CONSIDERATIONS RELATED TO DRILLING METHODS IN PLANNING AND PERFORMING BOREHOLE-GEOPHYSICAL LOGGING FOR GROUND-WATER STUDIES

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Multiply	By	To Obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter

The following units are used in this report:

seconds (s)
pound per gallon (lb/gal)
ohm-meter (ohm-m)

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ABSTRACT

This report reviews various aspects of drilling, sampling and borehole geophysical logging that affect the effectiveness of well-log interpretation and the precision of well-log calibration using recovered samples, cuttings, or driller's logs. Because well logs are designed to measure the properties of geologic formations in situ, borehole conditions and the disturbances introduced by drilling are some of the most important factors controlling the effectiveness of geophysical logs in characterizing the hydrologic properties of rocks and sediments. This report reviews the operating principles and other factors related to commonly run geophysical logs that are likely to determine the accuracy and effectiveness of measurements made in boreholes. Geophysical logging tools discussed in detail are caliper, gamma, gamma spectral, gamma-gamma, neutron, electric, acoustic velocity, acoustic televiewer, temperature, and flowmeter tools. This report also reviews the various aspects of auger and hydraulic and air rotary drilling techniques that are most likely to affect logs, and lists some of the ways in which the drilling program can be modified to improve log quality in certain geological environments.

INTRODUCTION

Borehole-geophysical logging is an aspect of a drilling program that is frequently neglected until a project is well underway. Logging, when performed properly and when implemented with a well-planned sampling and testing program, can provide invaluable and often otherwise unobtainable information. Logs provide a means of obtaining continuous depth profiles of a geological formation, but data are given in terms of a geophysical measurement not normally of interest to the hydrologist. The combination of continuous profile and calibration of geophysical measurements in terms of hydrologic variables measured using discrete aquifer samples provides information not obtainable by either logging or sampling alone. This information can help the geologist or hydrologist achieve project goals more effectively. It is especially important to coordinate logging, sampling, and equipment calibration to insure optimum effectiveness in a given situation. If logging operations are not carefully designed to suit field conditions, geologic environment, and borehole environment, valuable information may be irretrievably lost.

In theory, well logs provide access to formation properties in situ. Therefore, the presence of a fluid-filled borehole surrounding the logging tool is one of the most important considerations in well-log interpretation. For this reason, drilling and sampling techniques, borehole conditioning, and well-completion methods need to incorporate the best technology and completion materials available for "constructing" the borehole. All procedures need to be considered with the goal of obtaining the best borehole-geophysical log data regardless of project objectives. However, in many instances borehole-geophysical logging is done only as an afterthought. As a consequence, the borehole condition is usually not optimized to provide the best environment for geophysical logging.

This report describes factors that need to be considered when planning a drilling/geophysical logging program. Specifically this report (1) describes scheduling and operational logistics, (2) describes the types of logging tools that may be of use, (3) describes various drilling methods and techniques that can minimize borehole damage, and (4) describes the proper conditioning of a borehole prior to borehole-geophysical logging.

SCHEDULING AND OPERATIONAL LOGISTICS

A number of items need to be considered once the decision is made to begin a drilling and logging program. These items include, but are not limited to: location and access of the drill site, logging equipment rig-up, and logging intervals.

Site Location and Access

Choosing a drilling site normally is based on two primary considerations: (1) a location where the most meaningful data for the project can be obtained; and (2) a location that has the easiest access for performing all drilling and testing operations. The first consideration is beyond the scope of this report. The second, however, is described here.

A site needs to be chosen that will permit ample space for maneuvering the drill rig, drilling-related equipment, and other borehole-testing equipment, including the geophysical logging vehicle. The site needs to be arranged in such a manner as to provide unobstructed access to the borehole. Commonly the drilling rig is set up on the site such that the rig is positioned between the borehole and the only other point available for the geophysical logging truck to be properly located. This positioning produces a difficult and dangerous logging situation, and may prevent some logs from being run. For small-scale logging operations in shallow boreholes, equipment positioning may not be a problem, and little thought or planning is needed concerning site access for logging. In large scale operations where rig time is strictly apportioned on the basis of a project budget, positioning and access considerations could limit the amount of data available in a given interval, and could degrade the accuracy of depth scales on the log. The more difficult the access to the borehole the greater the chance for error and personal injury or accident risk, equipment damage, and ultimately, loss of valuable geophysical-logging data.

Logging Rig-Up

The type of logging and drilling equipment that will be used and the borehole conditions will determine the kind of rig-up facilities needed. For instance, a small mineral-logging unit using light, small-diameter tools will require little space and will not necessitate leaving a drill rig or tower over the borehole. Conversely, a large oil-field type logging unit using much heavier, larger diameter borehole-logging tools will require a drill rig or tower over the borehole and a large operational area around the well. If logging will be done with the drill rig positioned over the borehole a rig needs to be selected that will permit clear access into the borehole from a sheave hung from the drill-rig tower. The project leader needs to contact the geophysical-logging services provider prior to drilling regarding type and size of the geophysical-logging tools to be used, and to identify any other special rig-up requirements that may be required. Communication between all parties early in the planning stages can minimize problems that could develop during the study.

Information that the geophysical-logging personnel needs to be made aware of early in the program include:

(1) Hole diameter;
(2) On-hole drill rig or service-mast availability;
(3) Bottom hole depth;
(4) Wellhead pressure and whether pressure-control devices will be needed;
(5) Borehole conditions likely to affect logging including borehole wall stability, washout areas, clay squeezes, zones of lost circulation, casing, cement, screens, high temperatures, unusual mud conditions, corrosive formation fluids, or hazardous or toxic substances.

Logging Intervals

The selection of logging intervals becomes more important and more difficult the deeper a well is to be drilled. Generally, there are three choices of when to log: (1) Open-hole logs (before any casing is installed); (2) Cased-hole logs (after casing is installed); or (3) Some combination of both hole conditions. It is advantageous to obtain geophysical logs in an open hole whenever possible. Open-hole logging permits the collection of a full suite of logs, many of which can not be obtained after permanent casing has been installed. Logging through casing causes log-response effects that interfere with quantitative log-analyses interpretations. Hole diameter, the amount and type of grout or backfill behind the casing, and any voids in the grout or backfill are a few of the log-response effects that the log analyst will have difficulty compensating for in a cased hole. Whenever feasible a well that has been drilled using multiple casings needs to be logged prior to setting each casing. Most log analysts believe that logging needs to be accomplished in uncased hole whenever hole stability is not a problem. The decision to risk running logs such as caliper and resistivity depends upon the severity of the hole-stability problems and logging-data needs. In all cases where borehole stability is expected to be a serious problem, natural gamma and other nuclear logs need to be obtained after casing the borehole. **UNDER NO CIRCUMSTANCES SHOULD A TOOL THAT USES A NUCLEAR SOURCE BE PUT INTO AN UNSTABLE BOREHOLE BEFORE CASING IS INSTALLED.** To do so would run the risk of losing a radioactive source, resulting in possible ground-water contamination, loss of license, and great expense trying to retrieve the source.

It is usually advisable to have the well logged prior to performing other types of borehole testing (such as borehole-packer testing). Frequently, packer tests cause damage to the borehole wall. This damage can adversely affect the log response. Packers can occasionally become lodged in the borehole, making subsequent logging and other activities impossible. Geophysical logs are also useful in identifying intervals where packers will seat effectively or in locating depths where borehole constrictions could affect packer recovery. While geophysical logging is not without its risks, the likelihood of logging probes becoming stuck in a borehole is less than for most other types of well-testing equipment. Any time a downhole testing device is introduced into a borehole, it could become lodged and unretrievable.

Establishment of a permanent depth reference point or datum frequently is overlooked. The chosen reference point needs to be easily accessible throughout the entire duration of the project. Location of the logging winch controls with respect to the reference point can be an important consideration because such factors as visibility and distance between winch controls and wellhead can affect the accuracy of the depth scale on the logs. Reference-point locations usually selected are: (1) Top of the rotary table; (2) top of the casing; or (3) land surface. However, there are disadvantages to each of these that must be considered. The rotary table is gone once the drilling rig is removed from the borehole. The top of casing is probably the best location for a reference point, but also can change unless it is permanent. Often the surface casing is temporary and probably will be removed after completion of drilling. The third commonly chosen reference point is land surface. This is a favorable reference point for all log-elevation data, but its exact elevation is subject to change. For example, excavating, backfilling, or collapse around the casing would change the land-surface elevation. No matter what reference-point datum is chosen, it needs to be surveyed as soon as possible and every effort made to maintain its integrity throughout the life of the well.

TYPES OF LOGGING TOOLS

A well-planned geophysical-logging program not only can provide information not obtainable by other methods but also can help with other borehole testing. Natural gamma and electric logs are very useful for locating formation contacts. The high-resolution, short-spaced gamma-gamma density log is very useful for distinguishing thin beds, particularly in coal sequences. Gamma-gamma density and neutron-porosity logs are used for measuring formation density and porosity in a borehole. Caliper, flowmeter, and televiewer logs are especially useful for determining zones of fluid inflow and outflow in the borehole, for identifying zones of fracturing and hole enlargements, and for determining where to set packers. Geophysical logs enable the hydrologist or geologist to obtain a continuous picture of borehole lithology. Logs can be used to detect lithologic variations in the core or cuttings that might be otherwise overlooked, and they can be used to fix the location and character of intervals of lost core. Geophysical logs also can be used to identify which borehole-fluid or cored zones in the borehole to sample for laboratory analysis. Geophysical logs have innumerable uses, and most projects would benefit from using them.

Detailed reviews of geophysical logging equipment techniques are given by such standard tests as Hearst and Nelson (1985), Tittman (1986), and Keys (1991). The following brief discussion of types of logging tools emphasizes principles of operation and sensitivity to borehole conditions that are most important in planning logging operations, and in evaluating the effects of drilling operations and borehole conditions on logs.

Caliper Tool

There are several different configurations of caliper tools available, but all of them serve the primary function of measuring borehole diameter. The single-arm caliper is usually used in conjunction with a tool such as the density or neutron porosity tool. The purpose of the single-arm caliper in this configuration is to decentralize the main body of the density and neutron-porosity tools, but it also measures borehole diameter. Probably the two most commonly used caliper tools for geohydrologic-exploration purposes are the three-arm and four-arm calipers. The three-arm caliper has three arms that operate on one central mandrel, giving a single trace that graphically represents the average borehole diameter. Some four-arm calipers have two pairs of arms that operate at right angles to each other. These tools are very useful in providing a qualitative indication of borehole conditions such as rugosity (fine-scale wall roughness), washouts, or constrictions that could affect subsequent logging operations. The four-arm caliper produces two diameter traces called the X and Y axis. Some other four-arm calipers have arms that operate independently giving four independent and usually compass oriented curves. The three- and four-arm calipers frequently have different length replaceable arms that permit optimization of the resolution of different diameter sizes within the borehole. The project engineer needs to insure that proper length caliper arms will be available for logging in a particular borehole diameter. Another type of caliper tool is used for producing a casing-inspection log. This tool has many arms or feelers that have a very short dynamic range (usually 1 in. or less). The casing-inspection tool is a very high-resolution tool used for checking casing integrity.

Gamma Tool

The gamma tool measures the gamma radiation emitted by the rock surrounding the borehole. The detector portion of the logging tool will have either a Sodium Iodide (NaI) crystal or a Geiger Mueller (GM) tube detector. The NaI crystal has greater measurement sensitivity but it also is more fragile. The outside diameter of gamma-logging tools usually range from about 1 to 4 in., and those usually used for geohydrologic studies range from 1.25 to 2.5 in. in diameter. The gamma tool can be run in either dry or fluid-filled open or cased boreholes. Gamma logs often are the primary logs used for interpreting lithology and for stratigraphic correlation. The gamma tool usually is incorporated into most large, multifunction logging tools run by the larger commercial geophysical-logging companies. It provides the trace on which most all depth corrections are made. The gamma log is relatively insensitive to borehole diameter changes, and provides a qualitative indication of lithology that can be used as a field check on the accuracy of the driller's log.

Gamma-Spectral Tool

The gamma-spectral tool also measures the gamma radiation emitted by the rock surrounding the borehole, but the gamma-spectral tool measures the distribution of energies of gamma disintegrations (recorded on a spectrum analyzer) as compared to the gamma tool which measures a gross gamma count. Depending on the arrangement of the gamma-spectral system used, logs can either be made with several selected isotope energy-level windows, or they can record the total energy spectrum to determine radioactive isotopes that may be present. This tool is particularly useful for studies involving radioactive-waste sites. It also is being used more frequently for recording potassium, uranium, and thorium concentrations in rock, and for monitoring the movement of uranium in boreholes. Most commercial geophysical-logging companies run what is referred to in oil-field logging as a KUT log (K-Potassium, U-Uranium, T-Thorium). However, the geohydrology field has not as yet developed this capability to a large extent because most spectral tools are about 4 in. in diameter to accommodate the large crystal required. However, there are a few small diameter KUT tools in the uranium-logging field, and a small-diameter gamma-spectral tool has been developed by the U.S. Geological Survey. The gamma-spectral tool can be run in dry, wet, cased, or uncased boreholes, and is relatively insensitive to borehole diameter effects; however, counting efficiency requires very slow logging speeds or a series of stationary measurements. Logging operations need to be scheduled to allow an extended period for gamma spectral logging if useful logs or a significant number of stationary measurements are to be made.

Gamma-Gamma Density Tool

This tool uses a radioactive source and requires certain legal and precautionary steps to be taken. Consult your logging contractor about these restrictions. The gamma-gamma density tool is used primarily for obtaining bulk density of the formation. The basis of operation is that the greater the formation density the smaller the quantity of radiation that travels from the tool source through the rock to the detectors. Although most density tools are collimated during measurements so that the measurement is relatively insensitive to borehole fluid properties, some of the tools used for geohydrologic studies are omnidirectional. The term "collimated" refers to density tool configurations such that the gamma detector is insulated so as to count only those gammas coming from the formation side when the tool is decentralized (forced against the side of the borehole). "Omnidirectional" refers to tool configurations where gammas arriving from all sides of the receiver are counted. The omnidirectional tools are much more sensitive to borehole conditions than collimated tools. Tool diameters range from 1.5 in. for the omnidirectional tools up to 4 in. for the larger collimated tools. The density tool can be run in either a dry or fluid-filled hole, but the log run in a cased borehole is of little value.

Neutron Tools

This tool uses a radioactive source and requires certain legal and precautionary steps to be taken. Consult your logging contractor about these restrictions. Although the primary use of the neutron tool is to obtain porosity values, it is also valuable as a lithology or correlation tool. In certain tool configurations, the neutron tool is used to measure soil-moisture. For all of these uses the neutron response is controlled by the hydrogen content of the rock around the borehole. Usually a saturated rock has a larger hydrogen content than that in an unsaturated rock, a smaller neutron count rate, and a larger porosity indicated by the log. Most neutron-porosity tools are calibrated in terms of known porosity response in limestone calibration blocks; thus, the scale is labeled "Apparent Limestone Porosity" on most neutron-porosity logs. As a result, a correction for lithology type has to be applied for lithologies other than limestone. The neutron tool is usually run in an open borehole under saturated conditions. If it is run in a dry hole above the water table, it will be an indicator of moisture content of the formation and not porosity, and the volume over which water-filled porosity is sensed can be many times that associated with similar measurements in saturated environments. In some situations where saturation is especially low, source-to-detector separations used in conventional neutron logs may be too short to give a useful log. If the tool is run in a dry borehole, a completely different calibration curve needs to be developed for the tool that indicates moisture content and not porosity. Most neutron tools used in geohydrologic investigations are omnidirectional and range in diameter from 1.25 to 2.5 in. Because these tools are not collimated they are very sensitive to borehole diameter, and significant borehole diameter correction may be required for a calibrated log. Neutron-porosity tools used for oil-field logging purposes are about 4 in. in diameter and usually are collimated and decentralized.

Electric Tools

The term electric log is a generic name for several types of logs that measure the resistivity and spontaneous potential or self potential of the rock. In mineral and geohydrologic-investigation logging, the term usually means a point resistance, or a normal resistivity (16- and 64-in. normal) log. In oil-field investigations, the term also may mean a lateral, guard, induction, or any number of focused or microresistivity logs. All electric logs except induction logs need to be run in an uncased borehole filled with an electrically conductive fluid. Recently available slim induction probes can be used in open, air-filled boreholes, or in boreholes cased with plastic or other non-conductive material. However, these devices measure formation conductivity rather than resistivity, so that resolution is lost in relatively non-conductive formations (resistivity greater than 200-300 ohm-m).

Formation resistivity measured in ohm-meters can be obtained from all but the point resistance logs. Each electric log tool has a different depth of investigation and, as such, is affected in varying degrees by the borehole rugosity and depth of drilling fluid invasion. Operation of all electric logs except for some single-point resistance tools and induction logs requires establishment of a return current electrode connecting the system electronics with the geologic formation. The electrical contact is established by burying the end of a cable in moist soil or immersion in the mud pit. If the wellsite is dry, a supply of water will be needed to wet the soil around the electrode. Principal uses of the electric tool in geohydrologic investigations are for determining formation resistivity and for obtaining water-quality information (which is interpreted from bulk formation resistivity). The point resistance and normal tools are usually 1 to 2 in. in diameter, whereas other electric tools usually are 3 to 4 in. in diameter. Most of the electric log tools also require a 25 to 50 ft. long isolation bridle thereby making them impractical for shallow boreholes. The bridle is not required for induction logging so that the recently available slim induction tools are especially useful in small diameter, shallow boreholes. Quantitative interpretation of electric logs almost always requires knowledge of borehole fluid properties and formation temperature, so mud resistivities and mud-pit and bottom-hole temperature need to be measured as part of the logging program.

Acoustic Velocity Tool

Acoustic-velocity logging and acoustic full-wave recordings are becoming more widely used in the geohydrologic-logging industry. They are useful for lithologic correlation, for characterizing fractures and, with other logs, for determining formation porosity. Most acoustic-velocity tools are about 2.5 to 4 in. in diameter and consist of a transmitter and several receivers. The acoustic-wave traveltime is computed from the time it takes the compressional wave to travel from the transmitter to the receiver or between two receivers. The acoustic-velocity tool needs to be run in a fluid-filled borehole, and useful logs are obtained in cased boreholes only in consolidated formations.

Acoustic Televiewer Tool

The acoustic televiewer is an acoustical device that measures the amplitude of the reflected acoustic signal obtained using an ultrasonic energy source (500-1500 kilohertz). The log produced by this tool is a 360-degree photographic image of the inside of the borehole wall that is oriented with magnetic north on each edge and south in the middle. It is a very useful tool for determining strike and dip of fractures, bedding planes, and direction of stress from breakout patterns in a borehole. Because it is an acoustical device, it needs to be run in an uncased fluid-filled borehole. It also can be used in a cased borehole for making an unoriented casing-inspection log. In those investigations where the televiewer logs are going to be compared with impression packer images, the log analyst needs to compare the mirror image of the impression packer with the televiewer logs. This is required because the televiewer log is seen from inside the borehole, whereas the packer image is viewed from the outside. There are some slim acoustic televiewer tools in use that are about 2 in. in diameter but most measure about 3 to 3.5 in. in diameter. Because of timing circuits for the transmit and receive pulse, most acoustic televiewers cannot log a borehole less than 4 in. or larger than 24 in. in diameter. The televiewer is capable of producing a log with much greater vertical resolution than most other logs. For this reason, it is very important to insure that depth scales are accurate, and that reference depth points to core or sample are as unambiguous as possible.

Temperature Tools

The temperature log can be used to give a useful profile of the thermal conductivity of rocks adjacent to the borehole and a measurement of the local geothermal gradient when the borehole is allowed to stabilize for a period of time (at least several days) after drilling ceases, assuming there is no convection in the borehole. The temperature log can be used to indicate where water is entering or exiting a borehole, where there is flow in the borehole, and to trace a dynamic fluid-temperature front between wells. Temperature logs need to be run in fluid-filled boreholes, either cased or uncased. Most temperature tools range from 1.0 to 1.5 in. in diameter.

Flowmeter Tools

The flowmeter tool is a geophysical-logging tool that is being more frequently used, especially for hazardous-waste studies. It is a very useful tool for locating permeable fractures and aquifers because vertical flow profiles made during pumping or injection indicate depths where water is entering and leaving the borehole. Flowmeter-tool diameters range from approximately 1.25 in. to 6.00 in. Although flowmeter tools can be simple to operate, conventional spinner flowmeters require a certain minimum flow to operate (usually about 5 ft/min). Because of this limitation, considerable planning is required to design a pumping or injection program for most effective identification of permeable zones.

DESCRIPTION OF DRILLING METHODS

In the following sections of this report, auger drilling, hydraulic-rotary drilling, and air-rotary drilling are emphasized because these drilling methods are the most frequently used by the U.S. Geological Survey during hydrologic investigations. Also, most test holes and observation wells are installed using one or all of these methods. A basic understanding of drilling equipment and terminology is assumed.

Auger Drilling

Auger drilling (solid- or hollow-stem augers) is an excellent method for collecting subsurface data for shallow unconsolidated materials and soft rocks. Stratification can be determined, and core samples obtained. Even without coring, disturbed samples of the materials penetrated by the augers can be collected and geophysical logs run in the augered hole. This method primarily is a dry-drilling method; however, drilling fluids can be used when drilling with hollow-stem augers (see section on Hydraulic and Air Rotary Drilling).

In general, the auger cuttings are lifted out of the hole and deposited at the surface by the screw action of the augers. Collection of the cuttings can be controlled by auger drilling through a hole cut in a sheet of plywood or similar material placed over the borehole. Although these samples are usually a mixture of the penetrated materials when drilling above the zone of saturation, they can be used quite effectively to construct a lithologic log of the borehole. This log can later be compared with the geophysical logs. However, when auger drilling saturated materials, the representativeness of auger-returned cuttings is quite uncertain; the auger-drill operator's expertise is of considerable importance when attempting to make visual lithologic interpretations. For this reason, it is important for the geophysical log analyst to compare geophysical logs with lithologic logs at the site to resolve discrepancies and clarify any misunderstandings while the driller is available.

Geophysical logging of the open hole can be accomplished upon withdrawal of the augers (either solid- or hollow-stem). However, if the competency of the open hole is doubtful, the hole can be logged with nuclear tools through the hollow-stem augers before they are removed. Logging through the augers presents the same limitations imposed by logging through casing, but might provide the only opportunity for obtaining these geophysical logs. Continuous drive samples or cores need to be obtained from one or more holes for analysis. These cores and samples, when combined with a reliable lithologic log and auger-drilled cuttings, make firm interpretations of geophysical logs possible (see Keys, 1991). Because geophysical logs do not directly measure lithology or hydrologic variables, and log responses cannot always be uniquely related to those variables, meaningful interpretation of geophysical logs is difficult without the cores and samples.

Geophysical logging of auger-drilled holes can present several problems. Affecting the severity of the problem is the drill operator's expertise. The integrity of the borehole wall, hole alignment, and abnormal enlargement of the borehole diameter (denoted as "wallowing out" by many drillers) can depend on several factors. Foremost of these are the physical condition of the equipment used and the technique and finesse used by the driller. For instance, excessive rotational speed or bent augers causes the auger string to wobble, which results in a wallowed out hole. Such a hole would be prone to caving and bridging after the augers are removed. Auger-rotational speed generally should not exceed 50 to 100 revolutions per minute while advancing the hole.

Attempts at logging a poorly auger-drilled hole will inevitably result in poor quality geophysical logs and present the possibility of logging tools being stuck. If the hole has been drilled into the zone of saturation using hollow-stem augers, the hole may remain open after the augers have been carefully retrieved. Geophysical logging then can be done without further difficulties. However, should the hole collapse as the augers are being withdrawn, the hole can often be salvaged as follows: (1) Immediately halt the removal of any further augers and measure the amount of remaining open hole through the inside of the augers; (2) if significant hole depth has been lost because of caving, redrill to the desired logging depth; (3) avoid pulling any of the caved materials up into the augers by slowly and carefully removing the pilot or plug assembly (if used) from inside the auger column; (4) mix an adequate quantity (enough volume to completely fill the auger string) of a water base, high-yield bentonite drilling fluid to a Marsh-funnel viscosity of about 50 to 70 s (Shuter and Teasdale, 1989) and a fluid weight of about 8.8 to 9.0 lbs/gal; (5) pour or pump the mixture into the hollow-stem augers, completely filling them; (6) slowly remove the augers from the borehole (preferably, without using any rotation); and (7) keep the augers and borehole completely filled with drilling fluid as each successive auger is removed. This technique often will prevent wall collapse by maintaining an outward load against the wall. As soon as all augers have been removed, open-hole geophysical logs normally can be run without any further borehole access problems.

Hydraulic and Air Rotary Drilling

Functions of a Drilling Fluid

Prior to describing the drilling methods, an explanation of the primary functions of a drilling fluid is given to enable one to have a better comprehension of the effects of mud (either direct or indirect) on geophysical logging. A drilling fluid is expected to accomplish the following as it exits the bit and moves up the borehole annulus: (1) Build a thin filter cake (or rind) on the borehole wall to prevent caving and fluid loss; (2) remove the cuttings from the borehole; (3) seal the borehole wall to prevent fluid loss and mud invasion (plugging) of the drilled formation materials; (4) keep the drilled cuttings suspended when drilling-fluid circulation is stopped; (5) cool and lubricate the bit; (6) lubricate the bit bearings, rig mud pump, and drill pipe; and (7) maintain positive pressure against the borehole wall to prevent caving. For a further explanation on the role of drilling fluids the reader is referred to Shuter and Teasdale (1989, p.19-22).

Hydraulic Drilling

The hydraulic-rotary method of drilling (sometimes referred to as direct-rotary drilling) is a fast and economical drilling method. Ordinarily, hydraulic-rotary drilling is accomplished as follows. A drilling fluid is circulated through a rotating string of drill pipe and exits through drilling-fluid passages (or ports) located in the lower part of the bit (bit kerf). The cuttings are lifted by the drilling fluid and transported out of the borehole through the annular space between the drill pipe and borehole wall. As rotation of the drilling tools continues and circulation of the drilling fluid is maintained, the rotating bit cuts the hole. Cuttings are carried out of the hole by the circulating liquid. The time delay between when cuttings are generated near the bit and when they appear at the surface increases with depth as the borehole is drilled. The hole is advanced by constantly lowering the drill-string assembly in the borehole.

Air Drilling

The air-rotary method of drilling (sometimes referred to as direct-air-rotary drilling) is another commonly used method. This method is extremely effective for drilling in hard rock, especially when a down-the-hole percussion hammer is used. Penetration rates with the hammer can be rapid compared with those obtained using a hard-formation, roller-type bit when drilling in hard rock.

The procedures for drilling with air are quite similar to those used in hydraulic-rotary drilling. Air takes the place of a circulating liquid, but water, drilling foam, polymers, and other liquid drilling additives commonly are used to enhance the performance of the circulating air. For instance, if drilling foam or other gel additives are introduced into the air stream, considerably less air velocity and annular pressure are sufficient to lift the cuttings from the borehole. Such additions are attractive for economic reasons when air-rotary drilling.

Causes of Borehole Damage

There are numerous drilling-related factors that contribute to borehole damage. Whether the damage is extensive or not, it probably will have adverse effects on the quality of the geophysical logs obtained. Extreme damage can even cause loss of downhole tools should the hole collapse while being logged. In some situations, the geophysical analyst will be required to evaluate whether it is more effective to log a poorly conditioned borehole or to postpone logging until after the borehole has been cleaned out. One will most often want to delay logging until the borehole is stabilized, but extensive efforts to clean out boreholes or to seal lost circulation zones can damage the borehole wall in critical zones of interest.

Major hole-damaging events that occur in both hydraulic-rotary and air-rotary drilled boreholes (including hydraulic fracturing of the materials) are caused by surging and swabbing actions of the downhole drilling tools. These problems usually occur because of a driller acting in haste or not correcting drilling-fluid control problems as soon as they happen. A prime example of a drilling-fluid control problem that causes accidental swabbing is when the solids content (particularly sand) is permitted to build in the fluid. When solids are permitted to build up (to greater than about 10 to 15 percent by weight) in the drilling fluid, its viscosity decreases, weight increases, and fluid loss will occur to highly permeable zones in the borehole. As a consequence, thick filter-cake rings are formed at the permeable zones. When the drilling tools are moved up or down past these permeable zones, the filter-cake buildup is knocked loose. Wall-stabilizing mud rind will also be scraped off, destroying the filtration properties of the drilling fluid. Consequently, the wall can collapse in these zones.

Another problem related to filter-cake buildup is bit-swabbing damage. As the drilling tools are moved up and down through the filter-cake rings, which are smaller diameter than the bits, mud and drilled cuttings are deposited on top of the bit and drill collars. In essence, this forms a swab or surge block on the bit and drill collars. Bridging or caving of the borehole can occur quite rapidly as the hole is swabbed when the drill tools are removed. The faster the tools are tripped out of the borehole, the more the resulting swabbing damage. These problems can be minimized or totally avoided by using a proper drilling-fluid control program to prevent filter-cake ring buildup. For a more detailed discussion of bit-swabbing damage, see Shuter and Teasdale (1989, p. 23-25).

To prevent borehole damage as the drilling tools are being removed, swabbing effects need to be minimized. According to Shuter and Teasdale (1989, p. 24), one should remove the string of drill pipe from the hole at a relatively slow rate to minimize differences in hydrostatic head between the formation and the hole. Equalization of these pressures can only be ensured if the inside of the drill string is vented to the atmosphere, allowing unrestricted movement of fluid out of the pipe and bit. Pulling a string of drill pipe without keeping the inside of the drill pipe open to the atmosphere (by using holes in the side of the pulling swivel or a regular water swivel) is referred to as dry pulling. However, if a vented string of drill pipe is pulled so fast that the mud cannot run out of the bit fast enough to keep the hole filled, bit-swabbing damage to the hole will still occur. A momentary pressure deficit in the hole will occur and the relative positive pressure in the formation will tend to cave the hole. Repeatedly lowering the string of drill pipe through tight spots when trying to remove the string needs to be avoided because resulting damage may necessitate extensive flushing and redrilling to get back into the hole. If geophysical logging or sampling of the hole is to be done, circulation during pulling should continue. This process is slow, but it usually prevents damage to the drill hole when removing drill pipe. This is accomplished by maintaining circulation at a slow rate through the string of drill pipe when it is being pulled. This guarantees that no great pressure differences will develop between the formation and drill hole and will prevent buildup of muds and sands on the bit which cause swabbing. These methods lengthen tripping time needed to remove the string of drill pipe from the hole and the cost of drilling, but the additional data afforded may be worth the extra effort and cost. In most cases, the added time at less than 2,000-ft depth is not a large factor in overall costs.

BOREHOLE CONDITIONING FOR GEOPHYSICAL LOGGING

Proper conditioning of a borehole is essential before running geophysical logs. Regardless of the drilling methods or type of drill used, the borehole-conditioning procedures are essentially the same. In essence, the drilled cuttings need to be removed from the borehole. If the hole has been drilled using a drilling fluid, fluid circulation needs to be continued after the hole reaches the desired depth. The purpose of continued circulation is to remove as much of the cuttings out of the hole as possible and to allow them to settle out in the mud pit. To prevent borehole damage and excessive wear of rig drilling-fluid pump and circulating-system components, the drilling-fluid effluent needs to be sampled frequently to ascertain the quantity of cuttings that remain in suspension and that are entering the settling mud pit. Sand content also needs to be measured and not permitted to exceed about 5 percent by weight for the same reasons. A sample obtained from the drilling-fluid effluent will determine if the cuttings are being dropped in the settling pit or merely are recirculated in the borehole. If the latter is the situation, the drilling mud needs to be thinned with water or commercial additive. The settling pit needs to be cleaned out and the rig suction hose needs to be kept off the pit bottom. The viscosity of the drilling fluid needs to be checked at this time to prevent the "mud" from becoming too thin. The viscosity must be properly maintained to prevent filtration loss and probable collapse of the borehole wall. A 35- to 40-s viscosity drilling fluid is ideal for most drilling conditions. However, if heavy gravels have been drilled, the viscosity might have to exceed 90 to 100 s. A mud-weighting agent such as barite also needs to be added to the drilling fluid when necessary to keep the borehole open; a mud weight of 11 lb/gal might be necessary.

For all of these reasons, it is imperative that the drilling-fluid viscosity be frequently adjusted to conform to the particular borehole conditions. The procedures need to be continued until the borehole is essentially clean and free from cuttings. The final stages of borehole conditioning need to be completed to permit lightweight geophysical logging tools to be lowered to the bottom of the hole. This conditioning might require complete replacement of heavy drilling mud used in the drilling process with a clean drilling fluid. Extreme care needs to be observed when changing the drilling fluid to avoid borehole collapse should the new mud be too thin or lightweight for the existing borehole conditions

ADDITIONAL SOURCES OF INFORMATION

One of the most complete listings of literature on borehole geophysics is contained in a report by Taylor and Dey (1985). The report by Keys (1991) is one of the most complete manuals available on geophysical logging tools. The report discusses such items as: principles of operation, volume of investigation, calibration and standardization, and interpretation and applications of the different logging tools. Other comprehensive textbooks describing geophysical logging equipment and analysis include Hearst and Nelson (1985), and Tittman (1986). Excellent reviews of log analysis techniques applied in hydrogeology are given by Keys (1986), DEC and others (1972), Alger (1966) and Kwader (1985). Most of the major geophysical-logging service companies have literature on log interpretation and applications, and also offer formal courses on log interpretation. However, these courses and manuals are mostly concerned with petroleum-related applications.

SUMMARY

The successful completion of a drilling and logging project depends a great deal on the initial planning. Care needs to be taken in arranging access to the drill site, and in designing flexibility in the plans of drilling and logging projects so that adjustments can be made to meet unexpected conditions. Because geophysical interpretation depends greatly on the effective integration of geophysical logs with other data such as lithologic logs and results of hydraulic tests run on core samples, it is important to insure that depth scales on logs can be made to correspond with the depth scales on other measurements. Probably the most important consideration in planning logging operations and later interpreting logs from a particular site is the evaluation of borehole conditions during logging. Care needs to be taken so that borehole effects do not invalidate geophysical-log interpretation for damaged or washed-out intervals. Borehole damage such as washouts, excessive mud invasion, caving, bridging, and mud-cake buildup can be prevented or at least minimized if proper drilling-fluid control is maintained. Drilling expertise plays an extremely important role in preventing borehole damage. By carefully considering the type of drilling method to be used, diameter of the borehole to be drilled, and the kinds of geophysical logs to be obtained, the project engineer or log analyst can increase the chances of a favorable conclusion to the project without excessive additional costs and delays, while maximizing the information available from a given suite of geophysical logs.

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GLOSSARY

(Drilling terms)

Annulus -- A space (annular space) between the outside diameter of the drill rods, drill pipe, or casing and the borehole wall.

Borehole conditioning -- The process of preparing a borehole for geophysical logging.

Core -- A cylinder of hard rock or unconsolidated material produced by the hollow, coring-type bit.

Bit -- A steel tool attached to the bottom end of the drill pipe which performs the actual drilling. Made in a variety of sizes, types, and shapes depending on type of lithology drilled, method of drilling, and depth and size of borehole.

Drill collar -- A heavy steel tool that is attached at the lower end of a drill-pipe string and just above the bit to provide weight and stability to the drill tools for rotary drilling or coring.

Drill pipe -- A special pipe, hollow, flush-jointed or coupled rods joined and threaded at each end, used to transmit rotation from the rig rotation mechanism (rotary table); thrust weight to the bit; conveys drilling fluid or air to remove cuttings from the borehole and cool and lubricate the bit.

Drilling fluid -- A liquid or gas medium used for transporting drilled cuttings from the borehole being drilled; stabilizes borehole wall; cools and lubricates bit and drill tools.

Filtration properties -- The ability of the solid components of a drilling fluid to form a thin filter cake (or rind) of low permeability on a porous formation.

High-yield bentonite -- A type of bentonite that will give a specific viscosity to the largest volume of water. The yield test relates the solid content to the viscosity of a clay-water mixture.

Marsh funnel -- The apparatus for measuring drilling-fluid viscosity. (1 quart of water passing through the funnel in 26 sec., all drilling mud is compared to water).

Drilling-fluid viscosity (or thickness) -- The resistance offered to flow by a fluid.

Mud weight (or density) -- The property of a drilling mud (fluid) that prevents the flow of formation fluids into the borehole causing hole collapse.

Swivel -- The connection device used on the rig standpipe to join a stationary hose into a rotating member, such as a kelly or drill rod, to allow passage of a drilling fluid or air and the free rotation of the rods.

Tripping -- The process of removing the drill pipe and tools either in or out of the borehole.

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