Basic Principles and Value of Electric and Radioactivity Log Interpretation

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LOGS AND MONEY

Where shall we drill? Is there oil in this zone? What is the best place to perforate? Where can we find water for this flood? From where is this water coming? How much oil is there in this zone? Where is the best place to inject? Did we pass up some good reserves? Why is the gas to oil ratio increasing?

The answers to these common questions result in decisions which both cost and make money. Proper use of electric logs can help solve these problems many times. For this reason production personnel should be familiar with the principles of log interpretation.

WHAT LOG INTERPRETATION IS AND ITS IMPORTANCE

An electric log is a record of the electrical resistivities and potentials for all of the formations in a well. The values actually observed on the log are corrected by various interpretation methods to obtain useful information such as pososity, percent of pore space occupied by oil or gas, and water salinity. Other information such as detection of shale free zones, pay thickness, top of pay, and subsea level depth are obtained by inspection.

A radioactivity log is a record of the natural radioactivity of the formations in a hole, plus in many cases, the artificial radioactivity created by neutron bombardment of the rock and fluids.

At present quantitative interpretation of radioactivity logs is limited to determination of porosity. Logs can be obtained both in open hole and through casing as contrasted with electric logging which must be done only in open hole. Detection of shale free zones, formation tops, pay thickness and sub sealevel depths can be obtained by inspection. Examples of various common logs are presented in Figures 1 to 4.

The purpose of this paper is to acquaint you with the importance of logs in various phases of crude oil exploration and production and to explain the principles of log interpre-

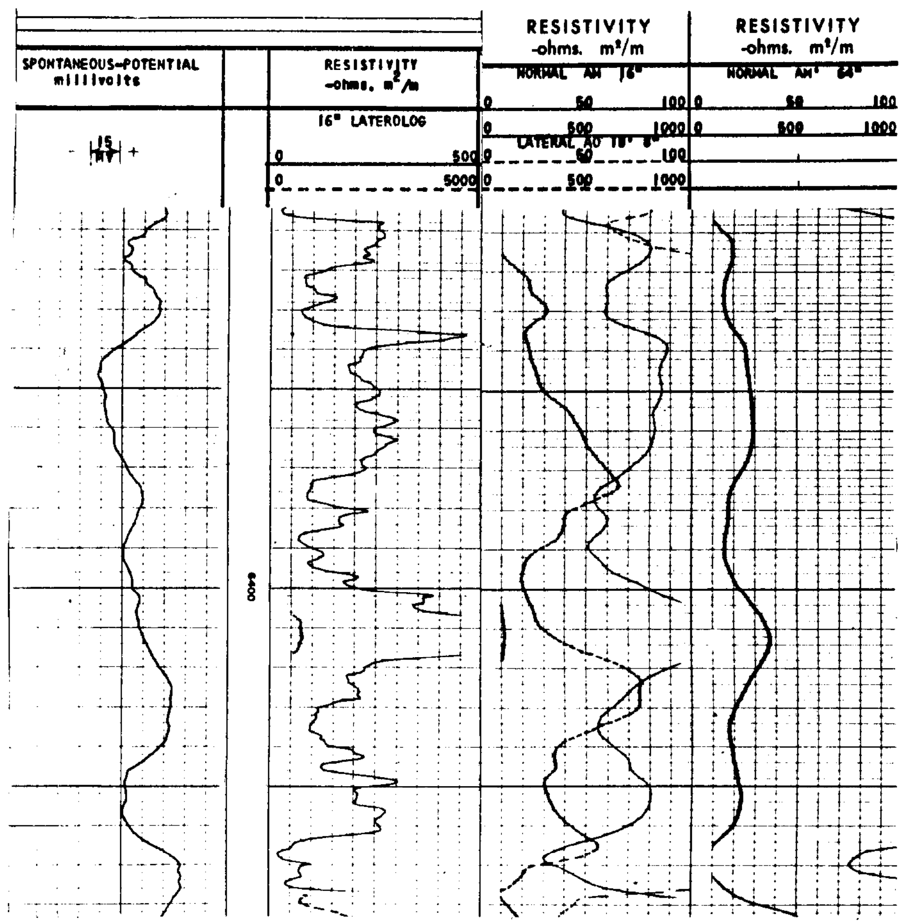

Figure 1. Conventional Electric Log and Laterolog (Portion)

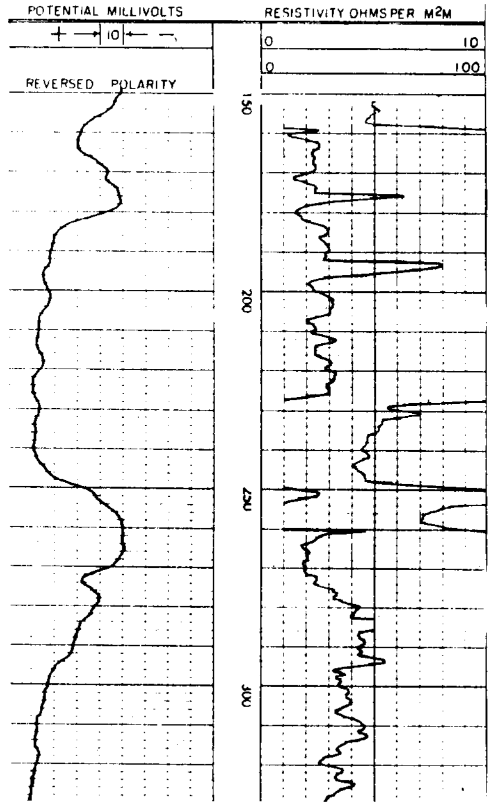

Figure 2. Portion of Guard Log

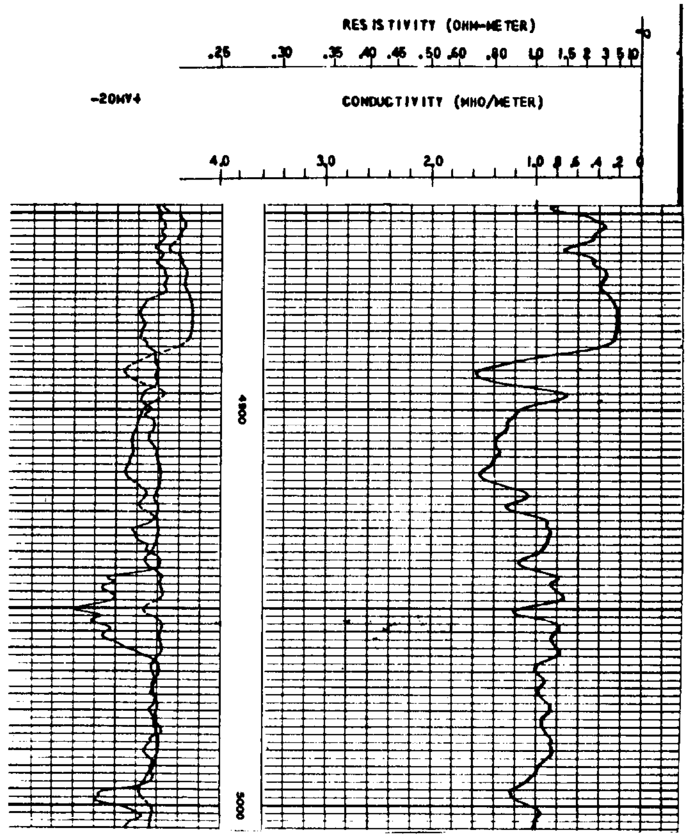

Figure 3. Portion of Induction Log

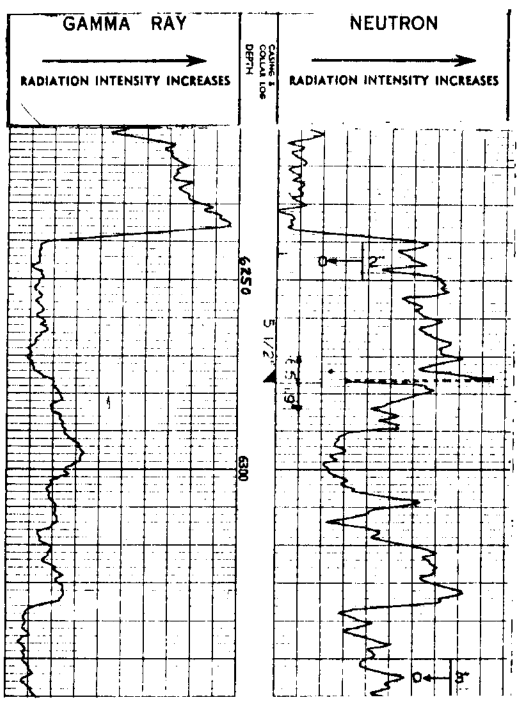

Figure 4. Portion of Radioactivity Log

tation. It is not a complete treatment of the subject, nor does it have charts or tables necessary for quantitative interpretation. These charts are available from companies that sell logging services. In some cases producing companies have their own interpretation aids.

RESISTIVITY

In order to appreciate how electric logs furnish valuable information, it is necessary to understand what resistivity is and what factors affect it.

Electrical resistance of a material (in ohms) can be determined by measuring the voltage across the material and the current (amperes) flowing through it.

$$\frac{E \text{ (volts)}}{I \text{ (amperes)}} = \text{Resistance in ohms}$$

The resistance of a square meter of material one meter long is called the resistivity of the material. The unit is called an ohm meter. For example, air has a higher resistivity than copper. Salt water has a lower resistivity than fresh water. An oil sand has a higher resistivity than when the pore space of the sand is filled entirely with water. Some typical resistivities are presented in Table I.

TABLE I

Typical Resistivities for Various Materials

Material	Resistivity (ohm-meters)
Aluminum	0.00000003
Copper	0.000000017
Quartz	10,000,000,000
Anhydrite	100,000,000
Air	100,000,000
Natural Gas	100,000,000
Crude Oil	10,000
Fresh Water	10 - 200
Sea Water	0.15 - 0.3
Formation Waters	0.05 - 2
Sand (oil or gas)	1 - 100
Sand (water)	0.1 - 100

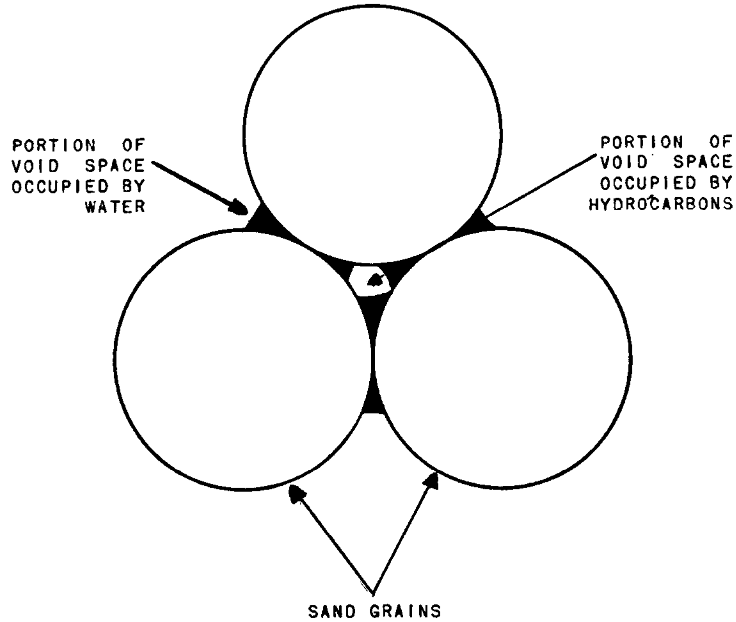

Figure 5. Representation of Water and Oil Distribution in the Void Space Between Sand Grains

All rock formations of interest to the oil industry consist of solids and fluids. The fluids are contained in the space between the solid particles (Figure 5) and can be water, oil, or gas. In rare cases the gas may be helium or carbon dioxide but for the most part it is what we call natural gas. From Table I it can be seen that the only part of a formation which can easily conduct electricity is the water, therefore, a cubic meter of formation which has a large percentage of water will have a lower resistivity than a formation which has a small percentage of the same water. The percentage of water depends on the porosity (volume of space between rock particles divided by total volume of rock and space) and the percent of the pore space occupied by water (called water saturation).

ARE THERE ANY OIL ZONES IN THIS WELL

The principle of using logs to answer the above question is to compare the electrical resistivity of a zone of interest with the resistivity that would exist if the zone contained all water. This principle is based on the previously mentioned fact that the only portion of a formation which can conduct electric current is the water in the pore space. It seems logical therefore that if a portion of this pore space were occupied by oil or gas of the formation (electrical insulators) that the electrical resistivity would be higher than for the case where the pore space was completely filled with water. So to answer the question "Are there any oil zones in this well?" it is necessary to know (1) the actual resistivity of a given formation (R_t) and (2) the resistivity of the formation if the pore space were completely filled with formation water (R_o). If the actual resistivity is more than four times that of the water case, the zone would generally be expected to produce hydrocarbons. If, on the other hand, the actual resistivity were about equal to that of a 100% water zone, the interval would be expected to produce water.

ACTUAL RESISTIVITY OF FORMATION (R_t)

The conventional electric log, the Laterolog, Guard Electrode, and Induction Logs are used to determine the actual formation resistivity (R_t). Generally because of mud filtrate invasion, mud resistivity, hole size, and bed thickness, the apparent resistivities (R_a), read from the logs, must be corrected, by means of graphs, in order to determine R_t. In the case of the Laterolog, Guard Electrode, and Induction Log the corrections are simpler. These latter devices have been designed to overcome most of the disadvantages of the conventional electric logs for finding R_t.

RESISTIVITY IF FORMATION CONTAINED ONLY WATER (R_o)

The resistivity of a zone containing only water (R_o) is determined by (1) the resistivity of the water (2) the porosity (fraction of bulk volume that is pore space) and (3) how the pores are connected.

It has been found that water zone resistivity is related to the above mentioned factors by a simple equation.

$$R_o = F\, R_w \quad (1)$$

where

- R_o is the water zone resistivity in ohm-meters
- R_w is the formation water resistivity at the formation temperature - ohm meters
- F is the formation resistivity factor, commonly called formation factor

For example, if F equals 20 and R_w equals 0.05 ohm meters, then R_o equals 1 ohm meter.

Water resistivities can be obtained from (1) measurements on produced water (2) use of water resistivity maps and (3) from the self potential curve of the conventional electric logs. The first two methods are recommended for use whenever possible. It should be noted that resistivity data is generally given at 68 F or 75 F and must be first corrected to formation temperature before using in equation (1). Corrections are available from service company data and in the literature.

Formation factors (F) can be determined by the following methods:

a. Direct measurement on cores
b. Calculation from the Microlaterolog
c. Calculation for porosities
d. Measurements on cuttings
e. Calculations from the Microlog or Contact Log
f. Visual estimation from inspection of samples

The direct measurement method is based on equation (1). A core plug is saturated (pore space filled) with water whose resistivity is known and the plug resistivity is measured. Knowing R_o and R_w, therefore, it is possible to calculate F

$$F = \frac{R_o}{R_w}$$

F can be obtained directly from the Microlaterolog, Microlog, and Contact logs directly and indirectly from the Neutron Log. The direct methods are based on the assumption that the formation immediately around the bore hold is flushed with mud filtrate. The resistivity of this portion of the formation (R_{xo}) is measured by the above mentioned logs.

F is obtained by dividing this resistivity by the mud filtrate resistivity (R_{mf}), or

$$F = \frac{R_{xo}}{R_{mf}}$$

The principle is similar to the determination from cores. The mud filtrate resistivity can be obtained by direct laboratory measurement followed by a temperature correction to the formation temperature or by special charts.

It has been found that the porosity is often related to the formation factor by the following equation.

$$F = \frac{1}{P^2}$$

Where P is the porosity, expressed in fraction of the bulk volume which is pore space.

For example, if the porosity is 0.2 then $F = \frac{1}{0.2 \times 0.2} = 25$

Other methods for determining F are of secondary importance because they are not as reliable but are often helpful when the better sources of F data are not available.

HOW MUCH OIL IS THERE IN THIS FORMATION

It was pointed out earlier in this section that when the actual resistivity (R_t) of a zone was greater than four times the resistivity of this zone, completely saturated with water (R_o or $F\ R_w$), the zone would be expected to produce primarily hydrocarbons. This criterion alone would suffice to answer the question, "Is this a hydrocarbon zone?".

Archie presented a quantitative relationship between R_o, R_t and water saturation, S. In its simplest usable form the equation is as follows:

$$S^2 = \frac{R_o}{R_t}$$

where S is the fraction of the pore space occupied by water.

If R_o = 1 ohm-meter and Rt = 4 ohm meters, R_o/R_t = 0.25 or S = 0.5

Since the fraction of the pore space not occupied by water is assumed to be occupied by gas or oil, the hydrocarbon saturation (H) equals 1-S or 0.50 in the above example.

It makes no difference (except for reporting results) whether the Archie Equation or the ratio of R_t/R_o is used to answer the question, "Are there any hydrocarbon zones in this well?". For the purpose of finding how much oil, it is necessary to know the actual saturation of hydrocarbons. Electric log interpretation for this purpose does not differentiate between oil and gas.

In addition to saturation it is necessary to know how thick the formation is and how porous.

For example:

There are 7760 barrels of volume per acre for a formation one foot thick.

If the porosity is 10% (obtainable from logs and/or core data), there are

7760 x 0.1 = 776 barrels of pore space per acre for a formation one foot thick.

If the hydrocarbon saturation (obtainable from log interpretation) (% of pore space occupied by hydrocarbons) is 70% then there are

776 x 0.7 = 543.2 barrels of hydrocarbons per acre for a formation one foot thick.

If the pay thickness (obtainable from logs) is 20 feet, there are

543.2 x 20 = 10,864 barrels per acre.

The producible barrels for the field depends on the number of acres, the percentage recovery, and the oil shrinkage.

Radioactivity Logging

As pointed out previously radioactivity logging is useful for location of shale free zones, and determination of formation tops, pay thickness, and porosity.

The gamma ray log is a record of the natural gamma radiation which originates from unstable uranium, thorium, and potassium salts that are found in many rocks but tend to be more concentrated in shales. Thus by inspection it is frequently easy to differentiate shale (non producers) zones from shale free zones (possible producers).

For example in Figure 4 the zone above 6236' produces more radiation than that below. Therefore the zone below would be interpreted to be essentially shale free.

On the logging tool (sonde) is also placed a neutron source (radium and beryllium). When these neutrons are slowed down sufficiently they are captured and the capturing atom gives off gamma rays (about thirty times more intense than the natural gamma rays). The more easily the neutrons are slowed down the more gamma rays reach the hole and are detected. Hydrogen atoms (as contained in water and hydrocarbons) are more effective in the slowing down process than are the rock grains, therefore, the more hydrogen atoms present in a given volume of rock the greater number of gamma rays produced. The greater the porosity therefore the more gamma rays will be produced because there are more hydrogen atoms present. By arranging the gamma ray detector a minimum distance from the source, it is possible to have the more porous zone show the least deflection to the right of the log. For example in Figure 4 the shale free zone at 6338' is more porous than that at 6340'.

Charts and methods are available which allow for calculation of porosity from the neutron log.

WHERE SHALL WE DRILL

The decision concerning the location of the next or even the first drilling site in a field can be reached with the aid of logs from nearby wells. When the sub sea level depth of a formation can be found from these logs it is possible to locate a structure favorable for accumulation of oil. This can be done because the logs of formations frequently have characteristic shapes that can be detected by inspection.

For example:	Well No. 1	Well No. 2
(1) Surface Elevation (above sea level)	2430'	2115'
(2) Top of Formation (Log Reading)	5003'	4695'
(3) Sub Sea Level Depth ((2) - (1))	2573'	2580'

Or, Well No. 2 is 7 feet deeper than Well No. 1.

SUMMARY

Correct log interpretation is a useful aid for exploration, completion, production, and reservoir problems. Table 2 summarizes possible applications of electric and radioactivity log interpretation.

TABLE II

SOME APPLICATIONS OF ELECTRIC AND RADIOACTIVITY LOG INTERPRETATION

Type of Log Interpretation	Applications	Logging Devices
Top of formations	Correlation, geology, location of performation depths	Conventional electrical survey, radioactivity logs
Pay thickness	Reserve estimation	Conventional surveys, Mirco and contact logs, Guard, Laterolog, Induction Log, Radioactivity logs
Porosity	Reserve estimations	Micro and contact logs, Microlaterolog, Neutron Log
Saturation (Hydrocarbon and water)	Exploration, reserve estimations	Conventional Survey, Porosity logs (above) plus Laterolog, Guard Log
Shale Free Zones	Exploration, reserves	Conventional Survey, Induction Log, Self potential and Gamma Ray
Water Salinity	Reserves, injection	Self potential curve