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

Chapter E2

BOREHOLE GEOPHYSICS APPLIED TO GROUND-WATER INVESTIGATIONS

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Book 2

COLLECTION OF ENVIRONMENTAL DATA

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

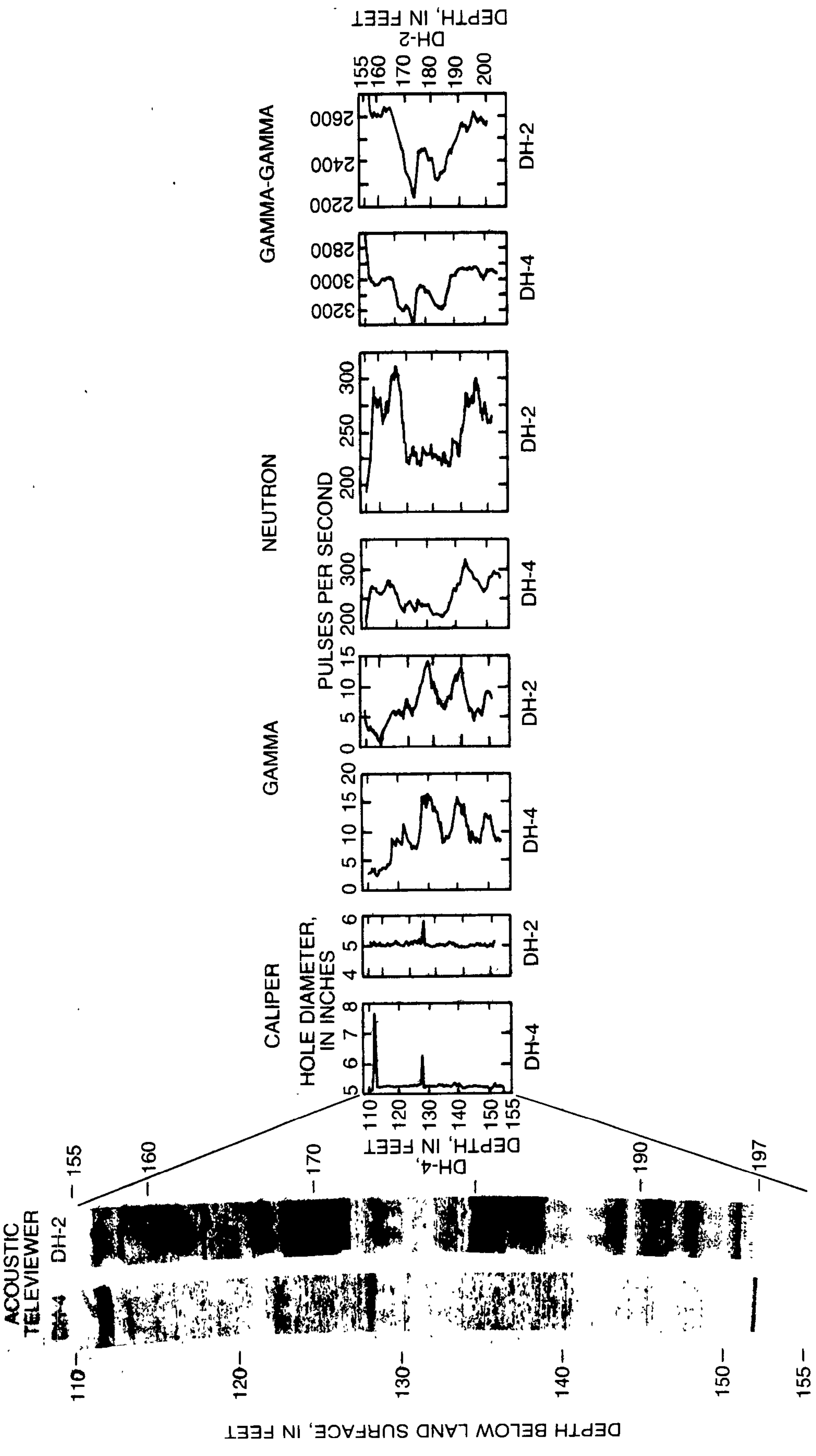

Figure 6.—Correlation of lithologic units between two drill holes, based on acoustic-televiewer, caliper, gamma, neutron, and gamma-gamma logs, Cook County, Ill. (modified from Nicholas and Healy, 1988).

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.

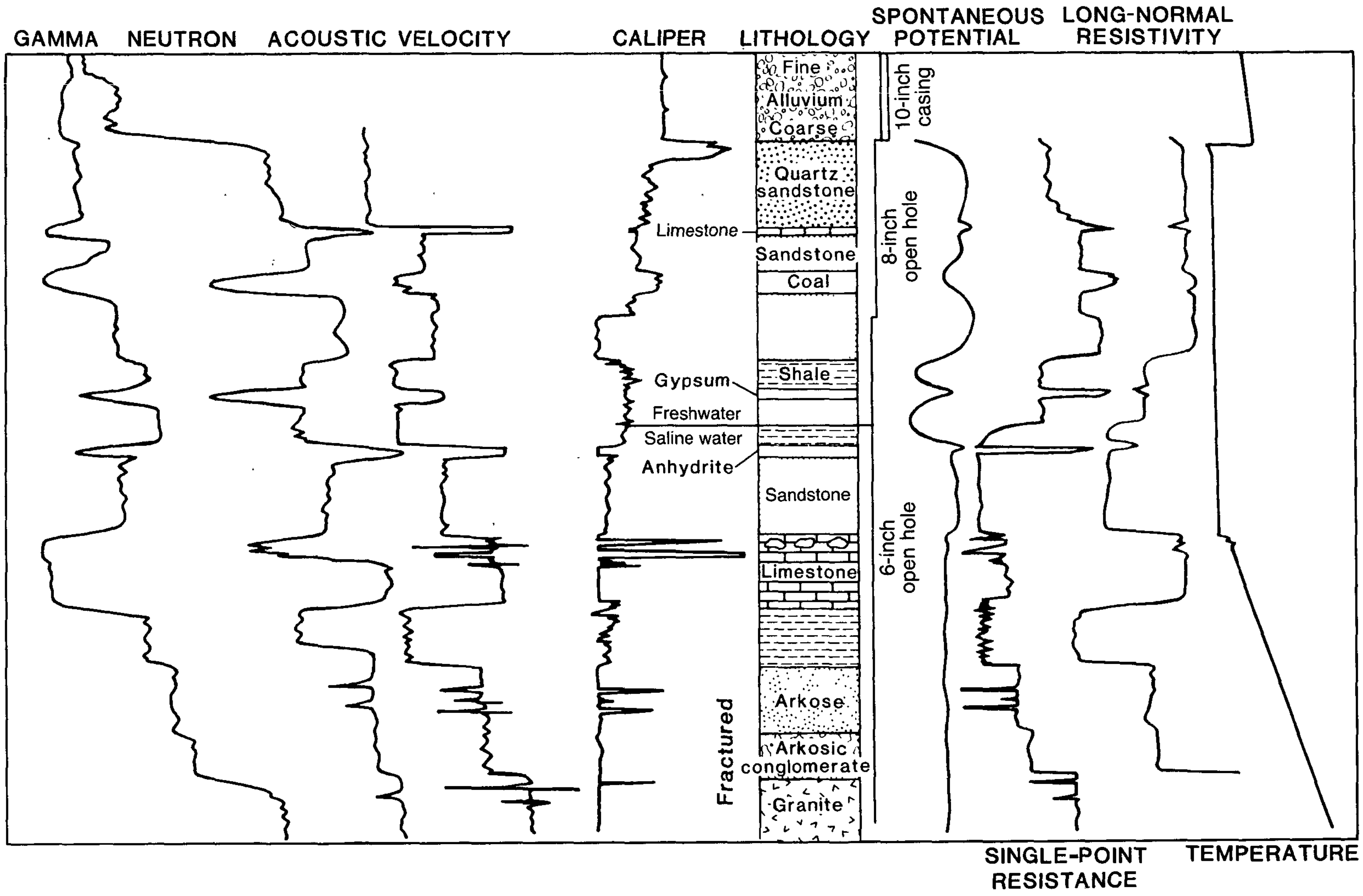

Figure 7.—Typical responses of a suite of hypothetical geophysical well logs to a sequence of sedimentary rocks. The measurement units for all logs except the neutron and acoustic velocity increase to the right.

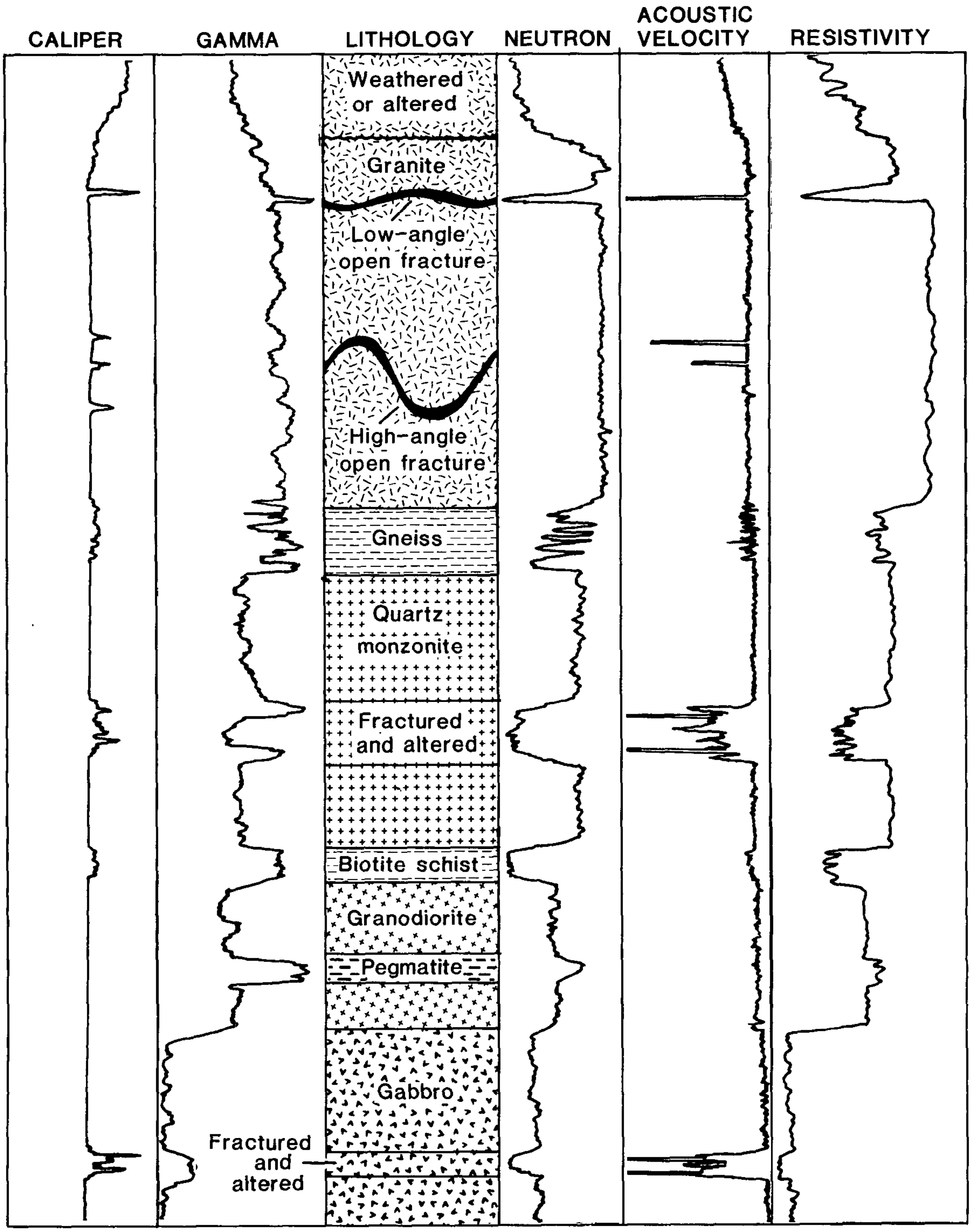

Figure 8.—Typical responses of hypothetical caliper, gamma, neutron, acoustic-velocity, and resistivity logs to various altered and fractured crystalline rocks. Porosity increases to the left on the neutron and acoustic-velocity logs; scales increase to the right on the other logs.

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

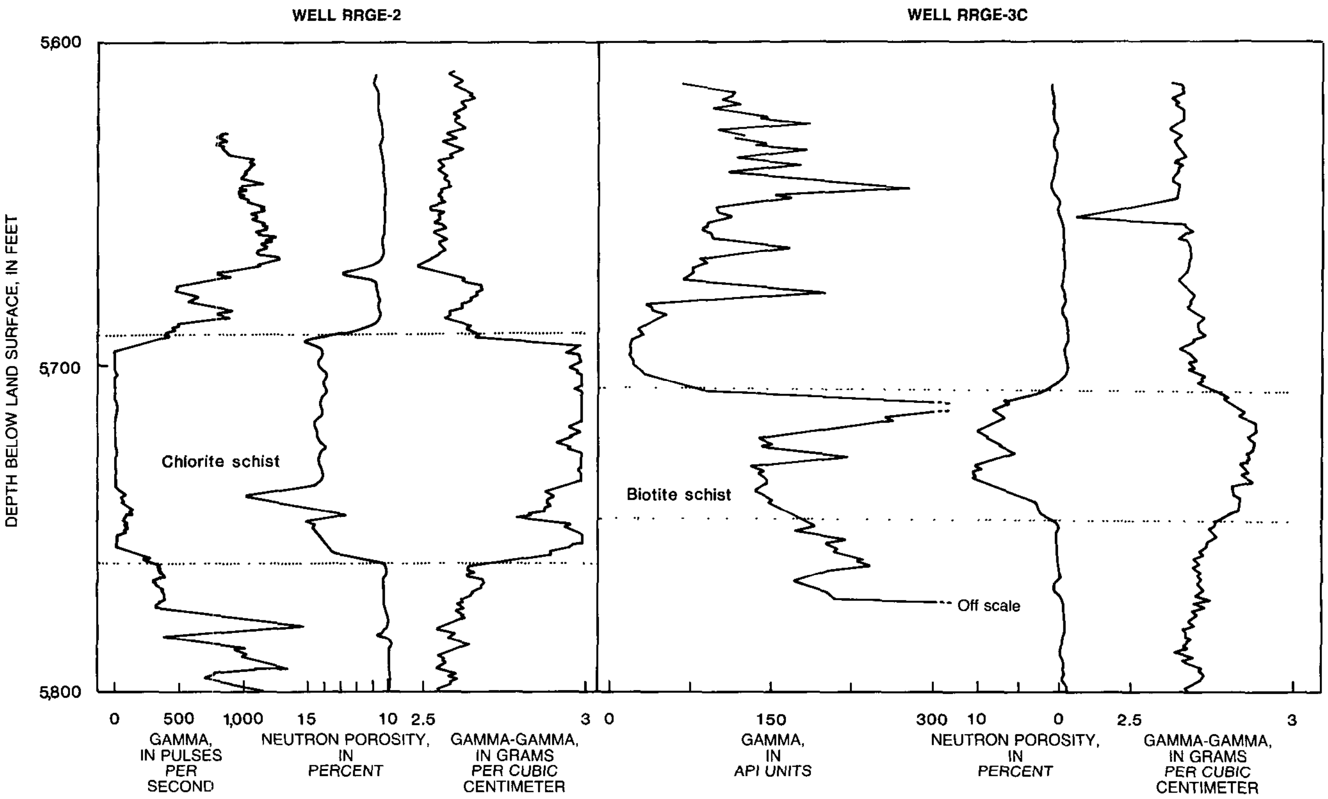

Figure 9.—Gamma, neutron, and gamma-gamma logs for two wells in the Raft River geothermal reservoir, Idaho.

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

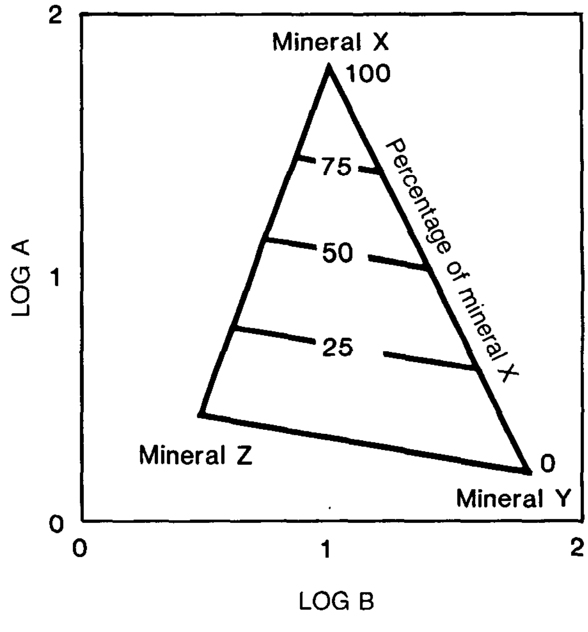

Figure 10.—Format of cross plot of two logs with three mineral matrices (modified from MacCary, 1978).

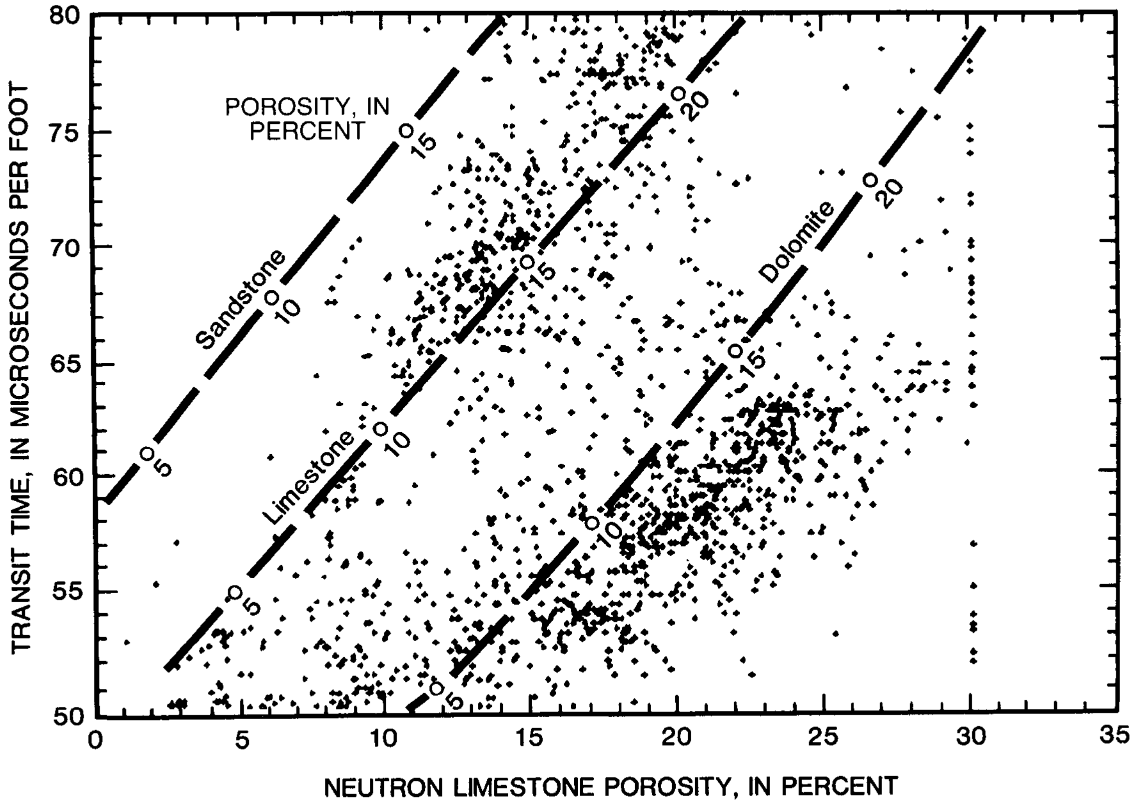

Figure 11.—Acoustic transit time versus neutron porosity, Madison Limestone test well 1, Wyoming.

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.

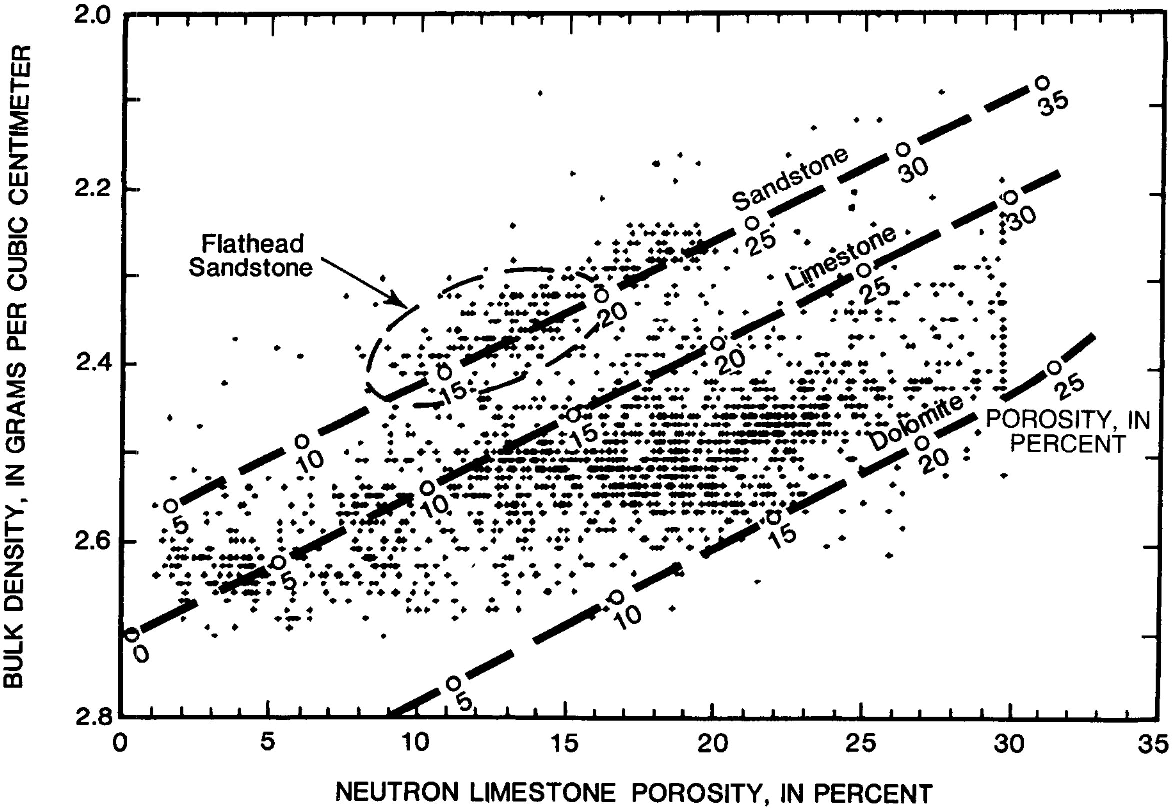

Figure 12.—Bulk density versus neutron porosity, Madison Limestone test well 1, Wyoming. The line of data points at 30-percent neutron porosity shows that the log was artificially limited at this value.

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

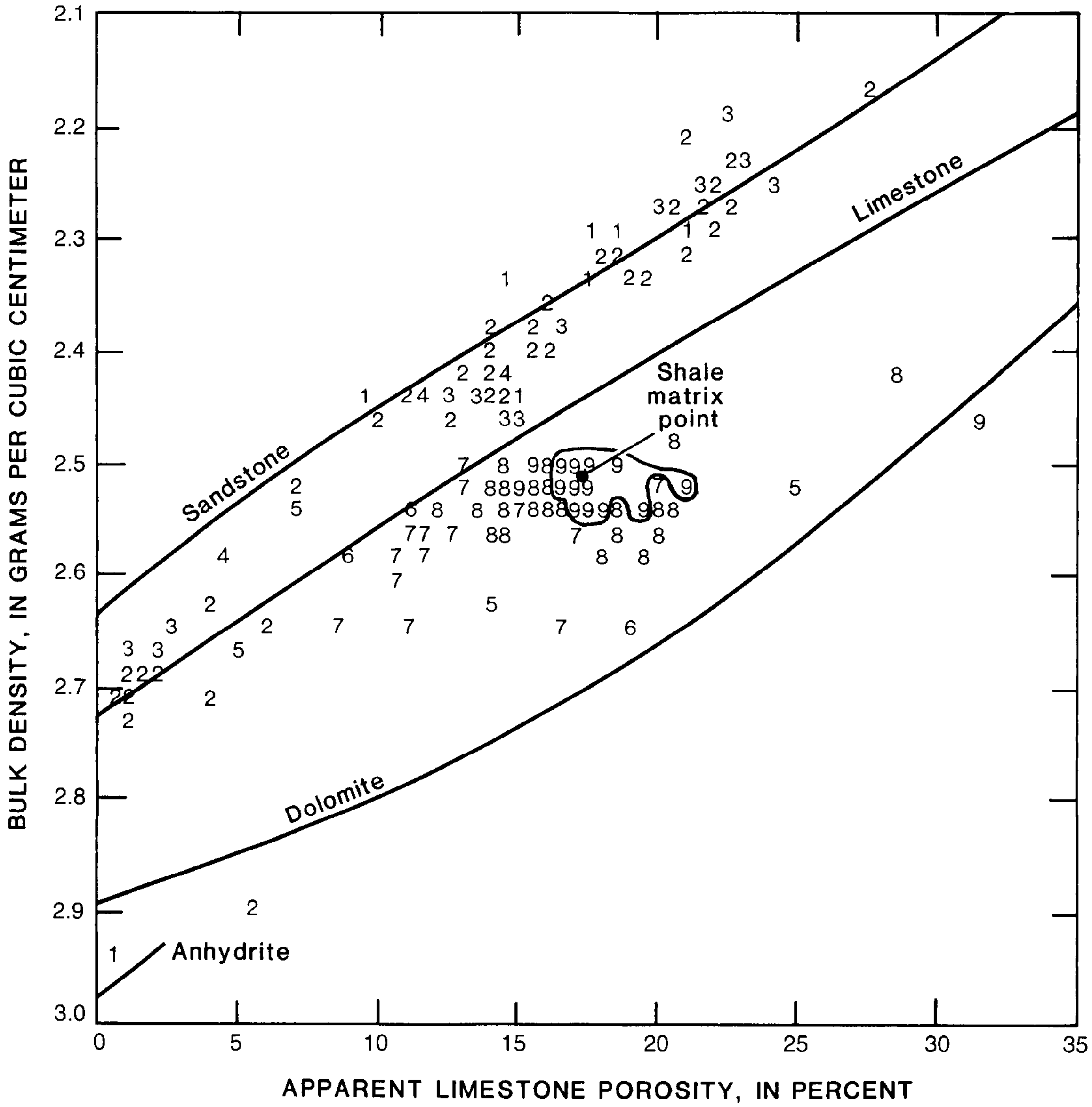

Figure 13.—Z-axis plot of gamma-log response versus gamma-gamma-log and neutron-log responses for the upper part of the Minnelusa Formation (modified from Head and Merkel, 1977). Numbers (1–9) represent a weighted function of the gamma-log response; values of 9 indicate the presence of shale.

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

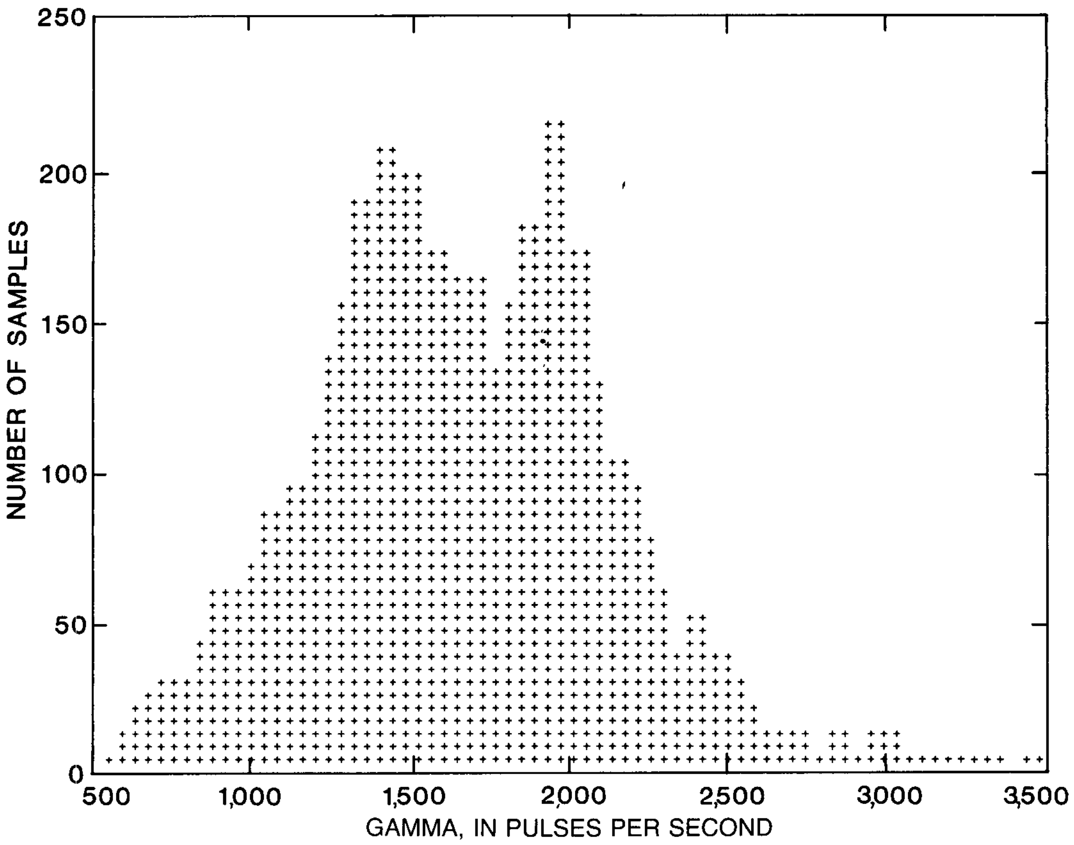

Figure 14.—Histogram of gamma-log response for a deep well near Raleigh, N.C.

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).

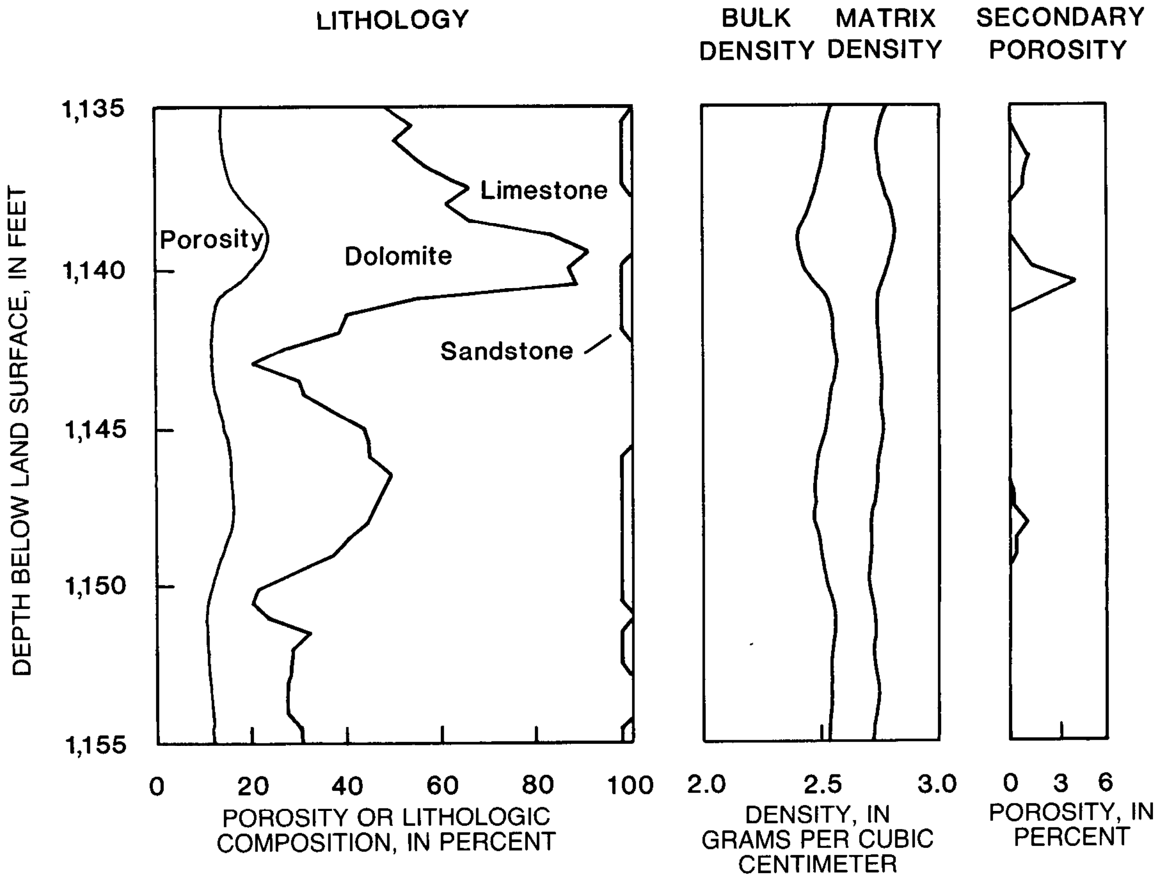

Figure 15.—Computer plots showing lithology, bulk density, matrix density, and secondary porosity based on geophysical logs of the Edwards Limestone near San Antonio, Tex. (from Merkel and others, 1976).

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.

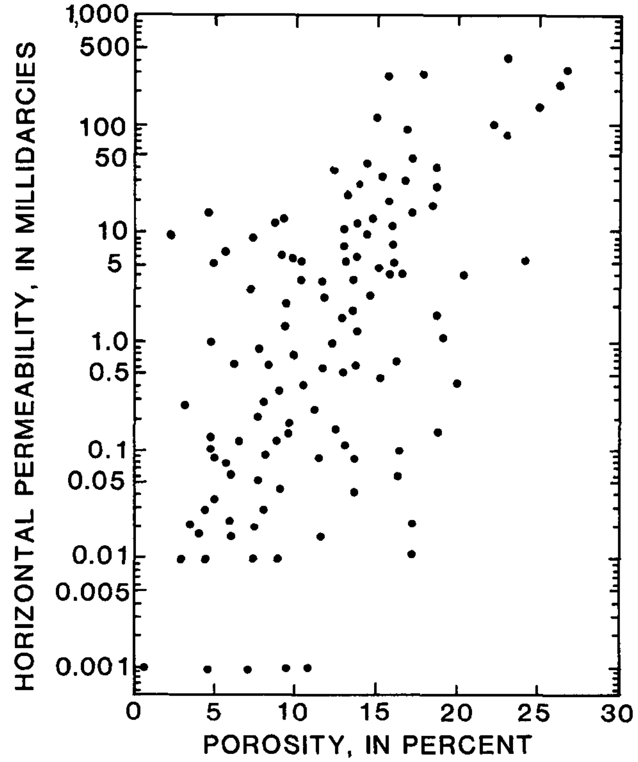

Figure 16.—Relation of porosity and horizontal permeability for replacement dolomites in the Madison Limestone (modified from Thayer, 1983).

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

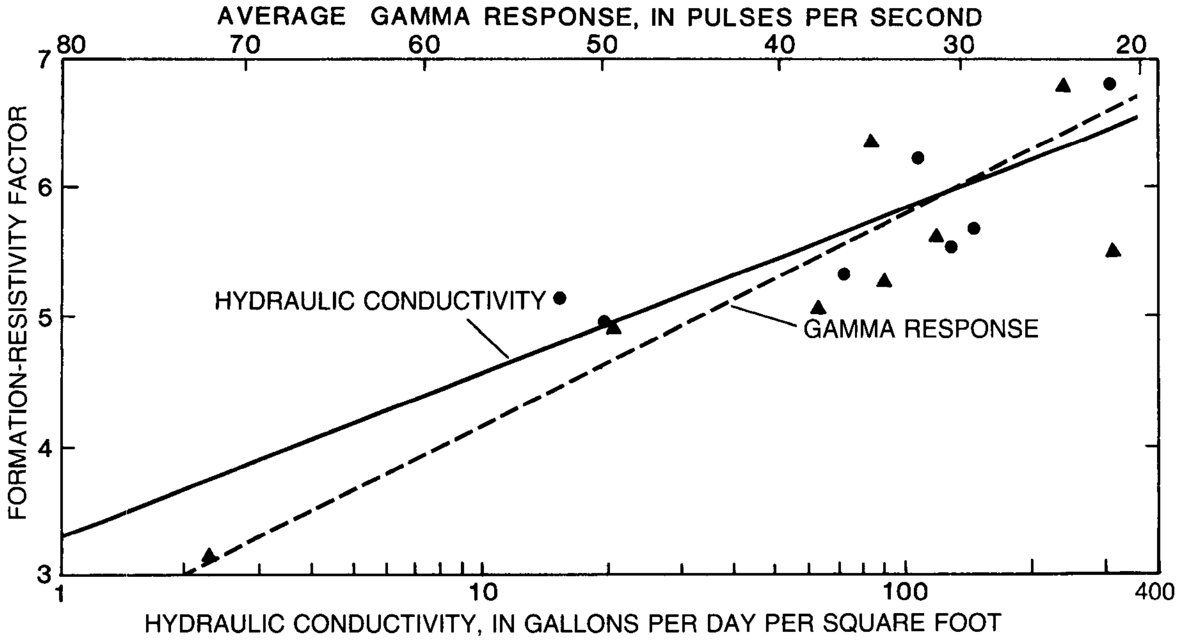

Figure 17.—Hydraulic conductivity and gamma response versus formation-resistivity factor for a limestone aquifer in Florida (modified from Kwader, 1982).

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.

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.

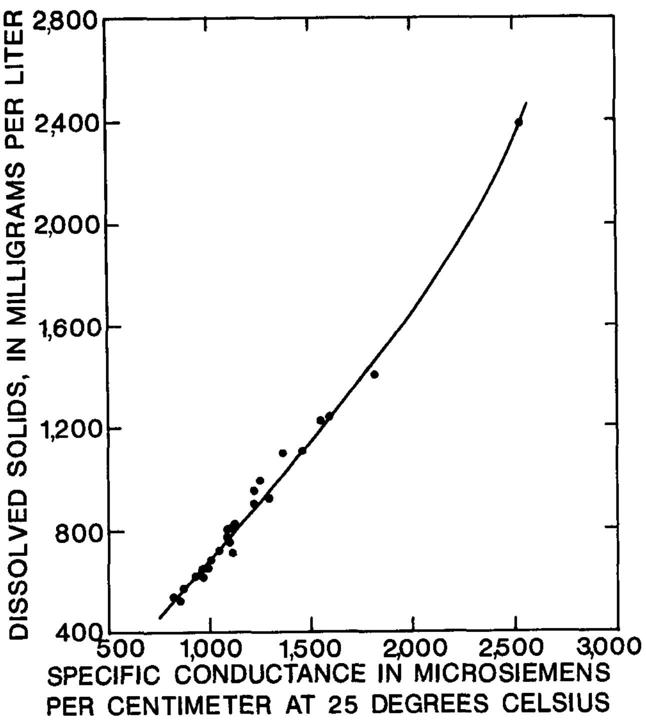

Figure 18.—Relation between specific conductance and dissolved solids in water from 25 wells completed in the Lockport Dolomite, Ohio (modified from MacCary, 1971).

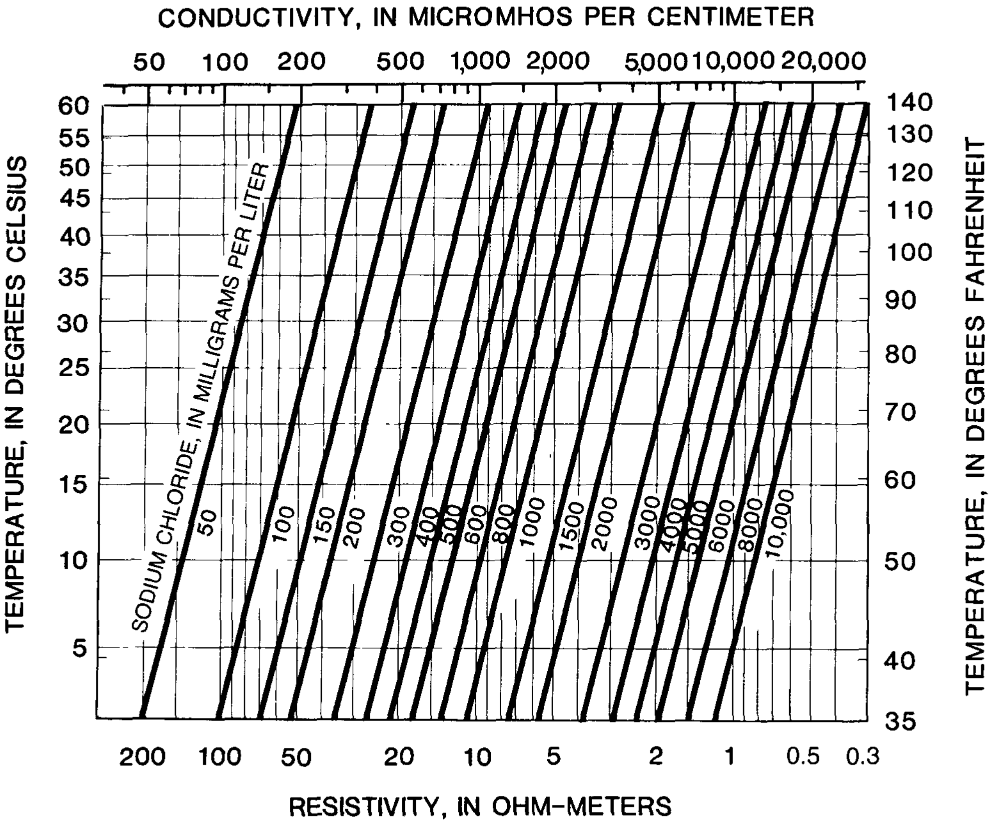

Figure 19.—Electrically equivalent sodium chloride solution plotted as a function of conductivity or resistivity and temperature (modified from Alger,1966).

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.

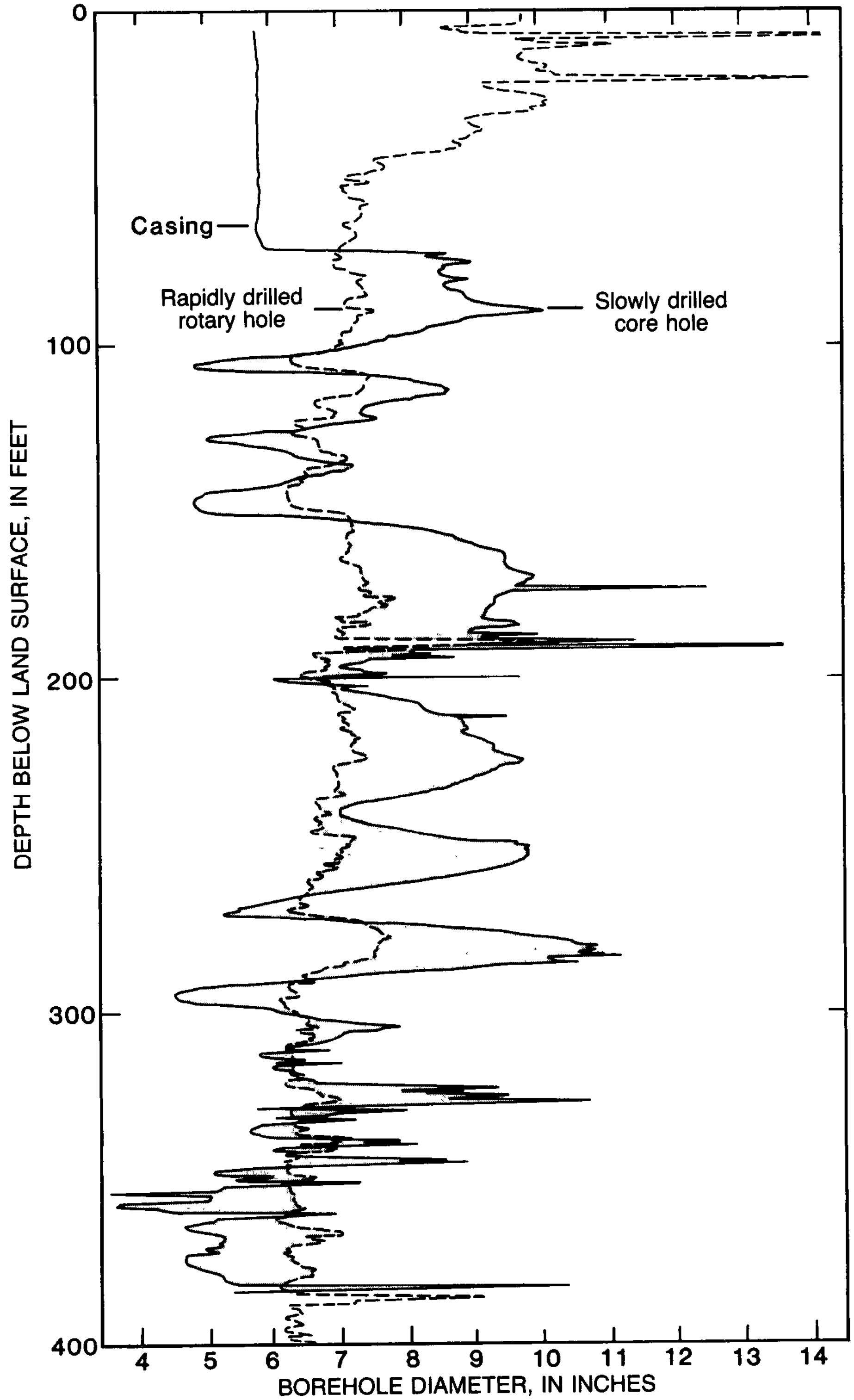

Figure 20.—Effect of drilling technique on borehole diameter. The boreholes are close together in an area of persistent lithology, Upper Brazos River basin, Texas.

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,

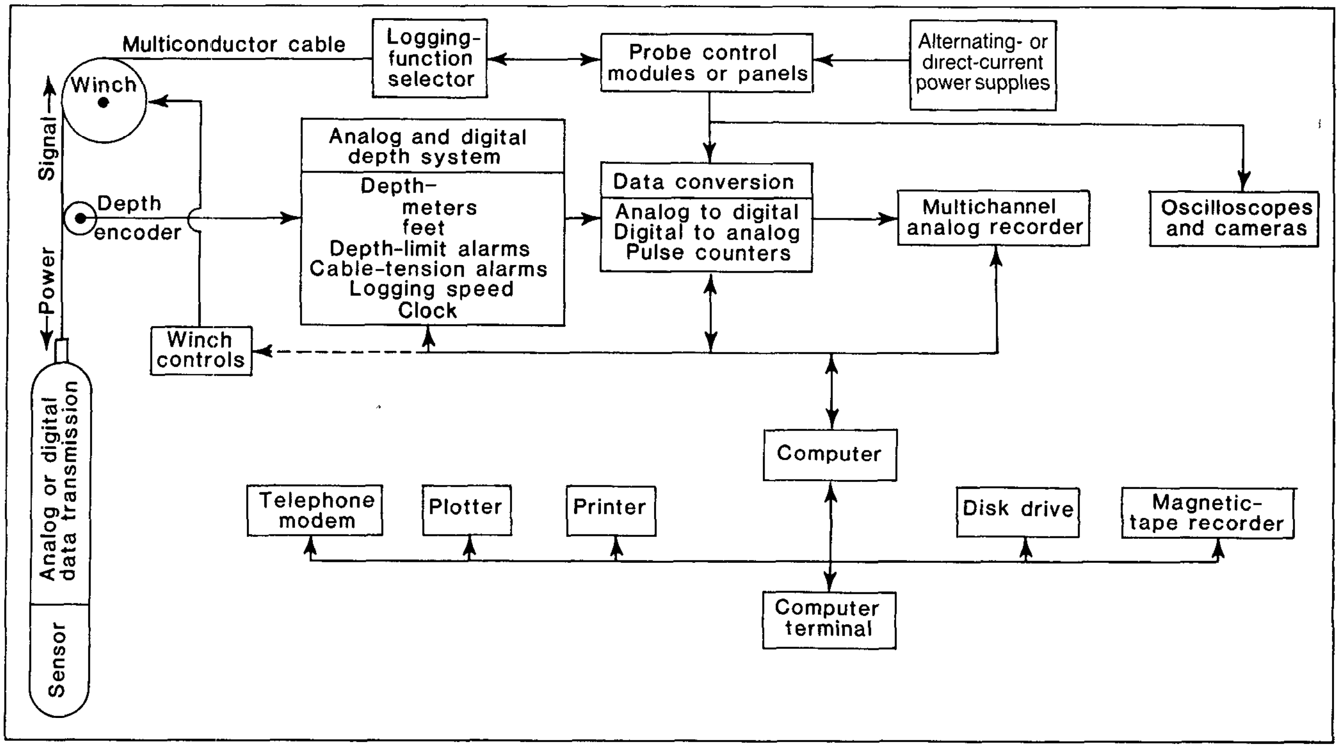

Figure 21.—A modern analog and digital logging system.

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