmittance logs have been used to detect changes in porosity caused by injecting sediment-laden water and subsequently redeveloping the well.

Today (1985) most drillers use special additives to control the weight, viscosity, and gel strength of drilling mud. Artificial drilling mud has different physical and chemical characteristics than the rocks penetrated and the associated native fluids. The chemical composition of the water used for mixing the drilling mud is seldom the same as the chemical composition of the ground water in the area. The contrast between the electrical conductivity of the fluid in the borehole and in the adjacent rocks will determine the magnitude and direction of deflection on a spontaneous-potential log. Invasion by drilling fluids may change the electrical conductivity of the pore water and may decrease porosity and permeability in the vicinity of the borehole. Drilling muds frequently are thinned and circulated prior to logging to reduce density and resistivity contrasts. If this is done, the tendency for caving may increase, so logging must proceed rapidly.

Hydraulic fractures can be induced in consolidated or crystalline rocks by excessive hydrostatic pressure during drilling. Drilling-induced fractures commonly are observed on acoustic-televiewer logs; these fractures not only may affect log response, but also may increase vertical permeability. The circulation of air during air-rotary drilling tends to remove moisture from the material adjacent to the borehole; thus it affects the response of logs that provide data on porosity and moisture content. The character of the drilling fluids in and adjacent to the borehole affects the response of most logs; the character of the fluids must be considered when planning the logging operation and interpreting the logs.

It is beyond the scope of this manual to describe the various drilling techniques and how they might be modified to provide the best logs or the most productive well. A companion report in this series by Shuter and Teasdale (1989) contains an excellent description of drilling and sampling techniques used in water-resources investigations; it should be consulted before planning a drilling and logging program.

One technique that is available for determining the extent of alteration of properties of rock and fluid adjacent to a borehole is the use of different spacings between the source and detector in acoustic or nuclear probes or between electrodes in resistivity probes. Longer spacing usually increases the size of the volume of investigation or increases the percentage of the signal that is derived from material farther from the borehole. Logs made with focused-resistivity devices and induction logs are less affected by near-borehole conditions than are commonly used normal-resistivity logs. Comparison of a log that measures material close to the borehole, such as a microresistivity log, with a log that measures properties deeper in the formation, such as a focused-resistivity log, will indicate the depth of invasion that has taken place.

Borehole diameter

Although many logs are termed "borehole compensated" or "borehole corrected," almost all logs are affected to some degree by substantial changes in borehole diameter. All boreholes, except those drilled in well-consolidated or crystalline rocks, have thin intervals where borehole diameter exceeds bit size sufficiently to cause anomalous log response. For this reason drilling must be planned to minimize changes in borehole diameter, and high-resolution caliper logs should be made to detect such changes. For purposes of log interpretation, borehole-diameter changes are subdivided into those caused by bit size, where only the average diameter is affected, and thin intervals of considerable rugosity, or roughness, caused by a combination of drilling technique and lithology. Most logs can be corrected for average borehole diameter, but logs made in thin zones of different diameter are difficult to correct.

A high-resolution caliper probe may enable detection of mud cake or mud rings that are thick enough to cause a significant error in log response. Mud rings commonly are the result of clay being extruded into the borehole; these rings may cause logging probes to get stuck. Mud rings can gradually increase in size, even after drilling has been terminated, and they eventually may close the borehole.

Drilling technique can have a major effect on variations in borehole diameter. The difference in borehole diameter between a rotary-drilled borehole and a nearby core hole in an area where the sedimentary rocks change very little laterally is shown in figure 20. The first rotary hole was drilled rapidly to minimize borehole-diameter changes. The second borehole was drilled very slowly, with considerable circulation of drilling mud to maximize core recovery. Core recovery was almost 100 percent from the well-cemented mudstone and sandstone, anhydrite, and dolomite. The drilling and coring procedure caused considerable variations in borehole diameter, partly because of solution of halite cement and veins during the lengthy drilling process, which included numerous trips with the core barrel. The core hole produced some poor quality logs; an example is discussed in the section on gamma-gamma logging. Although increases in borehole diameter occurred at the same depth in both drill holes, the range of diameter was much greater in the core hole. Stratigraphic correlation in this area can be done with caliper logs because borehole-diameter changes are related to rock type. The very prominent log deflections just above 200 ft reflect the solution of halite veins. The very rugose interval below 300 ft probably is the result of thin-bedded layers of anhydrite and mudstone.

Better logs generally are obtained from smaller diameter boreholes. However, the chance of having a probe stick in a borehole generally is decreased if the probe does not fit the borehole too tightly. Centered and decentralized logging tools yield different responses; many tools are intentionally decentralized to decrease variations in response caused by changes in the distance of the probe from the borehole wall.

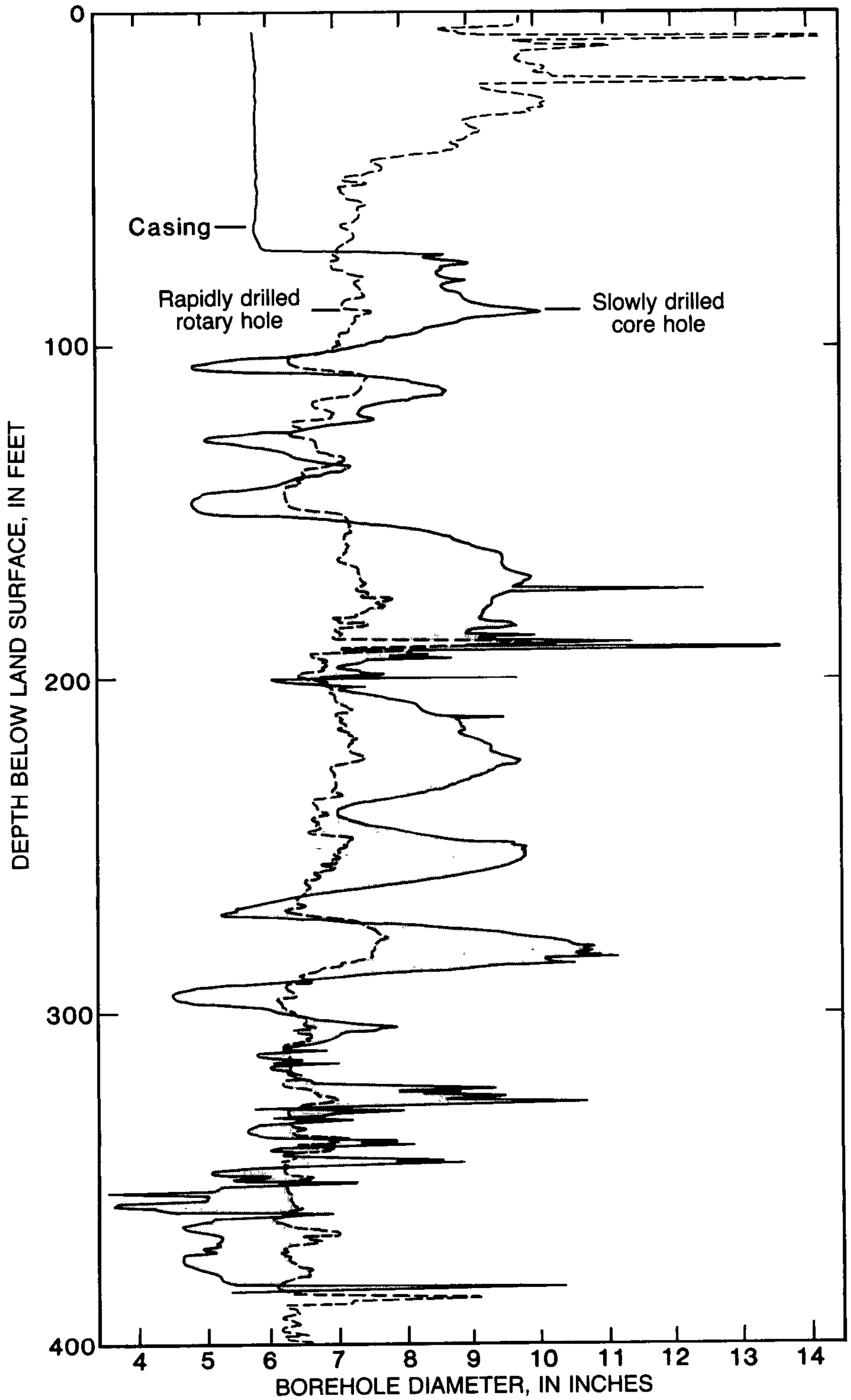


Figure 20.—Effect of drilling technique on borehole diameter. The boreholes are close together in an area of persistent lithology, Upper Brazos River basin, Texas.

Almost all boreholes become deviated from the vertical as depth increases; drilling procedure has a major effect on that deviation. Because of deviation, logging probes are assumed to be traveling along the wall of the borehole most of the time. Forced decentralization likely decreases periodic departure from the borehole wall caused by rugosity, or by changes in direction of deviation of the borehole.

Charts in commercial log-analysis handbooks permit correction for diameter of the borehole, but corrections for rugosity or rapid variations caused by either lithologic changes or by drilling techniques are extremely difficult. The correction charts usually refer to average drilled diameter, not the diameter of a short, irregular interval, as measured by a caliper log. Many borehole-compensated probes employ two detectors at different distances from the source of the signal, and the log is based on the ratio of output from these detectors. In theory, the different lengths of the paths traveled to these detectors allow cancellation of the effect of near-borehole cavities or washouts. The short-spaced detector is supposed to be affected by the cavity; the far-spaced detector is not. The usefulness of such techniques under a variety of borehole conditions is questionable.

From the standpoint of quantitative log analysis, the best procedure is to eliminate from consideration those depth intervals that have borehole-diameter changes that would substantially affect the logs. It is possible that this method could eliminate one lithology, such as salt or swelling clay. Determining the significance of borehole-diameter changes might be done in several ways. Data from a specific probe may indicate the expected magnitude of the response of the log to changes in borehole diameter. If the log being analyzed shows deflections that closely match the intervals where the caliper log shows borehole-diameter changes, those intervals can be eliminated from quantitative analysis. Although such borehole-diameter changes might be caused by a different lithology, log response caused by differences in lithology is very difficult to separate from that caused by an increase in borehole diameter. Also, not all borehole-diameter changes are caused by drilling. Solution openings, open fractures, and vesicles can exist at great depths, and they are an intrinsic part of the rock fabric to be considered during log analysis. An acoustic televiewer can be particularly useful in distinguishing such primary features from drilling-induced borehole enlargements. Borehole-diameter changes behind casing have a considerable, but undetermined, effect on through-the-casing logs. Thus, a caliper log should be made before casing is installed, if possible.

Well construction

Casing, cement, and gravel pack have substantial effects on log character. Some logs are designed specifically to provide information on the location and character of casing and cement. These logs, described in the section on well-construction logging, are useful in interpreting logs that might provide information on the rock behind the casing. For most wells, nuclear logs are the only type that will receive a signal from outside the casing, gravel pack, and cement, although acoustic logs are a possible source of such information if the cement is properly bonded to the casing and to the wall rock. In general, the thinner and more uniform the material between the logging probe and the rock that is to be measured, the better the results.

Nuclear logs can provide data about the materials behind the casing, but thinner casing of uniform thickness will produce better results. Changes in casing thickness, such as threaded couplings, will produce anomalies on gamma-gamma logs. Two strings of casing decrease the magnitude of the signal from the rocks penetrated. Usually, each string of casing will cause an offset in log response that can be used to locate the bottom of one string of casing outside another. The composition of the casing is less important than its thickness and uniformity; neutron logs will detect changes in rock character through plastic casing in spite of its considerable hydrogen content, just as gamma-gamma logs will detect changes through thick steel casing. Such changes may represent a small part of the total signal received by a probe; uniform casing will represent a uniform background to this signal. Accurate information on casing location and character are prerequisite to any useful interpretation of through-the-casing logs.

Cement and gravel pack present similar difficulties in the analysis of logs in terms of rock character. Uniformity in thickness and in physical properties is important but more difficult to attain than for casing. Varying borehole diameter causes one boundary of this annular material to be indefinite, unless a precompletion caliper log is available. Gravel pack tends to be nonuniform, as does most fill material behind the casing, because it usually includes materials slumped from the borehole wall. Gamma logs can be misleading if made through gravel pack derived from radioactive granitic rocks. Similarly, neutron logs made to measure moisture content through casing may give inaccurate results for many months after cementing, because of moisture changes as the cement cures. Dry sand is probably a better backfill material for test holes if neutron logging will be important. Backfill problems and solutions have been described by Keys and Brown (1971) and Brown and Keys (1985).

Geometric Effects

Geometric effects are produced on logs by variations in the relationship between the volume of investigation of a logging probe and the borehole and intersected rocks. The volume of investigation must be considered in log analysis, because it has a substantial effect on response to borehole characteristics and to beds of varying thickness.

Volume of investigation

The volume of investigation is defined, for the purposes of this manual, as that part of the borehole and surrounding rocks that contributes 90 percent of the signal that is recorded on a log. The radius of investigation is the distance from the sensor to the 90-percent boundary. One should not infer from these definitions that the volume of investigation is spherical or that the boundary is distinct. Instead, a gradual decrease in contribution to the signal occurs. The size and shape of the volume of investigation changes in response to varying borehole conditions and to the physical properties and geometry of boundaries in the rock matrix. The effect of changes in porosity and bed thickness on the volume of investigation of a neutron probe are described in the section on neutron logging. Not only do the size and shape of the volume of material measured by the probe change, but the porosity and bed-thickness values derived from the log are affected. In the case of neutron logs, the radius of investigation is shorter in saturated porous rocks. In contrast, gamma and gamma-gamma logs have a longer radius of investigation in more porous (less dense) rocks than in less porous (more dense) rocks. If the drill hole penetrates a series of thin beds having different properties, the volume of investigation has an irregular shape, which is defined by those properties.

The borehole also can affect the size and shape of the volume of investigation. For example, a resistivity log made in a well filled with very saline water or brine may provide little information on surrounding rocks that exhibit substantial resistivity because most of the electrical current will flow through the borehole. Within the volume of investigation, for most logging systems, materials closest to the sensor have more effect than those farther away. The most significant exception to this rule includes some resistivity probes, for which the zone of maximum influence is located some distance from the pickup electrodes. Decentralized, side-collimated, dual-detector probes commonly are called borehole compensated because they may decrease the percentage of the total signal coming from the borehole and the mud cake. In general, longer spacing between the source of energy and the detector increases the radius of investigation and decreases borehole effects, but also decreases resolution. The radius of investigation may vary from fractions of an inch for short-spaced probes to tens of feet for ultralong-spaced probes. Thus spacing should be considered when designing the logging program and interpreting the logs.

Techniques for logging the material between two boreholes can decrease borehole effects. These cross-hole, or transmittance, logging techniques are experimental; they have relatively limited vertical resolution, but they may be advantageous under some conditions. Both gamma-gamma and neutron transmittance logs have been used by the U.S. Geological Survey between boreholes located several feet apart (Keys and Brown, 1971). One of the limitations of this technique is the difficulty of drilling two boreholes that are straight and parallel.

Bed thickness

Bed-thickness effects on log response can be best explained using the concept of volume of investigation and its relation to source-to-detector spacing. If a bed is thinner than the vertical dimension of the volume of investigation or thinner than the source-to-detector spacing, the log seldom provides accurate measurement of the thickness or physical properties of that bed because, under these conditions, the volume of investigation includes some of the adjacent beds, so that the signal recorded on a log is an average of several lithologic units. A radiation detector will begin to receive some data from a bed before it is opposite the bed. When the detector is centered on the contact between two beds of sufficient thickness, half of the signal will be derived from one unit, and half from the other; selection of contacts at one-half amplitude for nuclear logs is based on this fact. If a nuclear log or other slow-responding log is recorded too fast, contacts will be difficult to pick and apparently will be displaced. If a bed is too thin with respect to the probe spacing, it may not cause any response on the log; this becomes a problem at rapid logging speeds. Contacts on some electric logs are picked at the inflection point where the slope of the curve changes.

Some long-spaced resistivity logs, such as the 64-in normal log commonly used on water-well logging equipment, display an anomalous response, called cratering or reversal, in thin beds. This effect is discussed in more detail in the section on resistivity logging extraneous effects. Thin, resistive beds between less resistive beds actually may be logged as having a smaller resistivity than the adjacent rocks—a reversal. Most multielectrode logs will show reversals under some conditions and may provide erroneous data on bed thickness. A single-point-resistance log is valuable under these conditions because it never reverses and provides high resolution in thin beds. Thus, it is an excellent log for determining lithology,

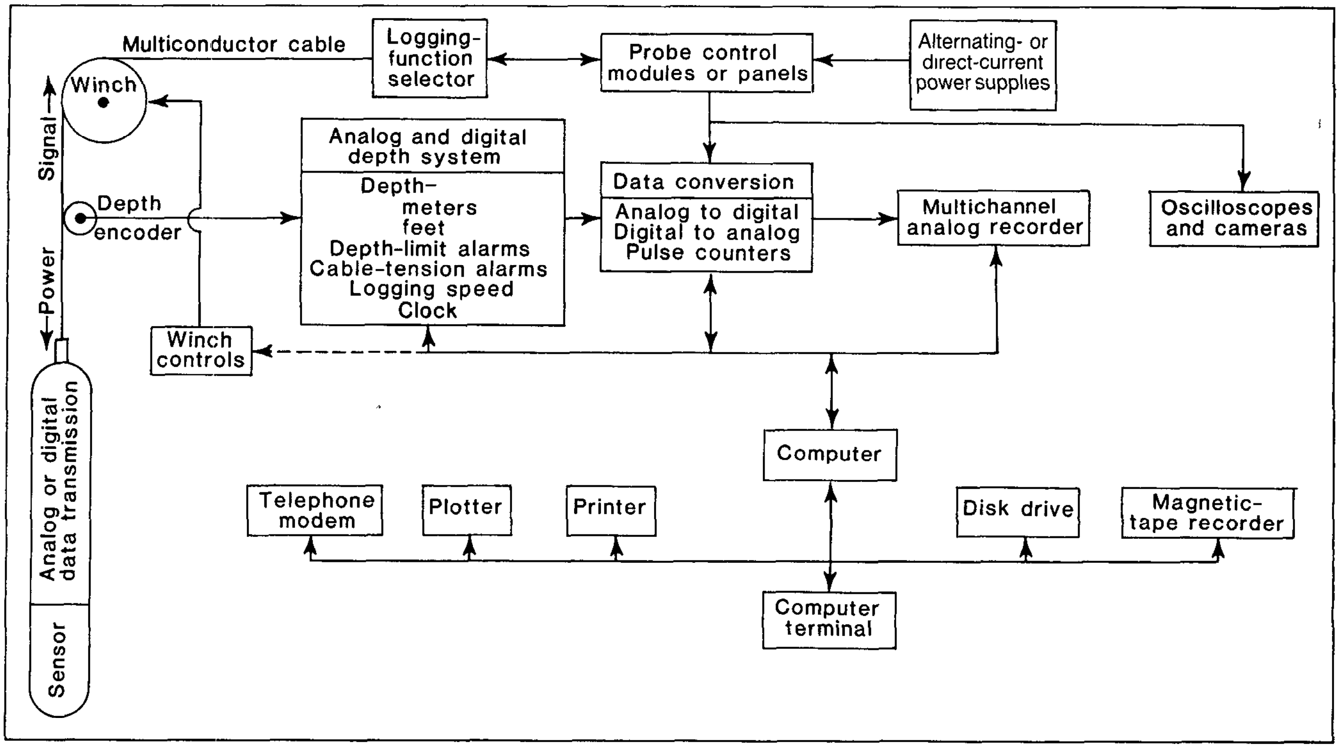


Figure 21.—A modern analog and digital logging system.

although it does not provide quantitative measurement of resistivity. A spontaneous-potential log may provide useful data on bed contacts, but the log tends to be featureless in many water wells. A high-resolution caliper log may provide unambiguous location of contacts in some kinds of lithology.

Logging Equipment

A thorough understanding of the theory and principles of operation of logging equipment is essential for both equipment operators and log analysts. Equipment operators need to know enough about how each logging system works to be able to recognize and correct problems at the well site and to select the proper equipment configuration for each new logging environment. Log analysts need to be able to recognize, by looking at the logs, logging-system malfunctions and improperly recorded logs. The maximum benefit usually is derived from a logging operation in which operators and analysts work together in the logging truck to select the most effective adjustments for each log and to obtain more detailed logs on sections of interest.

A logging system can be subdivided into subsystems or components to simplify the description. A schematic block diagram of a modern analog and digital logging system is shown in figure 21. The logger components shown in this diagram can be mixed or matched in the fashion of modern computer systems. In this manual, logging-system components are described in the following categories: probes, cable and winch (including depth system), control modules, and recording. Specific information on each type of logging probe and ancillary equipment is included in the section on that type of log. Other related information is discussed in the sections on planning the logging operation, quality control, and calibration and standardization.

Probes

Logging probes, also called sondes or tools, enclose the sensors, sources, electronics for transmitting and receiving signals, and power supplies. The probes are connected to the cable by a cable head screwed onto the top of the probe. Most probes are made of stainless steel or other noncorroding materials. Electric-logging probes commonly have lead electrodes; acoustic probes incorporate rubber and plastic materials for acoustic isolation and transmission. Probes vary in diameter from less than 1 in to more than 4 in. The standard size used in most oil-well operations is 3⅝ in; most probes used in ground-water studies are smaller. Lengths vary from about 2 to 30 ft or more; weight may be as much as several hundred pounds. Some electric- and acoustic-logging devices are flexible; others are rigid. They are designed to withstand pressures of many thousands of pounds per square inch, based on the maximum depth they are expected to reach, plus a safety factor for heavy drilling mud.

Most probes used in ground-water hydrology today (1985) transmit an analog signal to the land surface for processing. The signal usually is a varying voltage or pulses that vary in frequency. The new generation of probes converts variations in response to a digital signal for transmission up the cable. With this approach, some of the data processing can be done in the probe. For example, count rates can be divided by a constant to decrease losses in the cable. Data from several sensors also can be transmitted in a single probe. Digital probes offer the added advantage of easy switching and control from the land surface by means of a computer keyboard.

Most older probes, including many used in ground-water hydrology, are axially symmetric and are not side collimated. That is, they send and receive signals 360° from the probe axis; they are not intentionally decentralized. Many modern nuclear probes, often called borehole-compensated probes, are decentralized and side collimated, and they use several detectors. They are decentralized with caliper arms or bow springs, and are side collimated with appropriate shielding material around the source of energy and the detector. Using the ratio of count rates from two detectors provides some amount of compensation for borehole effects. Compensated acoustic-velocity probes are centralized with bow springs or rubber fingers; they may use two transmitters and four receivers to transmit an average signal. Operation of centralized probes in greatly deviated boreholes can be very difficult. If centralizers are rigid enough to center the probe adequately, sometimes the probe will not go down the hole.

As wells get deeper and geothermal exploration increases, temperature becomes a limiting factor for many probes and must be considered when selecting probes for such an operation. Few standard logging probes will operate properly at temperatures greater than 100 °C, and many demonstrate thermal drift before that temperature is reached. Thermal drift caused by changes in the temperature of the electronics in a logging probe is common and may produce a misleading log. A temperature log of a well in which temperature drift is suspected may be useful in confirming drift in other logs, but only a test in a controlled-temperature environment will provide direct evidence that the problem exists and data to allow the logs to be corrected. The U.S. Geological Survey has designed and tested probes that have operated at temperatures as high as 260 °C, but such probes are large and expensive (Keys, 1982).

Water leaks are rare in logging probes, but they do occur. Most probes are sealed with double O-rings at the joints; faulty O-rings usually are responsible for leaks. O-rings need to be kept clean and lightly greased and must be inspected frequently for nicks. If a probe does fill with fresh water, it usually is possible to remove the electronics, which are mounted on long boards, and dry them out at the well site, so that logging operations can be resumed. Probes may operate for years with no malfunctions; most failures can be attributed to a broken or intermittent solder joint. Commonly, a broken joint can be located and repaired at the well site. If a probe cannot be repaired, it usually is possible to send it to the manufacturer or a repair facility and to receive a similar probe by return air freight, so that the logging job can be completed. The replacement probe must be calibrated if the logs are to be used quantitatively.

Probes should be stored and transported with care. Large probes usually are stored horizontally in a probe rack where they can be locked down to prevent movement; small probes may be stored in a vertical rack. Logging probes stored in a strong, well-padded box will be less likely to sustain damage.

Cable and winch

Most logging cable is double-wrapped with steel wire to protect the insulated conductors inside and to serve as a strength member. This armor serves as one of the electrical conductors in single-conductor cable. Many portable water-well loggers still use single-conductor cable because it is lighter and less expensive than multiconductor cable. However, in recent years there has been a trend toward using four-conductor cable for water-well logging, because it permits quantitative resistivity and acoustic logs to be recorded. Other advantages of multiconductor cable are that it allows a large number of logs to be recorded at one time and has greater strength for use with heavy probes and in deep wells. Cable having seven conductors is standard for oil-well logging and is used in deep water wells and geothermal wells. A Teflon type of insulation should be used on high-temperature cables; special steel is needed for the armor if corrosive fluids may be encountered.

Logging cable is expensive and must be treated with care if it is to be useful for a long time. Kinks should be avoided at all times. The cable should be wiped or washed before it is stored on the drum after logging in corrosive fluids, and light oiling may be helpful to prevent rusting. Cable wipers and line coolers can be used to clean the cable automatically as it comes out of the well. A line cooler is essential for hot cable because hot cable may crush the drum as it shrinks if it is not precooled. The cable should be spooled on the drum with a level wind; any backlashes on the drum can be carefully removed manually. Shorts or open conductors occur more frequently in mistreated cable and may necessitate cutting the cable and reinstalling the cable head.

The cable head usually is the most troublesome component of a logging system. Electrical leakage in a cable head is common; when this occurs, the cable head usually must be reinstalled, a time-consuming procedure. A volt-ohm meter is carried on every logging truck to check for cable and cable-head leakage and shorts. To decrease the occurrence of leaks, the O-rings in the cable head should be examined and greased frequently, and the cable head filled with grease as specified by the manufacturer. When a cable head is being reinstalled, the correct number of strands in the armor must be cut so the breaking strength is decreased to less than that of the cable. The purpose of eliminating some strands is to ensure that the cable will part or pull out at the head if the probe becomes lodged in the well. Retrieving or fishing for a lost probe is easier if there is no cable above it; cable also is expensive and difficult to grind up with a drill bit if it is left in a well. Drawings and dimensions of the cable head and all probes should be kept on the logging truck as aids in fishing for lost probes. With this information, a fishing tool can be made that may enable the probe and cable head to be removed from the well. Some commercial firms will rent or sell fishing tools and supervise the retrieval operation. Proper tightening of the joint between the cable head and the logging probe and continuous awareness of well conditions are important in decreasing the chance of losing a probe.

Most winches are powered by alternating-current electric motors or are driven mechanically or hydraulically from a power takeoff on the truck. They need sufficient power to break the cable if necessary. If the winch is powered by an alternating-current generator, the generator should be oversized for the load, so that voltage decrease does not affect the electronics. Some suitcase-type loggers have a hand-crank winch, but this is practical only to depths of 500 ft, and only if the probes are light in weight. An adjustable, powered, level wind is needed to prolong cable life. Slip rings provide the electrical connection between the cable and the electronics at the land surface. Although they tend to be trouble free, they should be inspected and cleaned periodically, particularly if noise caused by winch rotation is observed on logs.

Logging cable is passed over a measuring sheave between the winch and the well. Electrical signals from an optical encoder, or selsyn, or a speedometer type of cable are used to transmit the rotation of the measuring sheave to the recording systems. The measuring sheave is precisely machined to provide accurate cable measurement and must be kept free of dry drilling mud and ice. The accuracy of cable-measuring systems should be checked periodically. When the measuring point on a probe reaches the reference point at the wellhead, the magnitude of any error should be recorded on the log. Depth errors tend to be greater with lightweight probes and rapid logging speeds, probably because of slipping on the measuring sheave. Depth errors can come from many sources; most result from operator error rather than equipment malfunction, and frequent checks are needed to detect them.

Two types of warning systems are used in some logging trucks to decrease the chance of loss of or damage to equipment. A weight indicator is essential for logging deep wells to warn the operator if the probe has become lodged in the hole while moving in either direction. The weight indicator may be connected to an adjustable audio alarm so the operator does not have to watch the indicator constantly. A depth alarm, which can be preset to sound before the bottom and top of the well have been reached, can be helpful to a busy operator who has many duties during logging.

The cable leads from the measuring sheave over one or more sheaves at the wellhead before going down the borehole. These sheaves should be sufficiently large in diameter to avoid damage to the cable, and the groove in the sheave must be machined to fit the diameter of the cable. For water-well logging, a sheave that will attach to different-sized casing in several different ways can be carried on the logging truck. Surface casing may vary from 2 to 20 in or more in diameter; wells may be located in pump houses, where access is difficult.

If the logging equipment is to be used regularly to log a large number of test holes and water wells, an adjustable boom with a sheave mounted on the end can save considerable time in setting up to log. A boom similar to that shown in figure 22 also can make it much easier to handle long and heavy probes. Small folding booms have been designed that will mount on the roof of a carryall or station wagon. When large probes are being used and neither a boom nor a drill rig is available for mounting the sheave, a tripod can be constructed out of heavy pipe. A large logging truck like that shown in figure 22 is necessary only if a large suite of heavy probes is carried or if deep wells are logged.

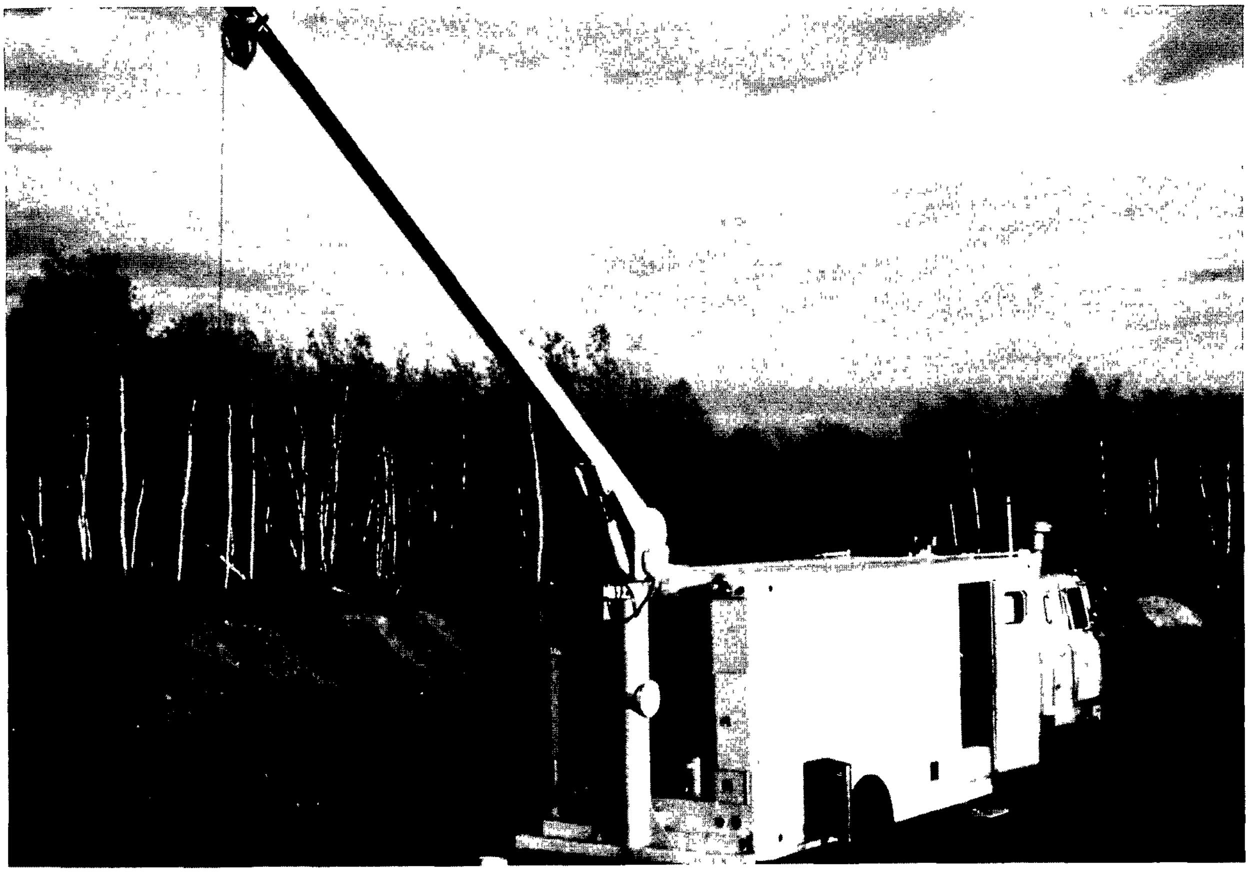


Figure 22.—Large logging truck used for deep-well logging.

Control modules

Control modules or panels are used to make most of the adjustments necessary to obtain each type of log. Plug-in modular design is desirable, because the modules can be replaced readily in the event of failure. If a widely used design is selected, modules can be bought from several different manufacturers, and modules can be added as funds permit. Modules also take up less space than panels and usually can be connected to a common power supply. A photograph of the inside of a U.S. Geological Survey research logging truck is shown in figure 23. Both control modules and panels are mounted in standard relay racks. Although this logging truck contains more than the usual number of modules and panels, many of the modules are of standard design, widely used in water-well logging.

Most logging equipment includes a function-selector switch that allows the operator to choose the proper combination of modules, panels, and power supplies to record each kind of log. On some loggers, switching is accomplished by plugging wires into the appropriate module or panel. A pilot light on each module or panel shows that the power is on. The module may contain controls for adjusting the voltage and current of the power to the probe; meters may be included to indicate these values. Additionally, the module or panel will have switches to select recording scales and positioning of the pen on the recorder. Further selection of scales and positioning usually is possible with controls located on the recorder. Additional controls or switches that may be on a module or panel, depending on the logging function, include time-constant adjustment or smoothing, recorder-channel selection, and internal calibration.

Some modern logging trucks use a computer instead of modules or panels to control logging functions (fig. 24). The operator determines the way each log is to be run, and instructions, based on displayed questions, are entered from a terminal keyboard. These instructions can be transmitted to probes, power supplies, modules or panels, and recorders.

Recorders

A variety of recorders is available for geophysical-logging equipment because almost any recorder man-

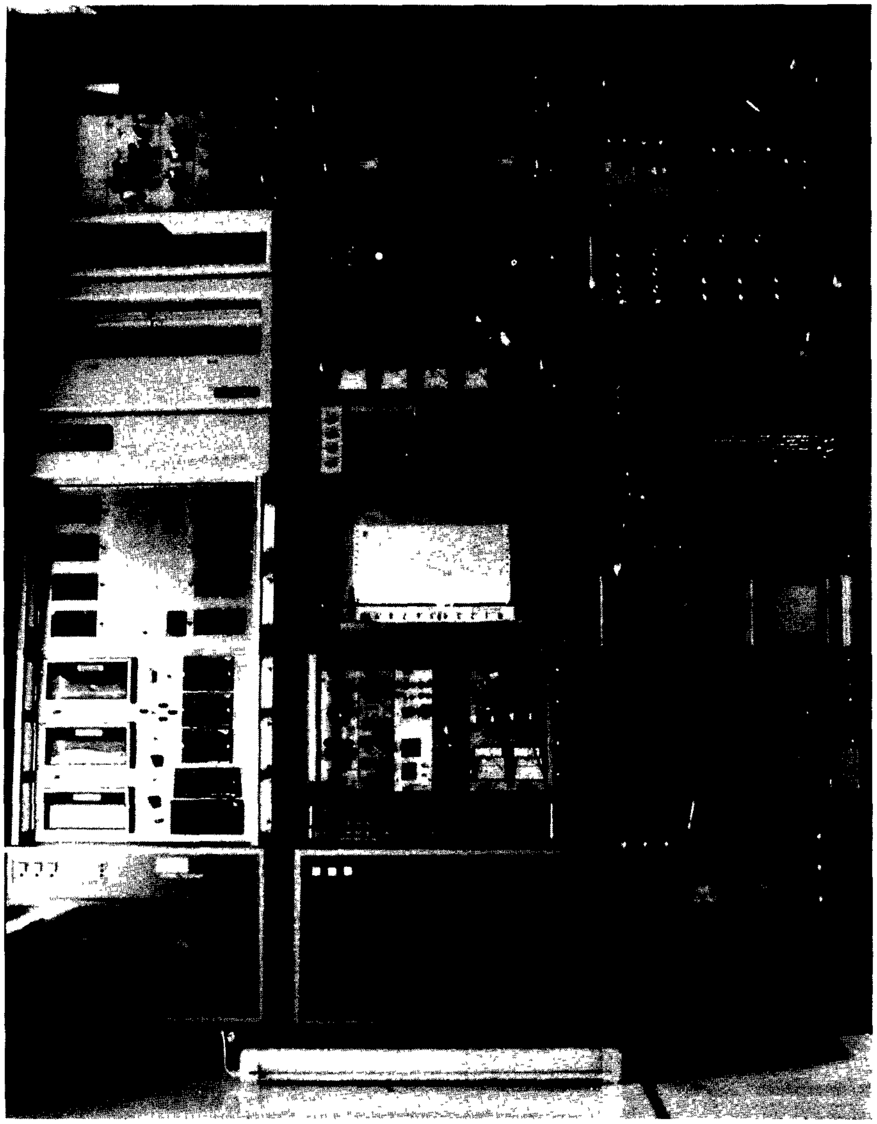


Figure 23.—Electronic control panels and modules, and analog and digital recording systems, in a modern logging truck.

ufactured today can be adapted to this use. Most of the recorders currently (1985) used in ground-water applications are of the pen-and-ink type, with one to four pens. Ozalid-type recorders, using light-sensitive paper, are widely used in oil-well logging by commercial service companies; laser recorders are coming into use. Ozalid recorders are suitable for logging very deep wells and recording a large number of curves simultaneously; the disadvantage is that the log cannot be studied as it is being recorded, but only after it is finished. Also, it is difficult for the untrained eye to distinguish all the overlapping curves on such a log, even when dots and dashes are displayed.

Pen-and-ink recorders are relatively inexpensive and are widely available in many styles. Pens are available in many colors, so that traces can be readily distinguished. The common pen types are ink-reservoir or capillary, felt-tip, and ballpoint. All these pen systems have shortcomings, but felt-tip and ballpoint pens can be replaced easily, which makes them more suitable for a logger that is not used on a regular basis. Ink-reservoir pens that are used and cleaned frequently provide good service, but they may leak ink during rapid pen travel. An important consideration in selecting the type of pen is legibility of copies made on a duplicating machine. Different colors may be indistinguishable on copies, and some colors may not reproduce well.

The number of pens or recording channels is a function of the number of logs that can be recorded

Figure 24.—Winch controls and computer in a modern logging truck.

simultaneously and the cost of additional channels. Recorders should have at least two channels, so that spontaneous-potential and single-point-resistance logs can be recorded simultaneously. Four channels permit two normal-resistivity logs, a spontaneous-potential log, and a gamma log to be recorded at the same time, if the probe is properly designed. Two or more channels also permit recording of a log on several scales to provide the needed response range and sensitivity. Extra channels also provide spares that can be easily selected if a channel malfunctions. Most analog recorders permit independent adjustments for each channel; these usually are gain or attenuation and position or basing. Gain allows the operator to control the amplitude of pen deflection for a given probe signal. Positioning permits the manual location of the pen on the chart without changing gain. Recorders generally are among the more trouble-prone surface components of a logging system.

Chart paper is marked with vertical and horizontal divisions consistent with the logs to be made. In the United States, a 1-in scale in both directions, subdivided into tenths, is most common. In other parts of the world, paper with scales in metric units is used. For oil-well logging, an American Petroleum Institute (API) horizontal scale is used for many logs; a logarithmic scale is used for some. Most of the paper used in these commercial service trucks has two recorder tracks, 2.5 and 5 in wide, and the logs are confined to those tracks. Recorders from 2 to 10 in wide are used for ground-water applications, but 10 in is practical for most purposes, except the portable suitcase type of loggers. For greatest versatility, all pens should be capable of recording on the full width of the paper.

When a log is started, depth should be adjusted so that even footage to the nearest 10 ft plots on a major division on the paper. Most loggers used for ground-water purposes do not have a system for automatically indicating the depth on the chart paper. Depths frequently need to be manually written on the chart paper, and checks should be made to ensure that the readings from the depth indicator agree with the divisions on the chart paper. The horizontal-scale values also should be written on the log at the time it is set up, and the pen positions, set by internal calibrators, should be marked across the entire span of log response. Selection of the appropriate log scales is essential to obtaining the maximum information from logs; scale selection is described in the section on quality control. Recording paper that is too narrow will not permit adequate resolution of a large range of data. Backup curves are provided on most commercial logs as a solution to this problem, but they tend to make log reading difficult.

Because log headings are not put on the log until after it is completed, all pertinent information should be written on the log as it is being recorded, including information about the well, probe, module adjustments, logging speed, and calibration. Log headings can be used as a reminder to ensure that all pertinent information is noted.

Many modern loggers incorporate digital recording equipment, so that data from the probe are recorded simultaneously in digital and analog format. Although digital recording is becoming standard, it will never completely replace analog recording because of the need to study a log as it is being made. Without analog capability, malfunctions or incorrectly selected logging parameters may not be recognized until it is too late for correction. In addition to use in computer interpretation, digitizing of logs onsite has several other benefits. Because the digital record contains all the unprocessed data before it is sent to the analog recorder, no information is lost if the analog trace goes off scale. This allows the horizontal scale on the analog record to be selected at optimum sensitivity to display small-amplitude features. Valid logs can be plotted later from the digital data, even though the analog surface equipment may have malfunctioned. In some logging trucks, replotting with corrections immediately after the log is made also is possible. If a modem is available, a digitized log can be transmitted over the telephone, or the tape or disk can be mailed, for rapid data processing.

Several different types of digital recorders are used. The most common at the present time (1985) is magnetic tape, either standard computer-compatible tape or cassettes. The larger reel-to-reel tape has the capacity to store more data from deep wells or many logs. Floppy disks also can be used; they have the advantage of smaller size, they allow random access, and they also can be used to store computer programs for onsite processing of data. Either a digital display or a printer usually is available to display the digital data being recorded. Most logs are digitized at 0.5-ft intervals; 0.1-ft intervals may be desirable if high resolution is needed in shallow wells, but sampling with more than a few data points in one sample volume is redundant and does not improve resolution. Digital recording does not slow the logging speed of most logs. However, for nuclear logs, recording one to three samples of the count rate at each depth usually is desirable. The need to space these samples sufficiently close together for thin-bed resolution may require logging speeds of about 25 ft/min or slower.

Probes that transmit pulses, such as nuclear probes and some temperature probes, require only a digital ratemeter at the land surface to send data to a digital recorder. Probes that transmit an analog signal, such as the analog voltage from resistivity electrodes, require an analog-to-digital converter. Newer probes that transmit digital information up the cable require no data conversion at the land surface. Digital-to-analog converters are required to replot digitized logs. Replotting can be done on the analog recorder in the logging truck or on a computer-compatible X-Y plotter.

Planning a Logging Program

The first decision to be made in planning a logging program is the equipment and operators to be used. The selection may be based in part on the needed logs, because some of the more expensive and newer equipment may not be available from all sources. Within the U.S. Geological Survey three basic options are available: (1) buy or rent the equipment and do the logging with staff personnel, (2) pay for logging by an internal service unit on a job basis, or (3) contract for logging by a commercial service company.

Buying a logger

Although ordering a logger from a catalog may seem simple, many options must be considered that are beyond the scope of this manual. Several basic decisions need to be made regarding the logger. How much cable is needed? The answer is, At least 500 ft more than the deepest hole anticipated. How many conductors should the cable have? At least four if quantitative logging is needed. What kind of recording should be used? At least two-pen analog, or four-pen analog if multiconductor cable is to be used, and digital recording if computer-log-analysis techniques are to be used.

Owning logging equipment is justified only if it will be used on a regular basis. The main advantages of owning equipment are availability whenever needed, complete control over logging procedures, and, possibly, smaller costs per foot of borehole logged.

In-house service logging

At present (1985), logging is available on a fee-per-job basis within the U.S. Geological Survey; major private companies may have a similar arrangement. The main advantages of paying by the job are that someone else takes care of equipment maintenance and operator training, and costs may be less if logging is infrequent. This approach will mean better use of equipment but only fair availability and control of log quality. The last factor depends to a large degree on the training and experience of the operators. Onsite quality control by the group paying for the logs is just as necessary for Government-owned equipment as for commercially owned equipment. The procedures described in the section on quality control should be followed.

Contract logging

Commercial logging services are available throughout the United States and in many foreign countries, from companies that range from multinational corporations to one-person operations. The larger companies are based almost entirely on oil-well operations; smaller companies rely mostly on water wells, mineral test holes, or coal-exploration holes. Oil-well-logging equipment is larger and, therefore, more expensive, so the costs per foot of log are much greater. Oil-well-logging probes may be too large for some ground-water test holes, and a large drill rig is needed on the hole to suspend the upper logging sheave. The major service companies have trucks available only in oil-exploration or producing areas, and mileage costs are substantial. In spite of these drawbacks, oil-well type of equipment increasingly is being used in ground-water studies and development, because deeper production and disposal wells justify the cost and may require this type of equipment.

A number of smaller local companies specialize in water-well or mineral logging; some drillers own their own logging equipment. Usually, the smaller equipment owned by these companies does not permit all the logging techniques available from larger companies; digital recording may not be available. Depth charges, standby time, and mileage costs will be less for these small companies, but they may not have the calibration facilities that most larger companies have. Even if calibration is available, the written agreements or disclaimers from most commercial service companies contain a statement to the effect that the accuracy of the data is not guaranteed.

The total cost of commercial logging may be difficult for the inexperienced person to calculate from price lists, because of the various unit costs involved. Depth and operation charges usually are listed per foot, and a minimum depth is specified. Mileage is usually charged for distances of more than 150 mi per round trip. The well must be ready for logging when the equipment arrives because standby charges are relatively expensive. The customer is required to sign an agreement before any logging is done, stating that he or she assumes full responsibility for the cost of any probes that are lost, the cost of all retrieval or fishing operations for lost probes, and the cost of any damage to the well. If a radioactive source is lost, fishing is required by law, and the well must be filled with cement if the source is not recovered. Probe-protection charges may be paid per probe, or per trip in and out of the borehole, but this form of insurance cannot be legally purchased by Government agencies because they are considered to be self-insured. Some Government drilling contracts include the cost of commercial logging, and the driller may pay for probe protection.

Selecting a suite of logs

The most effective logging programs are designed on the basis of the information that is needed, the rock types to be penetrated, and the construction of the test holes or wells to be logged. Commonly, all logs available are made, even though an examination of controlling factors, based on an understanding of the principles of the various logging techniques, would allow preselection of only those logs most likely to produce useful data. This is because bringing a logging truck back to a well to record an essential log that was not recorded on the first trip is expensive. For example, an acoustic-velocity log probably will not provide useful data in unconsolidated or slightly consolidated sediments, but might yield information on the strength of some unconsolidated formations, and this information might be useful in some situations. The caliper log is essential to the interpretation of most logs and always is made in an open hole, so that caliper logs are almost always run even when caliper logs would not provide a direct measurement of formation properties. If not enough logs of different types are made, the results from synergistic log analysis are likely to be inferior.

Some types of logs, resistivity, flowmeter, and caliper logs among others, are available in several varieties. For example, a bow-spring caliper is inappropriate when high-resolution hole-diameter information is needed, and a three-arm averaging caliper will provide no useful information in a borehole that has substantial deviation. An understanding of the differences between the various probes is essential for selection of the right one for the job. The detailed information needed for this selection is presented in the sections on the various logging techniques. The basic information needed to simplify selection among the more commonly used logs is provided in table 2. A cross reference to more detailed descriptions of the types of logs listed in the first column also is provided (in the second column).

Table 2.—Criteria for selection of logs

Type of log	Varieties and related techniques	Properties measured	Potential applications	Required hole conditions	Other limitations
Spontaneous potential.		Electric potential caused by salinity differences in borehole and interstitial fluids.	Lithology, shale content, water quality.	Uncased hole filled with conductive fluid.	Salinity difference needed between borehole fluid and interstitial fluids correct only for NaCl fluids.
Single-point resistance.	Conventional, differential.	Resistance of rock, saturating fluid, and borehole fluid.	High-resolution lithology, fracture location by differential probe.	Uncased hole filled with conductive fluid.	Not quantitative; hole-diameter effects significant.
Multi-electrode.	Normal, focused, or guard.	Resistivity, in ohm-meters, of rock and saturating fluids.	Quantitative data on salinity of interstitial water; lithology.	Uncased hole filled with conductive fluid.	Normals provide incorrect values and thicknesses in thin beds.
Gamma.	Gamma spectral.	Gamma radiation from natural or artificial radioisotopes.	Lithology—may be related to clay and silt content and permeability; spectral identifies radioisotopes.	Any hole conditions, except very large, or several strings of casing and cement.	
Gamma-gamma.	Compensated (dual detector).	Electron density.	Bulk density, porosity, moisture content, lithology.	Optimum results in uncased; qualitative through casing or drill stem.	Severe hole-diameter effects.
Neutron.	Epithermal, thermal, compensated activation, pulsed.	Hydrogen content.	Saturated porosity, moisture content, activation analysis, lithology.	Optimum results in uncased; can be calibrated for casing.	Hole-diameter and chemical effects.
Acoustic velocity.	Compensated wave form, cement bond.	Compressional wave velocity.	Porosity, lithology, fracture location, and character, cement bond.	Fluid-filled, uncased, except cement bond.	Does not see secondary porosity; cement bond and wave form require expert analysis.
Acoustic televiewer.	Acoustic caliper.	Acoustic reflectivity of borehole wall.	Location, orientation, and character of fractures and solution openings, strike and dip of bedding, casing inspection.	Fluid-filled, 3- to 16-inch diameter.	Heavy mud or mud cake attenuate signal; very slow log.
Caliper.	Oriented, 4-arm high-resolution bow spring.	Hole or casing diameter.	Hole-diameter corrections to other logs, lithology, fractures, hole volume for cementing.	Any conditions.	Deviated holes limit some, significant resolution difference between tools.
Temperature.	Differential.	Temperature of fluid near sensor.	Geothermal gradient, in-hole flow, location of injected water, correction of other logs, curing cement.	Fluid-filled.	Accuracy and resolution of tools varies.
Conductivity.	Resistivity.	Most measure resistivity of fluid in hole.	Quality of borehole fluid, in-hole flow, location of contaminant plumes.	Fluid-filled.	Accuracy varies, requires temperature correction.
Flow.	Spinner, radioactive tracer, brine tracer, thermal pulse.		In-hole flow, location, and apparent hydraulic conductivity of permeable interval.	Fluid-filled.	Spinners require higher velocities. Needs to be centralized.

Quality Control of Logs

Control of the quality of geophysical logs recorded at the well site is the responsibility of all concerned, from the organization making the logs to the analyst interpreting them; the ultimate responsibility lies with the professional who ordered and accepted the logs. Commercial logging-service companies require that a representative of the customer (for example, the U.S. Geological Survey) be at the site to sign for and accept responsibility for the operation and for the logs. Oil companies commonly assign a project geologist or engineer to this job, and he or she is expected to ensure that the logs meet minimum quality standards. Neither private logging companies nor Government logging organizations accept responsibility for the accuracy of the data recorded. Agreements signed prior to logging by commercial companies usually include a disclaimer regarding the accuracy of the log data; therefore, the customer needs to ensure that the best practices are followed. A quality-assurance program begins before the logging truck arrives at the well site; this program requires continuous input from the inspector or observer at the site. The quality control of oil well logs has been described in detail by Bateman (1985).

Prelogging contacts

To obtain the most useful data, the logging program should be discussed in detail with a local representative of the Government organization or the private company that will do the logging. Such discussions also may aid in deciding what logs to order. The following information is needed during prelogging discussions and will decrease the possibility of problems:

1. Purpose of logging—What information is needed from logs?
2. Construction of well—Depth, diameters, deviation, caving, or lost circulation zones, casings, cement, screens, junk in the borehole, fluid type, temperature, and pressure range expected.
3. Access for logging—Roads, parking for logging truck, drill rig on borehole (required by most commercial logging companies), wellhead construction (in detail, if a lubricator is needed), and time available for logging.
4. Conditions—Lithologic, fluid, or hole conditions that might affect log response.

Item 4 includes a number of factors that might not be evident; they are described in detail in the section on borehole effects and in the sections on individual types of logs. For example, rocks having unusually large or small values of bulk density may require special scales or probe modifications. If forewarned about large resistivity or inadequate cementation, the logging organization may be able to suggest electric and acoustic probes that would provide more accurate data.

If quantitative logs are required, discussion of questions and logging specifications early in planning will improve the data and identify potential errors; examples of these questions follow:

1. How is each probe calibrated, and how often?
2. What field standards are carried on the logging truck? Is system response checked against these standards before and after each log?
3. What is the range of resistivity, porosity, bulk density, and so forth within which each probe will operate and for which each probe is calibrated?
4. What vertical and horizontal scales are available? If onsite digitizing is requested, what digitizing intervals are available, and what is the recording medium and data format?
5. What will be the logging conditions, such as speed, scales, calibration and standardization, reruns to demonstrate repeatability, and so forth?

Quality control at the well

A geoscientist who understands the project objectives and the local geohydrology should be in the logging truck during the entire operation. This observer's first task is to specify the order in which the logs are to be made. Usually, fluid logs are run first, if the fluid in the well has had time to reach equilibrium; nuclear logs are always run last, or through the drill stem if necessary, to lessen the possibility of losing a radioactive source. Logging sequence is also based on the need for one log to help select the optimum logging criteria for a later log. For example, single-point-resistance and gamma logs may indicate the thicknesses of potential aquifers and thus aid in selection of the resolution needed, and a caliper log may indicate that certain logs would not be meaningful.

The observer usually makes preliminary interpretations of the logs as they come off the recorder. Based on the immediate analysis of field prints of logs, reruns can be requested, if problems on the logs can be demonstrated. Usually, at least partial reruns will be made at no additional cost, if the contractor is at fault and the probe is still on the cable. After the logging truck has left the site, no-cost reruns are rarely possible. The observer should ask questions if he or she does not understand part of the operation. Notes on problems that occur can be abstracted on log headings. A few symptoms that may indicate equipment malfunction can be recognized during logging; these include periodic oscillations, nonlinear response, temperature drift, noisy sections, and rapid transients. Almost-straight sections (no horizontal pen response) are not always invalid, but generally they indicate problems. If reruns do not repeat within the statistical range expected, the observer may request periodic repeats to determine if well conditions actually are changing. Most reruns are at least 100 ft long and include intervals where log values change markedly. In evaluating new logs, copies of logs previously run in the well, or in nearby wells, are helpful. If old logs are not available, a description of the rock types penetrated by the well will aid in anticipating log response. When the logs appear to be incorrect, changes in speed, time constant, scales, spacing, and so forth may improve the record.

Selection of the horizontal and vertical scales that will provide the most useful data and the required resolution without "noise" is difficult, but is among the most important aspects of log-quality control. To some degree, the ability to digitize logs onsite permits more latitude in the selection of scales, because later the digitized logs can be plotted at more suitable scales; however, the digitizing intervals must have been properly chosen for this to be possible. Advice on scales to use may come from the log analyst, based on objectives and real-time analysis of the logs as they come off the recorder. Vertical scales are chosen on the basis of hole depth, needed bed resolution, and ease of comparing with other data. A vertical scale of 10 ft of borehole per inch of chart paper is common for shallow holes, for which detailed information is required, but 20 ft of borehole per inch of chart paper is probably the most widely used scale over a depth range of several hundred to several thousand feet. The most common vertical scale for logs of oil wells is 50 ft/in; 100 ft/in also is used. The U.S. Geological Survey has used 2 ft/in or less, when fractures were being studied and when other logs were being compared directly with an acoustic-televiewer log. Selection of horizontal scales is even more difficult, because of the range of data that may be present and the need to detect small changes. Except for temperature and fluid-resistivity logs, logs are recorded while the probe is being pulled up the borehole. Logging up allows operators to observe the responses of most probes, except caliper, on the trip down the borehole, to help select the best scale. Many commercial logs are recorded on a scale that is too compressed, in the interest of simplifying the logs by eliminating multiple backup curves. The wider paper used on much water-well equipment permits expanded scales without backup curves. If the data range is too great for the resolution needed, the best technique is to record the signal from the probe on two different recorder channels at different gain settings. Thus, one log will remain on scale, and the other will show the needed detail. This technique is commonly used on temperature logs of geothermal wells, where a great temperature range is expected, but small changes may indicate depths where water is entering the well. In a shallow well, reruns to observe changes or at different scales may be economically justified; in deep wells, however, the cost of standby time and the larger logger may make reruns too expensive.

Logging speed usually is checked with a stopwatch, using the depth indicator, because many logging speedometers are not accurate. Depth readout should be checked periodically against the analog record and at the depth reference point for the well when the probe returns to the land surface. The direction and size of the depth discrepancy is noted on the log heading. Depths are recorded frequently on the log. A common practice on large commercial trucks is to manually add a depth correction when the magnetic cable markers differ substantially from the depth display. This practice should be discouraged, or at least a note should be made of the depth at which corrections are made. A uniformly distributed error can be corrected easily in a computer; random, unknown corrections by the operator cannot be reconstructed. Depth errors that are not consistent throughout a suite of logs usually can be recognized by careful correlation of anomalies between logs. Core data may provide some information on correct log depths; however, core depths commonly are incorrect. Lack of depth correlation between logs made at various times by different organizations is common and usually results from the use of a different depth reference. Most commercial logs are referenced to the kelly bushing on the drill rig, which may be 17 ft or more above ground level.

Depth errors can be caused by both equipment malfunction and operator error. A mechanical backup measuring system will help detect errors caused by a malfunctioning electronic measuring system. An incorrectly machined measuring sheave or a sheave that is coated with ice or mud will affect both types of measuring systems. If either the logging truck or the sheaves at the well are allowed to move, a depth error will be introduced. The sag in the cable from the rear of the logging truck to the well will decrease gradually as the weight of the cable in the well increases, and this will introduce an error. Cable stretch is a significant factor only in deep wells and can be corrected for, but errors caused by the probe sticking, while traveling either up or down, are more difficult to interpret. Hole deviation is common and must be corrected for if vertical depth must be known. The recorder-paper drive can slip, and the paper may not be "scale stable" because of humidity changes. Common operator errors include setting the starting depth on the display incorrectly, writing the starting depth incorrectly, and not allowing for the mechanical slack present in most paper-drive systems.

The observer must remember so many factors to help control the quality of logs that many major oil companies provide a quality-control checklist (Lynch, 1962). Most of these lists are many pages long, because they include specific items for each type of log. The checklist that follows has been shortened by combining many of the log-specific criteria; expanded checklists for individual logging operations can be created from the detailed descriptions of the various logging techniques elsewhere in this manual. A check-mark is adequate to indicate that the particular requirement has been met; a significant deviation from that requirement should be noted in detail. Logging programs for special purposes may require additional checklist items. For example, logging a series of ground-water monitoring wells at a waste-disposal site will require careful cleaning of probes and, possibly, of the cable between wells; care must be taken to avoid contamination of personnel. Log headings that have blanks for a complete set of well and log data also can serve as partial quality-control checklists. An example checklist follows:

LOG QUALITY-CONTROL CHECKLIST

Hole no.________ Location ____________________ Date ________

Logging organization ____________________ Type of log ________

Observer ____________________

Log heading completed ____________________

Depth reference and errors noted ____________________

Proper logging speed maintained ____________________

Pre- and post-logging standardization recorded ____________________

Repeat-log interval ____________________

Scales and changes labeled ____________________

Curves readable with no off-scale deflections ____________________

Sample of drilling mud or water collected ____________________

Changes in fluid resistivity recorded ____________________

Logs appear reasonable ____________________

Problems noted on log headings ____________________

Did operator make requested changes? ____________________

Log headings

Log headings contain information of two types: information on the well, and data pertaining to the logging equipment and operations. Well information usually is provided by the observer, but it is recorded by the logging operator. Data on the equipment and logging operations are best recorded before the logging tool is removed from the cable. The completed heading should be attached to the analog record at the well site. A short reference to the log-heading information entered on the digital recording of each log enables the two records to be related. This reference should include the following information, at a minimum: borehole number, date, log type, and run number. If necessary, the log heading can be typed in the office and permanently attached to the original of the log, so it will appear on all copies. The format of a log heading is not important; the information is essential.

The well-information section of the heading should contain all of the following, if known:

- Well name and number (lease, operator, and field name if in an oil field)
- Location—township, range, section, distance from nearest town, and so forth, and owner (API number if in an oil field)
- Name of driller, date drilled, drilling technique, and depth drilled
- Elevation of land surface
- Height of casing above land surface
- Depth reference
- Complete description of all casing, type, size, and depth intervals
- Location of cement, perforations, and screens
- Borehole diameter (or bit size) and depth intervals
- Fluid type, level, resistivity of mud and mud filtrate at measured temperature, and bottom-hole temperature

The log-information section of a heading should contain different information for each type of log, although the same heading can be used for similar logs. The following information is needed on the heading for each log:

- Type of log, run number ____ of ____ , date _____
- Number or description of logging truck

- Names of logging operator(s) and observers
- Probe number and description—diameter, type, detector(s), spacing, centralized or decentralized, source type and size, and so forth
- Logging speed
- Logging scales—vertical (depth) and horizontal, including all changes and depths at which changes were made
- Recorder scales—millivolts (span) and positioning
- Module or panel settings—scale, span, position, time constant, and discrimination
- Power supply—voltage and current
- Calibration and standardization data—pre- and postlog digital values recorded on heading and annotated at selected points on the analog strip-chart record
- Other logs of the well run on the same date
- Problems or unusual responses during logging (mark at appropriate depth on log)

Incomplete log headings prevent quantitative analysis of logs and make qualitative analysis much more difficult. The increasing emphasis on ground-water-quality problems means that logs will be used more for monitoring in the future and that preexisting logs may provide baseline data, if they are properly labeled. Lack of information on well construction may make even the simplest log analysis impossible. Log headings may be printed up in quantity, with blanks for each item large enough for all needed data. For small records of geophysical data, such as pictures of oscilloscope traces or acoustic-televiewer photographs, stick-on labels have proven effective in encouraging the recording of essential data.

Calibration and Standardization of Logs

If logs are to be used for any type of quantitative analysis or to measure changes in a ground-water system over time, they must be properly calibrated and standardized. The importance of standardization can be illustrated by the gamma log, which is most commonly used to identify lithology and stratigraphic correlation. Studies in various sedimentary basins throughout the world have demonstrated locally that the gamma log can also identify particle-size distribution and permeability. Such relations cannot be demonstrated unless the logs used have a standardized response. A gradual change in gamma response across a depositional basin may signal a change in the percentage of clay and silt, or it may be a result of equipment drift. A change in gamma response over several years may signal migration of uranium daughter products in ground water, or equipment drift. Calibration and standardization also may help establish comparability between logs made with different equipment.

For purposes of this manual, calibration is considered to be the process of establishing environmental values for log response in a semi-infinite model that almost simulates natural conditions. Environmental values are related to the physical properties of the rock, such as porosity and acoustic velocity. The signal from a probe may be recorded in units, such as pulses per second, that can be converted to environmental values with calibration data. Calibration usually is done before going to the well site to log. Standardization is the process of checking the responses of the logging probes at the well site, usually before and after logging. Standardization involves the use of some type of a portable field standard that most likely is not infinite and may not simulate environmental conditions. Because the terms "calibration" and "standardization" are not used in the same way in the oil-well-logging industry, the user must understand the procedure to know with certainty what has been accomplished. The basic principles of these techniques are described in the following sections, but the specific procedures are described in the sections for each type of log.

Calibration

Calibration of probe response should be done in a medium that closely simulates the chemical and physical composition of the earth materials that are to be measured. For example, a neutron probe that is to be used to measure the porosity of sandstone would not be calibrated in limestone unless the correction factor is known. Calibration pits or models are nearly infinite with respect to probe response. In a model that is infinite with respect to probe response, the response of the probe does not change substantially if either the diameter or the thickness (height) of the model is increased when the probe is located in the center of the model.

Calibration pits or models are maintained by the larger commercial service companies; these are not readily available for use by other groups, although it is possible to arrange to use some of the private pits. Four sets of calibration pits or models currently (1985) available for public use are listed in table 3. The American Petroleum Institute maintains a limestone pit for calibrating neutron probes and a simulated shale pit for calibrating gamma probes at the University of Houston, Houston, Tex.; these have been accepted internationally as the standards for oil-well

Table 3.—Calibration pits available for public use

[in, inch; ft, feet; gm/cc, grams per cubic centimeter]

Name and location	Who to contact	Probes that can be calibrated	Physical properties	Drill-hole sizes	Dimensions of pits	Remarks
American Petroleum Institute Calibration Facility; University of Houston, Houston, Tex.: two pits.	University of Houston, Cullen College of Engineering.	Two pits: 1. porosity-neutron gamma-gamma;	1. Six stacked blocks of limestone and marble; stacks average 1.9, 19, and 26 percent porosity.	7⅞ in diameter, uncased.	1. 6 ft diameter, 18 ft high;	Call to reserve; daily fee.
		2. simulated shale-gamma.	2. Concrete twice as radioactive as the average midcontinent shale, with concrete of low radioactivity above and below.	5½ in diameter, inside casing.	2. 4 ft diameter, 24 ft high.	
Department of Energy, Grand Junction, Colo.: 20 models or pits.	Department of Energy, Grand Junction Operations office, or the prime contractor at the Department of Energy office.	Gamma calibration in percent U_{238}; and gamma spectra in percent K; and parts per million U and Th. Also gamma-gamma and magnetic susceptibility.	Uranium ore mixed with concrete; barren zones above and below. Content of radioactive elements, water, and bulk density known for most pits. Magnetic susceptibility.	Most 4+ in, uncased; 2- to 8-in hole-size calibration. Some cased, 2, 4, 6, and 8 in inner diameter.	4 to 7 ft diameter, 4.5 to 16 ft high.	Call to confirm available; no charge.
Bureau of Mines density pits; Denver Federal Center, Lakewood, Colo.: three pits.	U.S. Geological Survey, Water-Resources Division, Borehole Geophysics Research Project, Building 25, Denver Federal Center, or Geologic Division, Geophysics Branch.	Gamma-gamma, acoustic, resistivity, and magnetic susceptibility.	Concrete of known density: 1.73, 2.33, and 3.00 gm/cc.	2, 3, 5, and 8 in.	4.3 and 12.5 ft diameter, 8.2 and 9.2 ft high.	Usually available weekdays; call to confirm; no charge.
Department of Energy: Fractured igneous rock calibration models; Denver Federal Center, Lakewood, Colo.: three models or pits.	U.S. Geological Survey, Water-Resources Division, Borehole Geophysics Research Project, Building 25, Denver Federal Center, or Geologic Division, Geophysics Branch.	Fracture detection probes, neutron, gamma-gamma, short-spaced resistivity, and acoustic velocity.	Coarse-grained and medium-grained granite and altered diabase with artificial fractures intersecting and 6 in to 1 ft from the borehole. Known porosity, bulk density, acoustic velocity, and resistivity.	7⅞-in core hole.	8 ft diameter (octagonal), 20 ft high.	Usually available weekdays; call to confirm; no charge.

logging. The pits are available for a nominal daily fee, but they are used enough that reservations are advisable. Pits for calibrating gamma-gamma probes are available for no charge at the Denver Federal Center, Lakewood, Colo. At the same location, three pits constructed of blocks quarried from three different igneous rocks are available for calibrating several types of probes. The igneous rock pits are probably the first ever made for these rock types. They contain artificial fractures of several different orientations that intersect the borehole and fractures that do not intersect the borehole. These fractures are discussed in more detail in the section on acoustic televiewers. The U.S. Department of Energy maintains a set of gamma probe calibration pits in Grand Junction, Colo. This complete set of pits provides several different borehole sizes in blocks having the same concentration of radioisotopes, a desirable feature because borehole-diameter effects always must be considered when applying calibration data to logs.

Boreholes that have been carefully cored, and the cores analyzed quantitatively, also may be used to calibrate logging probes. To decrease depth errors, core recovery in calibration holes should be about 100 percent for the intervals cored; log response can be used to select samples for laboratory analysis. A computer technique for matching core and log depths has been described by Jeffries (1966). The importance of using log response as the basis for selecting cores for analyses is shown in figure 25. The neutron log and cores are from Madison Limestone test well 1, Wyoming. The log is shown only for the cored intervals. Although the overall trend in porosity matches fairly well, average porosity from the core is less than average porosity from the log. A plot of the core analyses versus values from the neutron log at corresponding depths is given in figure 26. Based on the core analyses, it is apparent that porosity cannot be read directly from this commercial neutron log, which was calibrated for limestone. The scale on the log was labeled "porosity index," so no claim was being made for correct porosity values. The cross plot in figure 11 indicates that considerable dolomite is present in this well, which is probably the reason for the large values on the neutron log. A cross plot like the one in figure 11 can be used to correct porosity values for matrix effects, and it does provide values that are more similar to the core measurements.

Because of the possibility of depth errors in both core and logs, and of bed-thickness errors, samples should be selected from thicker units, where log response is consistent. The number of samples to be analyzed is a function of the variability of the property being measured; a completely homogeneous, isotropic material needs only one sample; an infinitely variable material needs an infinite number of samples. The statistics of sampling are beyond the scope of this manual. The core should be analyzed for more than the required properties, such as porosity or bulk density. Mineralogy and chemical composition are important because the responses of many logs depend on rock chemistry. The chemistry of interstitial fluids also may be important; changes in pore fluid during the period the borehole is being used for calibration may cause errors, as will core resaturated with water of different quality for laboratory tests. Laboratory analyses should measure the same physical property that controls log response, if possible. For example, effective porosity does not control the response of neutron and gamma-gamma logs unless it is the same as total porosity.

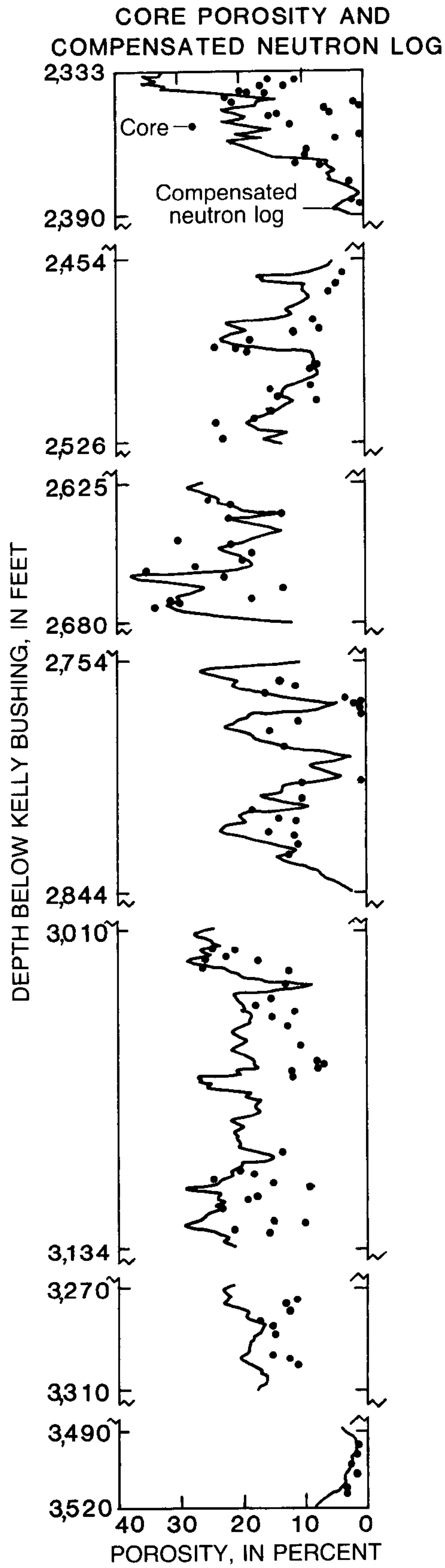


Figure 25.—Porosity from core analyses and compensated neutron log for cored intervals, Madison Limestone test well 1, Wyoming.

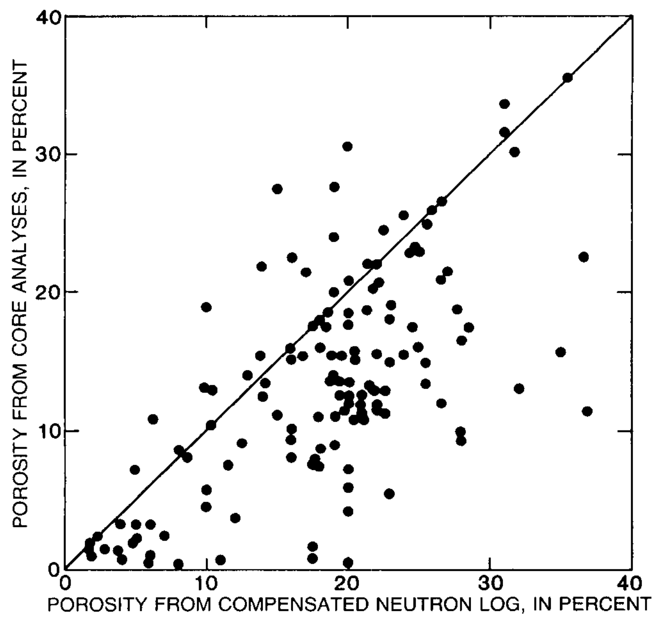


Figure 26.—Porosity from core analyses versus porosity from a compensated neutron log, Madison Limestone test well 1, Wyoming.

Care must be taken to ensure that the components of a calibration facility—the fluid, rock matrix, and borehole—do not change over time. An example of change is wear of the borehole caused by centralizing or decentralizing bow springs or caliper arms. A well frequently used for testing the acoustic televiewer at Mobil Oil's Dallas Research Center has three obvious grooves worn by the centralizing bow springs of televiewer probes.

At least three, and preferably more, values are needed to establish a calibration curve using pits; many more values are needed if core is used. Log values for calibration should be based on both continuous logging runs and stationary measurements. Measurements are best made at depths where the physical property being measured is consistent, if the depth interval is greater than the vertical dimension of the volume of investigation of the probe. Particularly for the nuclear probes, the logs should be run very slowly, and the stationary measurements should be long term to decrease statistical error. If spacings or other probe parameters are to be changed, then calibration is needed at each of these adjustments. The field standards to be used on the logging truck should be checked before and after calibration to determine the relation between log values given by these standards and calibration values, and to ensure probe stability during the testing period. Corrections to nuclear logs may have to be made for the decay of radioactive sources based on half-life.

Standardization

Field standards should be checked before and after each log is recorded, and the values should be written on the log if the data are to be used quantitatively. Frequent standardization of probes provides the basis for correcting for system drift over time. Radioactive decay of sources used in probes or in calibration is the only form of drift that can be calculated; standardization is needed to check the calculations. Obviously, equipment for checking field standards must be portable and easily used, but it also must be stable and affected little by the different conditions at each well site. An example of a nonstable standard is a once-used commercial neutron "calibrator" that changed as the plastic insert gradually absorbed water. Most field standards are not infinite with respect to the probes on which they are used, so they are affected by the environment. The best that can be done to reduce these extraneous effects is to raise the standard and probe off the ground and move away from the logging truck. Neutron probes, for example, are affected by moisture changes at the ground surface near the probe; a pair of folding sawhorses is useful for reducing ground effects. Values for field standards usually are point values, and these digital values should be recorded on the log heading. Several long-time readings, at least 100 s, are needed for nuclear probes. While the readings are being recorded, the analog recorder should be operated on time drive so variations in probe output are recorded as a function of time. If drift is observed on the analog record, the final measurement should be made after the readings have stabilized. The long-time value is then divided to produce the same count-rate units as the log.

Two or more field standards should be used to provide at least two values; more values may be included if size and time involved are not limiting factors. These values should be in the same range as the borehole data being recorded. For example, a 100-percent porosity value is fairly easily obtained for a neutron probe in a large volume of water, but this small count-rate point does not establish probe response at less than 1 percent porosity where the count rate will be more than an order of magnitude greater. Some standardization can be done in a borehole; zero resistivity can be measured in a water-filled steel casing of sufficient length to include all electrodes. Casing of known diameter also provides an excellent check of caliper and flowmeter calibration. Logs for which there are no standardization data cannot be used with confidence because all logging probes are susceptible to malfunction and drift and the effects of any malfunction or drift may not be identified readily on a rapidly varying log.

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

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

Electric Logging

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

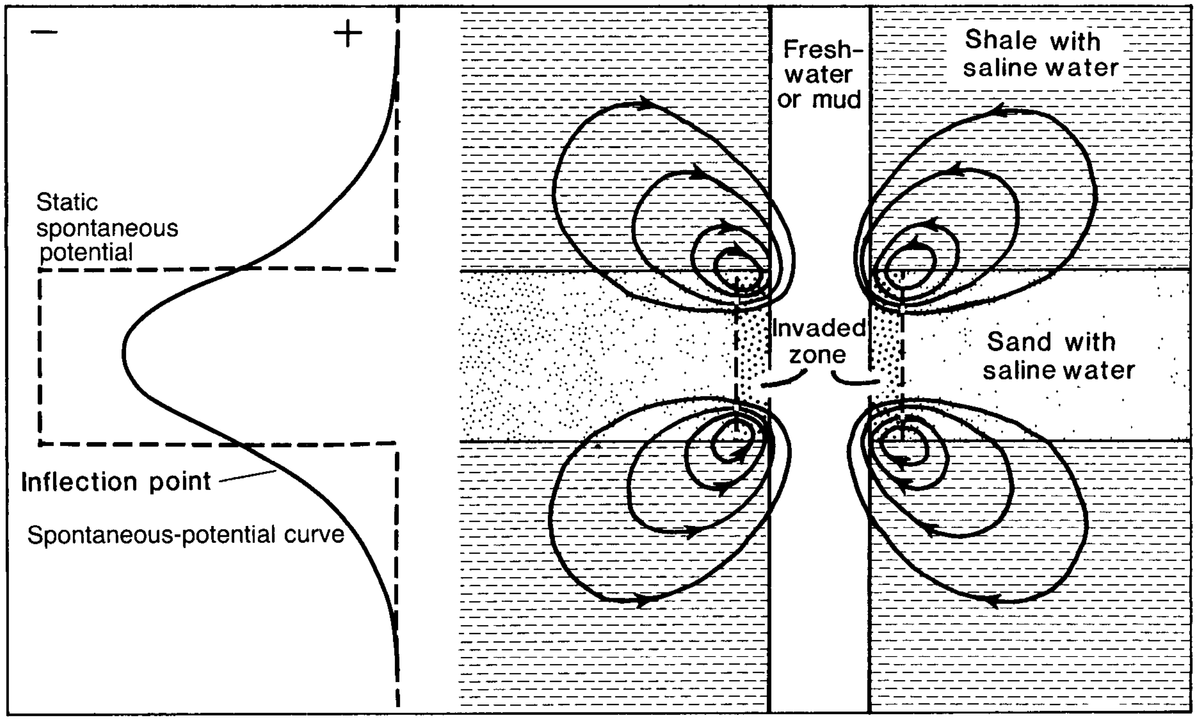


Figure 27.—Flow of current at typical bed contacts and the resulting spontaneous-potential curve and static values (modified from Doll, 1948).

Spontaneous-potential logging

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

Principles and instrumentation

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

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

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

Calibration and standardization

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

Volume of investigation

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

Extraneous effects

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

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

Interpretation and applications

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

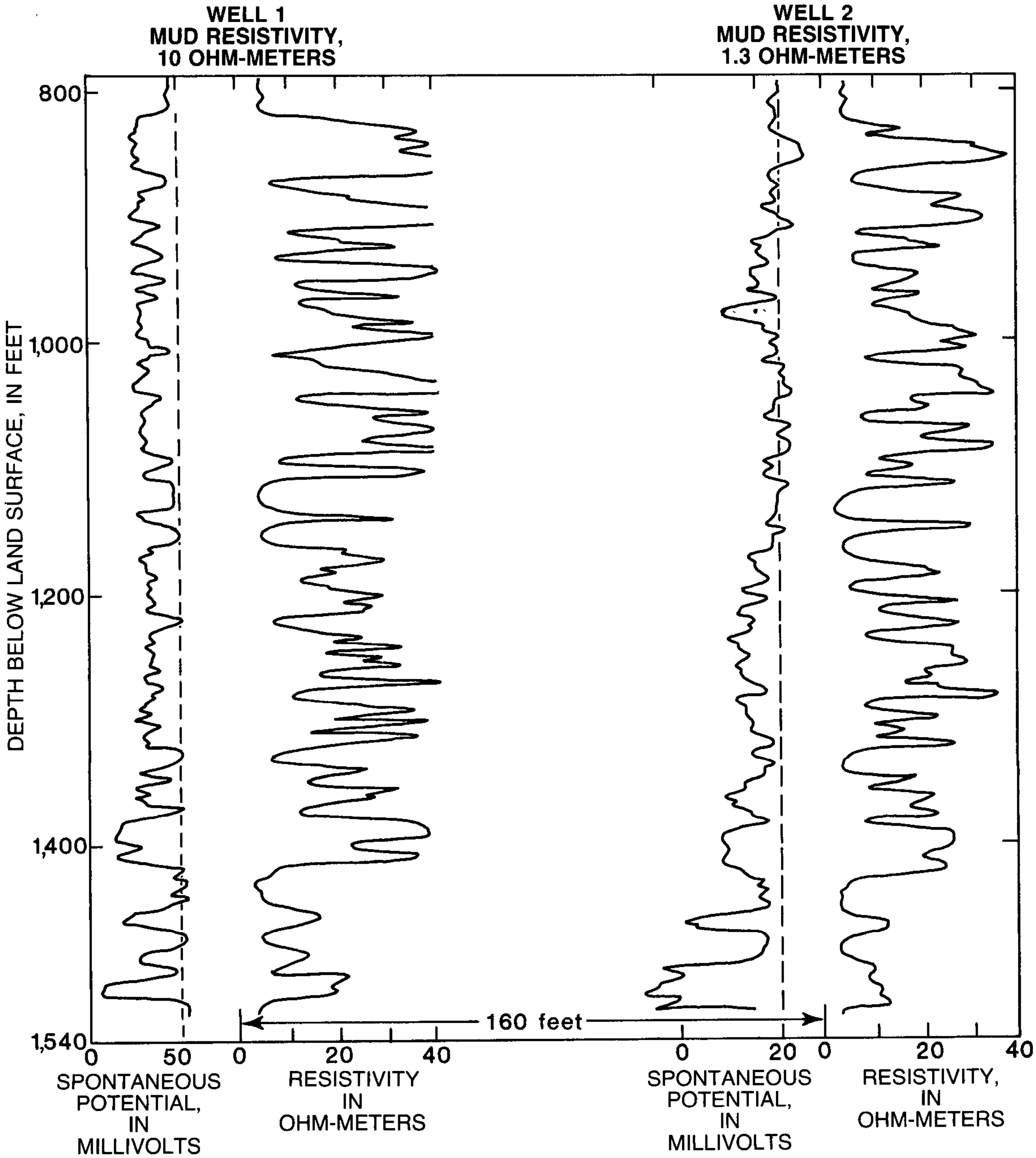


Figure 28.—Changes in spontaneous-potential and resistivity logs caused by differences in mud salinity in two closely spaced wells, Houston, Tex. (Guyod, 1966).

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

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

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

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

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

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

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

where

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

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

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

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

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

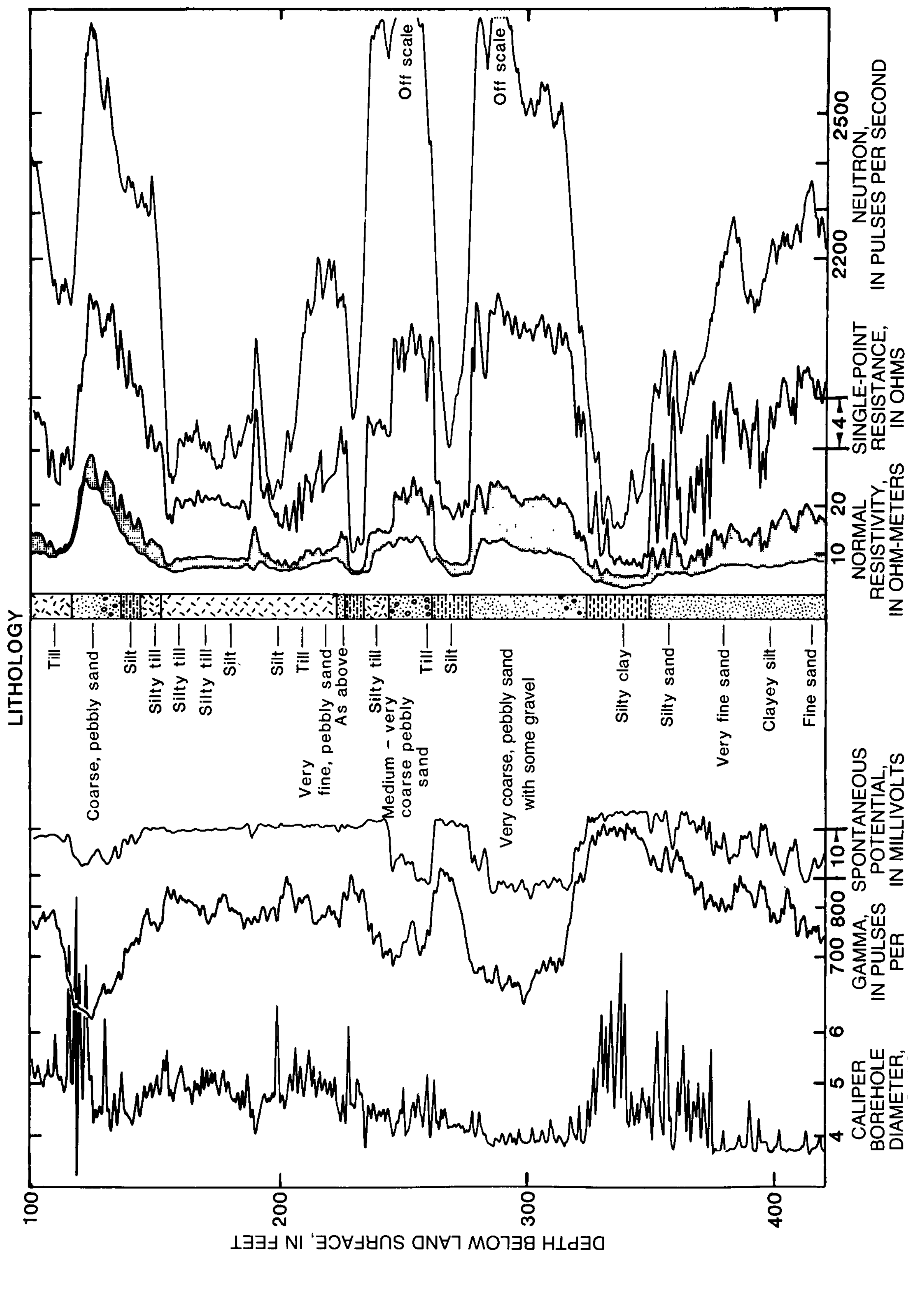


Figure 29.—Caliper, gamma, spontaneous-potential, normal-resistivity, single-point-resistance, and neutron logs compared with lithology, Kipling, Saskatchewan, Canada (Dyck and others, 1972).

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

Single-point-resistance logging

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

Principles and instrumentation

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

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

where

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

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

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

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

Calibration and standardization

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

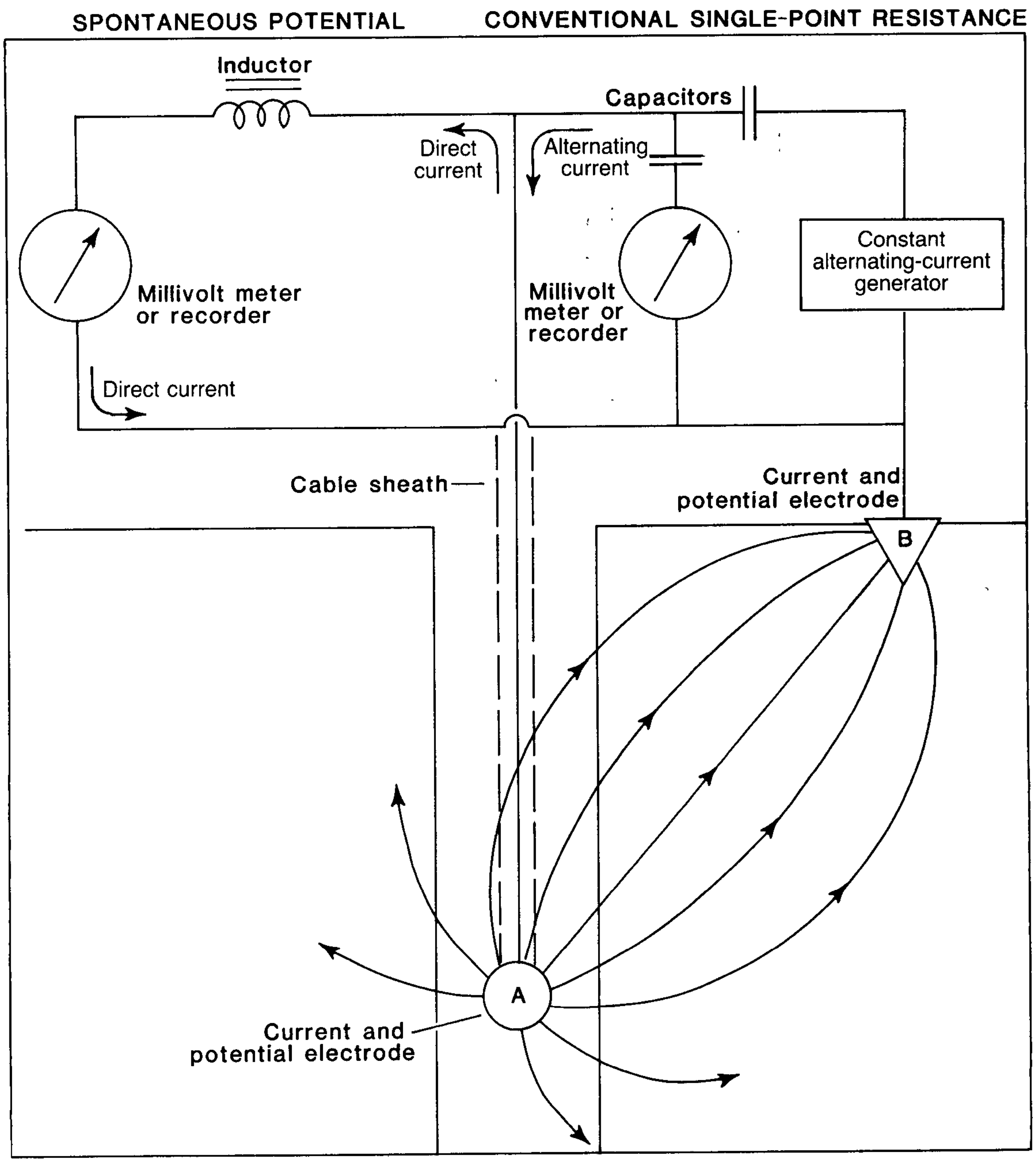


Figure 30.—System used to make spontaneous-potential and conventional single-point-resistance logs.

Volume of investigation

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

Extraneous effects

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

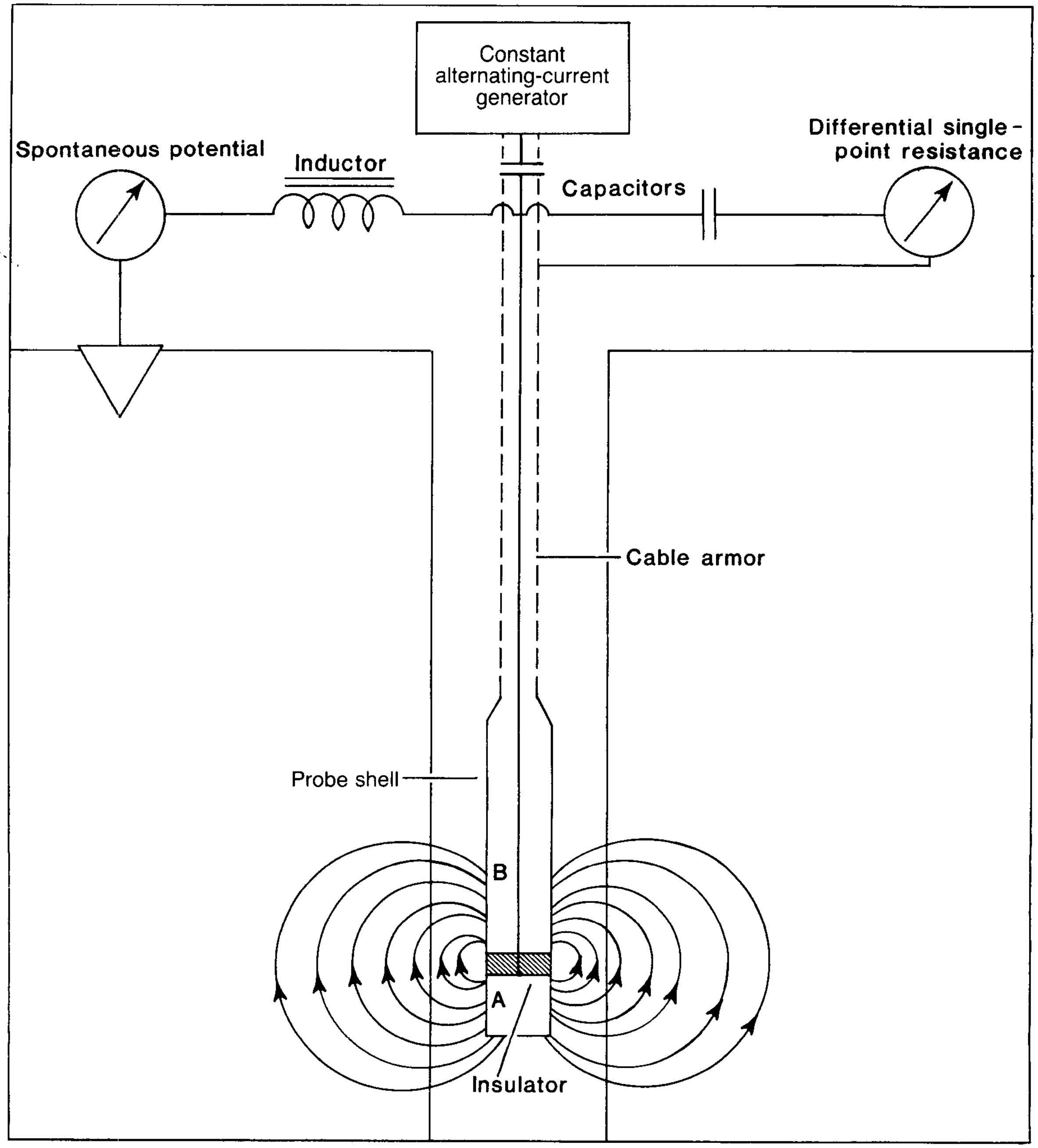


Figure 31.—System used to make spontaneous-potential and differential single-point-resistance logs.

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

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

Interpretation and applications

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

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

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

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

Normal-resistivity logging

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

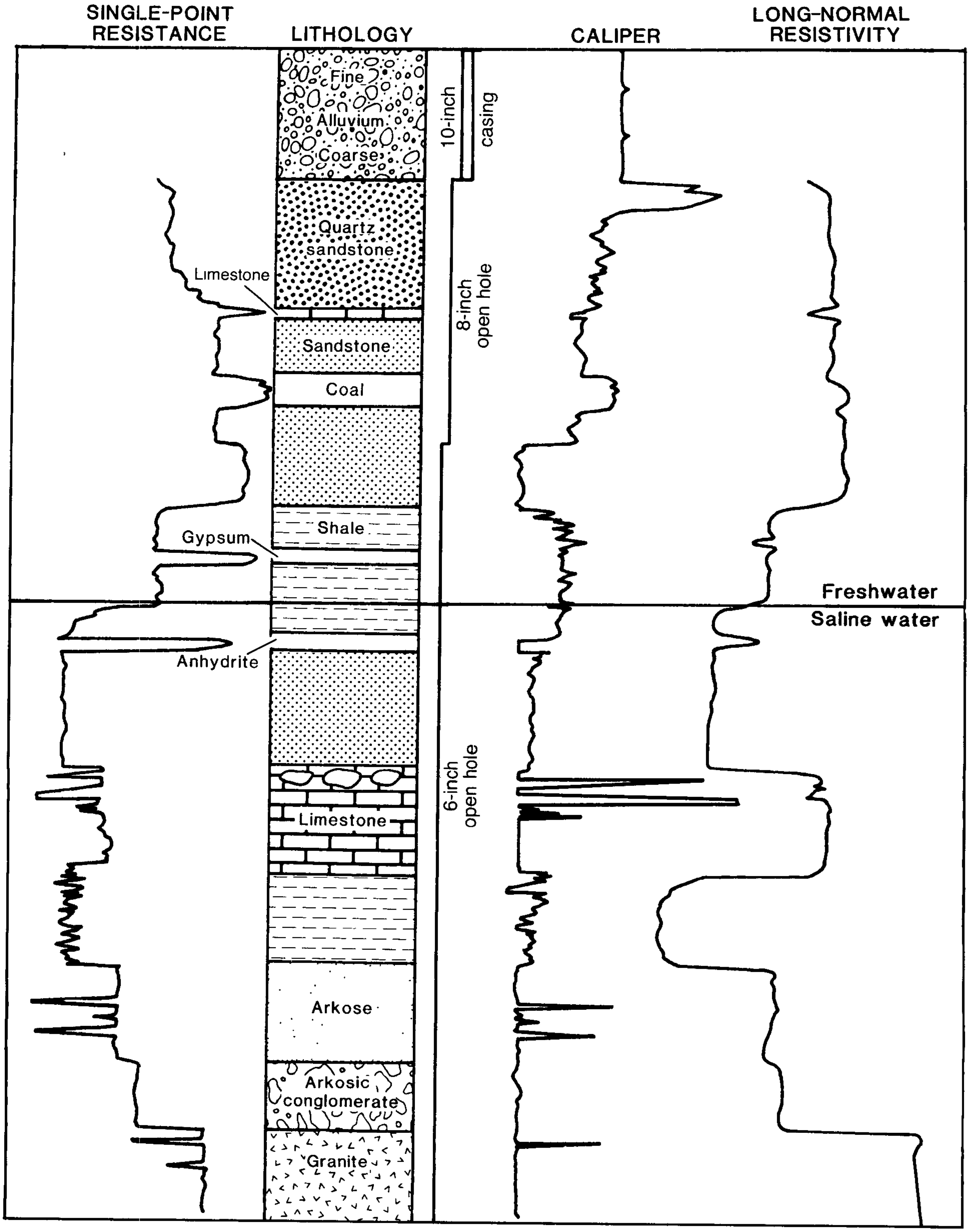


Figure 32.—Typical responses of single-point-resistance, caliper, and long-normal-resistivity logs to a sequence of sedimentary rocks.

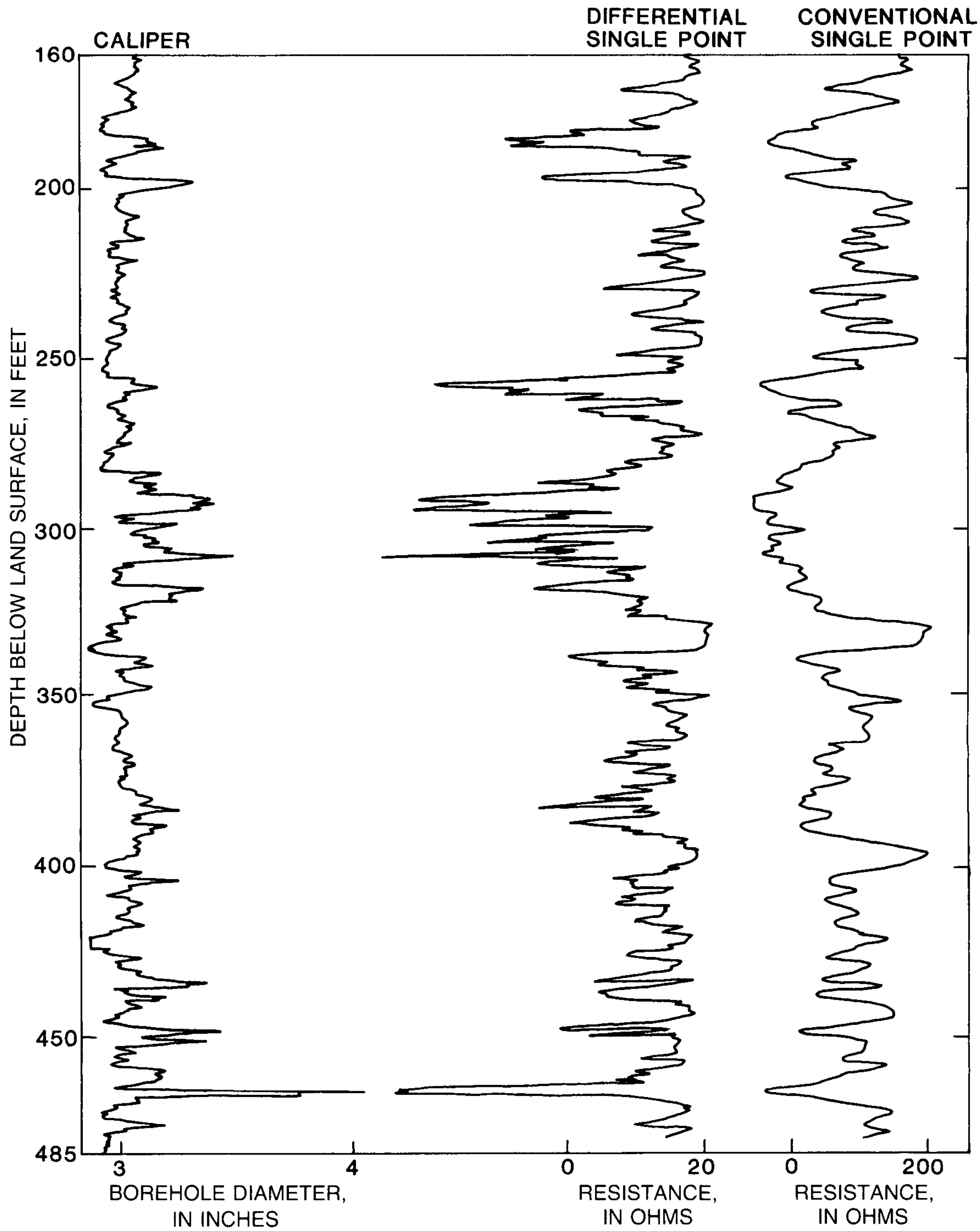


Figure 33.—Caliper and differential and conventional single-point-resistance logs in a well penetrating fractured crystalline rocks.

Principles and instrumentation

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

$$R=r\times S/L \tag{4}$$

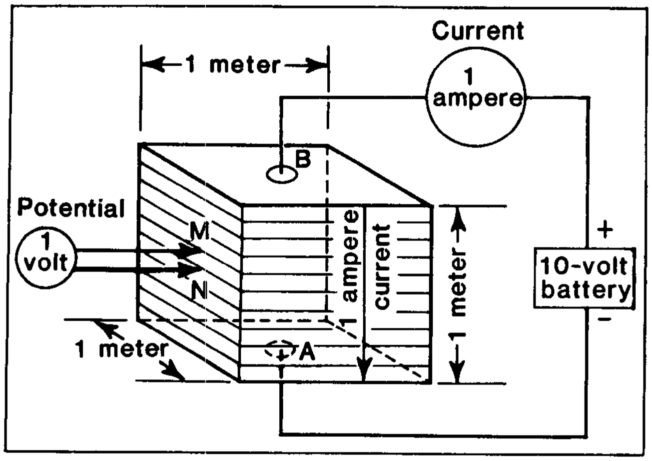


Figure 34.—Principles of measuring resistivity, in ohm-meters. Example is 10 ohm-meters.

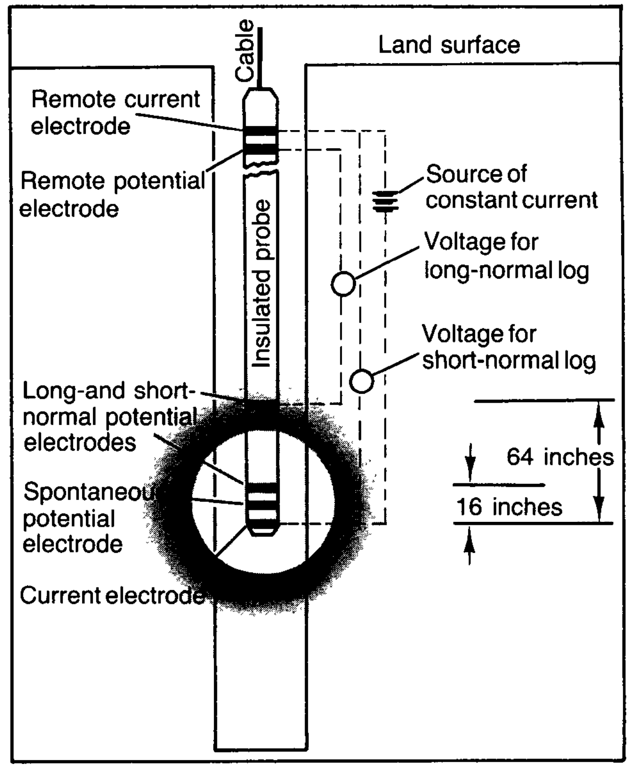


Figure 35.—System for making 16- and 64-inch normal-resistivity logs. Shaded areas indicate relative sizes of volumes of investigation.

where

R=resistivity, in ohm-meters;

r =resistance, in ohms;

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

L =length, in meters.

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

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

A simplification of a normal-resistivity logging system, without the letters identifying the electrodes, is shown in figure 35. Constant current is maintained between a current electrode at the bottom of the probe and a remote-current electrode at a distance of 50 ft or more. The voltages for the long-normal (64 in) and short-normal (16 in) logs are measured between a potential electrode for each, located on the probe, and a remote potential electrode. In an actual logging system, the remote-current and potential electrodes are distant from each other. An insulating section of cable (bridle) is used to ensure that the lower portion of the logging cable does not act as the return current electrode. The spontaneous-potential electrode is located between the short-normal potential and current electrodes. The relative difference between the volumes of material investigated by the two normal systems also is illustrated in figure 35. The volume for the long-normal system is shaded dark; the volume for the short-normal system is lighter and smaller. Because the depth-reference points for the long- and short-normal systems are different when logging up the hole, the long-normal log will show a change in resistivity before the short-normal log. The *long-*

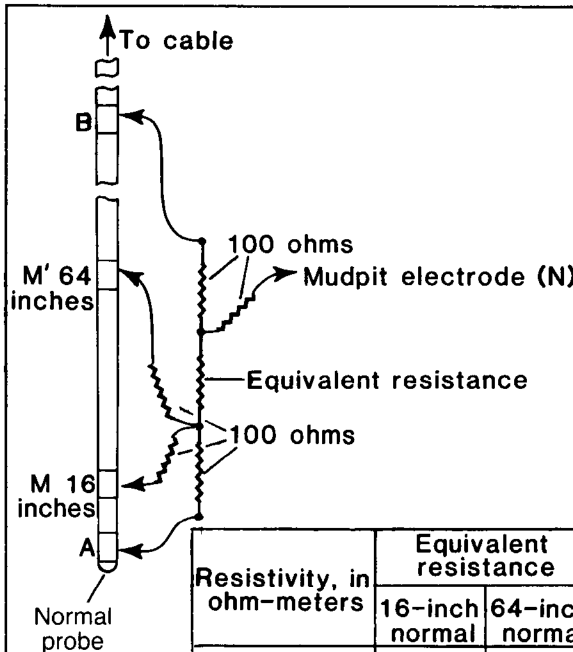
normal reference is 2 ft above the short-normal reference, but this can be corrected by adjusting the pens on the recorder. Usually, spontaneous potential is recorded in the left-recorder track and the resistivity curves, distinguished by different pen colors or patterned traces, are recorded in the right-recorder track. Because the resistivity of rocks penetrated by a borehole may vary considerably, backup scales are useful so information is not lost. Decreasing sensitivity so all data will be on scale can result in the loss of small changes that may be significant. Onsite digitizing of the data can solve some of these problems.

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

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

Calibration and standardization

Normal-resistivity logging systems can be calibrated at the land surface by placing fixed resistors between the electrodes. A schematic diagram of a system used by the U.S. Geological Survey is shown in figure 36. The formula for calculating the apparent



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

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

resistivity (*Ra*) of an infinite medium, in ohm-meters, incorporates a geometric factor with Ohm's law:

$$Ra = E/I \times 4AM \qquad (5)$$

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

$$r_f = Ra/4AM \qquad (6)$$

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

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

Volume of investigation

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

Extraneous effects

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

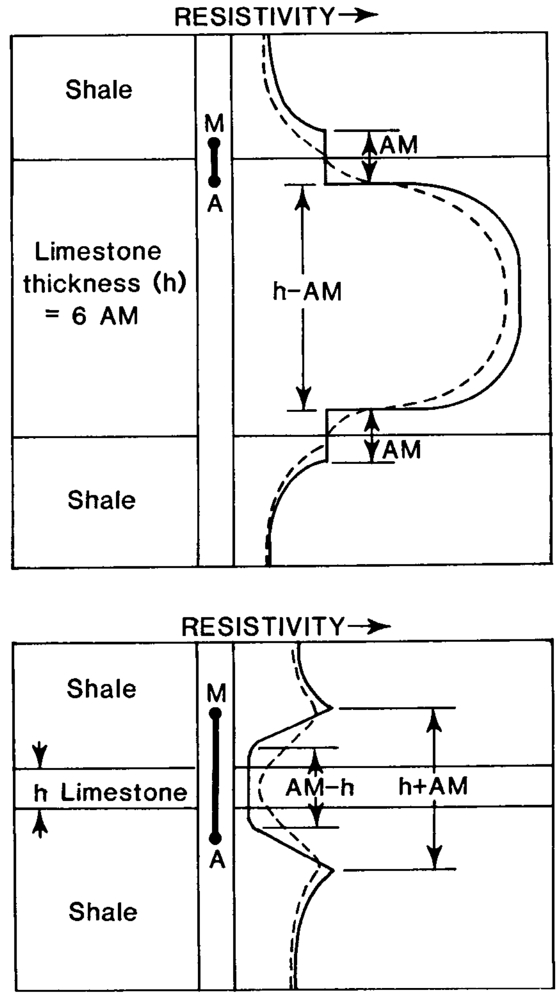


Figure 37.—Relation of bed thickness to electrode spacing for normal probes at two bed thicknesses (modified from Lynch, 1962). (Solid line is theoretical-resistivity curve, and dashed line is actual log.)

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

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

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

Interpretation and applications

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

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

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

$$Rw = 10{,}000/\text{specific conductance} \tag{7}$$

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

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

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

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

Focused-resistivity logging

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

Principles and instrumentation

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

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

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

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

Calibration and standardization

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

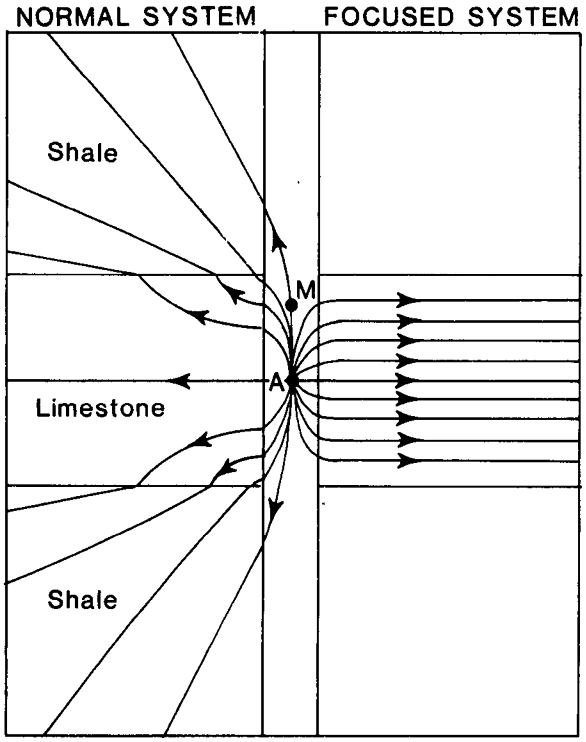


Figure 38.—Current distribution around a normal-electrode system and a focused-electrode system (laterolog).

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

Volume of investigation

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

Extraneous effects

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

Interpretation and applications

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

Lateral-resistivity logging

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

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

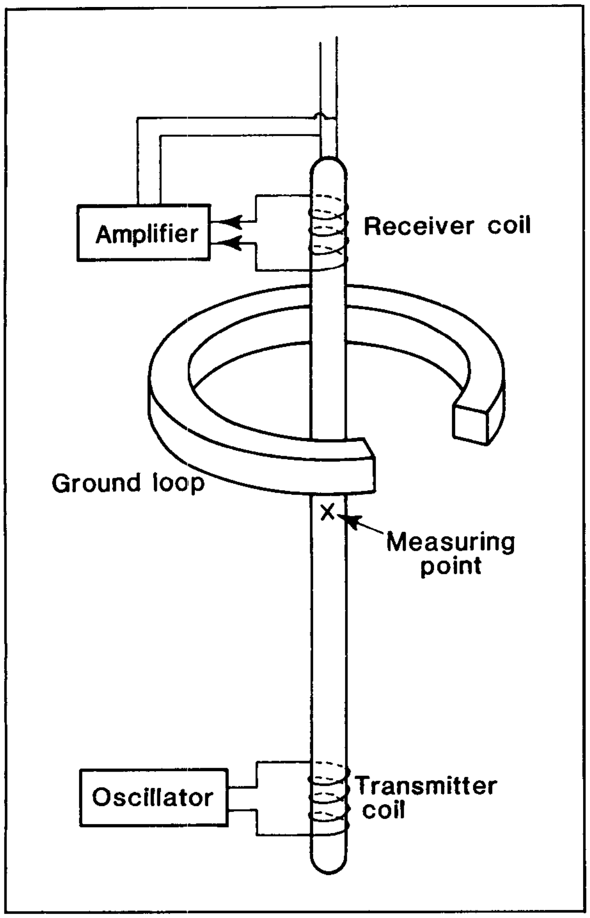


Figure 39.—System for making induction logs.

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

Induction logging

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

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

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

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

Microresistivity logging

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

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

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

Dipmeter logging

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

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

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

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

Test 2.—ELECTRIC LOGGING

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

Nuclear Logging

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

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

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.

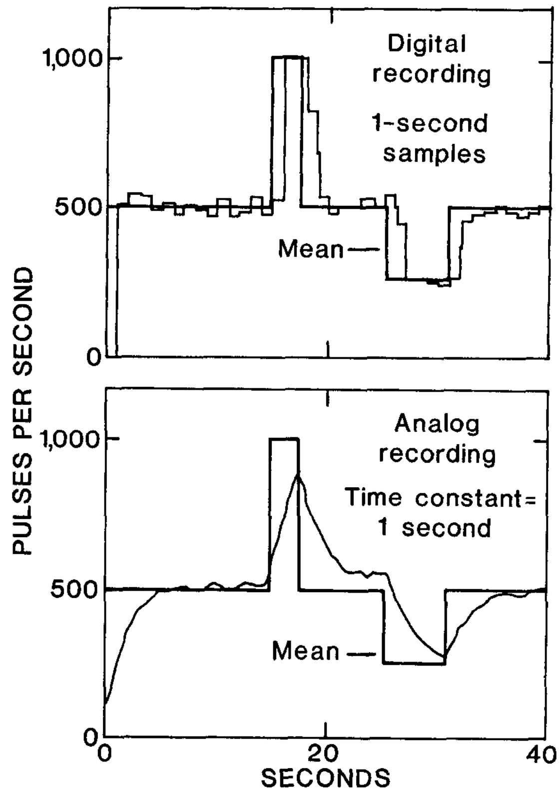


Figure 40.—Comparison of a digital recording of a gamma signal with 1-second samples and an analog recording with a 1-second time constant.

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:

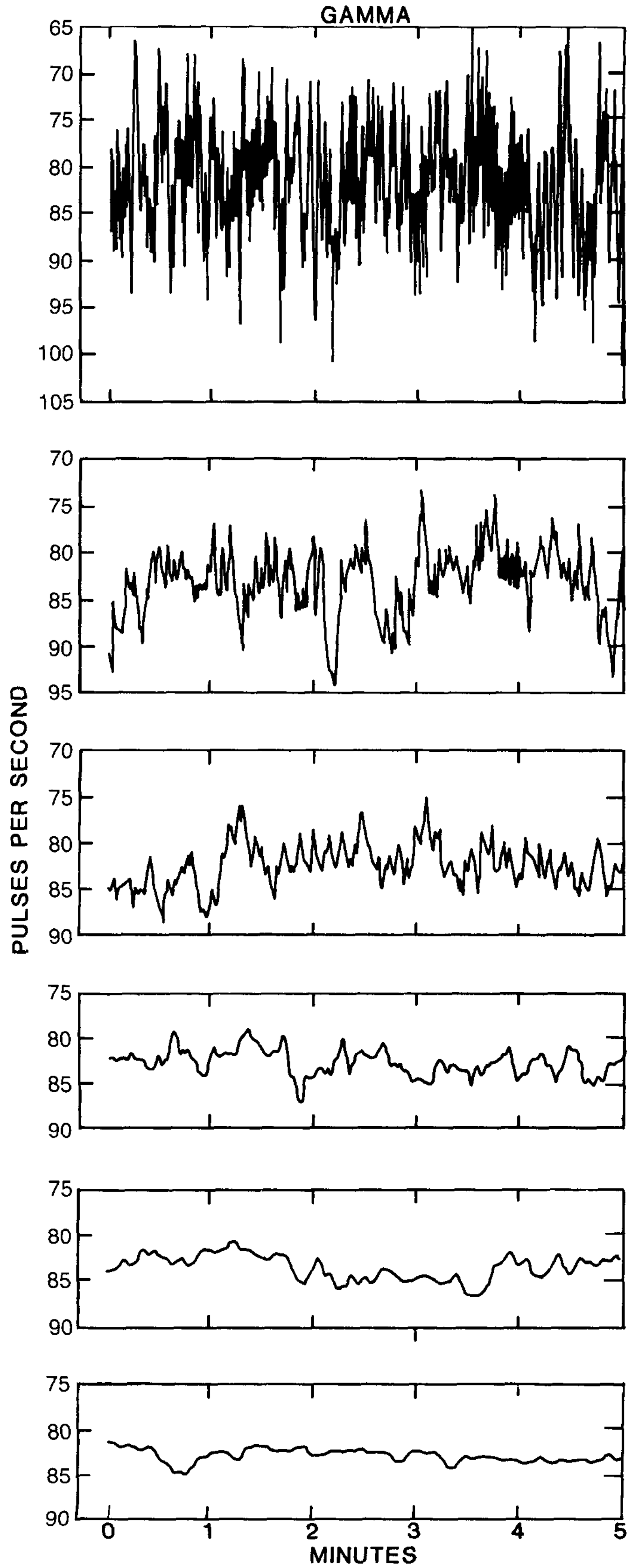
$$L' = (ls \times tc)/60 \qquad (9)$$

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).

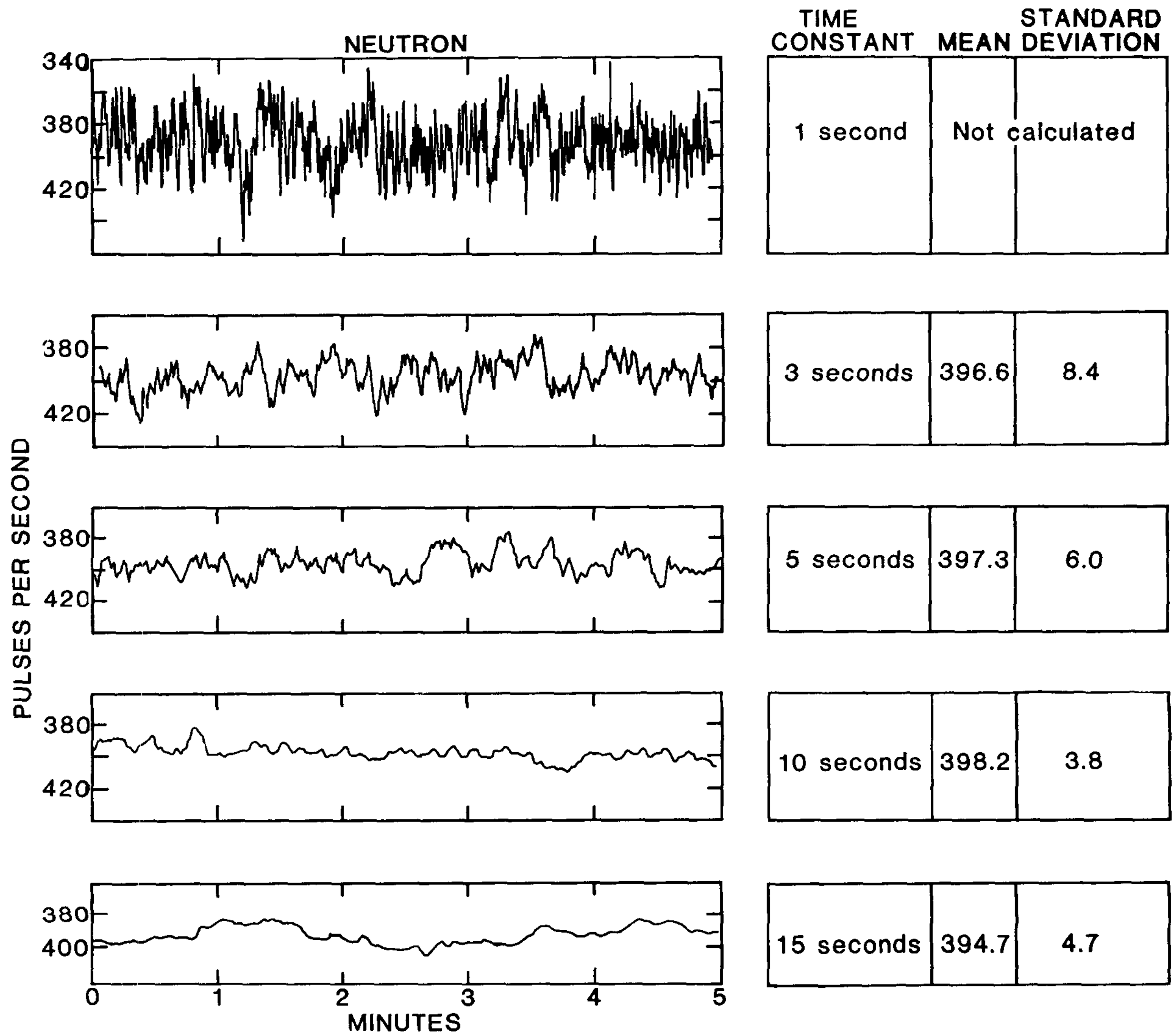


Figure 42.—Effect of time constant on data from a neutron probe at one position in a well (modified from Dyck and Reich, 1979).

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

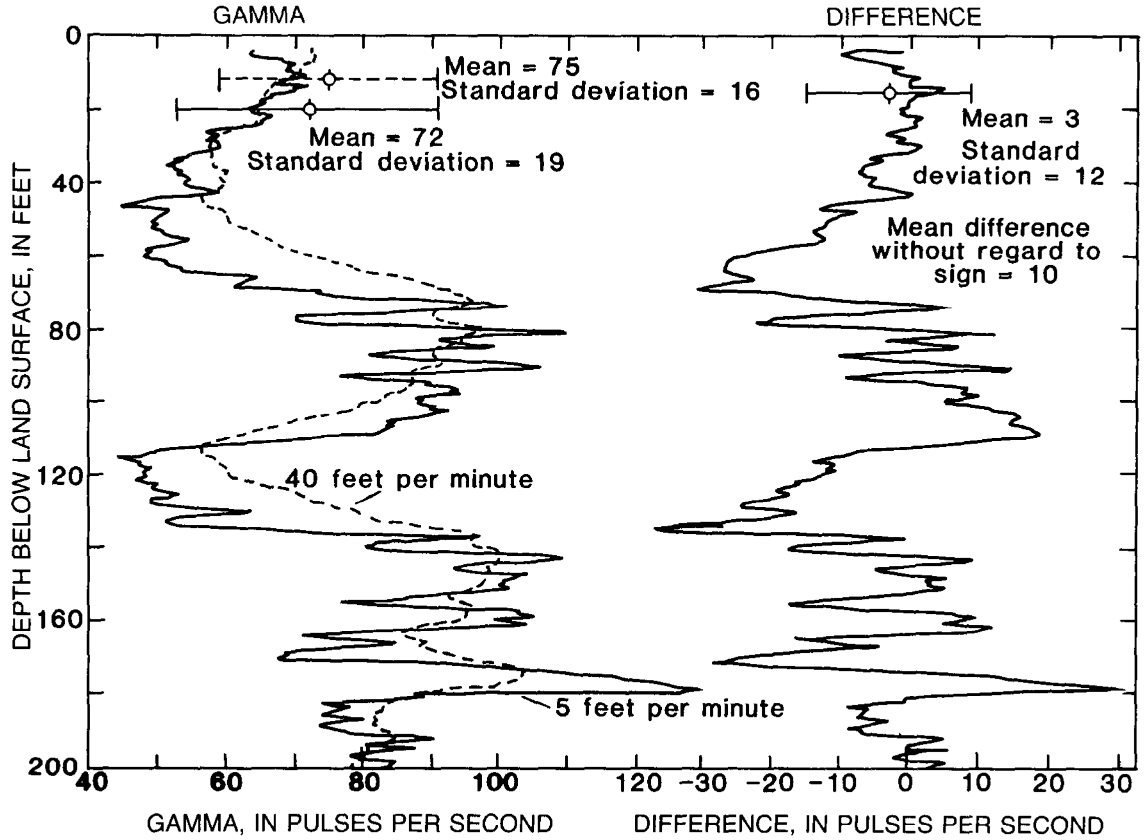


Figure 43.—Difference between gamma logs made at 5 and 40 feet per minute (modified from Dyck and Reich, 1979).

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

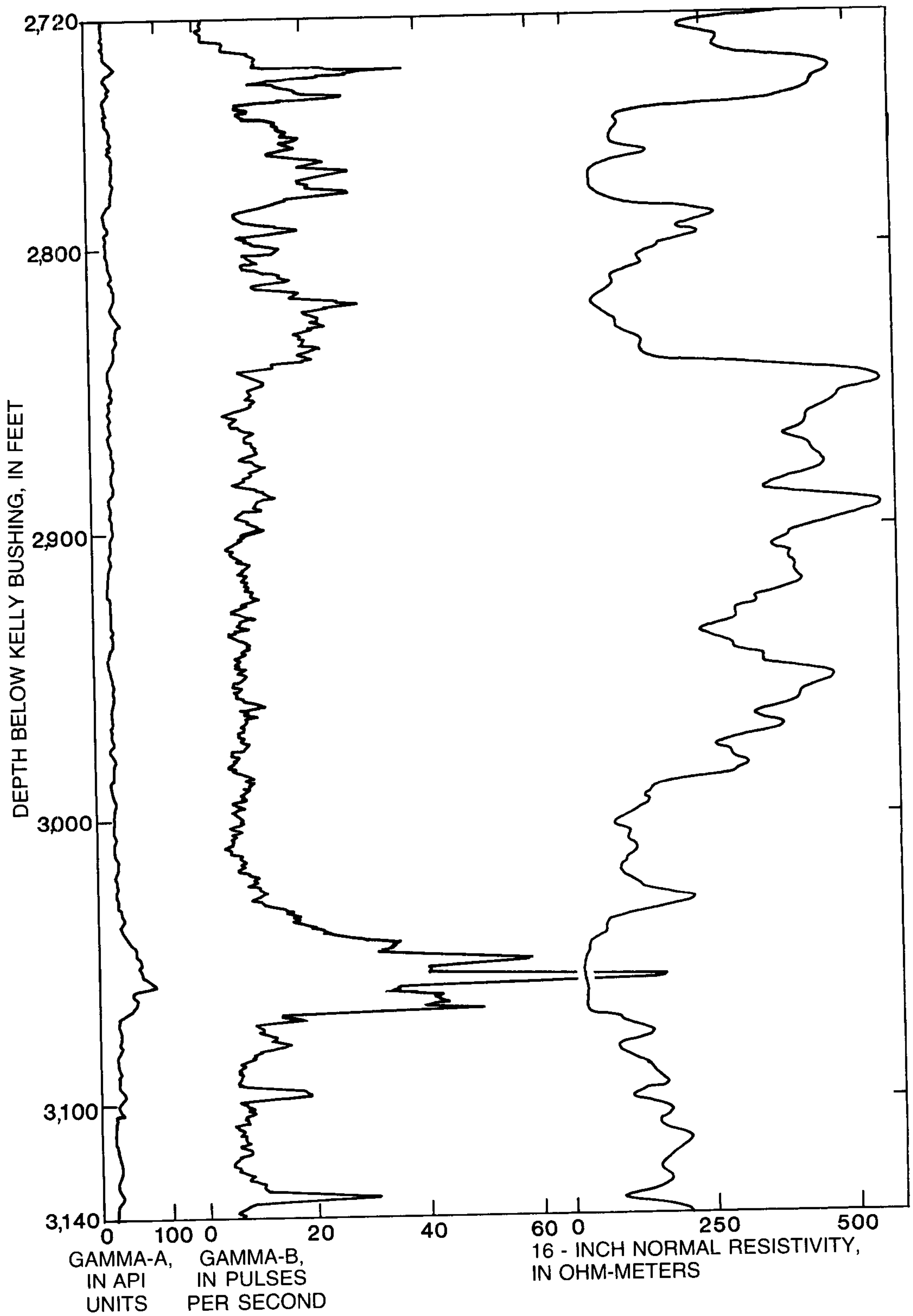


Figure 44.—Gamma logs made by a commercial service company (log A) and by the U.S. Geological Survey (log B), and a resistivity log to aid in identifying lithology, Madison Limestone test well 1, Wyoming.

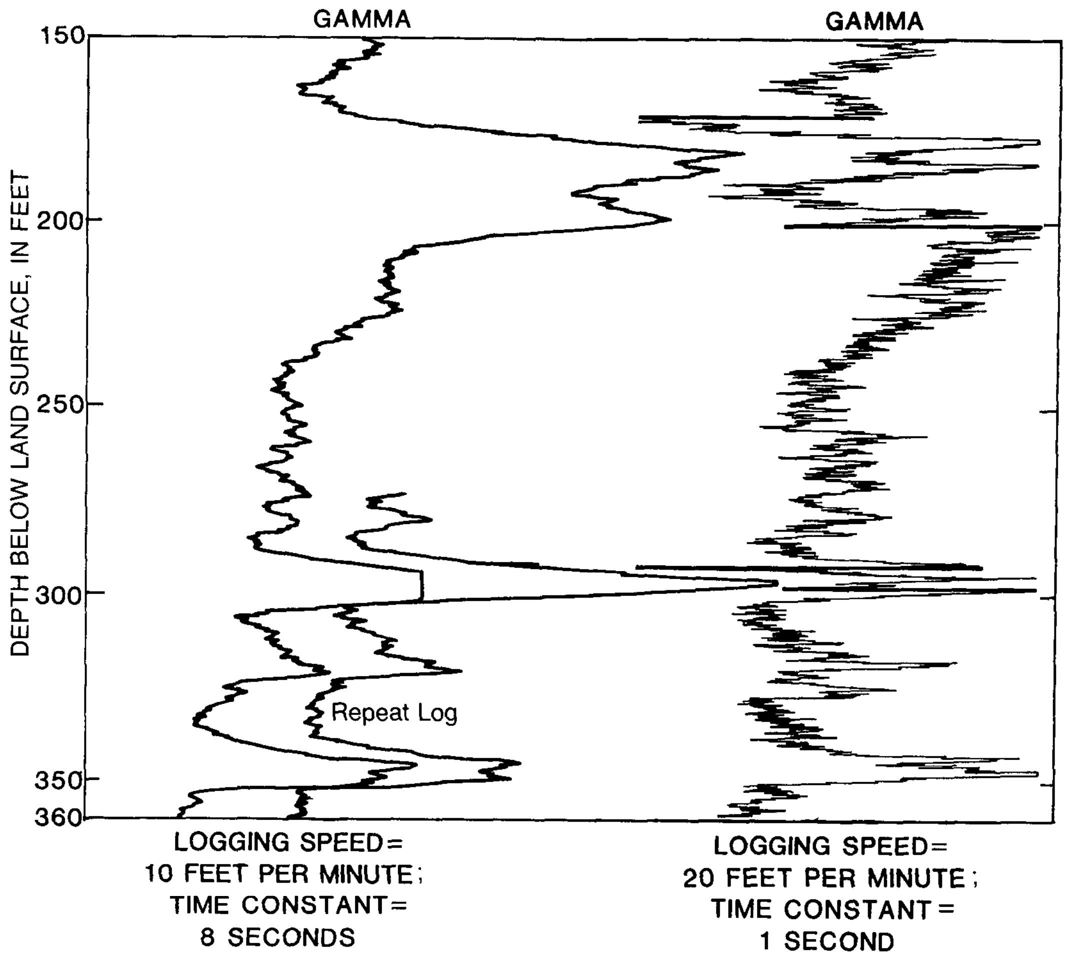


Figure 45.—Gamma logs recorded at two different logging speeds and time constants, well EX-1, Guam.

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.

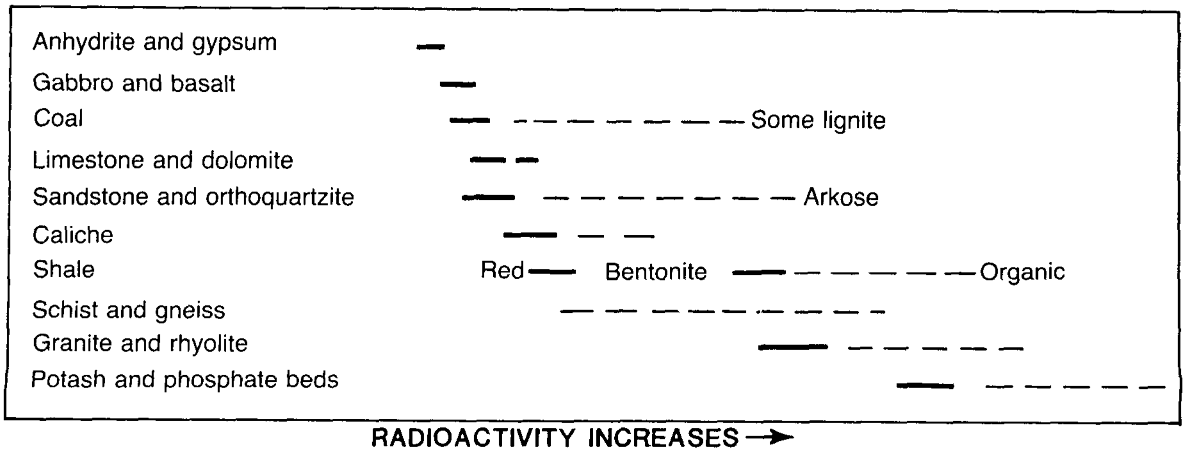


Figure 46.—Relative radioactivity of some common rocks.

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,

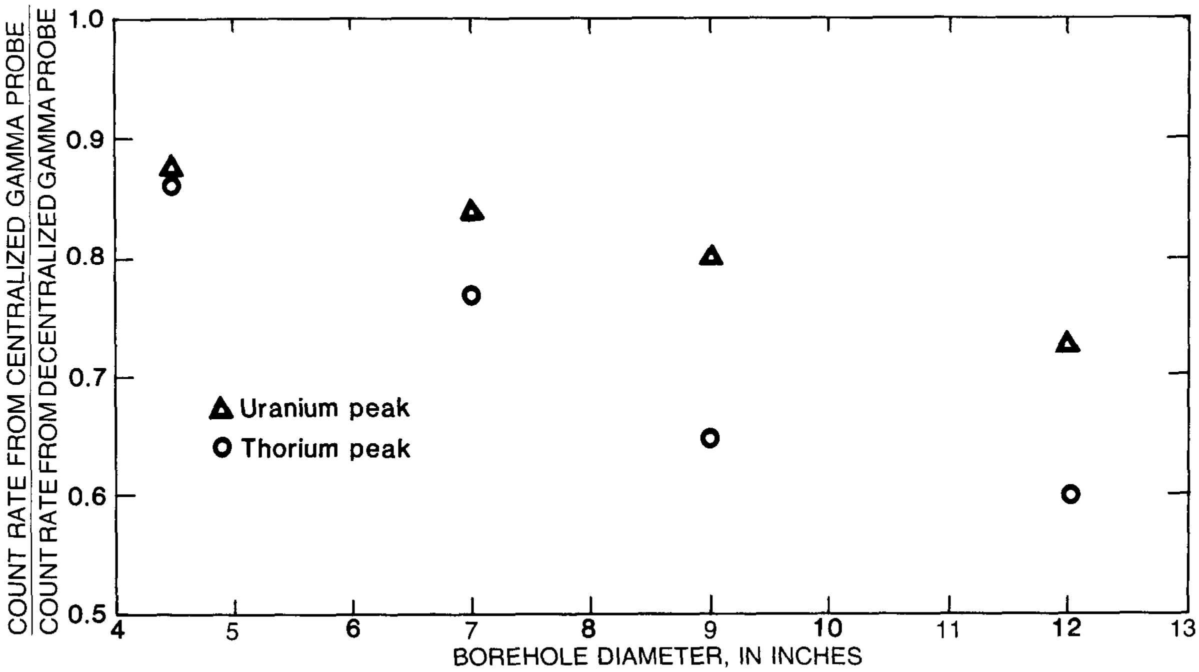


Figure 47.—Effect of position of a gamma probe in a borehole as a function of borehole diameter for uranium and thorium radiation (Ulrich Schimschal, U.S. Geological Survey, written commun., 1981).

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

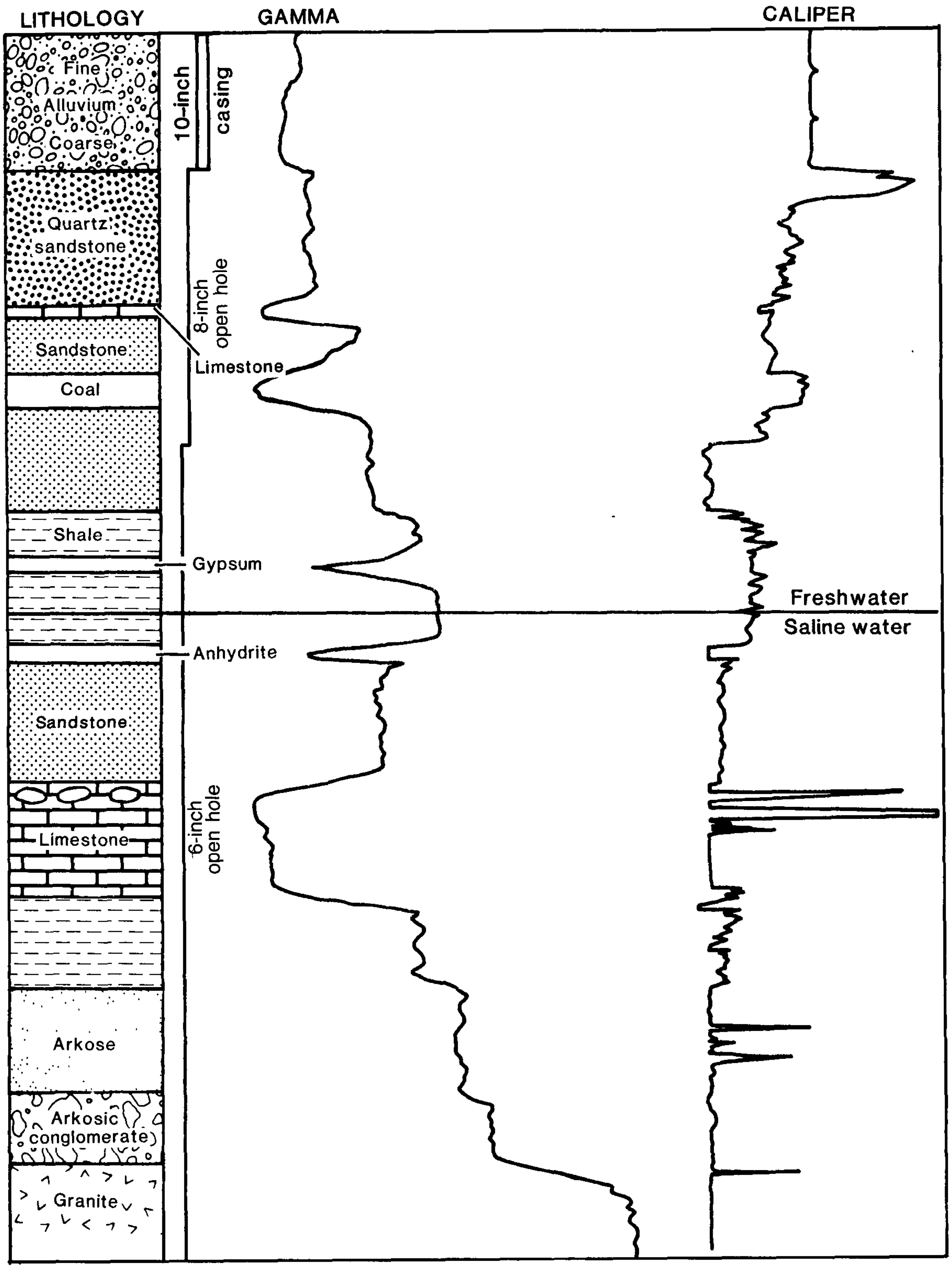


Figure 48.—Typical responses of gamma and caliper logs to a sequence of sedimentary rocks.

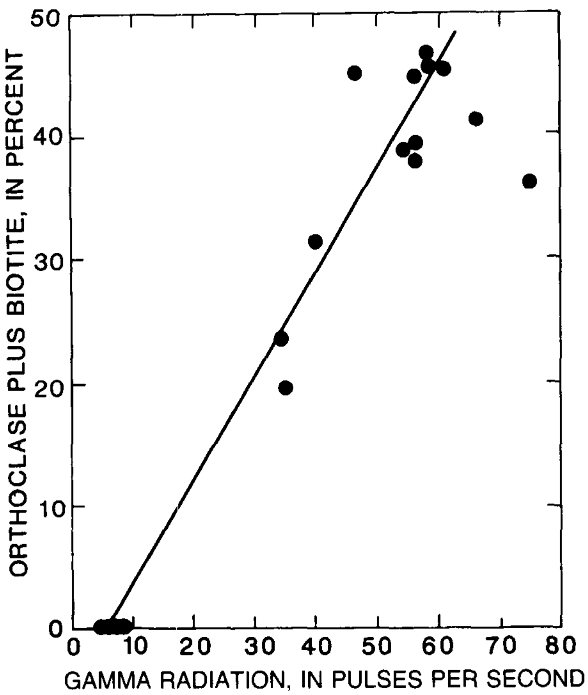


Figure 49.—Percentage of orthoclase and biotite versus gamma-log response in borehole CR-6, Ontario, Canada.

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

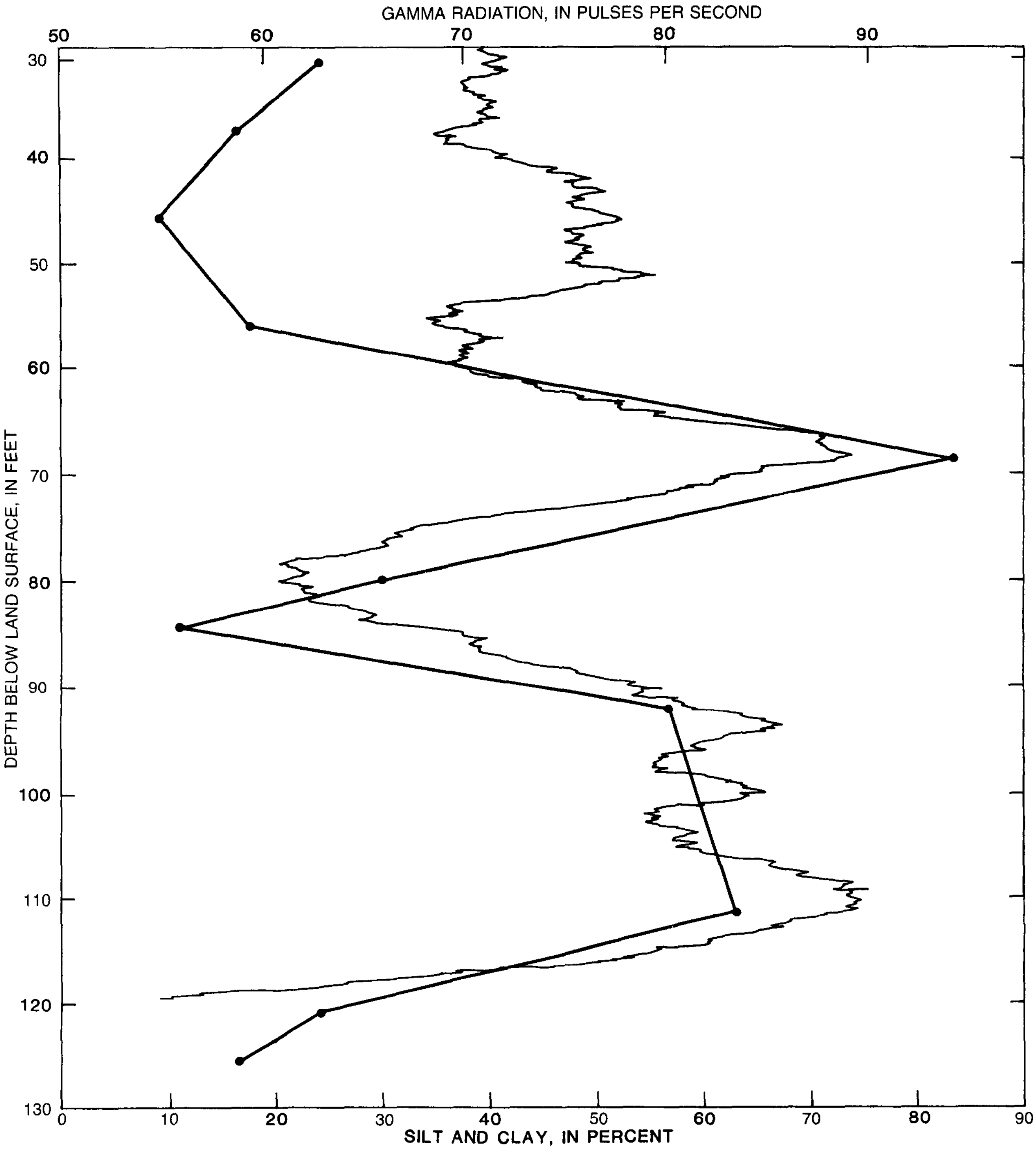


Figure 50.—Relation between percentage of silt and clay and gamma radiation from analyses of core samples from near Bear Creek, Colo.

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

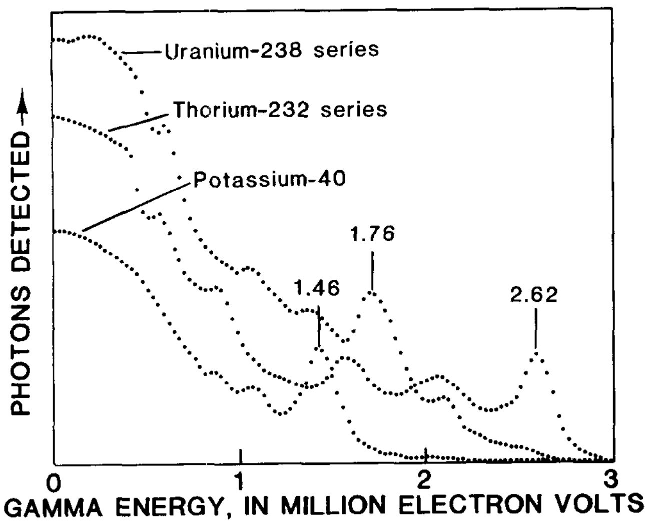


Figure 51.—Gamma spectra for the uranium-238 series, thorium-232 series, and potassium-40.

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.

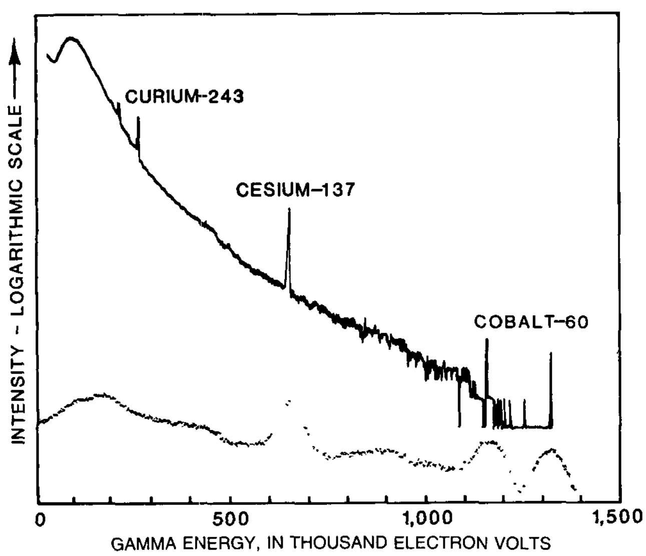


Figure 52.—Gamma spectra recorded in test hole 5-T83-5, Oak Ridge, Tenn. Upper spectrum recorded with a germanium detector; lower spectrum recorded with a sodium-iodide crystal (modified from Keys, Senftle, and Tanner, 1979).

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

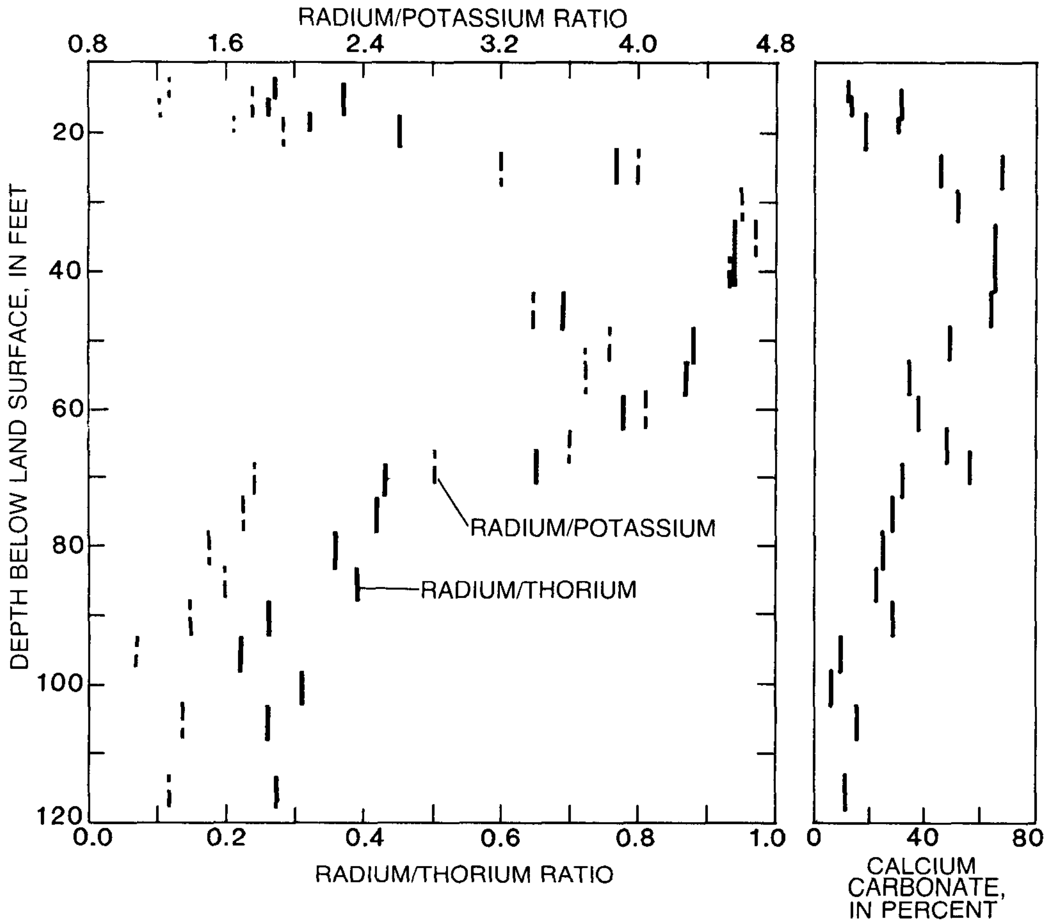


Figure 53.—Relation of calcium carbonate to radium/thorium and radium/potassium ratios from analyses of gamma spectra, Lubbock, Tex. (modified from Keys and Brown, 1971).

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

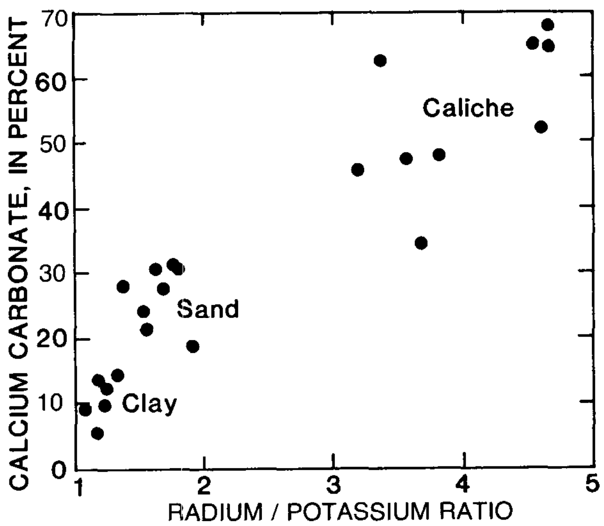


Figure 54.—Calcium carbonate versus radium/potassium ratio for a borehole in the Ogallala Formation (modified from Keys and Brown, 1971).

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.

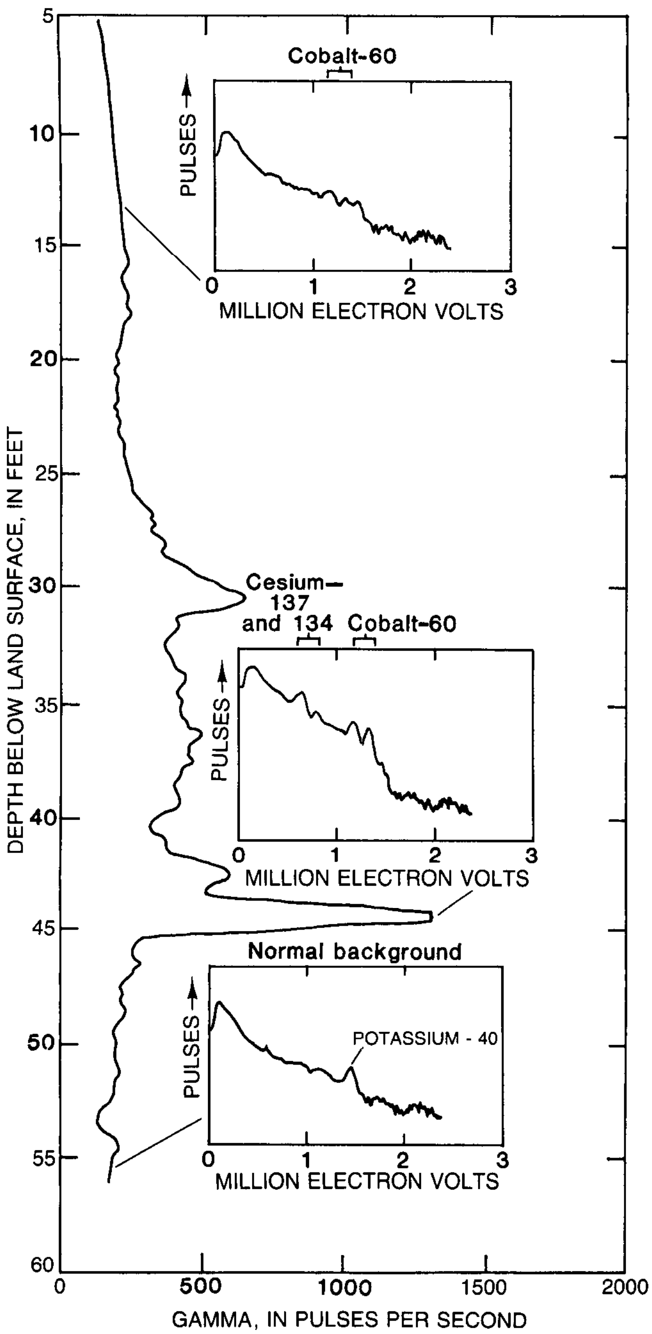


Figure 55.—Gamma log and gamma spectra at three depths, Maxey Flats, Ky. (Keys, Senftle, and Tanner, 1979).

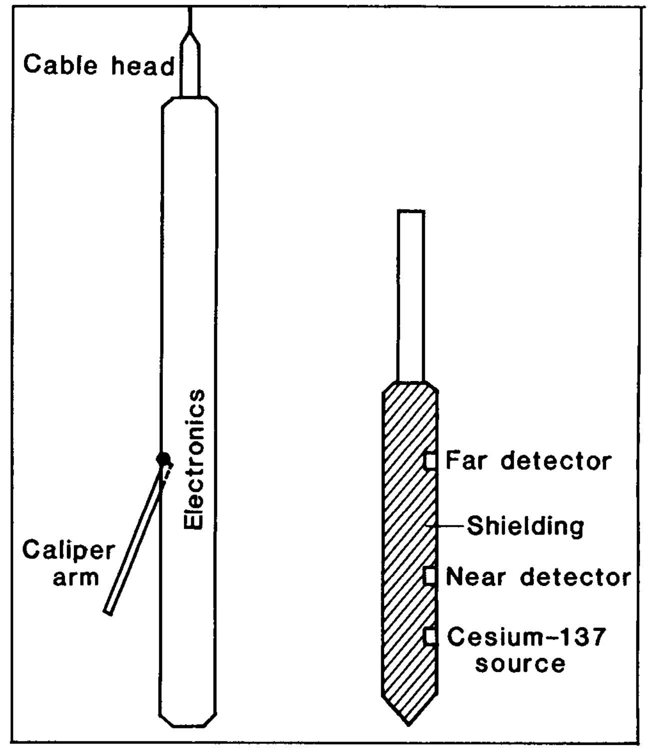


Figure 56.—Probe for making compensated gamma-gamma logs.

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.

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

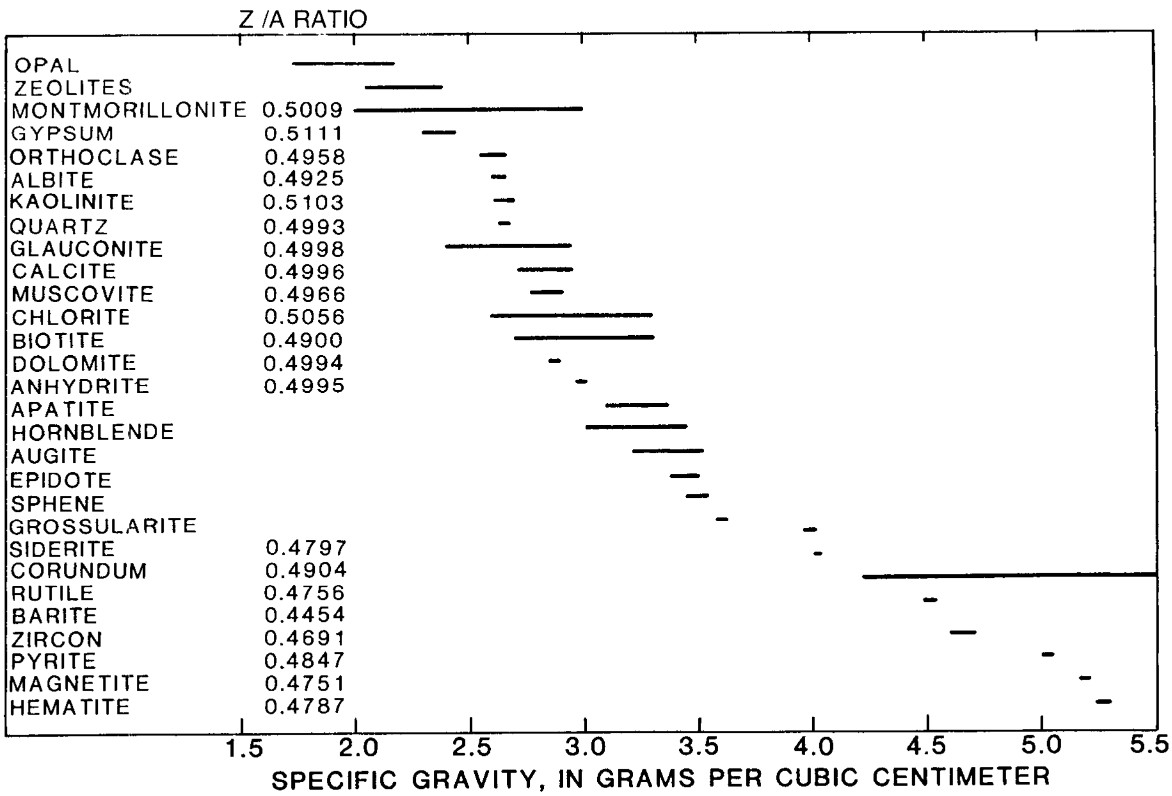


Figure 57.—Specific gravity and Z/A ratio for some common minerals (no value indicates Z/A ratio not available).

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.

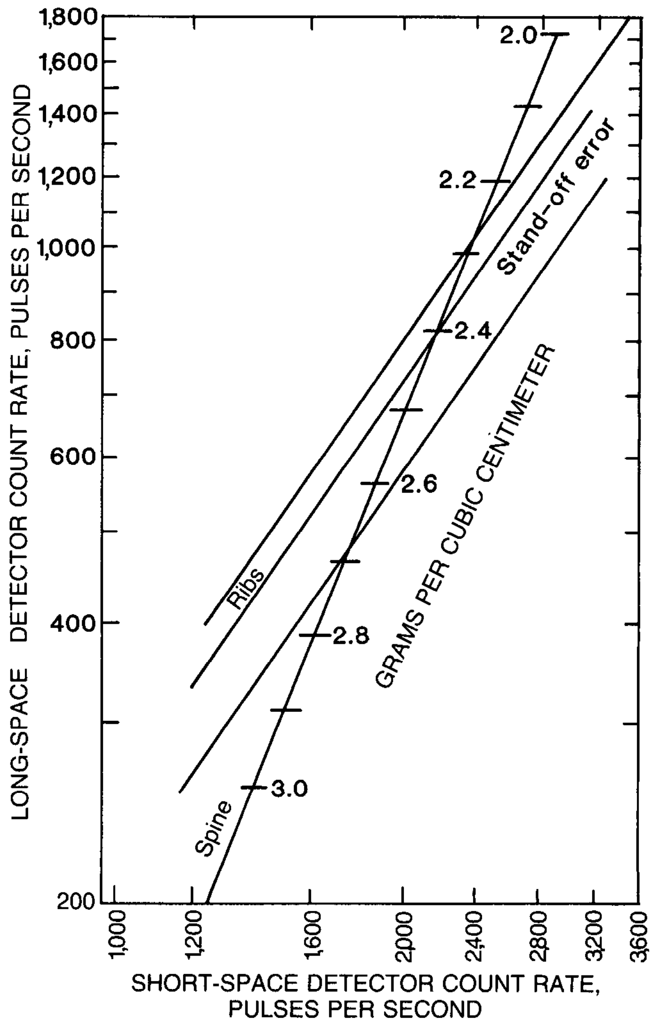


Figure 58.—Calibration plot for a dual-detector gamma-gamma probe. "Spine and ribs plot" permits correction for stand-off error.

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-

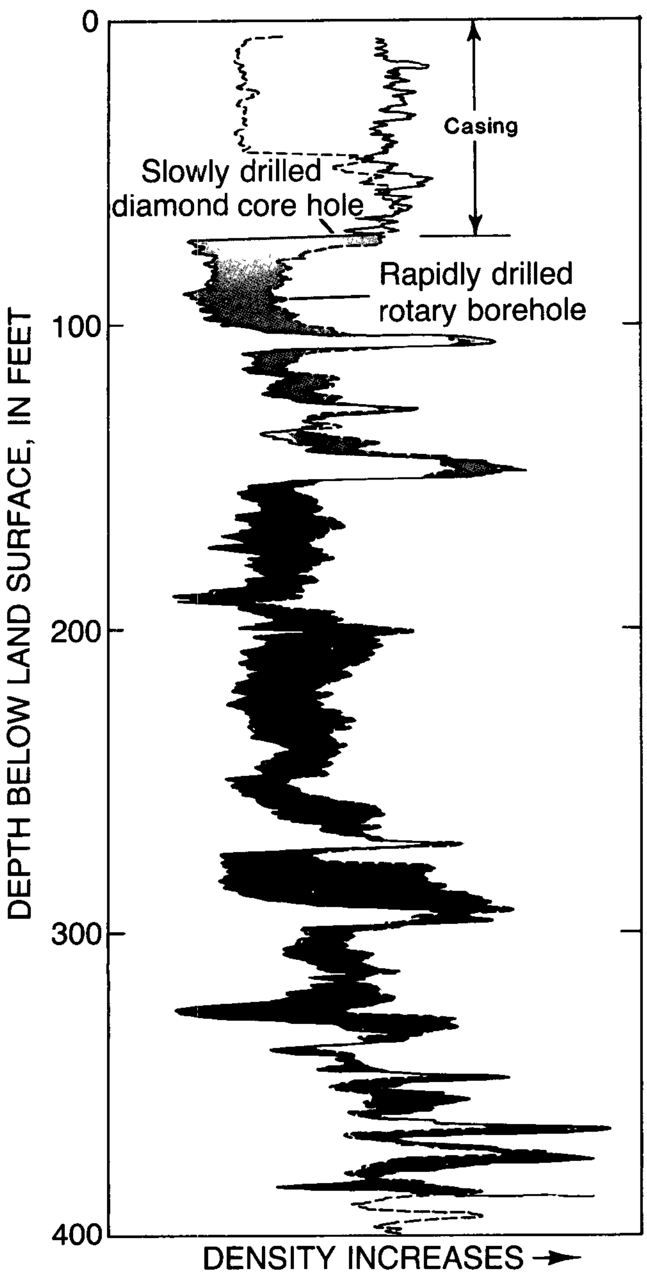


Figure 59.—Effect of drilling technique on gamma-gamma logs. (Note that the boreholes are close together in an area of persistent lithology.)

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 ground-water 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.

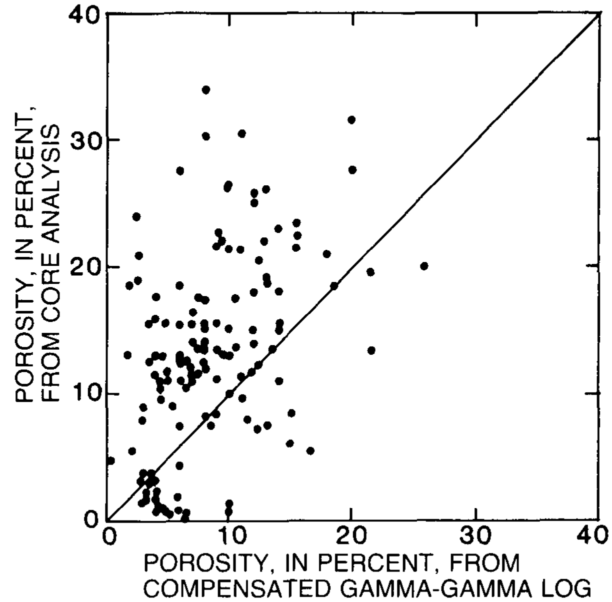


Figure 60.—Porosity from core analysis versus porosity from a compensated gamma-gamma log, Madison Limestone test well 1, Wyoming.

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

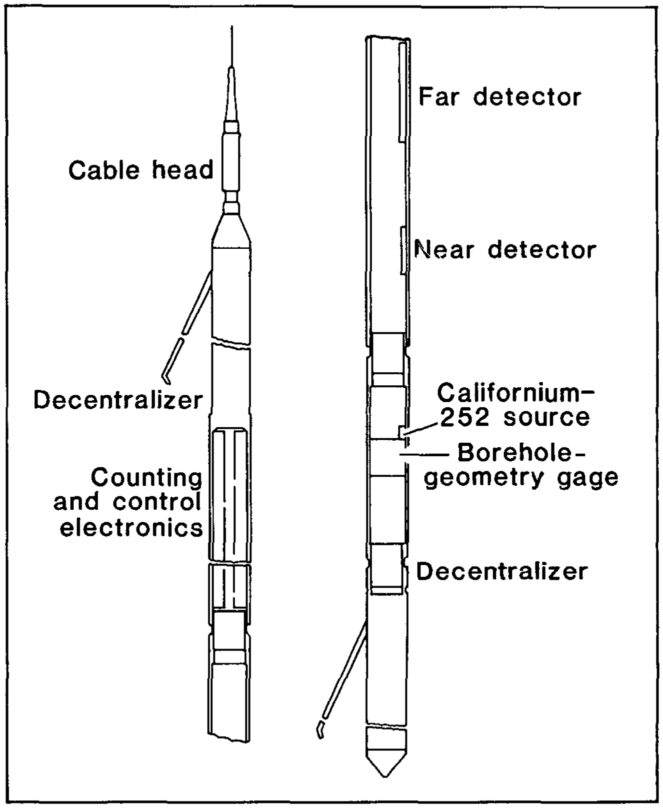


Figure 61.—Probe for making compensated neutron-porosity logs.

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

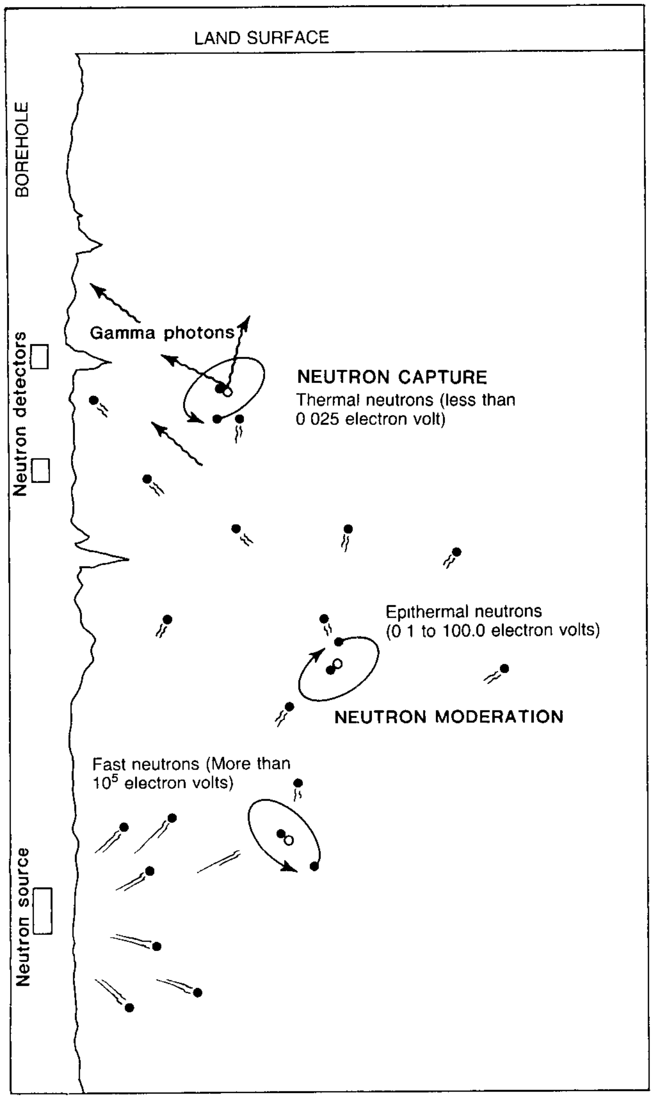


Figure 62.—Neutron processes, from source to detectors, through rocks surrounding a borehole.

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.

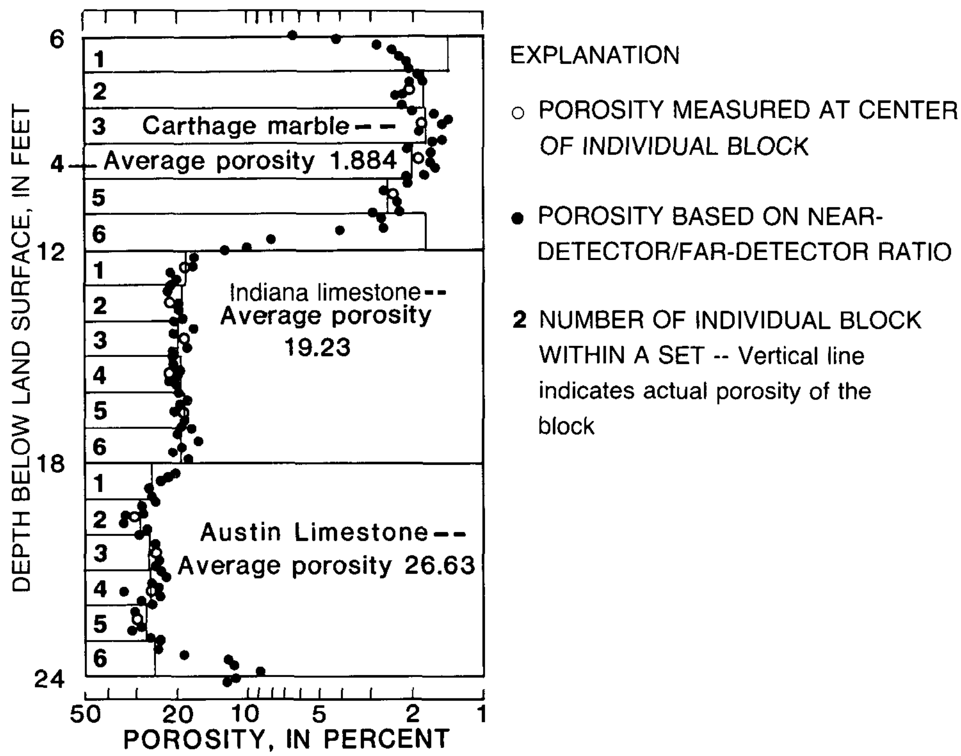


Figure 63.—Calibration data obtained with a compensated neutron-porosity probe in the American Petroleum Institute's calibration pit.

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

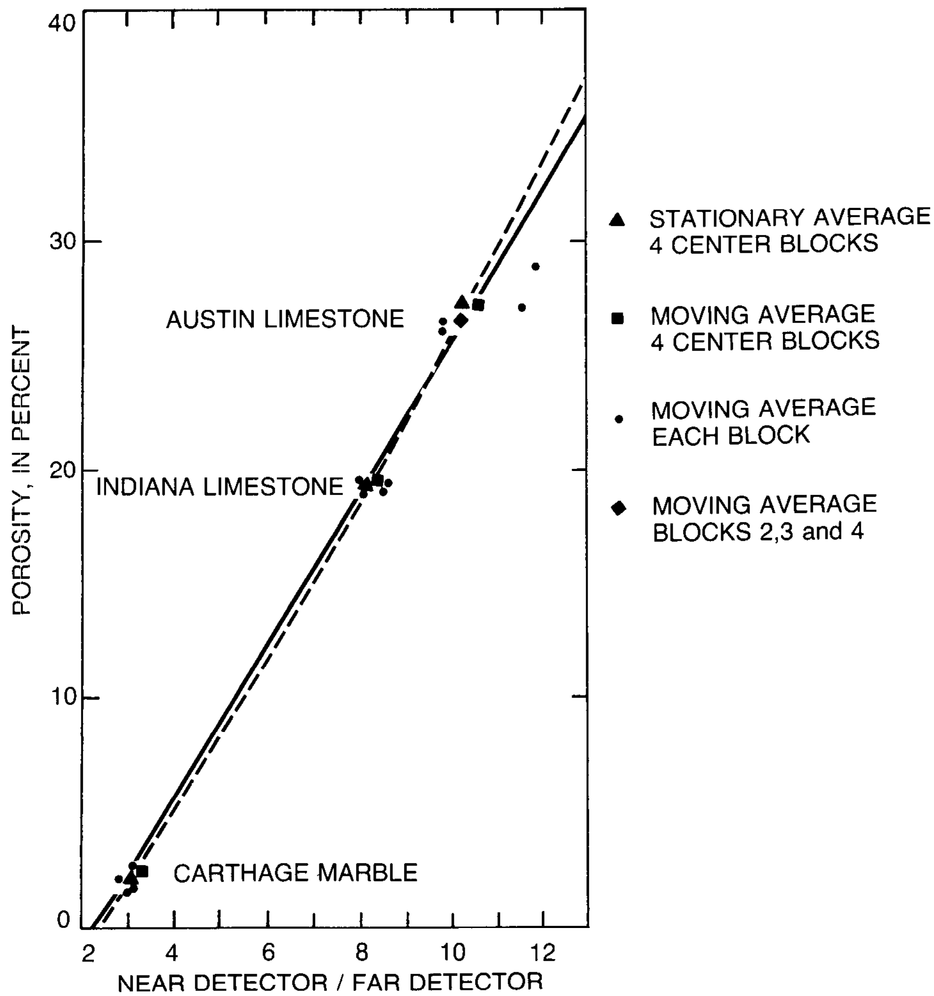


Figure 64.—Calibration curves for a compensated neutron-porosity probe based on data from the American Petroleum Institute's calibration pit. A straight line and a dashed curve have been calculated to fit the data.

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

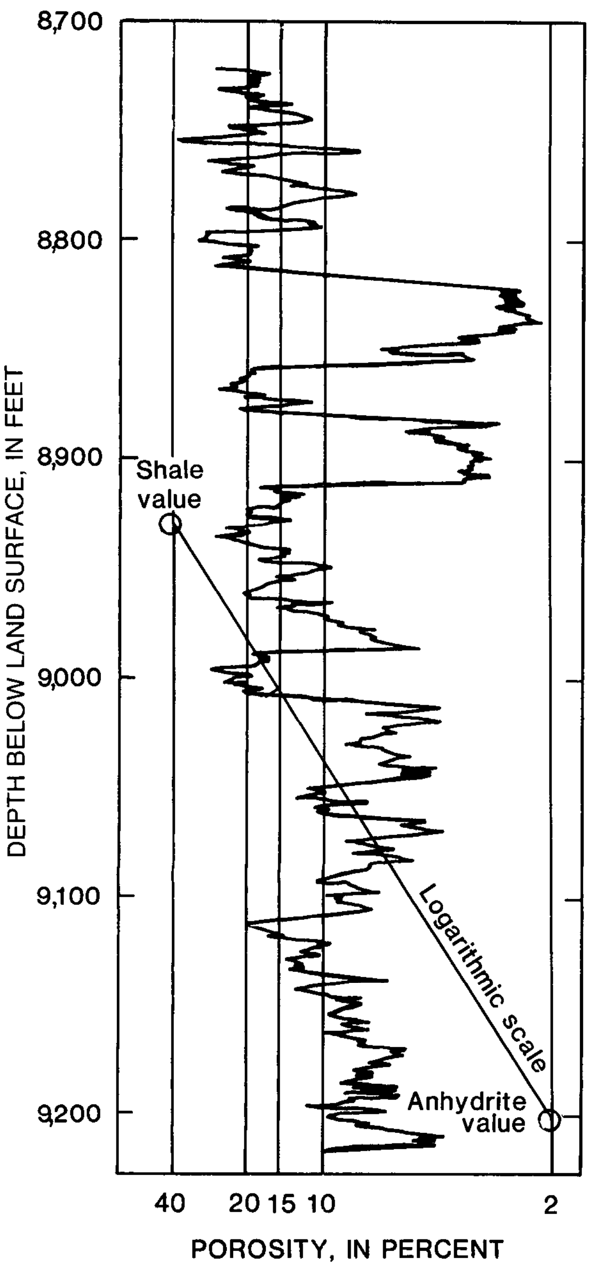


Figure 65.—Neutron log of the Red River Formation, Custer County, Mont., showing method for onsite calibration using estimated values of porosity for shale and anhydrite (modified from MacCary, 1980).

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,

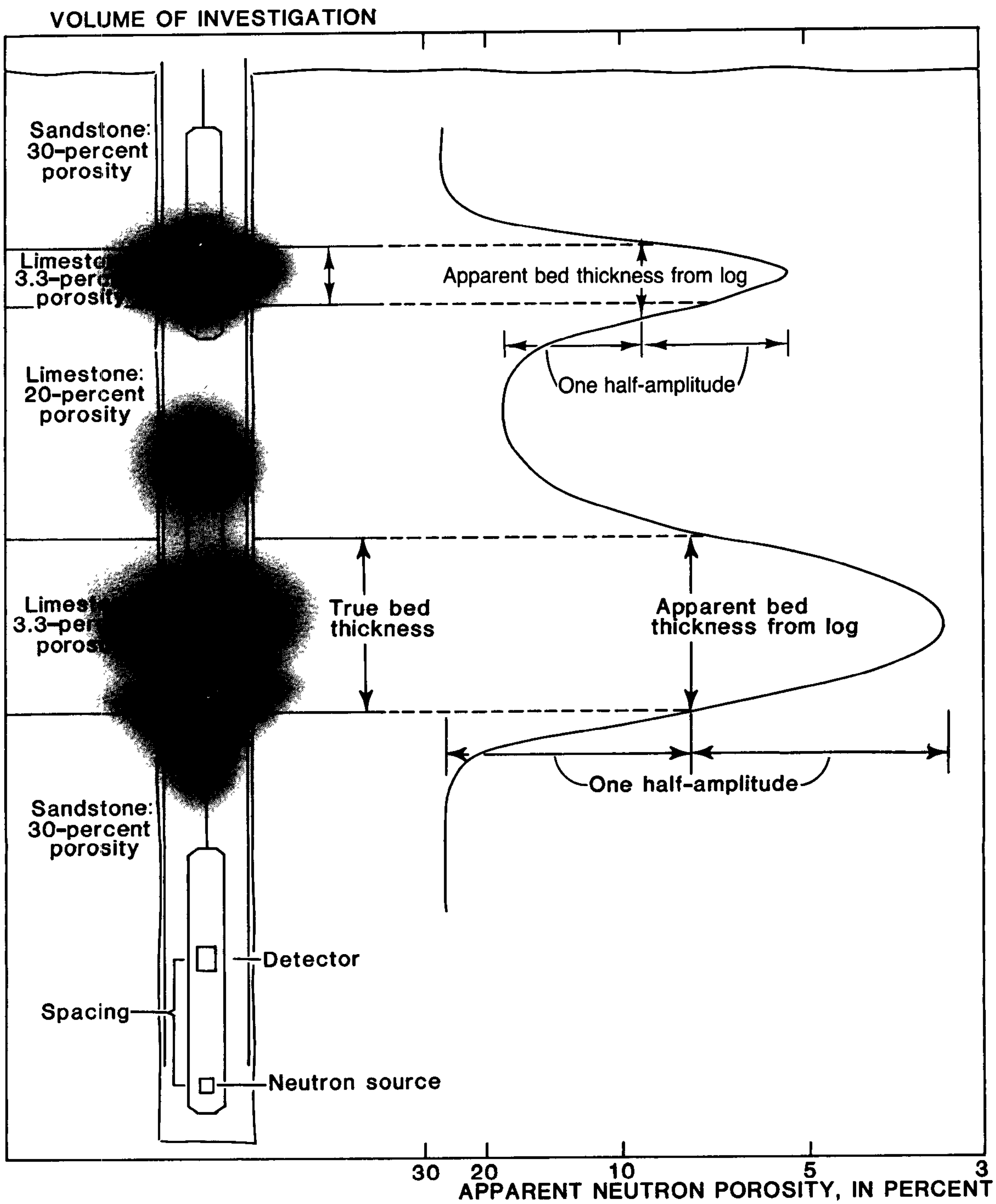


Figure 66.—Theoretical response of a neutron probe to changes in porosity and bed thickness. The shaded areas represent the volume of investigation at different probe positions.

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

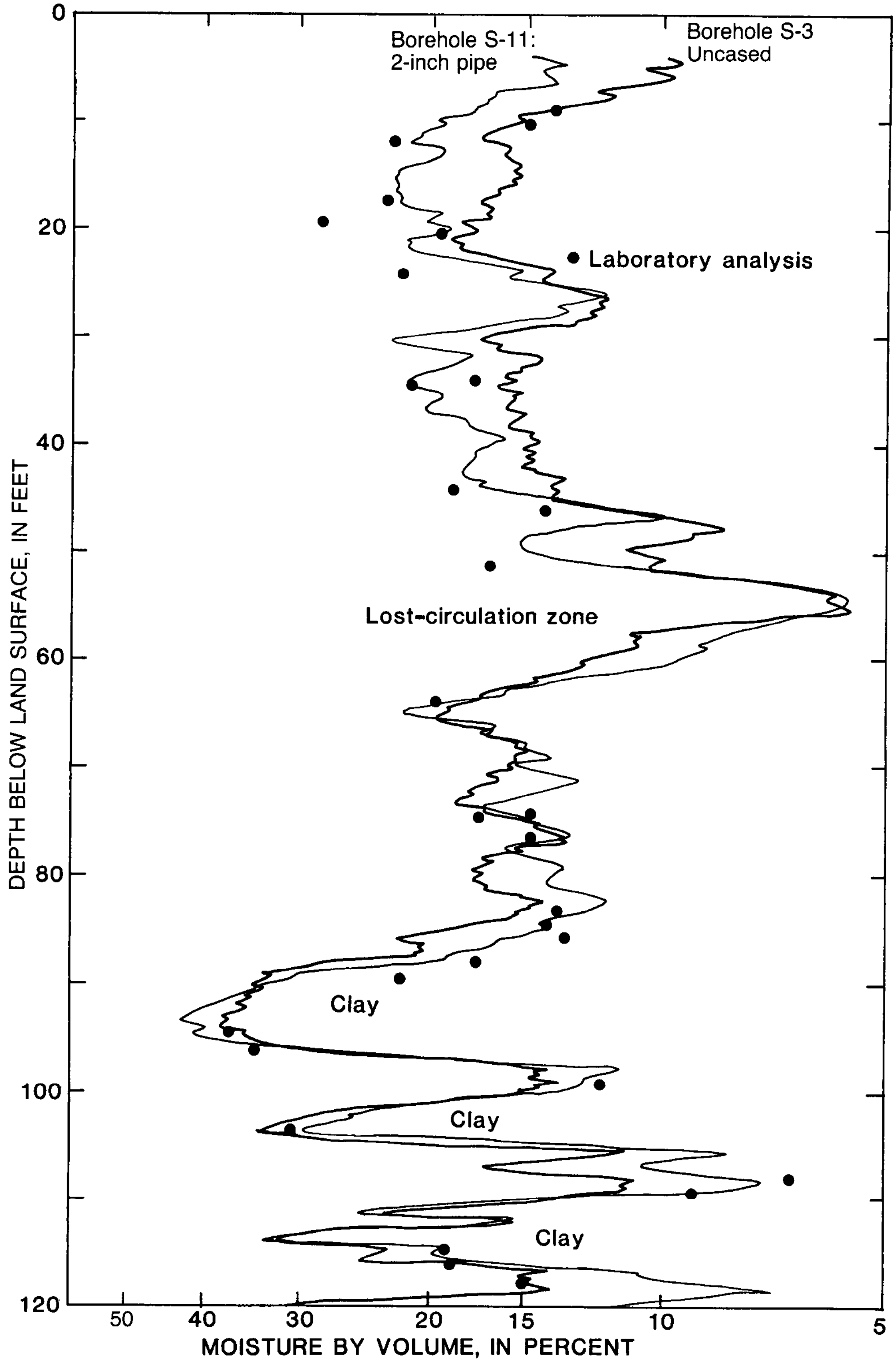


Figure 67.—Moisture content from core analyses compared with neutron logs in cased and uncased boreholes, Lubbock, Tex.

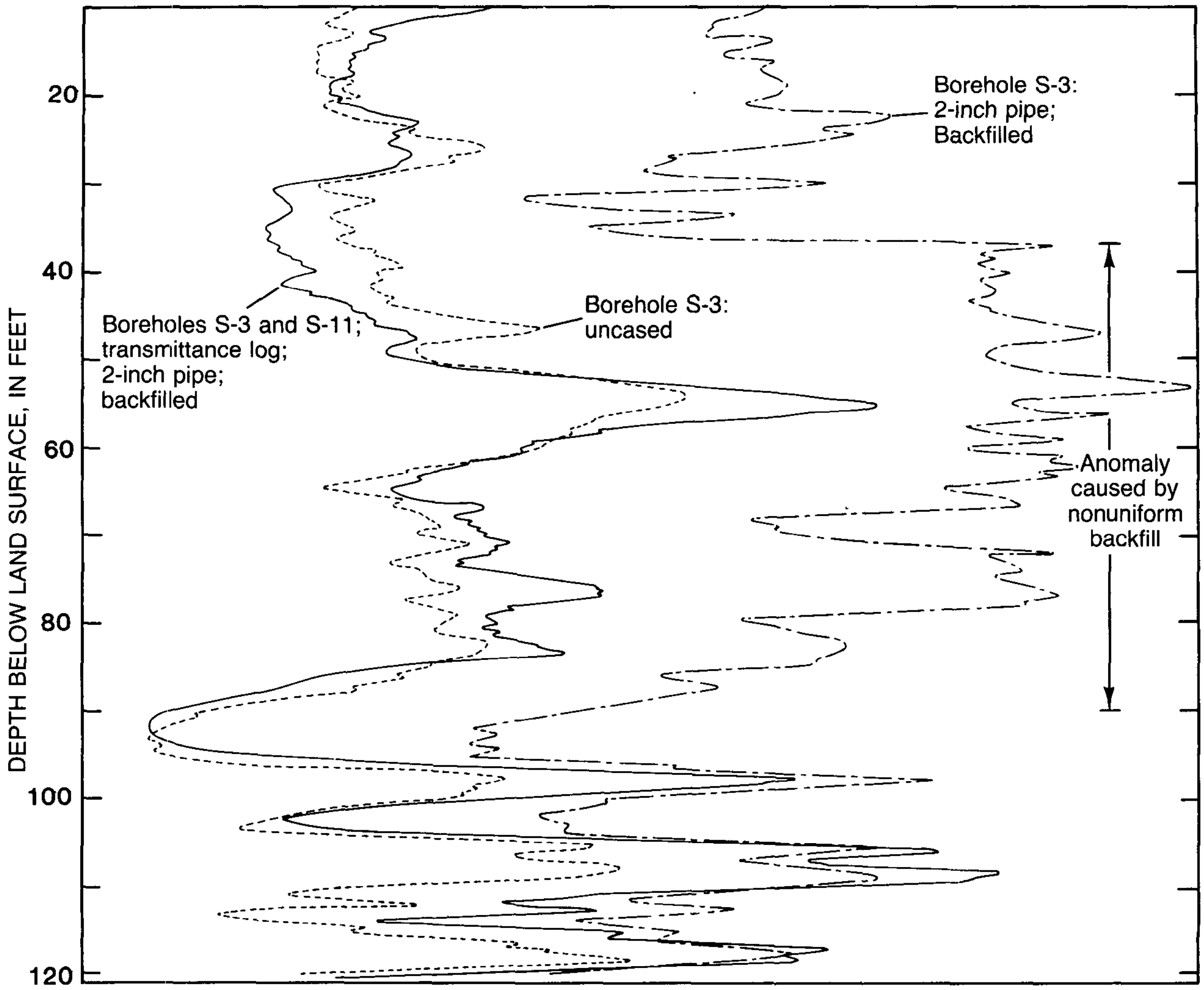


Figure 68.—Neutron-transmittance log between boreholes S-3 and S-11 compared with single-borehole neutron logs of borehole S-3, cased and uncased, Lubbock, Tex.

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

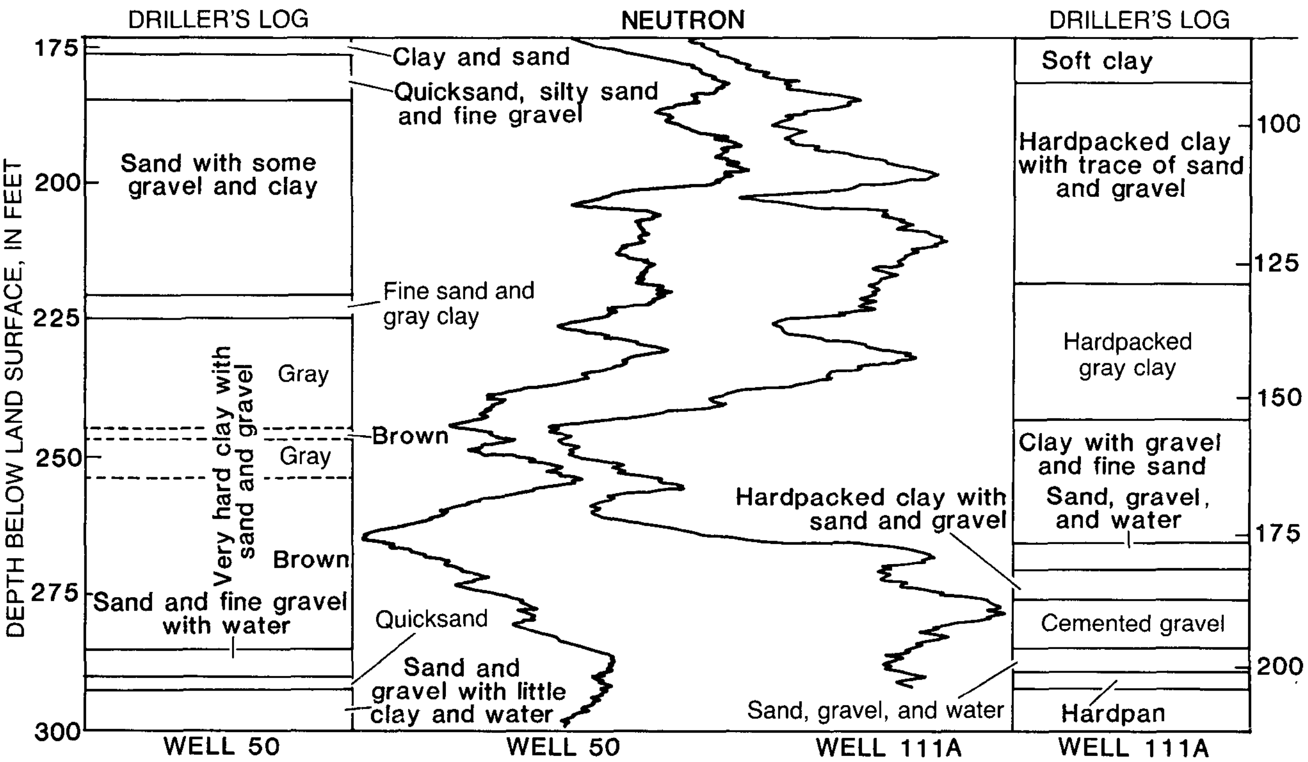


Figure 69.—Driller's logs and neutron logs of two closely spaced water wells completed in glacial sediments, Anchorage, Alaska.

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

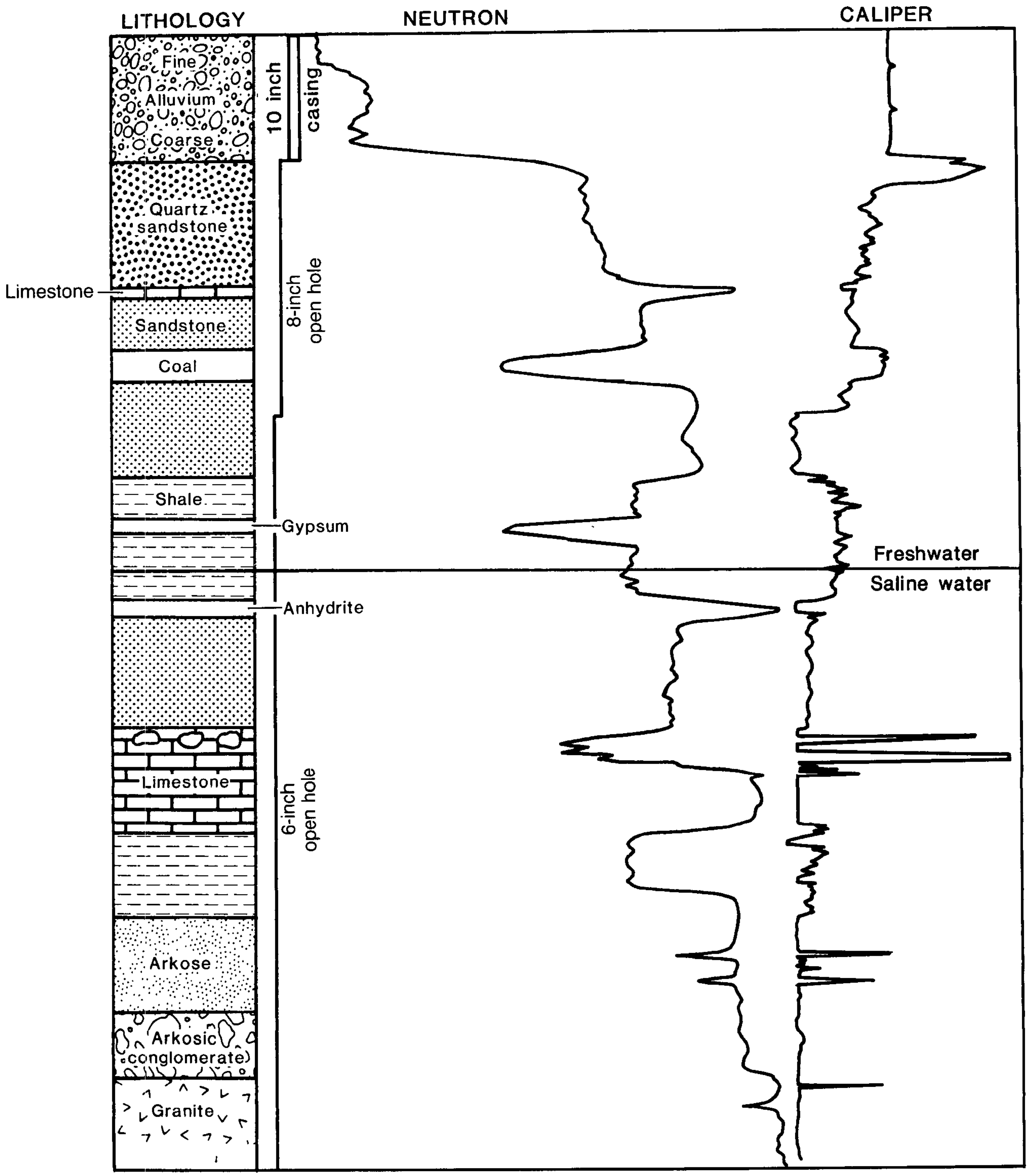


Figure 70.—Typical responses of neutron and caliper logs to a sequence of sedimentary rocks.

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*

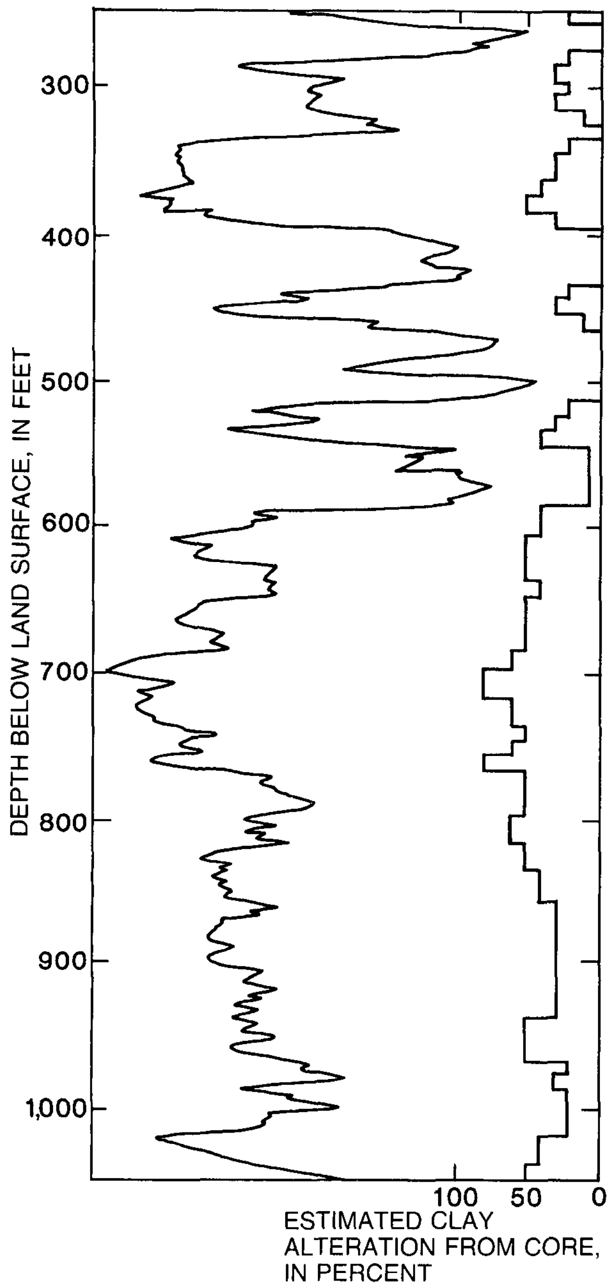


Figure 71.—Relation between a neutron log and the estimated clay content of core from a borehole penetrating crystalline rocks. Apparent porosity increases to the left.

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

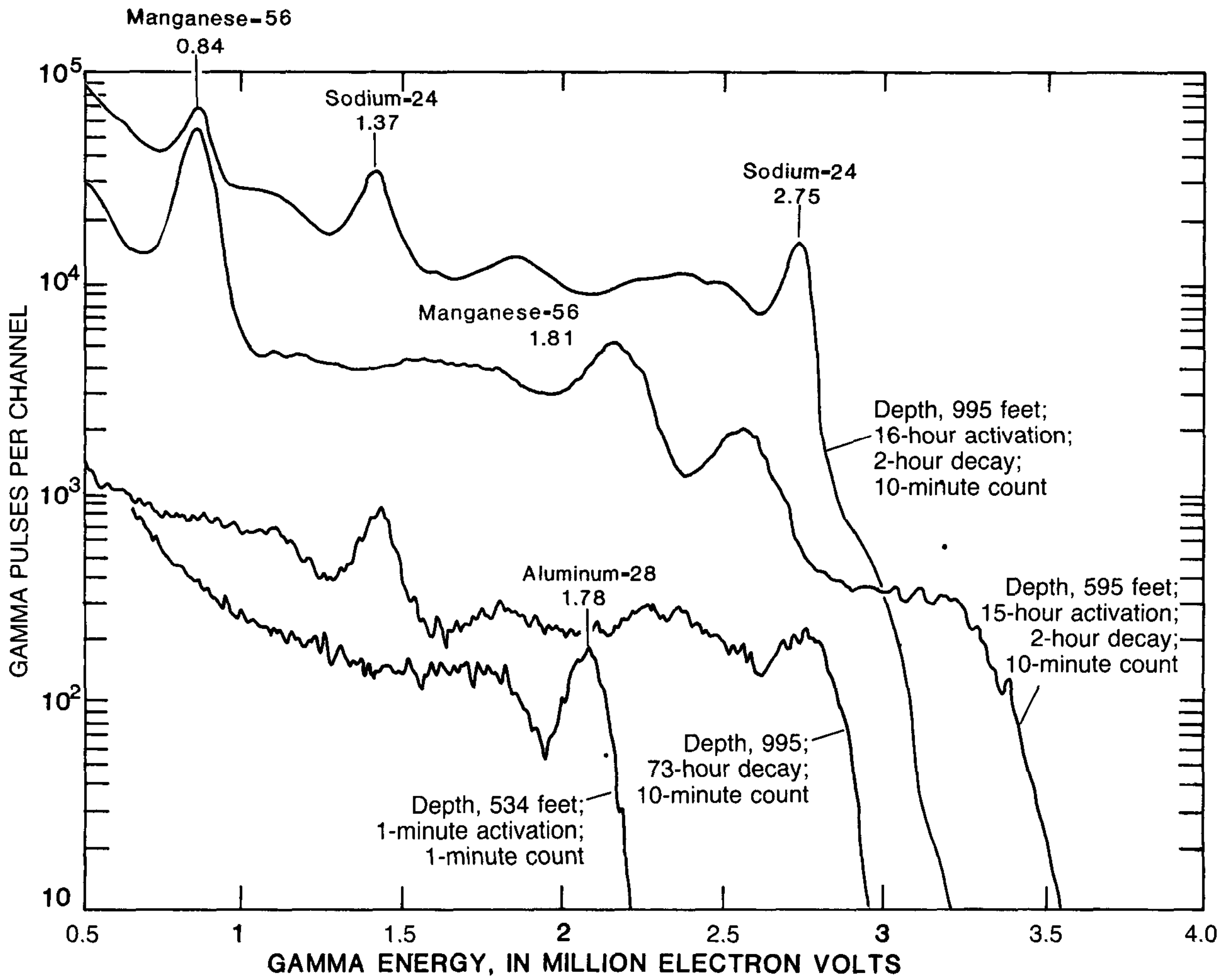


Figure 72.—Gamma spectra produced by neutron activation in a well using a 50-millicurie source of californium-252, near Aiken, S.C.

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.

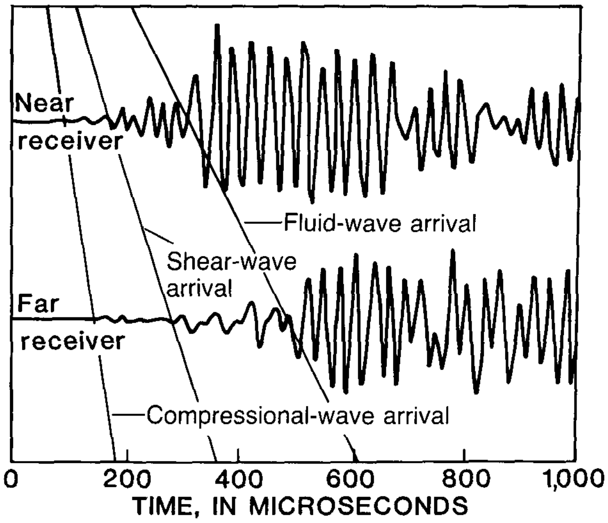


Figure 73.—Acoustic wave forms for a two-receiver system and arrival times of compressional, shear, and fluid waves (modified from Paillet and White, 1982).

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 way on borehole diameter and rock properties but usually is 10 to 25 kHz. Most acoustic-velocity probes have paired receivers located 1 ft apart; some probes have several pairs of receivers with different spacing; the pair that is to be used may be selected from the land surface. Some compensated probes have two transmitters and two pairs of receivers. Transmitter to near-receiver distance generally is greater than 2 ft. Compressional waves, or P waves, are propagated by movement of particles in an elastic medium in the direction of propagation. P waves have a faster velocity and a lower amplitude than shear waves, or S waves. S waves have a velocity about one-half that of P waves and are characterized by particle movement perpendicular to the direction of wave propagation. S waves are not transmitted directly by borehole fluid, but by means of an intermediate P wave. Fluid waves are slower and have higher amplitude than P and S waves.

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

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

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

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

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

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

[Single values are averages]

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

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

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

Calibration and standardization

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

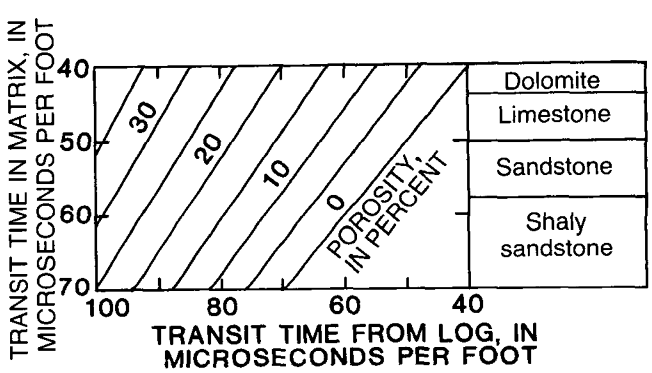


Figure 74.—Conversion of transit time from acoustic-velocity logs to porosity of various rock types.

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

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

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

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

Volume of investigation

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

Extraneous effects

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

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

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

Interpretation and applications

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

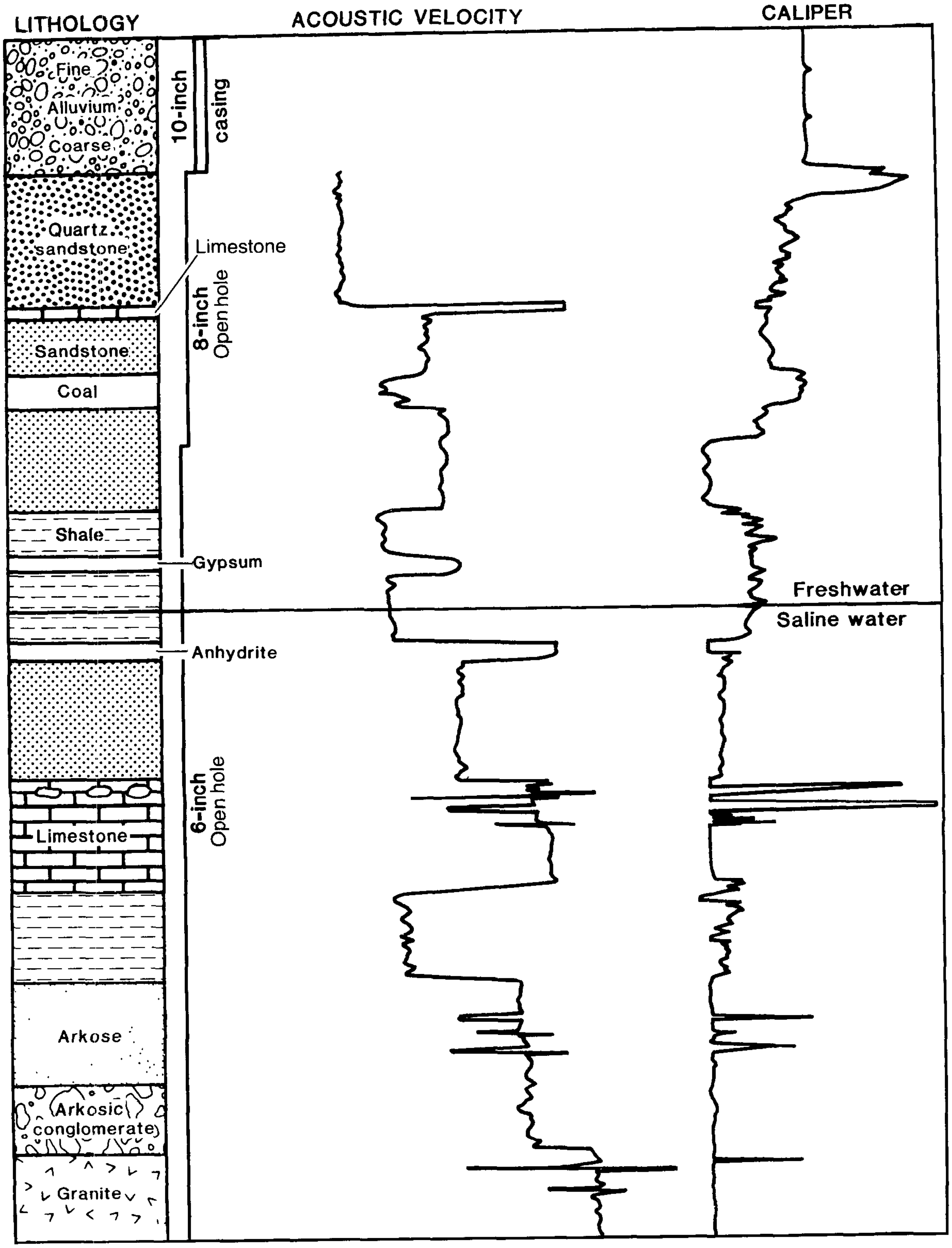


Figure 75.—Typical responses of acoustic-velocity and caliper logs to a sequence of sedimentary rocks.

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

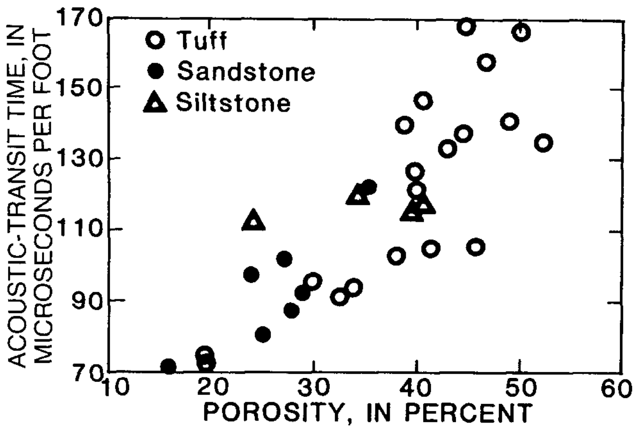


Figure 76.—Relation of acoustic-transit time to porosity for tuff, sandstone, and siltstone, Raft River geothermal reservoir, Idaho.

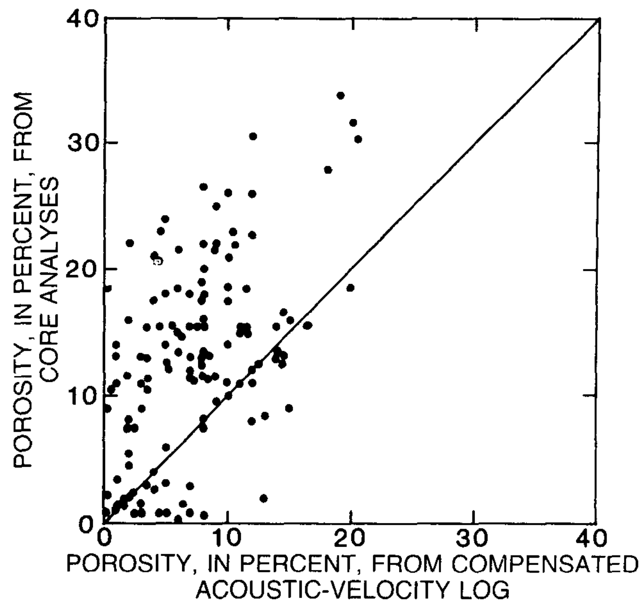


Figure 77.—Porosity from core analyses versus porosity from a compensated acoustic-velocity log, Madison Limestone test well 1, Wyoming.

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

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

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

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

Acoustic-wave-form logging

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

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

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

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

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

Acoustic-televiewer logging

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

Principles and instrumentation

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

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

Fractures and other openings in the borehole wall or in the casing appear as dark areas for several reasons. Increasing borehole diameter means that the acoustic signal must travel farther and that it will be more attenuated by the fluid in the borehole. In

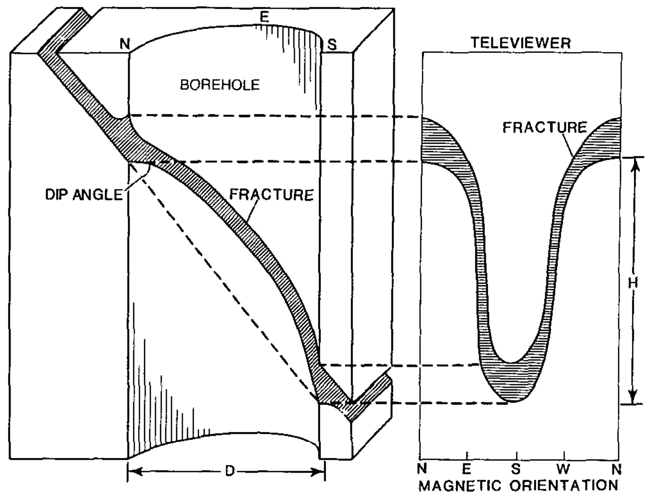


Figure 78.—Three-dimensional view of a fracture intersecting a borehole and appearance of the same fracture on an acoustic-televiewer log. D is the borehole diameter from a caliper log, and H is the length of intercept at the fracture in the borehole.

addition, where part of the surface of fractures and other openings is not at right angles to the incident acoustic signal, little of the signal will be reflected back to the transducer.

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

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

Calibration and standardization

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

Volume of investigation

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

Extraneous effects

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

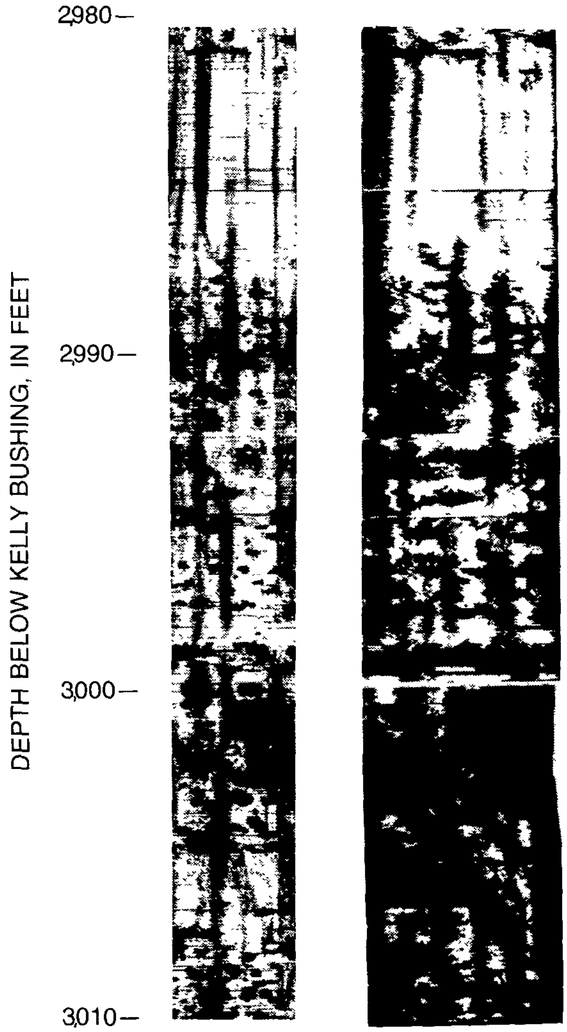


Figure 79.—Acoustic-televiewer logs made by the U.S. Geological Survey (left) and a commercial service company (right), Madison Limestone test well 1, Wyoming.

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

Interpretation and applications

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

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

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

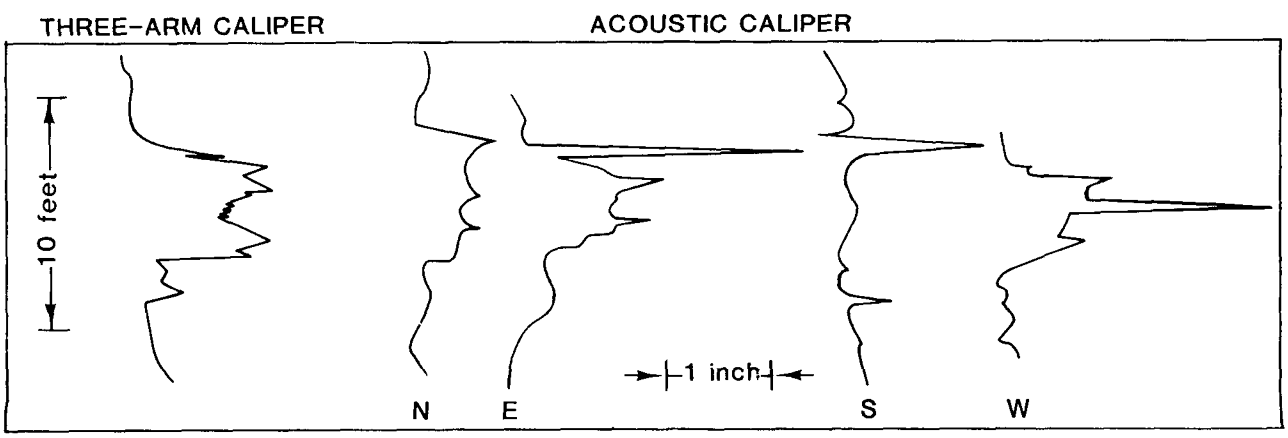


Figure 81.—Mechanical- and acoustic-caliper logs of producing zone A in a geothermal well, Roosevelt Hot Springs, Utah.

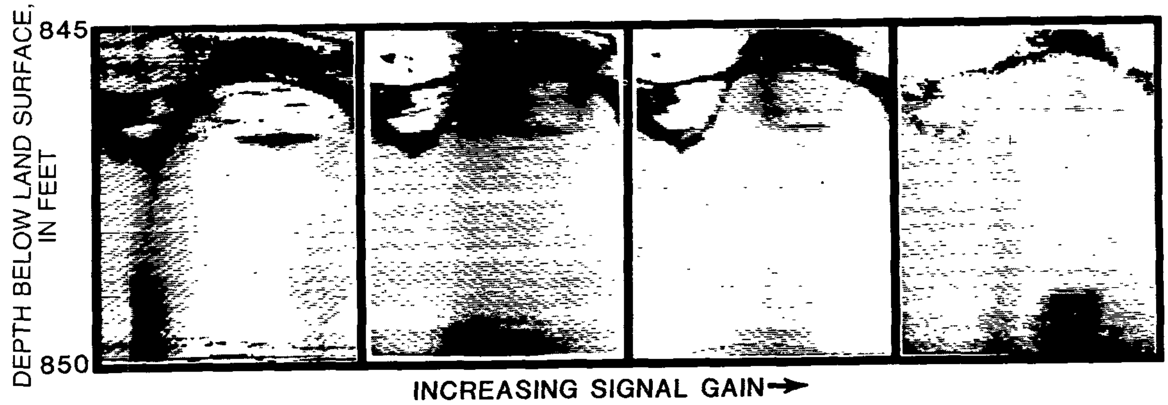


Figure 82.—Acoustic-televiewer logs of a 5-foot interval at four different gain settings, borehole CR-6, Ontario, Canada.

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

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

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

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

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

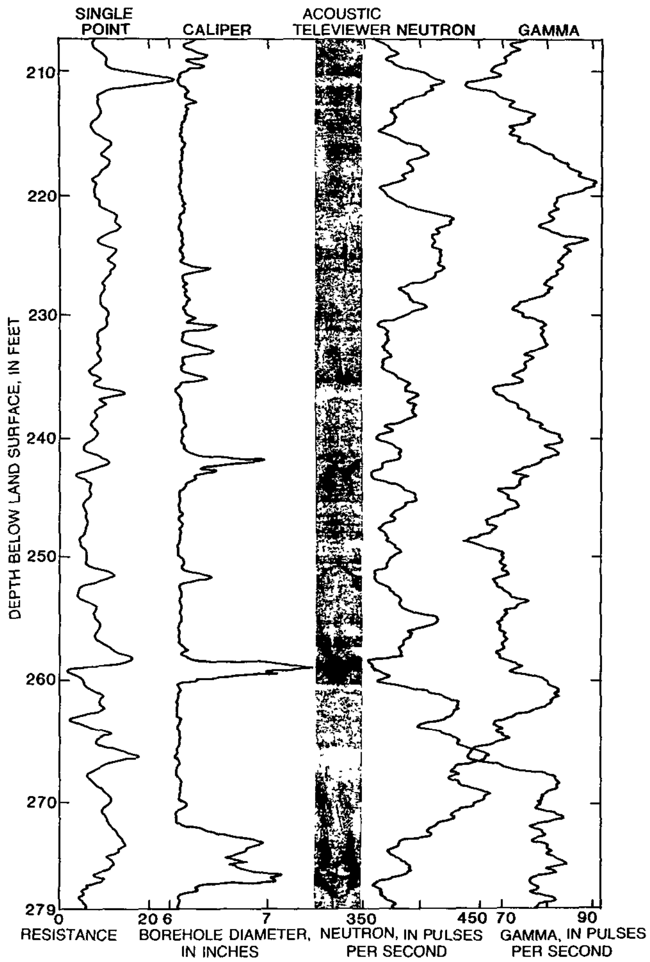


Figure 83.—Single-point-resistance, caliper, acoustic-televiewer, neutron, and gamma logs of a borehole penetrating the Monterey Shale, Calif.

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

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

Caliper Logging

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

Principles and instrumentation

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

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

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

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

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

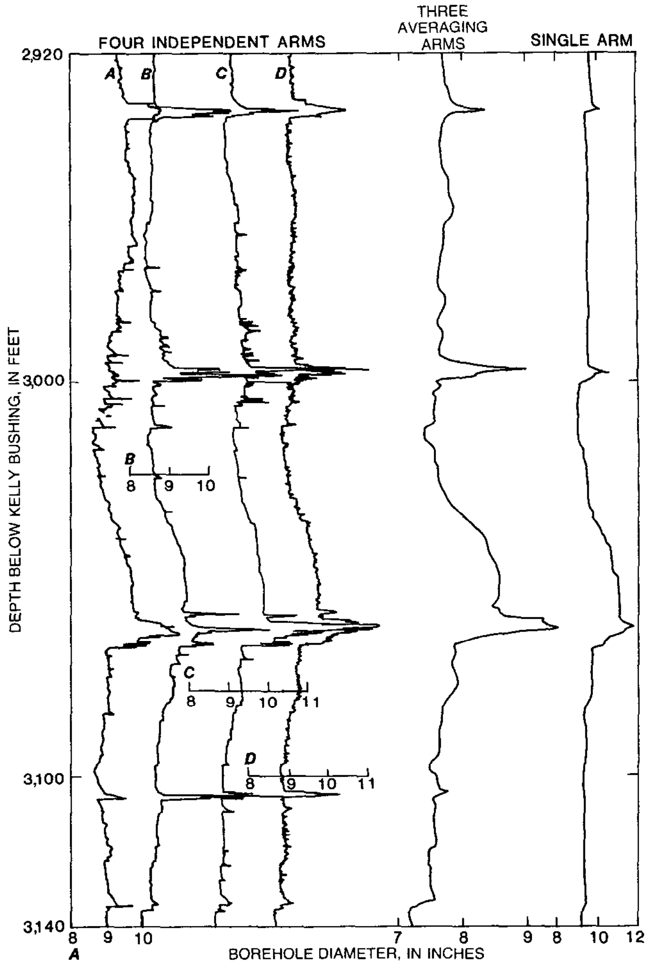


Figure 84.—Caliper logs from probes having four independent arms, three averaging arms, and a single arm, Madison Limestone test well 1, Wyoming.

Calibration and standardization

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

Volume of investigation

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

Extraneous effects

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

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

Interpretation and applications

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

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

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

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

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

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

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

Test 4.—ACOUSTIC AND CALIPER LOGGING

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

c. Require a different recording system than that used for acoustic-velocity logs.
d. Are used commercially to evaluate cement bond.

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

Fluid Logging

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

Temperature

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

Principles and instrumentation

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

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

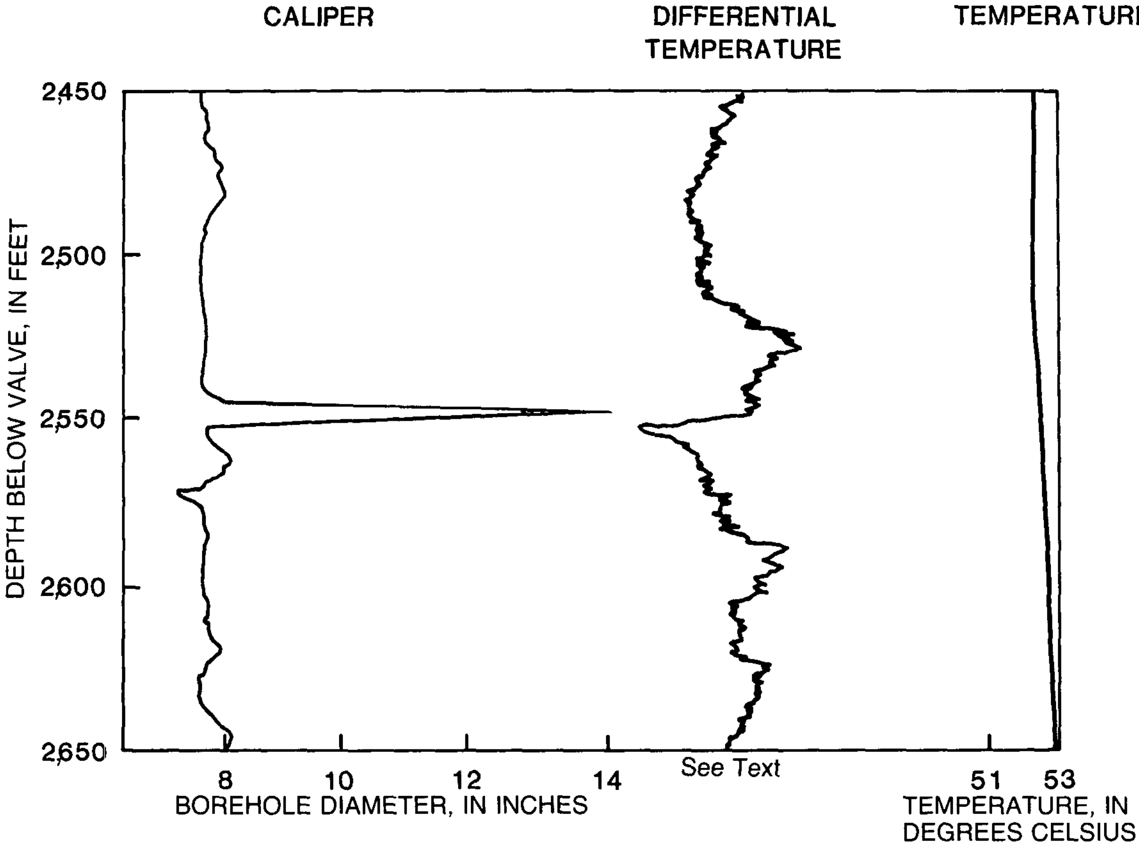


Figure 85.—Caliper, differential-temperature, and temperature logs for an interval in Madison Limestone test well 1, Wyoming.

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

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

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

Calibration and standardization

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

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

Volume of investigation

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

Extraneous effects

Errors on temperature logs can be caused by such instrument problems as thermal lag, drift of the electronics, and self-heating of the thermistor. None of these factors is significant in a well-designed probe.

A number of borehole conditions may cause misinterpretation of a temperature log. Drilling, testing, and cementing a borehole cause significant perturbations of the thermal system, and thermal equilibrium may not be reestablished for many years. Predicting the return of thermal equilibrium between the borehole and adjacent rock after drilling or injection of fluids or under conditions of natural vertical circulation is difficult. A theoretical method for calculating true formation temperature under these conditions has been described by Sanyal and others (1980). Movement of the logging probe disturbs the thermal profile in the fluid column. Unless rapid flow is occurring, each temperature log will be different. The degree of disturbance caused by any type of logging probe is related to speed of logging and to the diameter of the probe in relation to the diameter of the borehole. Fast logging speed and large-diameter probes will cause the greatest disturbance. The most accurate temperature log is made before any other log is made; the temperature log is recorded while moving slowly down the borehole. Logging speed is a function of response time of the probe; a speed faster than 25 ft/min seldom produces an accurate temperature log.

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

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

where

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

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

Interpretation and applications

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

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

The identification of fractures that are producing water from Triassic sedimentary rocks near Raleigh, N.C., is illustrated in figure 87. The temperature log on the left indicates several changes in temperature gradient that are clearly defined by the computer-derived differential-temperature log. The caliper log

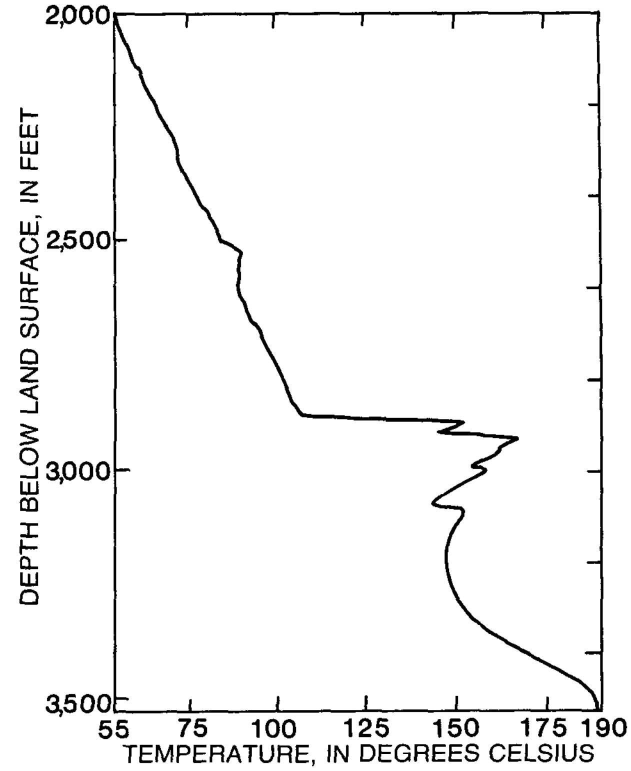


Figure 86.—Temperature log of a producing geothermal well, Roosevelt Hot Springs, Utah.

indicates that the water production may come from fractures, and this interpretation is substantiated by the acoustic-televiewer logs on the right. Differential-temperature logs usually display sharper anomalies that are easier to identify than the subtle changes in gradient in a temperature log.

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

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

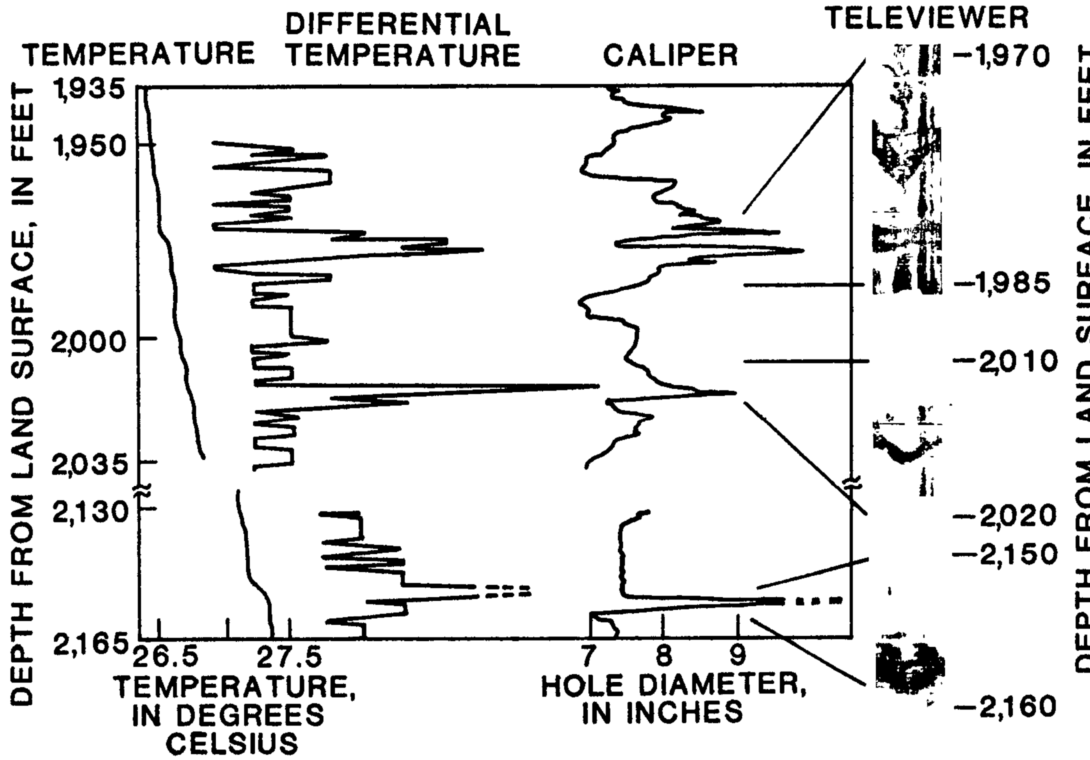


Figure 87.—Temperature, differential-temperature, caliper, and acoustic-televiewer logs of Sears test well 1 near Raleigh, N.C.

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

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

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

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

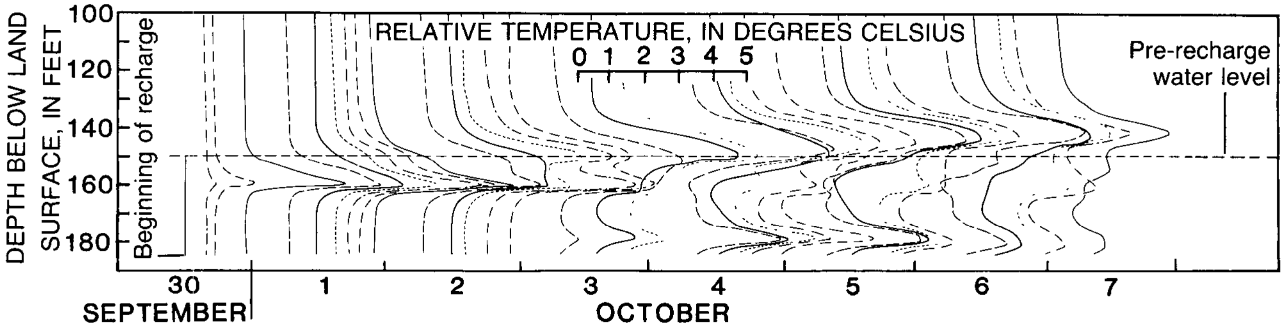


Figure 88.—Selected temperature logs made in a monitoring well located 39 feet from a recharge well, High Plains of Texas.

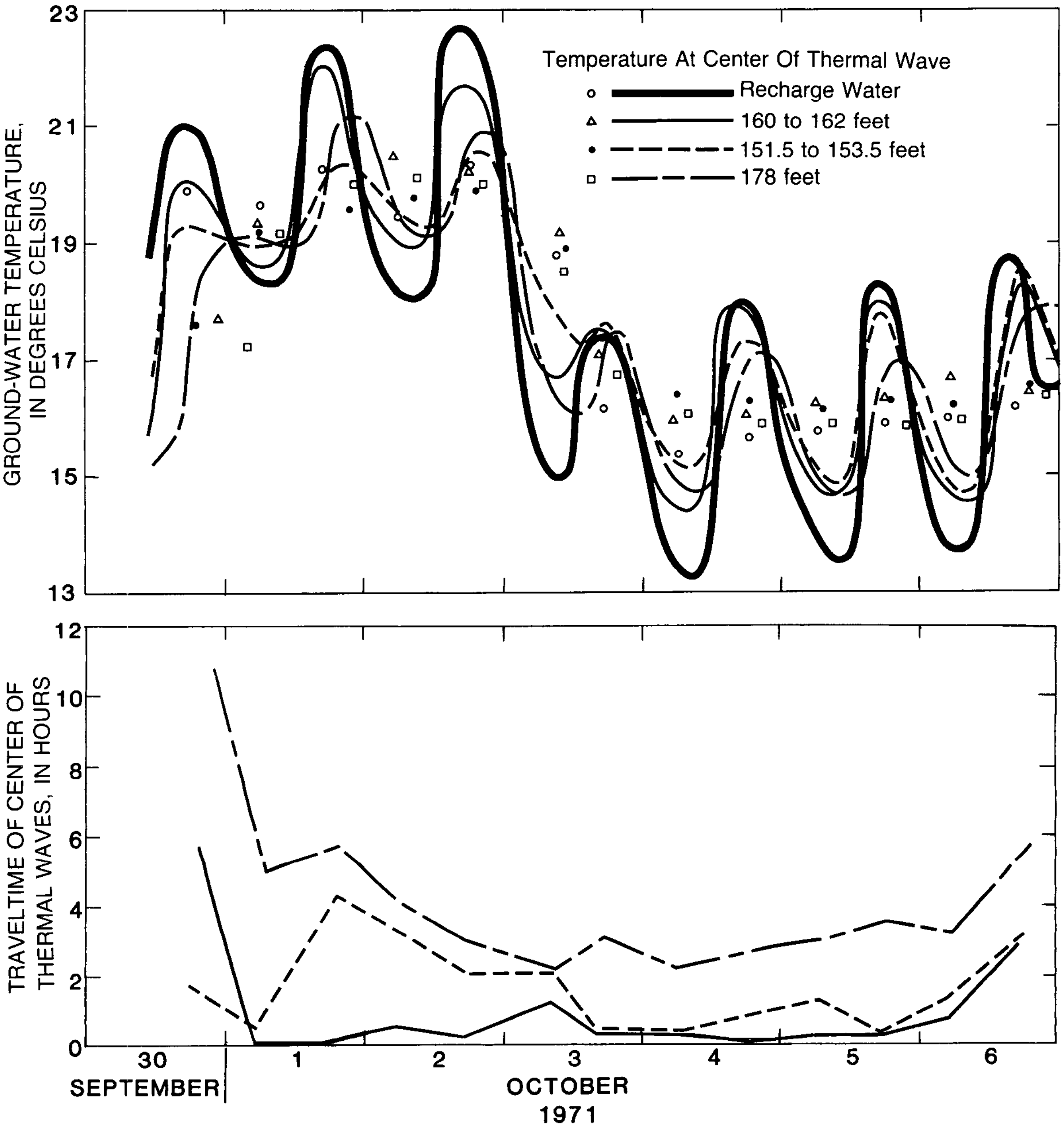


Figure 89.—Diurnal-temperature cycles and traveltimes of the center of thermal waves, based on temperature logs made in a monitoring well located 39 feet from a recharge well, High Plains of Texas.

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

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

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

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

Conductivity

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

Principles and instrumentation

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

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

Calibration and standardization

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

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

Extraneous effects

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

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

Interpretation and applications

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

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

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

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

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

Flow

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

Principles and instrumentation

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

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

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

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

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

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

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

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

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

Calibration and standardization

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

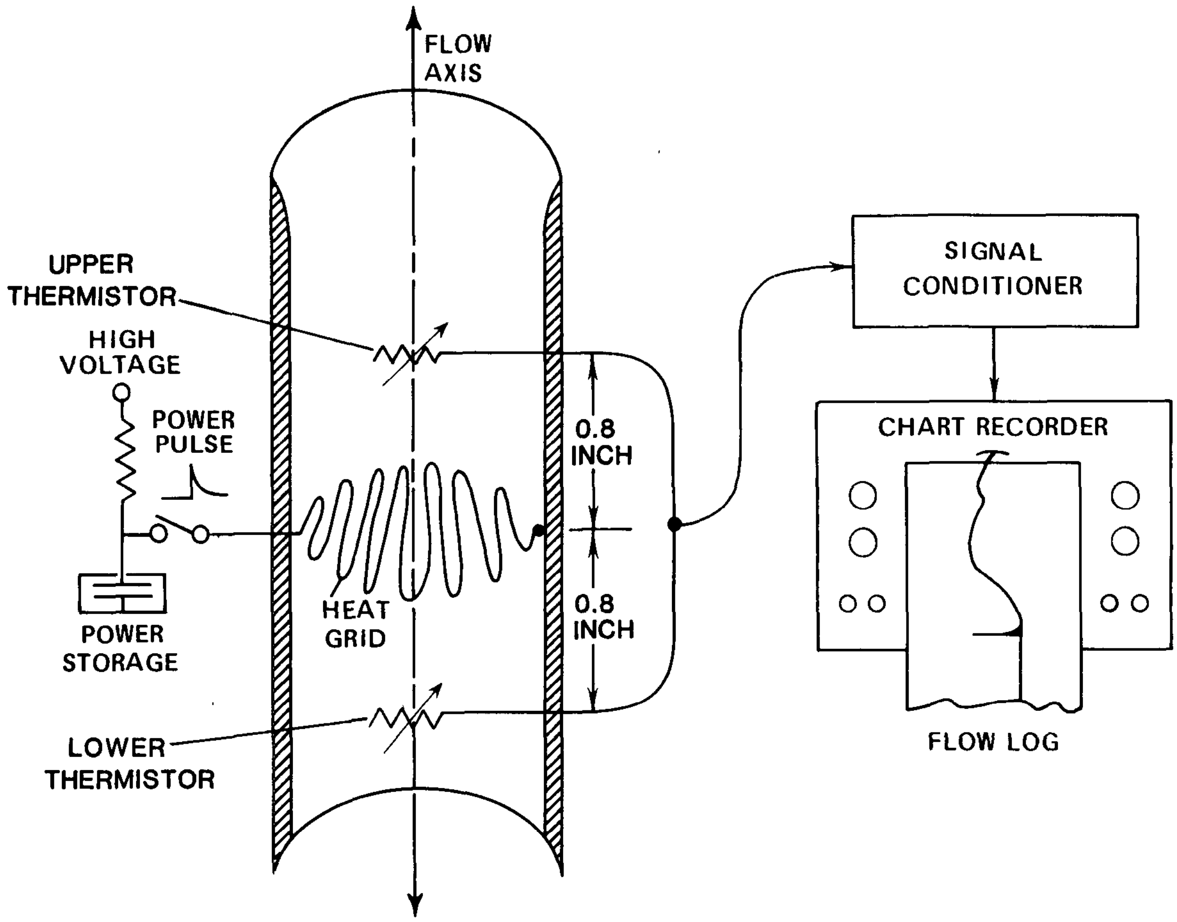


Figure 90.—Equipment for making heat-pulse flowmeter logs (modified from Hess, 1986).

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

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

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

Extraneous effects

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

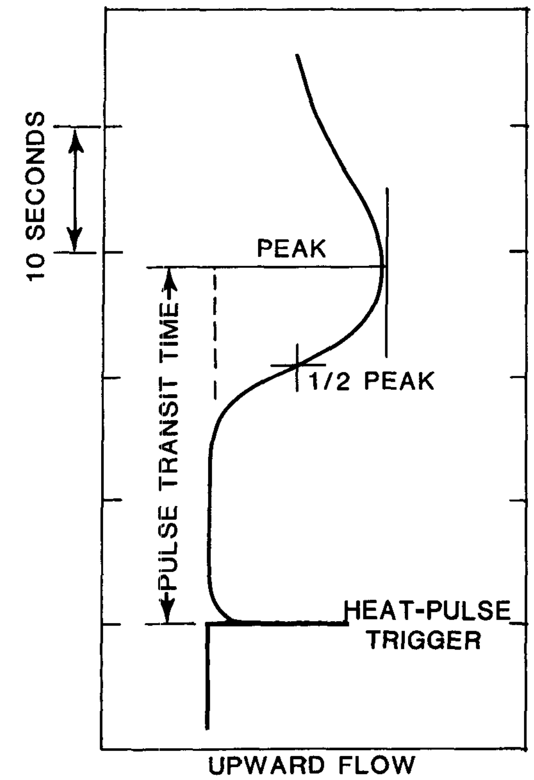


Figure 91.—Analog record of a heat pulse from a thermal flowmeter (modified from Hess, 1986).

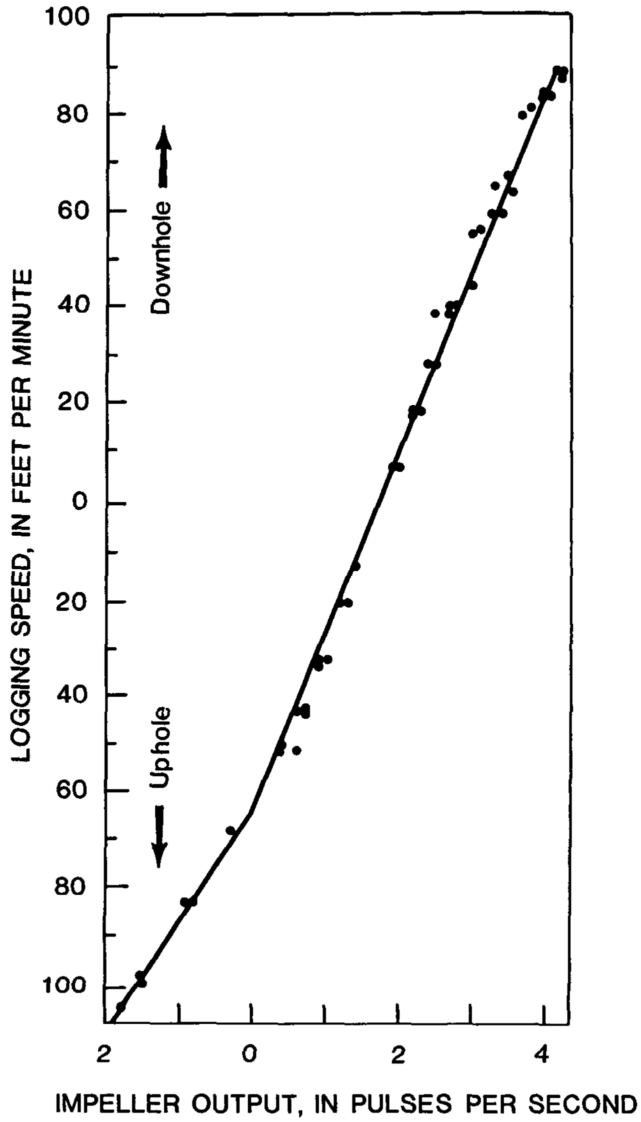


Figure 92.—Calibration data for an impeller flowmeter developed by moving the probe in a water well that was flowing.

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

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

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

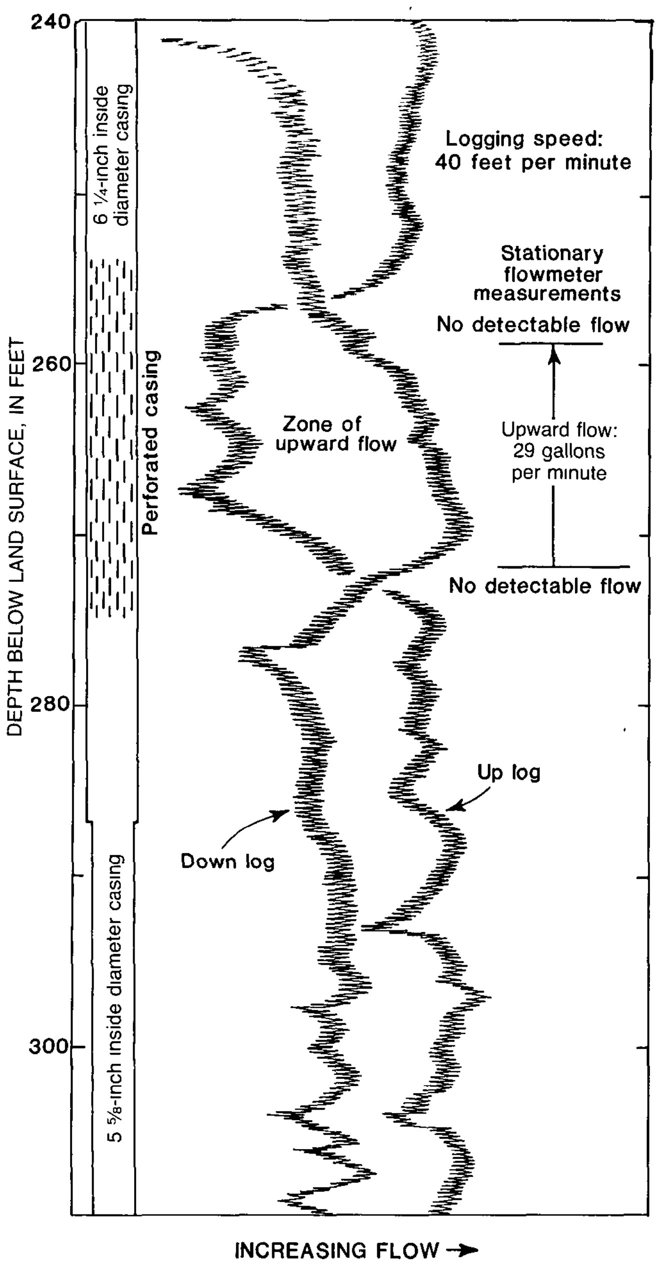


Figure 93.—Impeller-flowmeter logs made up and down a well where the casing was perforated opposite two aquifers.

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

Interpretation and applications

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

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

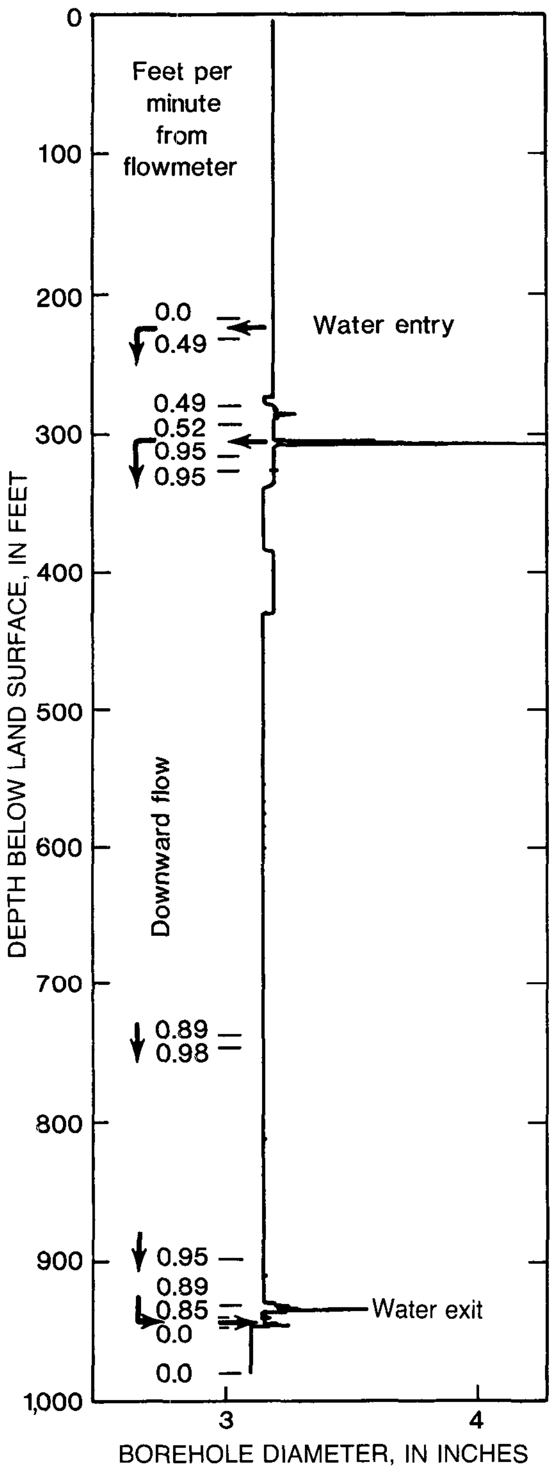


Figure 94.—Single-arm-caliper log and data from heat-pulse flowmeter showing zones of water entry and loss in a borehole penetrating granitic rocks in the Canadian Shield (modified from Keys, 1984).

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

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

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

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

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

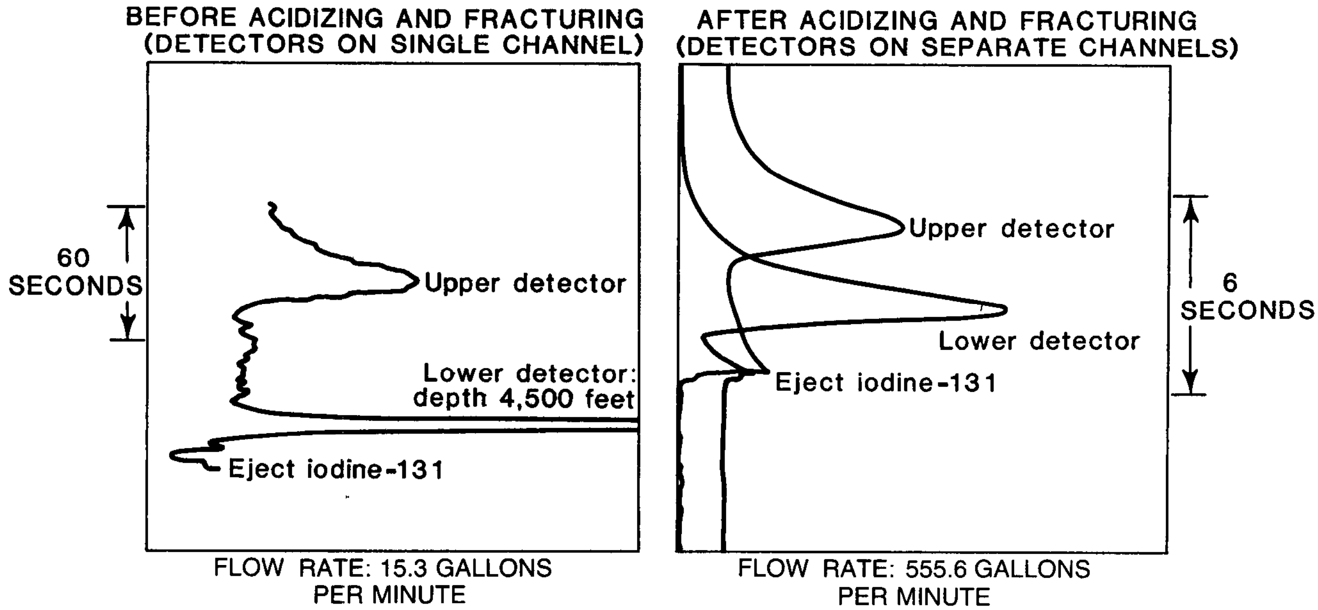


Figure 95.—Radioactive-tracer-injector logs before and after acidizing and fracturing of Madison Limestone test well 3, Montana (modified from Blankennagel and others, 1981).

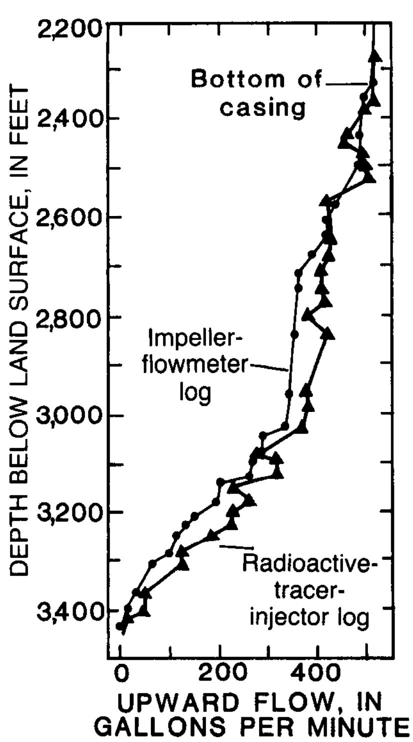


Figure 96.—Comparison of impeller-flowmeter and radioactive-tracer-injector logs, Madison Limestone test well 1, Wyoming (modified from R.K. Blankennagel, U.S. Geological Survey, written commun., 1977).

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

Well-Construction Logging

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

Casing logging

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

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

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

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

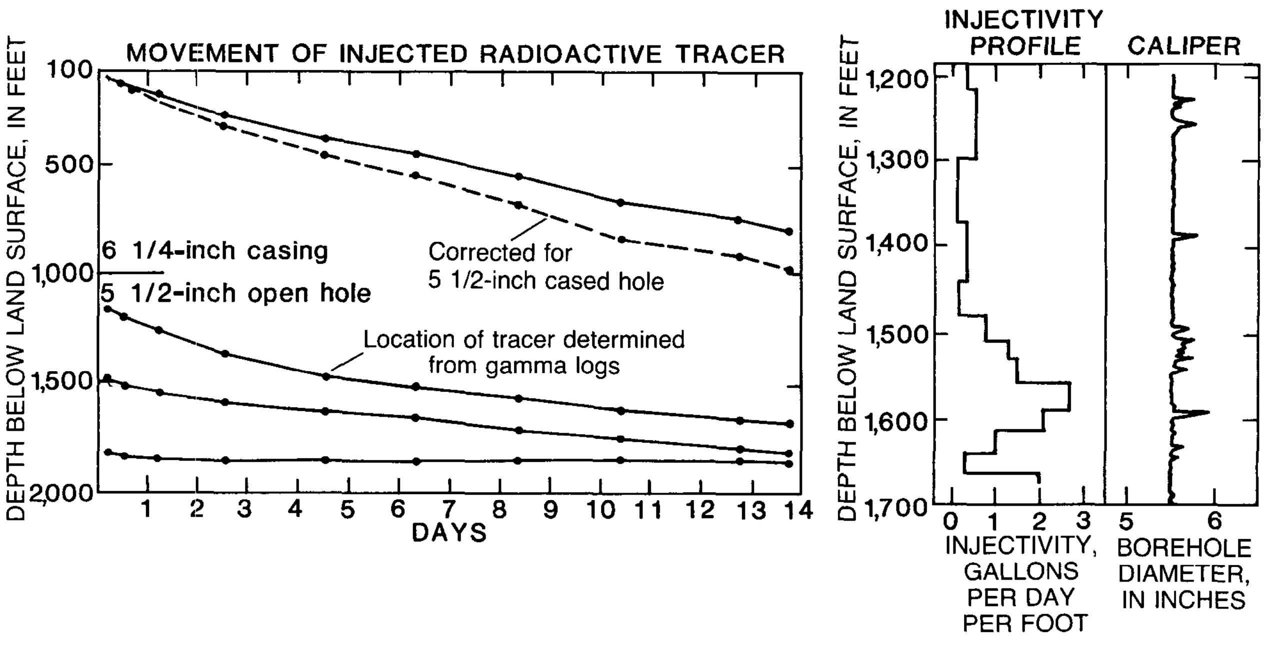


Figure 97.—Downward movement of four slugs of iodine-131 injected in a borehole penetrating granitic rocks near Aiken, S.C. The resulting injectivity profile plotted from periodic gamma logs shows water loss at fractures indicated by the caliper log.

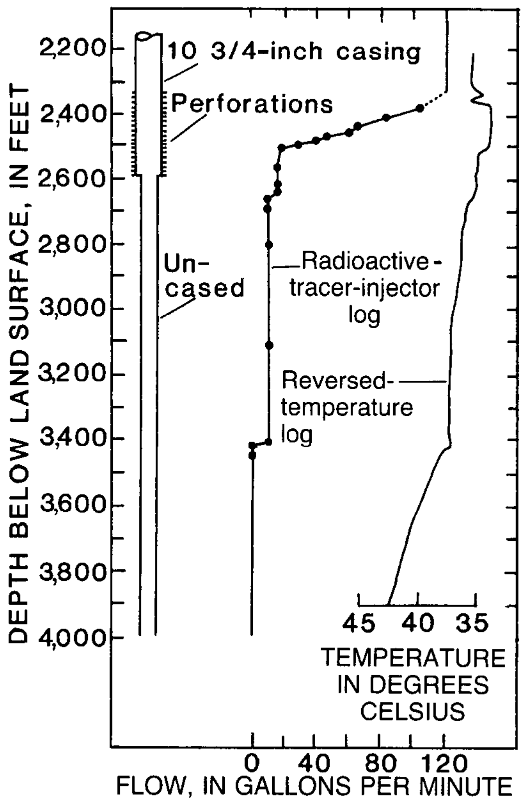


Figure 98.—Radioactive-tracer-injector and reversed-temperature logs made during pumping of test well USW H-5, Yucca Mountain, Nev. (modified from R.K. Blankennagel, U.S. Geological Survey, written commun., 1983).

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

Cement and gravel-pack logging

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

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

Borehole-deviation logging

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

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

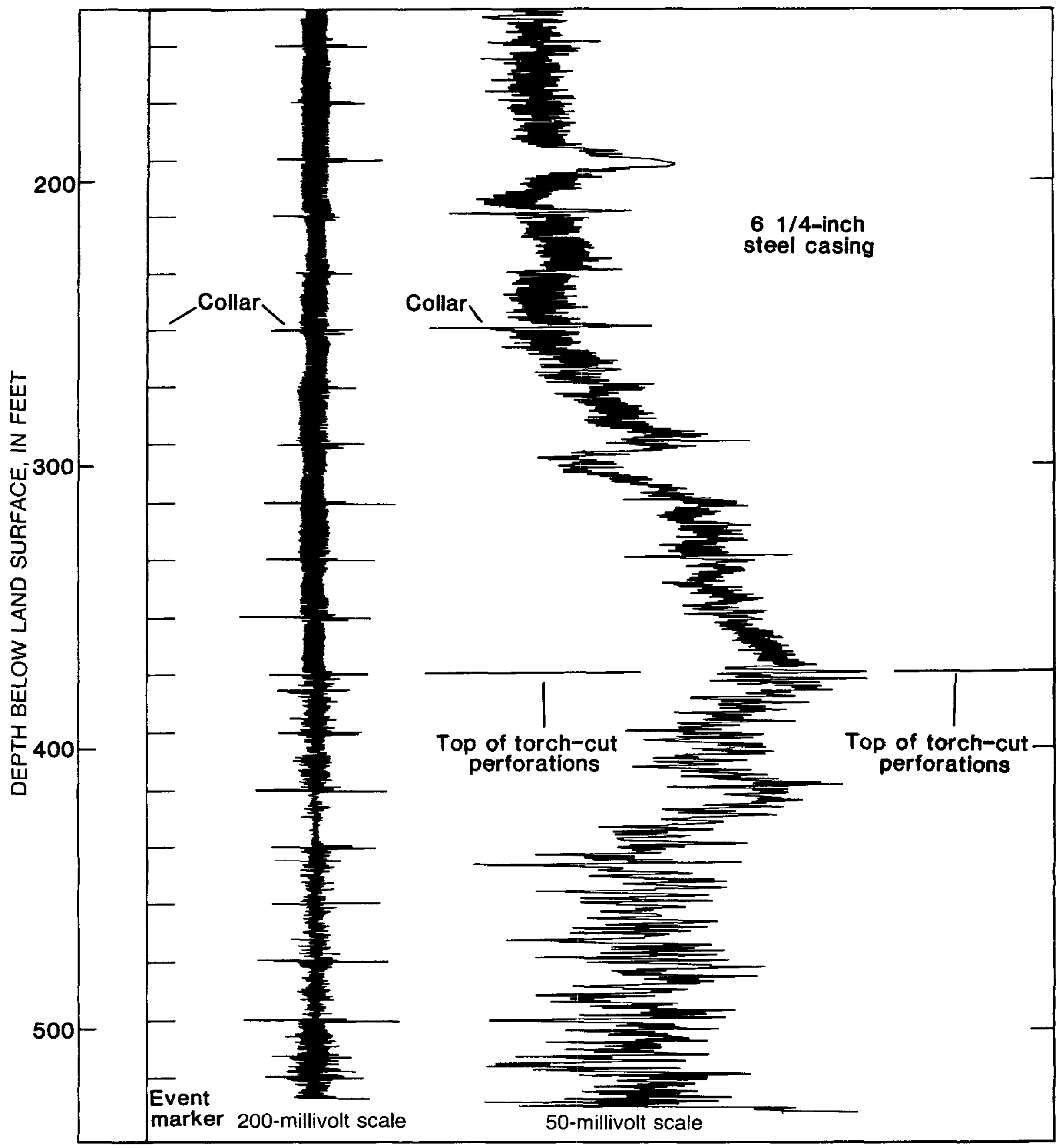


Figure 99.—Casing-collar-locator logs recorded by an event marker and analog recorder at two different gain settings.

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

Test 5.—FLUID AND WELL-CONSTRUCTION LOGGING

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

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

Summary—A Case History

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

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

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

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

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

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

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

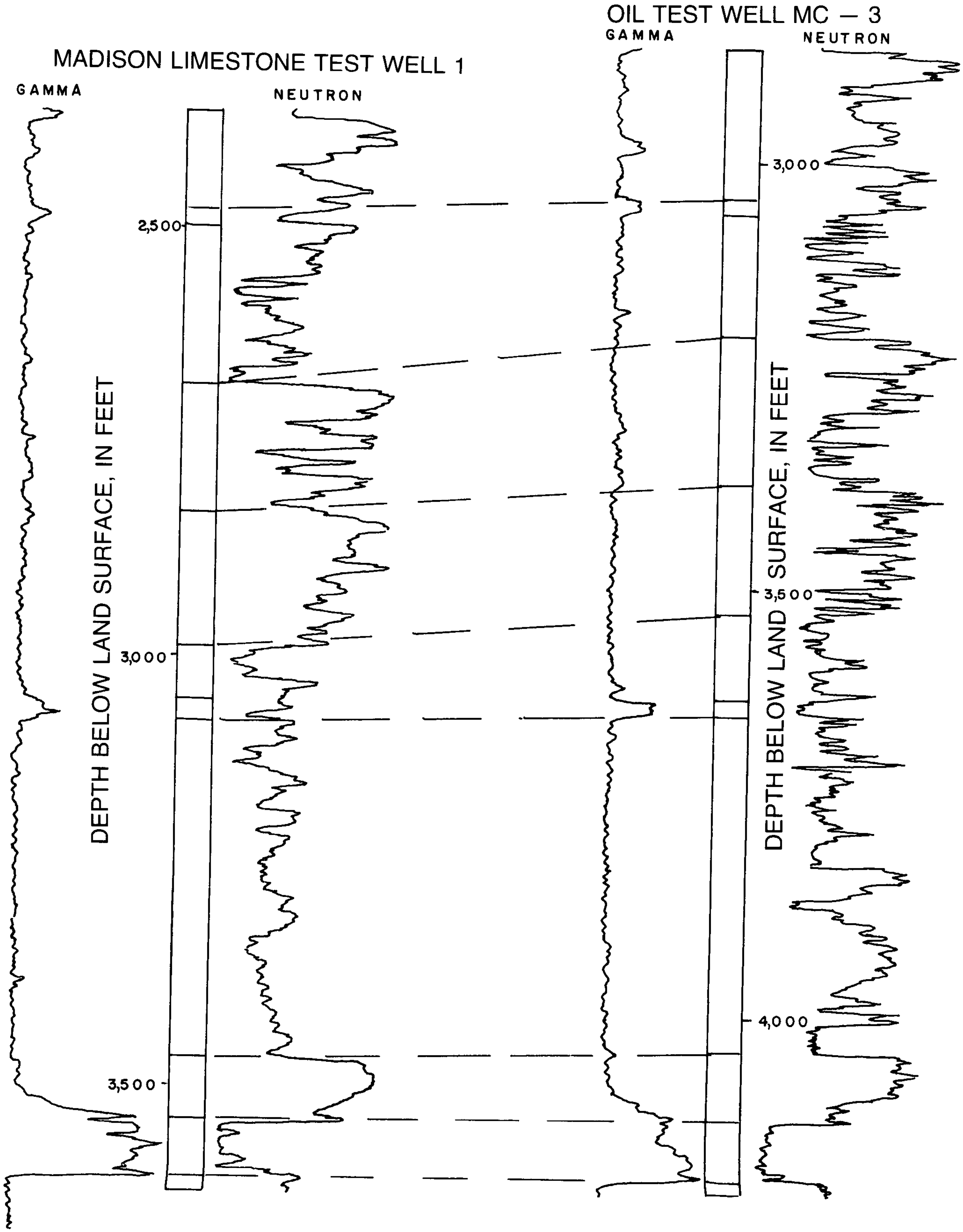


Figure 100.—Correlation of lithologic units between Madison Limestone test well 1 and oil test well MC-3 based on gamma and neutron logs, Wyoming.

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

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

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

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ANSWERS TO TEST QUESTIONS

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

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

Test 2.—Electric Logging

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

Test 3.—Nuclear Logging

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

Test 4.—Acoustic and Caliper Logging

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

Test 5.—Fluid and Well-Construction Logging

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