Mud logging

Mud logging, in its conventional implementation, involves the rig-site monitoring and assessment of information that comes to the surface while drilling, with the exclusion of data from downhole sensors. The term mud logging is thought, by some, to be outdated and not sufficiently descriptive. Because of the relatively broad range of services performed by the geologists, engineers, and technicians traditionally called mud loggers, the term "surface logging" is sometimes used, and the personnel performing the services may be called surface-logging specialists. Additional specialist designations may include:

- Pore pressure engineer
- Formation evaluation engineer
- Logging geologist
- Logging engineer

For the sake of generality, the terms mud logging and mud logger are used here with the understanding that the hybrid discipline encompasses much more than monitoring the mud returns and that the trained specialists perform engineering and geological tasks that span several traditional disciplines.

Contents

Objectives of mud logging

There are several broad objectives targeted by mud logging: identify potentially productive hydrocarbon-bearing formations, identify marker or correlatable geological formations, and provide data to the driller that enables safe and economically optimized operations. The actions performed to accomplish these objectives include the following:

- Collecting drill cuttings.
- Describing the cuttings (type of minerals present).

- Interpreting the described cuttings (lithology).
- Estimating properties such as porosity and permeability of the drilled formation.
- Maintaining and monitoring drilling-related and safety-related sensing equipment.
- Estimating the pore pressure of the drilled formation.
- Collecting, monitoring, and evaluating hydrocarbons released from the drilled formations.
- Assessing the producibility of hydrocarbon-bearing formations.
- Maintaining a record of drilling parameters.

Mud logging service first focused on monitoring the drilling mud returns qualitatively for oil and gas content. [1][2] This included watching the mud returns for oil sheen, monitoring the gas evolving from the mud as it depressured at the surface, and examining the drill cuttings to determine the rock type that had been drilled, as well as looking for indication of oil on the cuttings. Detection of the onset of abnormal formation pressures using drilling parameters was proposed with the introduction of the d exponent. [3] Gas chromatography, which was developed early in the 20th century, saw its introduction in mud logging in the 1970s when electronics became sufficiently compact, rugged, and robust to be used at rig sites. The literature provides excellent reviews of the early history. [4][5]

Computerized data acquisition and the ability to routinely transfer continuously acquired data to the office data center enabled the broader application of more sophisticated interpretive techniques and the integration of data from different sources into the geological and reservoir model, in near real time. This, coupled with the blossoming of measurement-while-drilling (MWD) and logging-while-drilling (LWD) tools, moved the mud-logging unit into a new role as a hub for rig-site data gathering and transmission. Starting in the 1980s, significant improvements to existing technologies, as well as major technical breakthroughs, have given the geologist and petroleum engineer a great number of powerful mud-logging tools to interpret and integrate geological, drilling, and geochemical data. These tools are discussed in subsequent sections of this chapter.

The traditional products delivered by a mud-logging vendor include:

- Geological evaluation
- Petrophysical/reservoir formation evaluation
- Drilling engineering support services

In this overview, we consider that these products support three basic processes associated with drilling and evaluation of wells:

- Formation evaluation (building or refining the geological and reservoir models)
- Drilling engineering and operations (the planning and execution of the well construction process)
- Maintaining drilling and evaluation operations with appropriate health, safety, and environmental (HSE) consideration

Mud logging data acquisition

Fig. 1 schematically shows the components of a drilling operation that have a part in mud logging. The most critical component is the drilling fluid (drilling mud), which, in addition to its role in drilling mechanics, carries most of the information from the formation up to the surface where it is acquired, decoded, or extracted from the mud stream by various techniques. Drilling liberates gas and liquid formation fluids, and circulation of the drilling fluid carries these to the surface (except during riserless drilling in a deepwater offshore environment, in which the drilling returns circulate only up to the sea floor). Cuttings, pieces of formation rock, are also carried in the circulated drilling fluid. MWD and LWD data are frequently encoded as pressure pulses and transmitted to the surface. Mud temperature is not a direct indicator of subsurface formation temperature, but monitoring the trend is important to understanding gas extraction efficiency and recycling. In deepwater drilling environments, the mud can be cooled significantly on the trip from the sea floor to the surface.

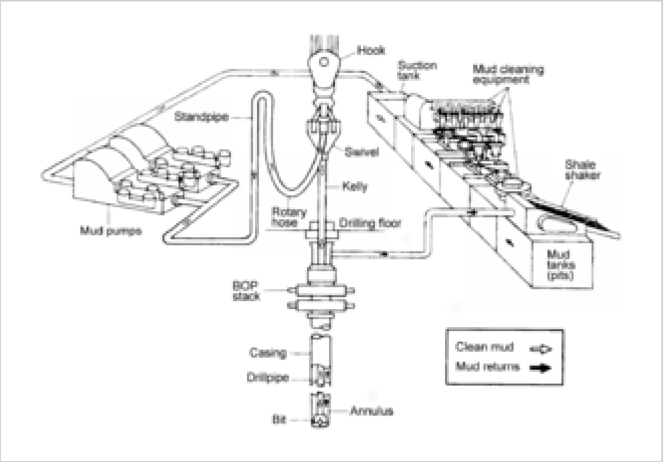

Fig. 1 – Drilling fluid flow path during drilling operations.

Drilling fluid is stored in the mud pit, drawn into the mud pumps, and pumped into the drillpipe via the kelly. Mud travels down the drillpipe, through any MWD tools and drill motors, and through the bit nozzles where its discharge aids drilling mechanics. At this point, the drilling fluid carries away rock fragments from drilled formation, along with any liberated reservoir fluids (water, oil, or gas). Cuttings and reservoir fluids are transported to the surface. Any gaseous components are dissolved in the base fluid of the drilling mud under most overbalanced drilling conditions. Drilling mud continues its flow up the wellbore drillstring annulus, through the casing-drillpipe annulus and the blowout preventer (BOP) stack, and, in the case of an offshore well, up the riser. At the bell nipple, the returning drill fluid is exposed to atmospheric pressure and flows down the mud return line. If an underbalanced drilling operation is being used, there is a rotating seal around the drillpipe, and the pressurized drilling returns stream moves through the "blooey line" to a separator and flair.

The return mud stream continues down the return line to the shaker box or "possum belly." This is the standard location for the "gas trap" gas extractor. Mud pours over the shaker screens, with cuttings getting discharged off the top of the screen, while the drilling fluid that falls through the screens travels on through the degasser, desander, and desilter to the mud pits. The mud logger takes samples or acquires data at the following points in the process:

- Whole mud samples are taken at the mud suction pit and at the possum belly and are used to do whole-mud extraction using a steam still. They may be taken on an occasional basis during coring and wireline logging to assess the effects of mud filtrate and solids.
- Drill cuttings samples are taken off the shaker screen and off a "catch board" where cuttings fall from the screen to disposal. These are used for lithological and mineralogical description, paleo description, and sometimes "canned" for laboratory-based carbon-isotope analysis, detailed geological examinations such as thin-section preparation and analysis, chemostratigraphy, and source rock evaluation.
- Gas sampling is done through an extractor at the possum belly, in some cases at the bell nipple or off the mud return line to minimize losses to the atmosphere, and at the mud suction line or mud pit to monitor recycle gas content of the mud. After extraction, gas analysis may be performed at the sampling location, [6] or, more routinely, the gas is continuously transferred via a vacuum line to the logging unit where it is passes through the manifold of analytical instruments (total HC, GC, MS, H_2S, etc) and may be captured for laboratory-based analysis (carbon isotope, molecular composition). [7]
- Mud temperatures are monitored at the mud suction pit and mud return line.

The mud engineer collects mud samples for analyses that are used to determine any adjustments to mud properties needed for drilling.

Contamination is defined here as any material that does not come from the formation that has been drilled at the time that a specific volume element of mud exits the bit. Mud contamination has several potential sources:

- Air, which can enter the top of the drillpipe when the Kelly-drillpipe joint is broken during a connection.
- Pipe scale and pipe dope from inside the drillpipe (pipe dope fluoresces and may interfer with show identification or description).

- Rock sloughing or rubbing off formations further up hole.
- Cuttings that have bedded or built up because of improper hole cleaning dynamics that are mobilized by changes in mud viscosity, pumping rate, or drillpipe or collar rotation.
- Uphole fluids that flow or are swabbed into the annulus.
- Cuttings that have built up on the shaker screen or in the possum belly.

The logger should be watching for any change in cuttings or mud-conveyed hydrocarbon fluids that indicate contamination. Mud additives such as weighting agents and lost-circulation material are not considered contaminants, but must be monitored because some of these interfere with analytical observations and descriptions or give interfering instrument responses. Some base mud fluids, particularly some of the synthetic fluids, create challenges for the mud logger, as do some chemical additives (e.g., some sulfate or sulfonate wetting agents may give a false positive H_2S indication).

Samples of the drill cuttings are taken at the shale shaker. Wellsite geologists or engineers should specify the appropriate procedure for collecting samples, which may be done by the mud logger or the mud logger's sample catcher. Cuttings have a relatively short residence time on the shaker screen. Sampling protocol should include taking a composite sample with portions from different areas of the screen, combined with cuttings that have been retained on a "cuttings board." A cuttings board is a wooden board, steel angle iron, or other such device that is hung just below the base of the shaker screens to catch cuttings as they fall off the edge of the screen. Immediately after samples are collected, the screen and catch board should be washed down with clean drilling mud base fluid. The logger should mix this composite sample and take divided portions for cleaning, interpretation, and bagging. The wellsite planner should specify the sampling frequency (typically a composite over 10-, 30-, or 90-ft intervals or on a timed basis).

Gas sampling is traditionally done with a mechanical degasser, generically called a "gas trap." **Fig. 2** shows an example. [8] Typically placed in the shaker box, the trap pulls in drilling mud through the centrifugal action of the stirrer. The mechanical action of the stirrer, combined with a slight vacuum pulled in the trap head space, allows the gas to partition between the liquid and gas phase. The head-space gas is pulled by vacuum through tubing, into the logging unit, and on through the gas analysis manifold.

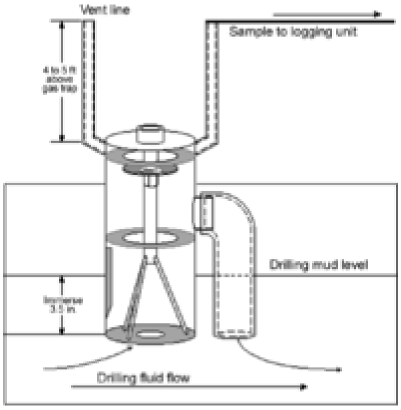

Fig. 2 – Schematic of a gas-trap type gas extractor.

Alternative methods for sampling gas may be accomplished by continuously operating controlled-volume mechanical or thermomechanical slip-stream gas extractors[9][10] and membrane-type extractors. [6] The mud logger may place the sampling point for these gas extraction devices at the bell nipple, the mud return line, or in the shaker box. Other methods require taking discrete samples, followed by thermal extraction techniques [such as the steam still, where samples of the whole mud are collected and portions heated in a steam-distillation apparatus (**Fig. 3**)] and microwave heating methods. [8]

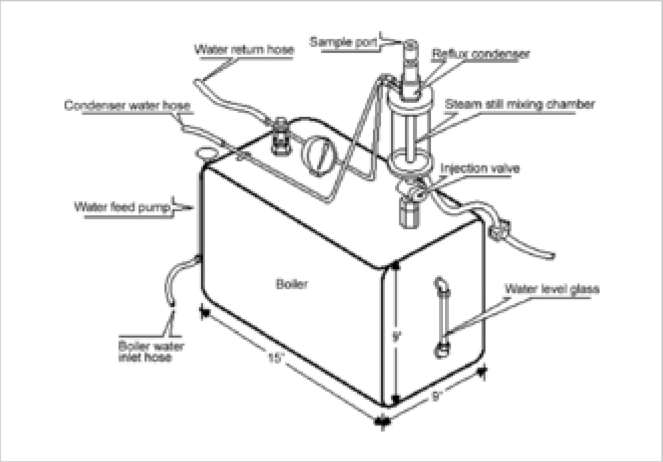

Fig. 3 – Schematic of a steam still-gas extractor.

The gas manifold may include provisions for a portion of the gas stream to be pumped into sample containers, either laminated gas bags or stainless steel tubes. [Personal communication with D. Coleman, IsoTech Laboratories, Champaign, Illinois (2002)] (see **Fig. 4**). These gas samples are then shipped from the rig for laboratory analyses. There are new mass-spectrometer-based techniques that may not require a bulk extraction of the gas from the mud for analysis. [11]

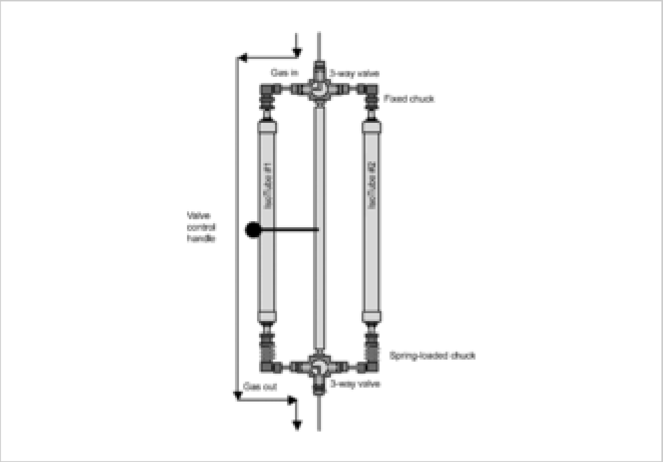

Fig. 4 – Low-pressure gas sampling tubes mounted two to a rack for continuous, sequential gas collection.

Once gas is extracted from the drilling fluid, various analytical techniques determine properties of the gas at the rig site. The basic measurements include a determination of the "total" gas concentration and the composition and concentrations of the constituent components.

Maintaining data quality

Many different data are available, obtained through technologies that range from tried-and-true classical "wet chemistry" techniques through high-tech sensors that use procedures established after countless years of thoughtful research, development, and field testing. Even the best planned operations may, from time to time, provide data of poor quality or even totally miss data from important geologic intervals. Proper planning of surface data logging operations should include provisions for "whole-system" qualification before starting the operation, as well as a plan for the occasional quality audit. Details will vary widely depending on the location of the operations, availability of staff, project magnitude, and economics. An appropriate quality assurance program may be as simple as receiving a weekly e-mail or fax with GC calibration information or as intensive as scheduling rig-site audits, depending on the exact circumstances and well logging objectives.

Drilling engineering and operations

There is significant overlap between data gathered for geological, petrophysical, and reservoir engineering needs vs. data gathered for the driller. Information about pore pressure, formation gas, and rock type and strength are an integral part of well planning. Continuously tracking these parameters as a well is drilled and comparing the actual data with what was used in the well plan allows for quick response by the driller when trouble occurs. It also allows the driller to “fine tune” his operations to optimize drilling performance, which is measured by drill rate, trouble time and cost, and delivery of well specifications (e.g., in terms of being a producing asset, an exploration well, or an appraisal well). We will leave these items in the “evaluation” bin, with the acknowledgement that they could just as easily be lumped into the drilling engineering category. This section discusses the data types and processes that are used to a large extent, and in some cases exclusively, by the driller.

Any measurable parameter that gives an indication of pore pressure provides the driller with an estimate of the degree of overbalance, which directly affects the rate of penetration (ROP). Mud weight will be adjusted to be within the desired window for a well’s particular set of drilling dynamics and rock strengths on the basis of modeled drill rate. The various measurements described in other sections of this chapter become important, to some degree, to the driller. These services may be provided by the mud logging contractor.

Weight on bit and rate of penetration

These data are collected to indicate drilling performance. The driller would like to know how to predict his drilling or penetration rate. Bourgoyne *et al.*[12] describes several models that have been developed and used. Jorden[3] proposed modifying the Bingham model and defined a normalized parameter called the drilling exponent (the *d*-exponent):

$$d_{\text{exp}} = \frac{\log\left(\frac{R}{60N}\right)}{\log\left(\frac{12W}{1{,}000d_b}\right)}, \text{ ....(1)}$$

where R = the penetration rate in ft/hr, N = the rotary speed in rpm, W = the weight on bit in Mlbf, and d_b = the bit diameter in inches. The d-exponent is sometimes corrected for mud density changes[13] by considering the effects of ρ_n, the mud density equivalent to a normal formation pore pressure, and ρ_e, the equivalent mud density at the bit while circulating:

$$d_c = d_{\text{exp}} \frac{\rho_n}{\rho_e} \text{ . ...(2)}$$

Mud pit level

Indicators specify changes in the volume of mud in the pit. The total volume of mud changes continuously with depth as the hole volume increases. Rapid increases in pit volume may mean an influx of reservoir fluids, and well control measures may need to be implemented. A rapid decrease in volume indicates a downhole loss of mud, and lost-circulation material will probably be added to the drilling fluid.

Mud chloride content

Mud chloride content is monitored in all systems, along with the water content in nonaqueous drilling fluid systems. Significant changes in content may indicate influx of formation water, which means that an underbalance condition may be close, and mud weight may need to be increased.

Lithology and mineralogy

Lithology and mineralogy may change as a fault is approached. Warmer water, with higher concentrations of dissolved salts, can flow along faults during some phases of their development. As the water moves into cooler zones, salts will precipitate, plugging pores and showing up in the cuttings. Indication of an approaching fault may warn of a potential jump across the fault, which, in some areas, is accompanied by a significant change in pore pressure. Advance knowledge of this allows the driller to adjust the mud weight before he encounters problems.

Total gas

Concentrations in the drilling fluid returns indicate the degree of overbalance or underbalance between the equivalent mud density and the formation pore pressure. The total gas concentration measured while drilling shales establishes a baseline or background level that is useful in tracking pore pressure, with the assumption that the shale pore fluids are in equilibrium with any neighboring permeable sands.

Fig. 5 indicates how trends of several parameters vary with pore pressure and depth. Monitoring and plotting these can give indications of the transition from normally pressured zones to geopressures. The ROP, drilling exponent, shale cutting density, and background total gas all follow a normal trend with depth. Attempts to calibrate these measurements directly to pore pressure have been somewhat successful and usually are on the basis of establishing the trend for normally pressured formations. When a deviation from the normal trend occurs, correlations specific to the basin or geographic region are used to estimate the formation pore pressure. Most logging companies offer pore pressure service, which requires experienced pore pressure engineers who, frequently through experience, add subjective input to the model as well as the objective parametric inputs.

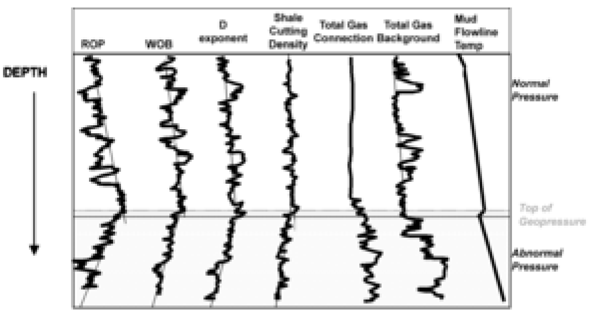

Fig. 5 – Schematic description of drilling and mud logging parameter changes with depth, normal pressure trends, and geopressure trends.

While the accuracy of these particular methods will vary from site to site, such plots are extremely useful in identifying the transition into geopressures (i.e., when passing from normally pressured to abnormally pressured zones). At the transition to geopressures, the trend lines change slope. Because some of the changes may be subtle, looking at all the available data helps pinpoint the transition.

Connection gas

As discussion on sample lagging describes, connection gas is a good indicator of swabbing the wellbore at the bit (i.e., reducing the mud pressure at the bottom of the hole to below the pore pressure). If the pore pressure is less than the swabbed bottomhole pressure, little or no connection gas is seen. Some knowledge of the dynamic rheology of the drilling fluid is needed to perform input into a "swab model."

Normal geothermal gradient

The normal geothermal gradient may shift on transition into geopressures. Other thermal nomalies, such as proximity to subsurface salt bodies, may interfer with this phenomenon. A more thorough discussion of these techniques and their application to detect overpressure may be found in several references. [3][4][12][13]

Monitoring the rate of cuttings return

As a formation is drilled, the cuttings should be circulated to the surface. Improper hole cleaning results in the downhole retention of cuttings, frequently as a cuttings bed on the low side of the hole in inclined wells. This causes an increased drag on the drillpipe and, if buildup is severe, may pack off the drillpipe, causing it to stick. Monitoring the rate of cuttings production from the drilling fluid returns indicates an approaching problem and warns the driller, which allows for remedial action before the pipe sticks. Watching for an increase in cuttings return rate can flag sloughing or extruding shale conditions, which call for an adjustment of mud density, as well as extreme washout conditions. Naegel *et al.*[14] describe a device for continuously weighing the cuttings as they come off the shaker screens and comparing this with what would be expected for a given ROP and mud pump rate.

Health, safety and environmental considerations

Various parameters measured for formation evaluation and to monitor drilling operations and equipment are also indicators of conditions that could pose health, safety, and environmental concerns. Pore pressure changes that result in loss of well control pose obvious safety concerns. Any loss of control that results in a hydrocarbon release also poses serious environmental issues. Ambient monitoring for natural gas is done for health and fire safety. Monitoring hydrogen sulfide (H_2S) is essential in areas in which the potential has been shown historically to exist, as well as in rank wildcat wells in which the characteristics of the geological basin are poorly known.

Hydrogen sulfide is detectable by GC but can not be measured with an FID. Thermal conductivity, MS, and solid state sensors detect H_2S. The Delphian Mud Duck, which uses an electrochemical sensor, monitors dissolved H_2S, HS-, and S^2- ionic concentrations to give total sulfide content of the drilling fluid. This tool continuously follows sulfide trends before its concentration increases to the point that gaseous H_2S is released from the mud. Draeger tubes are used for spot measurement of hydrogen sulfide, as a backup or as a check on other sensing equipment.

Nomenclature

d_c = corrected drilling exponent, dimensionless
d_{exp} = drilling exponent, dimensionless
R = penetration rate, ft/hr
ρ_e = equivalent mud density at the bit while circulating, m/L^3, g/cm^3
ρ_n = mud density equivalent to a normal formation pore pressure, m/L^3, g/cm^3

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