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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***

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, ***Director***

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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.

TECHNIQUES OF WATER-RESOURCES INVESTIGATIONS OF THE U.S. GEOLOGICAL SURVEY

The U.S. Geological Survey publishes a series of manuals describing procedures for planning and conducting specialized work in water-resources investigations. The manuals published to date are listed below and may be ordered by mail from the **U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, Colorado 80225** (an authorized agent of the Superintendent of Documents, Government Printing Office).

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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.
TWRI 2-D2.	Application of seismic-refraction techniques to hydrologic studies, by F.P. Haeni. 1988. 86 pages.
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.
TWRI 3-A2.	Measurement of peak discharge by the slope-area method, by Tate Dalrymple and M.A. Benson. 1967. 12 pages.
TWRI 3-A3.	Measurement of peak discharge at culverts by indirect methods, by G.L. Bodhaine. 1968. 60 pages.
TWRI 3-A4.	Measurement of peak discharge at width contractions by indirect methods, by H.F. Matthai. 1967. 44 pages.
TWRI 3-A5.	Measurement of peak discharge at dams by indirect methods, by Harry Hulsing. 1967. 29 pages.
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.
TWRI 3–B5.	Definition of boundary and initial conditions in the analysis of saturated ground-water flow systems—An introduction, by O. Lehn Franke, Thomas E. Reilly, and Gordon D. Bennett. 1987. 15 pages.
TWRI 3–B6.	The principle of superposition and its application in ground-water hydraulics, by Thomas E. Reilly, O. Lehn Franke, and Gordon D. Bennett. 1987. 28 pages.
TWRI 3–C1.	Fluvial sediment concepts, by H.P. Guy. 1970. 55 pages.
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–A2.	Frequency curves, by H.C. Riggs, 1968. 15 pages.
TWRI 4–B1.	Low-flow investigations, by H.C. Riggs. 1972. 18 pages.
TWRI 4–B2.	Storage analyses for water supply, by H.C. Riggs and C.H. Hardison. 1973. 20 pages.
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.
TWRI 5–A3.[1]	Methods for the determination of organic substances in water and fluvial sediments, edited by R.L. Wershaw, M.J. Fishman, R.R. Grabbe, and L.E. Lowe. 1987. 80 pages.
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.
TWRI 5–C1.	Laboratory theory and methods for sediment analysis, by H.P. Guy. 1969. 58 pages.
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:

$$^{\circ}\text{C}=(^{\circ}\text{F}-32)/1.8.$$

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

$$^{\circ}\text{F}=1.8\ ^{\circ}\text{C}+32.$$

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 unsymmetrical 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, 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.

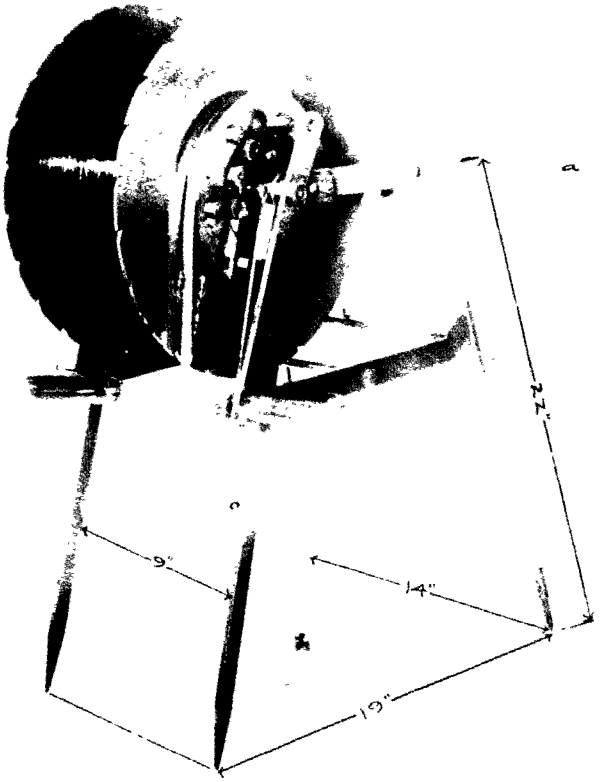

Figure 1.—Hand-cranked winch and cable used by the U.S. Geological Survey to make temperature logs prior to 1918 (from Van Orstrand, 1918).

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

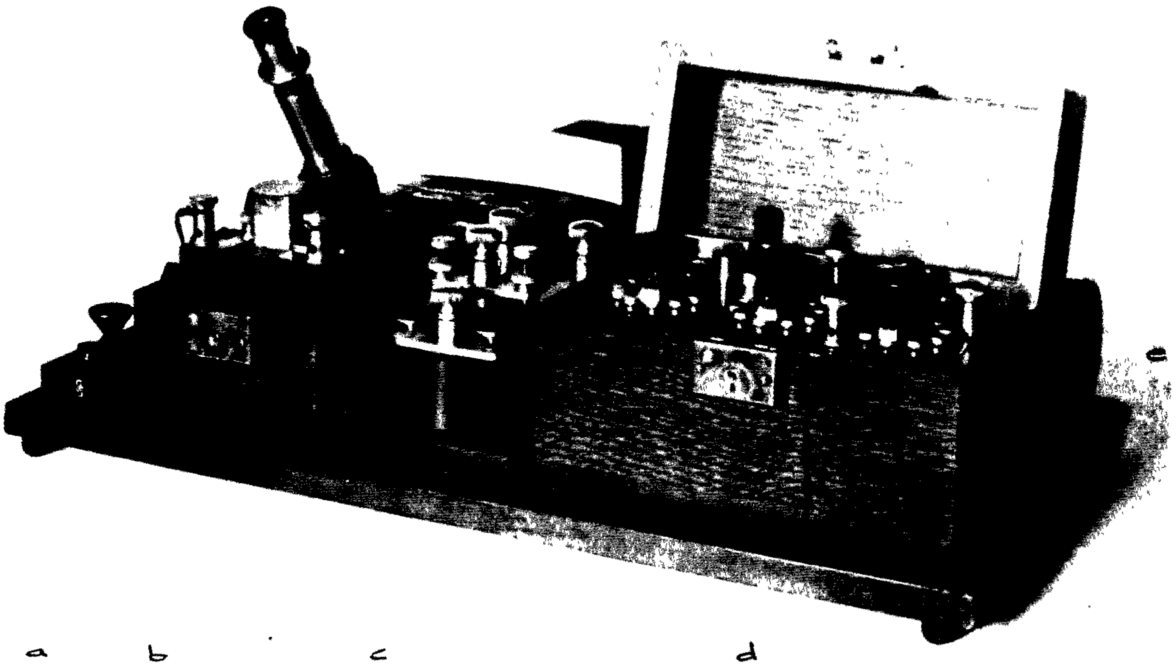

Figure 2.—Wheatstone-bridge system used to make depth-temperature curves or logs with a resolution of 0.01 degree Celsius (from Van Orstrand, 1918).

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).

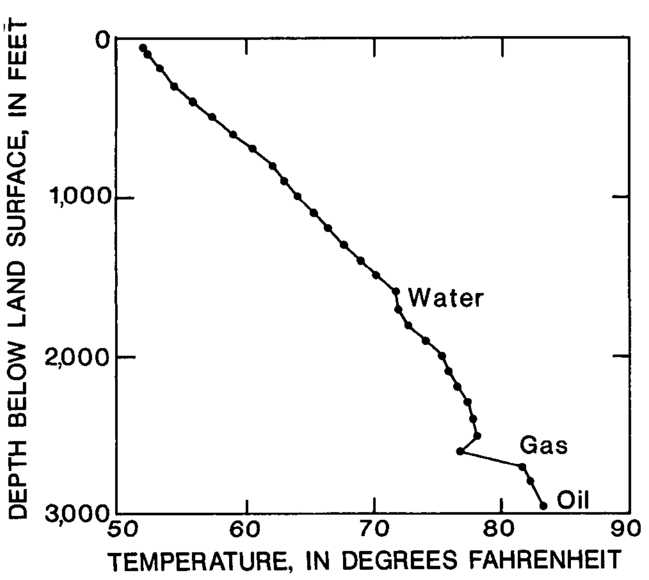

Figure 3.—Depth-temperature curve and interpretation (modified from Van Orstrand, 1918).

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

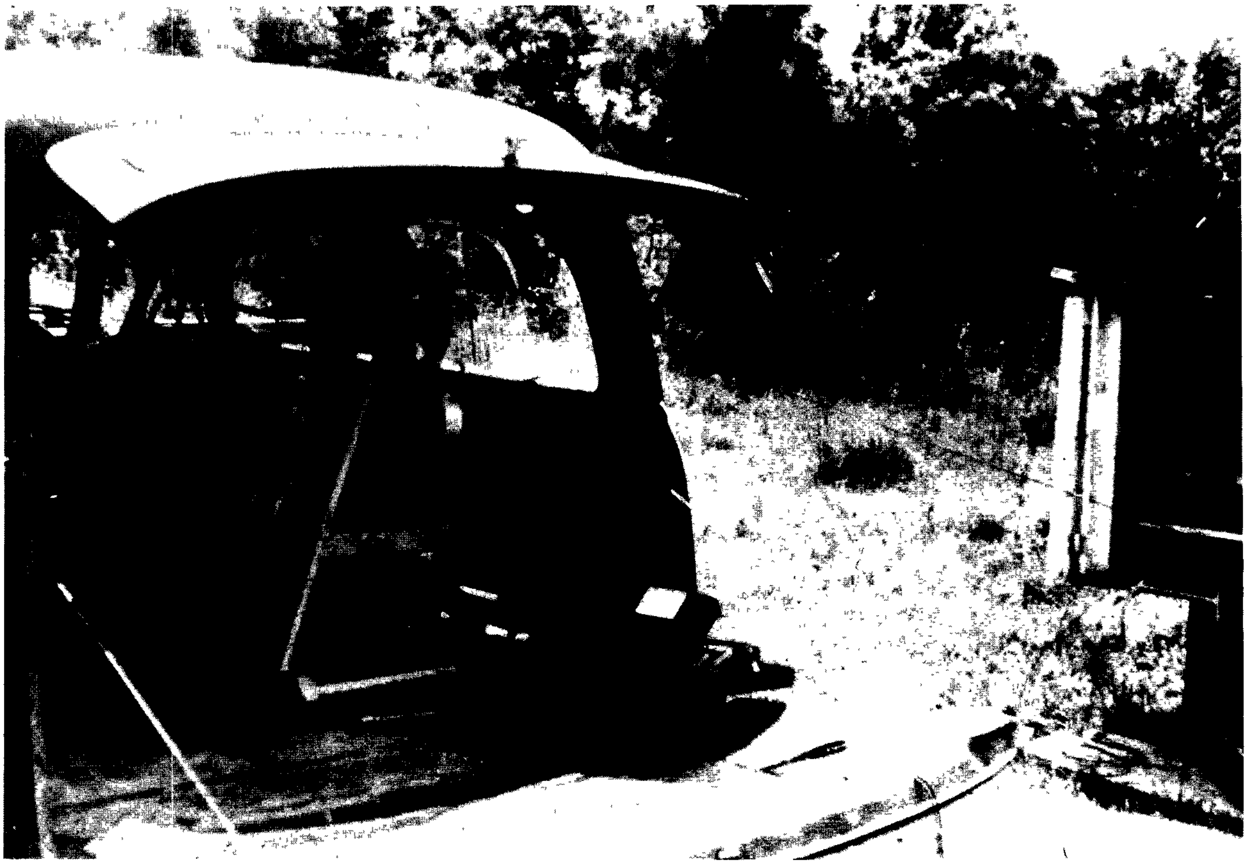

Figure 4.—First geophysical well logger for water-resources investigations bought by the U.S. Geological Survey in 1946.

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

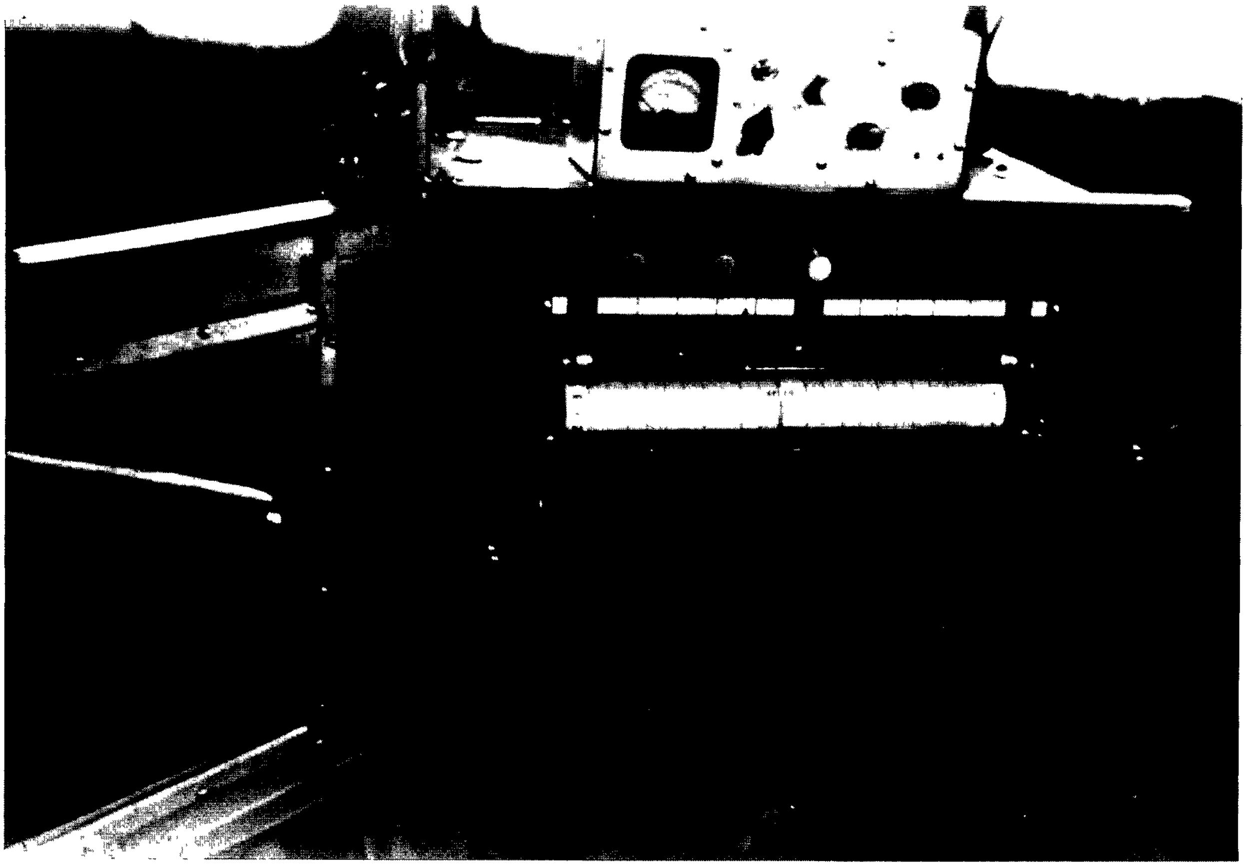

Figure 5.—Recorder and controls on 1946 logger. Single-point-resistance and spontaneous-potential logs were run with controls on the recorder. Gamma panel was added later.

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