Types of Logging

Well Logging

Mud logging, also known as hydrocarbon well logging, is the creation of a detailed record (well log) of a borehole by examining the bits of rock or sediment brought to the surface by the circulating drilling medium (most commonly mud). Mud logging is usually performed by a third-party mud logging company. This provides well owners and producers with information about the lithology and fluid content of the borehole while drilling. Historically it is the earliest type of well log. Under some circumstances compressed air is employed as a circulating fluid, rather than mud. Although most commonly used in petroleum exploration, mud logging is also sometimes used when drilling water wells and in other mineral exploration, where drilling fluid is the circulating medium used to lift cuttings out of the hole. In hydrocarbon exploration, hydrocarbon surface gas detectors record the level of natural gas brought up in the mud. A mobile laboratory is situated by the mud logging company near the drilling rig or on deck of an offshore drilling rig, or on a drill ship.

A mud logging technician in the modern oil field drilling operation determines positions of hydrocarbons with respect to depth, identifies downhole lithology, monitors natural gas entering the drilling mud stream, and draws well logs for use by oil company geologists. Rock cuttings circulated to the surface in drilling mud are sampled and analyzed.
The mud logging company is normally contracted by the Oil Company (or operator). They then organize this information in the form of a graphic log, showing the data charted on a representation of the wellbore.

The oil industry representative (or "company man") (also with the tool pusher, and geologist) provides mud loggers their instruction. The mud logging company is contracted specifically as to when to start well-logging activity and what services to provide. Mud logging may begin on the first day of drilling, known as the "spud in" date but is more likely at some later time (and depth) determined by the oil industry geologist's research. The mud logger may also possess logs from wells drilled in the surrounding area. This information (known as "offset data") can provide valuable clues as to the characteristics of the particular geo-strata that the rig crew is about to drill through.

Mud loggers connect various sensors to the drilling apparatus and install specialized equipment to monitor or "log" drill activity. This can be physically and mentally challenging, especially when having to be done during drilling activity. Much of the equipment will require precise calibration or alignment by the mud logger to provide accurate readings.

Mud logging technicians observe and interpret the indicators in the mud returns during the drilling process, and at regular intervals log properties such as drilling rate, mud weight, flowline temperature, oil indicators, pump pressure, pump rate, lithology (rock type) of the drilled cuttings, and other data. Mud logging requires a good deal of diligence and attention. Sampling the drilled cuttings must be performed at predetermined intervals, and can be difficult during rapid drilling.
Another important task of the mud logger is to monitor gas levels (and types) and notify other personnel on the rig when gas levels may be reaching dangerous levels, so appropriate steps can be taken to avoid a dangerous well blowout condition. Because of the lag time between drilling and the time required for the mud and cuttings to return to the surface, a modern augmentation has come into use: Measurement while drilling. The MWD technician, often a separate service company employee, logs data in a similar manner but whose data is different in source and content. Most of the data logged by an MWD technician comes from expensive and complex, sometimes electronic, tools that are downhole installed at or near the drill bit.

Scope

1" (5 foot average) mud log showing heavy (hydrocarbons) within the green line, in the sand (large area of yellow)

Mud logging includes observation and microscopic examination of drill cuttings (formation rock chips), and evaluation of gas hydrocarbon and its constituents, basic chemical and mechanical parameters of drilling fluid or drilling mud (such as chlorides and temperature), as well as compiling other information about the drilling parameters. Then data is plotted on a graphic log called a mud log. Example1, Example2.
Other real-time drilling parameters that may be compiled include, but are not limited to; rate of penetration (ROP) of the bit (sometimes called the drill rate), pump rate (quantity of fluid being pumped), pump pressure, weight on bit, drill string weight, rotary speed, rotary torque, mud volumes, mud weight and mud viscosity. This information is usually obtained by attaching monitoring devices to the drilling rig's equipment with a few exceptions such as the mud weight and mud viscosity which are measured by the derrick hand or the mud engineer.

Rate of drilling is affected by the pressure of the column of mud in the borehole and its relative counterbalance to the internal pore pressures of the encountered rock. A rock pressure greater than the mud fluid will tend to cause rock fragments to spall as it is cut and can increase the drilling rate. "D-exponents" are mathematical trend lines which estimate this internal pressure. Thus both visual evidence of spalling and mathematical plotting assist in formulating recommendations for optimum drilling mud densities for both safety (blowout prevention) and economics. (Faster drilling is generally preferred.)

Mud logging is often written as a single word "mudlogging". The finished product can be called a "mud log" or "mudlog". The occupational description is "mud logger" or "mudlogger". In most cases, the two word usage seems to be more common. The mud log provides a reliable time log of drilled formations.
Details of the mud log

- The rate of penetration in (Figure 1 & 2) is represented by the black line on the left side of the log. The farther to the left that the line goes, the faster the rate of penetration. On this mud log, ROP is measured in feet per hour but on some older, hand drawn mud logs, it is measured in minutes per foot.

- The porosity in (Figure 1) is represented by the blue line farthest to the left of the log. It indicates the pore space within the rock structure. An analogy would be the holes in a sponge. The oil and gas resides within this pore space. Notice how far to the left the porosity goes where all the sand (in yellow) is. This indicates that the sand has good porosity. Porosity is not a direct or physical measurement of the pore space but rather an extrapolation from other drilling parameters and therefore not always reliable.

Sample of drill cuttings of shale while drilling an oil well in Louisiana. For reference, the sand grain and red shale are approximately 2 mm. in dia.

- The lithology in is represented by the cyan, gray/black and yellow blocks of color. Cyan = lime, gray/black = shale and yellow = sand. More yellow represents more sand identified at that depth. The lithology is measured as percentage of the total sample, as visually inspected under a microscope, normally at 10x magnification. These are but a fraction of the different types of formations that might be encountered. (Color coding is
not necessarily standardized among different mud logging companies, though the symbol representation for each are very similar.) In you can see a sample of cuttings under a microscope at 10x magnification after they have been washed off. Some of the larger shale and lime fragments are separated from this sample by running it through sieves and must be considered when estimating percentages. Also, this image view is only a fragment of the total sample and some of the sand at the bottom of the tray can not be seen and must also be considered in the total estimation. With that in mind this sample would be considered to be about 90% shale, 5% sand and 5% lime (In 5% increments).

- The gas in is represented by the green line and is measured in units of ppm (parts per million) as the quantity of total gas, but does not represent the actual quantity of oil or gas the reservoir contains. In the squared-off dash-dot lines just to the right of the sand (in yellow) and left of the gas (in green) represents the heavier hydrocarbons detected. Cyan = C₂ (ethane), purple = C₃ (propane) and blue = C₄ (butane). Detecting and analyzing these heavy gases help to determine the type of oil or gas the formation contains.

**Gamma ray logging** is a method of measuring naturally occurring gamma radiation to characterize the rock or sediment in a borehole. It is sometimes used in mineral exploration and water-well drilling, but most commonly for formation evaluation in oil and gas well drilling. Different types of rock emit different amounts and different spectra of natural gamma radiation. In particular, shale’s usually emit more gamma rays than other sedimentary rocks, such as sandstone, gypsum, salt, coal, dolomite, or limestone because radioactive potassium is a common component in their clay content, and because the cation exchange capacity of clay causes them to adsorb uranium and thorium. This difference in radioactivity between shale’s and
sandstones/carbonate rocks allows the gamma tool to distinguish between shale’s and non-shale’s.

The gamma ray log, like other types of well logging, is done simply by lowering an instrument down the hole and recording gamma radiation at each depth. In the United States, the device most commonly records measurements at 1/2-foot intervals. Gamma radiation is usually recorded in API units, a measurement originated by the petroleum industry. Gamma logs are affected by the diameter of the borehole and the properties of the fluid filling the borehole, but because gamma logs are most often used in a qualitative way, corrections are usually not necessary.

Three elements and their decay chains are responsible for the radiation emitted by rock: potassium, thorium and uranium. Shale’s often contain potassium as part of their clay content, and tend to absorb uranium and thorium as well. A common gamma-ray log records the total radiation, and cannot distinguish between the radioactive elements, while a spectral gamma ray log (see below) can.

For standard GR logs the value measured is calculated from thorium in ppm, Uranium in ppm and potassium in percent. GR API = 8 × Uranium concentration in ppm + 4 × thorium concentration in ppm + potassium concentration in percent. Due to the weight of uranium concentration in the calculation anomalous concentrations of uranium can cause clean sand reservoirs to appear shaley. Spectral Gamma ray is used to provide an individual reading for each element so anomalies in concentration can be found and interpreted.
An advantage of the gamma log over some other types of well logs is that it works through the steel and cement walls of cased boreholes. Although concrete and steel absorb some of the gamma radiation, enough travels through the steel and cement to allow qualitative determinations.

Sometimes non-shale’s also have elevated levels of gamma radiation. Sandstone can contain uranium mineralization, potassium feldspar, clay filling, or rock fragments that cause it to have higher-than usual gamma readings. Coal and dolomite may contain absorbed uranium. Evaporite deposits may contain potassium minerals such as carnallite. When this is the case, spectral gamma ray logging can be done to identify these anomalies.

**Spectral logging**

Some specialized gamma radiation logging distinguishes the three component decay chains (potassium, uranium, and thorium) by the wavelengths of their characteristic gamma emissions.

The characteristic gamma ray line that is associated with each component:

- **Potassium**: Gamma ray energy 1.46 MeV
- **Thorium series**: Gamma ray energy 2.62 MeV
- **Uranium-Radium series**: Gamma ray energy 1.76 MeV

Another example of the use of spectral gamma ray logs is to identify specific clay types, like Kaolinite or Illite. This can be used for environmental interpretation as Kaolinite forms from Feldspars in tropic soils by leaching of Potassium; and low Potassium readings may thus indicate
paleosols. The identification of clay types is also useful for calculating the effective porosity of reservoir rock.

**Use in mineral exploration**

Gamma ray logs are also used in mineral exploration, especially exploration for phosphates, uranium, and potassium salts.

The *spontaneous potential log*, commonly called the *self-potential log* or *SP log*, is a measurement taken by oil industry well loggers to characterize rock formation properties. The log works by measuring small electric potentials (measured in mill volts) between depths in the borehole and a grounded voltage at the surface.

The change in voltage through the well bore is caused by a buildup of charge on the well bore walls. Clays and shale’s (which are composed predominantly of clays) will generate one charge and permeable formations such as sandstone will generate an opposite one. This build up of charge is, in turn, caused by differences in the salt content of the well bore fluid (drilling mud) and the formation water (connate water). The potential opposite shale’s is called the baseline, and typically shifts only slowly over the depth of the borehole. Whether the mud contains more or less salt than the connate water will determine which way the SP curve will deflect opposite a permeable formation. The amplitudes of the line made by the changing SP will vary from formation to formation and will not give a definitive answer to how permeable or the porosity of the formation that it is logging.
The SP tool is one of the simplest tools and is generally run as standard when logging a hole, along with the gamma ray. SP data can be used to find:

- Where the permeable formations are
- The boundaries of these formations
- Correlation of formations when compared with data from other analogue wells
- Values for the formation-water resistivity

The SP curve can be influenced by various factors both in the formation and introduced into the wellbore by the drilling process. These factors can cause the SP curve to be muted or even inverted depending on the situation.

- Formation bed thickness
- Resistivity’s in the formation bed and the adjacent formations
- Resistivity and make up of the drilling mud
- Wellbore diameter
- The depth of invasion by the drilling mud into the formation

The drilling mud salinity will affect the strength of the electromotive forces (EMF) which give the SP deflections. If the salinity of the mud is similar to the formation water then the SP curve may give little or no response opposite a permeable formation; if the mud is more saline, then the curve has a positive voltage with respect to the baseline opposite permeable formations; if it is less, the voltage deflection is negative. In rare cases the baseline of the SP can shift suddenly if the salinity of the mud changes part way down hole.
Mud invasion into the permeable formation can cause the deflections in the SP curve to be rounded off and to reduce the amplitude of thin beds.

A larger wellbore will cause, like a mud filtrate invasion, the deflections on the SP curve to be rounded off and decrease the amplitude opposite thin beds, while a smaller diameter wellbore has the opposite effect.

**Resistivity logging** is a method of well logging that works by characterizing the rock or sediment in a borehole by measuring its electrical resistivity. Resistivity is a fundamental material property which represents how strongly a material opposes the flow of electric current. In these logs, resistivity is measured using 4 electrical probes to eliminate the resistance of the contact leads. The log must run in holes containing electrically conductive mud or water.

Resistivity logging is sometimes used in mineral exploration and water-well drilling, but most commonly for formation evaluation in oil- and gas-well drilling. Most rock materials are essentially insulators, while their enclosed fluids are conductors. Hydrocarbon fluids are an exception, because they are almost infinitely resistive. When a formation is porous and contains salty water, the overall resistivity will be low. When the formation contains hydrocarbon, or contains very low porosity, its resistivity will be high. High resistivity values may indicate a hydrocarbon bearing formation.
Usually while drilling, drilling fluids invade the formation, changes in the resistivity are measured by the tool in the invaded zone. For this reason, several resistivity tools with different investigation lengths are used to measure the formation resistivity. If water based mud is used and oil is displaced, "deeper" resistivity logs (or those of the "virgin zone") will show lower conductivity than the invaded zone. If oil based mud is used and water is displaced, deeper logs will show higher conductivity than the invaded zone. This provides not only an indication of the fluids present, but also, at least quantitatively, whether the formation is permeable or not.

**Density logging** is a well logging tool determining rock bulk density along a wellbore. This is the overall density of a rock including solid matrix and the fluid enclosed in pores. Geologically, bulk density is a function of the density of the minerals forming a rock (i.e. matrix) and the enclosed volume of free fluids (porosity).

**Principle**

A radioactive source applied to the hole wall emits medium-energy gamma rays into the formation so these gamma rays may be thought of as high velocity particles which collide with the electrons in the formation. At each collision the gamma ray loses some of its energy to the electron, and then continues with diminished energy. This type of interaction is known as
Compton scattering. The scattered gamma rays reaching the detector, at the fixed station from the source, are counted as an indication of formation density.

The number of Compton scattering collisions is related directly to the number of the electron density of the formation. Consequently, the electron density determines the response of the density tool. Electron density is related through equation

$$\rho \dot{\varepsilon} = \frac{2\rho B \sum Z_{1i}}{M}$$

Where $\sum Z_{1i}$ is the atomic numbers of all the atoms making up the molecules in the compound, and $M$ is their molecular weight of the compound.

**Inferring porosity from bulk density**

Assuming that the measured bulk density ($\rho_{\text{bulk}}$) only depends on matrix density ($\rho_{\text{matrix}}$) and fluid density ($\rho_{\text{fluid}}$), and that these values are known along the wellbore, porosity ($\phi$) can be inferred by the formula

$$\phi = \frac{\rho_{\text{matrix}} - \rho_{\text{bulk}}}{\rho_{\text{matrix}} - \rho_{\text{fluid}}}$$

Common values of matrix density $\rho_{\text{matrix}}$ (in g/cm$^3$) are:

- Quartz sand - 2.65
- Limey, arkosic, or shale sand - 2.68
- Limestone - 2.71
- Dolomite - 2.87
A fluid bulk density $\rho_{\text{fluid}}$ of 1 g/cm³ is appropriate where the water is fresh; highly saline water has a slightly higher density. For flushed gas or oil reservoirs, even lower $\rho_{\text{fluid}}$ values should be assumed depending on the hydrocarbon density and residual saturation. In some applications hydrocarbons are indicated by the presence of abnormally high log porosities.

**Sonic logging** shows a formation’s interval transit time designated $D_t$. It is a measure of a formation’s capacity to transmit sound waves. Geologically, this capacity varies with lithology and rock textures, notably porosity.

Quantitatively, the sonic log is used to evaluate porosity in liquid filled pores. The sonic tool is only capable of measuring travel time. Many relationships between travel time and porosity have been proposed, the most commonly accepted is the Wyllie time average equation. The equation basically holds that the total travel time recorded on the log is the sum of the time the sonic wave spends traveling the solid part of the rock, called the rock matrix and the time spent traveling through the fluids in the pores.

A **caliper log** is a set of measurements of the size and shape of a bore hole commonly made when drilling oil and gas wells. This can be an important indicator of cave-in’s or shale swelling in the bore hole.

The caliper tool measures the variation in the bore hole diameter as it is withdrawn from the bottom of the hole. It is constructed with two or more articulated arms that push against the bore hole wall to take measurements. The arms show variable movements of the cursor by measuring electrical resistance, creating electrical variation. The variation in output is translated into
changes of diameter after a simple calibration. The caliper log is printed as a continuous series of values of the hole diameter with depth.

Known challenges with caliper logging include borehole spiraling. The position of the drill bit may recess as it drills; leading to spiraling shapes in the wellbore wall, as if the hole had been drilled by a screw. If the arms of the caliper log follow the grooves of the spiral, it will report too high an average diameter. Moving in and out of the grooves, the caliper will give erratic or periodically varying readings.