ESSENTIALS OF
MODERN
OPEN-HOLE LOG
INTERPRETATION

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INTRODUCTION

The aim of this book is to present modern log interpretation as simply and concisely as possible. The book is written for the geologist, petrophysicist, reservoir engineer, or production engineer who is familiar with rock properties but has little experience with logs. It will help him specify good logging programs with up-to-date tools and hand-interpret zones of interest with the latest techniques. The book will also familiarize him with computer-processed logs generated by the service companies at the wellsite.

Accordingly, obsolete logging tools are mentioned only in perspective. Very brief descriptions of the instruments in common use indicate how they apply to different logging conditions. Salient features of new tools, including Spectral Gamma Ray, Litho-Density, Dual Porosity Neutron, and Long-Spacing Sonic, emphasize how these tools fit into the everyday logging picture. The interpreter need not be overly concerned how a tool operates. What is important is the instrument's response to the various formation and borehole variables.

In a similar vein, interpretation equations and charts are kept to the minimum needed for routine evaluation of logs. Fundamental principles are stressed, rather than mechanical application of formulae. This is particularly true in the chapter on shaly formation interpretation where an effort has been made to draw together the latest concepts in this ever-changing field.

This book addresses the normal well situation where a standard set of logs is run in a liquid-filled open hole to locate hydrocarbons in place and where promising zones are then tested to evaluate their producibility. Abnormal situations such as empty hole, water well, and geothermal and mineral logging are not included.

To provide a little perspective, well logging is in its third major development stage. The first 20 years, from 1925–1945, saw the introduction and gradual worldwide acceptance of the so-called ES (Electrical Survey) logs. These logs were run with simple downhole tools and, while quite repeatable, were often difficult to interpret.

The second phase, from 1945–1970, was a major tool development era, made possible by the advent of electronics suitable for downhole use. Focused electrical devices were introduced, having good bed resolution and various depths of penetration. A variety of acoustic and nuclear tools were developed to provide porosity and lithology information. There was a progression through second- and even third-generation tools of increasing capability and accuracy. Simultaneously, much laboratory and theoretical work was done to place log interpretation on a sound, though largely empirical, basis.

The third and current phase, which began about 1970, may be called the log processing era. With the advent of computers, it has become possible to analyze in much greater detail the wealth of data sent uphole by the logging tools. Log processing centers, providing sophisticated interpretation of digitized logs transmitted by telephone and satellite, have been set up by service companies in strategic locations. Logging trucks have been fitted with computers that permit computation of quick-look logs at the wellsite. At the same time logging tools have been combined to the point that a full set of logs can be obtained on a single run.

The present state of the art is that logs are adequate to determine hydrocarbons in situ in medium- to high-porosity formations but are pushed to their limits in low-porosity, shaly, mixed-lithology situations. More precise determination of the matrix makeup, including amounts and types of clay present, is needed. Promising developments are underway.

Advances are being made in predicting the producibility of hydrocarbons found in place, but the critical factor, a continuous permeability log, is still lacking. Meanwhile, point-by-point permeability and pressure values can be obtained by repeat formation testing, a technique that is finding increased use.

Developments in the testing stage promise to provide more precise lithology information, better movable oil determination, and additional mechanical properties of formations. Unquestionably, answers obtainable from logs will continue to become more accurate and broader in scope.

Chapter 1

THE LOGGING ENVIRONMENT

Relatively little is learned about the producing potential of a well as it is being drilled. This is a surprise to the uninitiated, who have visions of early gushers. But the drilling mud actually pushes hydrocarbons, if encountered, out of the way and prevents their return to the surface. Examination of returned cuttings indicates the general lithology being penetrated and may reveal traces of hydrocarbons, but it allows no estimates of the amount of oil or gas in place.

Well logs furnish the data necessary for quantitative evaluation of hydrocarbons in situ. Modern curves provide a wealth of information on both the rock and fluid properties of the formations penetrated. From the point of view of decision-making, logging is the most important part of the drilling and completion process. Obtaining accurate and complete log data is imperative. Logging costs account for only about 5% of completed well costs, so it is false economy to cut corners in this phase.

THE BOREHOLE

When the logging engineer arrives at the wellsite with his highly instrumented logging unit, he finds ready to be surveyed a borehole that has the following characteristics:

- an average depth of about 6,000 ft but which may be anywhere between 1,000 and 20,000 ft
- an average diameter of about 9 in. but which can be between 5 in. and 15 in.
- a deviation from vertical that is usually only a few degrees on land but typically 20–40° offshore
- a bottom-hole temperature that averages about 150°F but may be between 100°F and 350°F
- a mud salinity averaging about 10,000 parts per million (ppm) but which can vary between 3,000 and 200,000 ppm; occasionally the mud may be oil based
- a mud weight averaging about 11 lb/gal but which can vary from 9 to 16 lb/gal
- a bottom-hole pressure averaging perhaps 3,000 psi but which can be as low as 500 and as high as 15,000 psi

approximately proportional to $1/\sqrt{\phi}$ where ϕ is the porosity. Other things being constant, invasion depth will double as porosity reduces from 36% to 9%, for example. However, many other factors come into play. About all that can be said is that invasion depths can vary from a few inches to a few feet, with typical values perhaps 1–2 ft.

The Picture Of Invaded Rock

Fig. 1–6 illustrates invasion as it is pictured. Proceeding outward from the wall of the hole, there is first a flushed zone, then a transition zone, and finally the unperturbed formation. In the flushed zone it is generally assumed that all of the formation water has been replaced by mud filtrate (which may not be quite true). If the formation is hydrocarbon bearing, then some but not all of the hydrocarbons will be pushed back by invading filtrate. The residual hydrocarbon saturation remaining will normally be in the range of 10–40%. The saturation will depend on the initial hydrocarbon content and on the contrast between the mobility of the filtrate and that of the hydrocarbon. Water displaces medium-gravity oil fairly well but displaces high-viscosity heavy oil and low-viscosity light gas quite poorly. The water fingers through these media.

In the transition zone some of the virgin water and some of the hydrocarbons, if present, have been replaced by mud filtrate but to a lesser extent than in the flushed zone. The transition zone initially is close to the borehole but gradually progresses away from it. It may take a few days after a formation is drilled for the invasion pattern to reach a more-or-less equilibrium condition.

In extremely porous and permeable sands the invading fluid can gravity-segregate vertically as well as progress laterally. Low-salinity filtrate invading a high-water-salinity sand will tend to rise to the top of the bed; water invading an oil sand will tend to drop to the bottom of the oil. Successive logs may show this progression.

Shales, by virtue of almost zero permeability, do not invade or build up mud cake. More often, fresh water in the drilling mud will cause the clay in the shales to swell, resulting in sloughing and caving of those formations. Suitable mud conditioning can minimize this problem.

SUMMARY

BOREHOLES

- Depths 1,000–20,000 ft; average 6000 ft
- Diameters 5–15 in.; average 9 in.

Definition of R_t

Now an appreciable fraction of the pore water is replaced by oil, resulting in the situation depicted in Fig. 2–1c. The same voltage, V, is applied, and current I_3 is measured. It will be less than I_2 since even less water is available for conduction. The ratio V/I_3 is R_t, the resistivity of the oil-bearing formation. It will be greater than R_o.

Water Saturation

Knowing R_o and R_t, water saturation, S_w, the fraction of pore space containing water, can be calculated. Again on general principles there must be a relation of the form

$$R_t = R_o/S_w^n \tag{2.5}$$

because when $S_w = 1$ (all water in the pores), R_t must equal R_o; and when $S_w = 0$ (all oil in the pores, if it were possible), R_t must be infinite, as both oil and rock matrix are insulators. Eq. 2.5 satisifies these conditions regardless of the value of the exponent n.

The constant n is termed the *saturation exponent*. It is close in value to m because the flow of current cannot distinguish between displacement of pore water by sand grains or oil globules of like sizes since neither conducts. Indeed laboratory experiments have shown n = 2.0 in the average case. Consequently, water saturation is given by

$$S_w = \sqrt{R_o/R_t} \tag{2.6}$$

This relation can be used directly to calculate the water saturation of a hydrocarbon-bearing zone when an obvious water-bearing zone *of the same porosity and having water of the same salinity is nearby*. An example would be a thick sand with an obvious water-oil contact in the middle.

In general there will not be a nearby water sand to give R_o, so Eq. 2.6 will not apply. Replacing R_o by Eq. 2.1 gives

$$S_w = \sqrt{FR_w/R_t} \tag{2.7}$$

Replacing F by Eq. 2.3 gives

$$\boxed{S_w = c\sqrt{R_w/R_t}/\phi} \tag{2.8}$$

where c = 1.0 for carbonates and 0.90 for sands.

Consequently, when the ratio of formation to mud resistivity is high, the currents will spread widely. There will be long flow paths in the borehole, and bed boundaries will be poorly defined. Conversely, when that ratio is

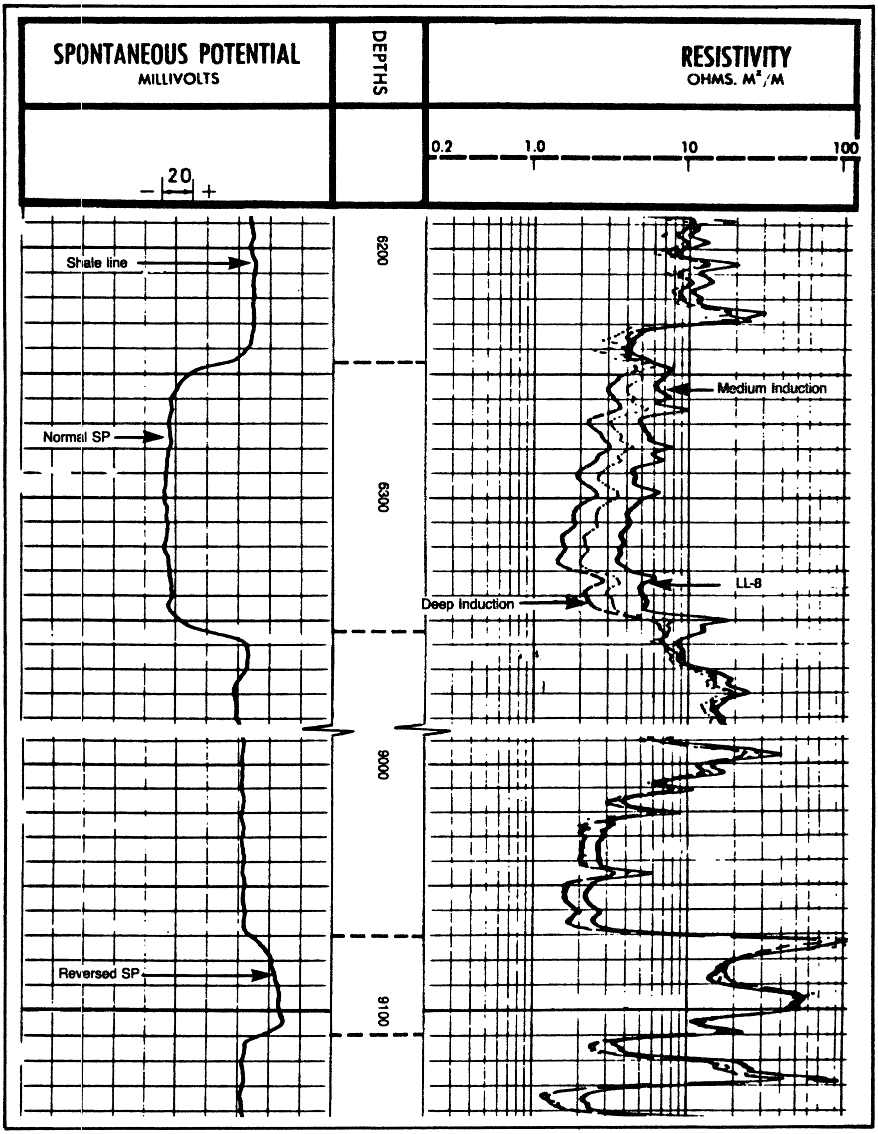

Fig. 3-3 Example of normal and reversed SP deflections

Chapter 4

RESISTIVITY LOGS

The basic interpretation relation in well logging, as developed in chapter 2, is the water saturation relation

$$S_w = c\sqrt{R_w/R_t}\,/\,\phi \qquad (4.1)$$

The most important input to this equation (since its value can never be guessed) is the resistivity, R_t, of the uninvaded region of the formation in question.

No resistivity-measuring tool has yet been designed that can reach deep enough to guarantee reading R_t under all possible invasion conditions while retaining good bed resolution. Therefore, from early days resistivity logs have consisted of three curves: deep, medium, and shallow investigation. With these three measurements and the assumption of a step invasion profile, correction can be made to the deep reading to obtain R_t.

Nevertheless, many logs have been run with only two curves, deep and shallow reading. These clearly show invasion effects but do not permit a correction to the deep reading, which must be assumed equal to R_t. The assumption is reasonable in high-porosity areas where invasion is shallow but can lead to significant errors in low-porosity regions where invasion may be deep.

Over the years there has been a continual succession of resistivity tools with improved designs replacing older ones. It would be convenient to forget the obsolete versions, but we cannot. Company files and log libraries still abound with old logs that are continually being reviewed for new drilling or production prospects.

CLASSIFICATION AND APPLICATION

Table 4–1 is a classification of the major resistivity tools that have been used or are in use. The curves are categorized by their radii of investigation, i.e., deep (3+ ft), medium (1.5–3 ft), shallow (0.5–1.5 ft), and flushed zone

Borehole effects for the SFL are normally negligible. All shallow resistivity curves tend to read resistivities too low if the borehole becomes quite large and invaded zone resistivity becomes high relative to mud resistivity (meaning low porosity). For borehole diameters of 6–12 in., SFL corrections are negligible up to $R_{SFL}/R_m = 2{,}000$. LL-8 or short Guard correction becomes significant at $R_{LL8}/R_m > 100$ and 16-in. Normal corrections significant if $R_{16}/R_m > 30$. Correction charts are found in service company chart books but are not often necessary.

LOG PRESENTATION

Fig. 4–10 shows a typical presentation of the 5-in./100-ft DIL-SFL log when it is run in combination with the Sonic log. The SP curve, which is obtained simultaneously, is recorded in Track 1 on a linear scale. Also shown is an R_{wa} curve; this is described in chapter 9. The three resistivity curves are recorded in Track 2 and half of Track 3 on a logarithmic scale

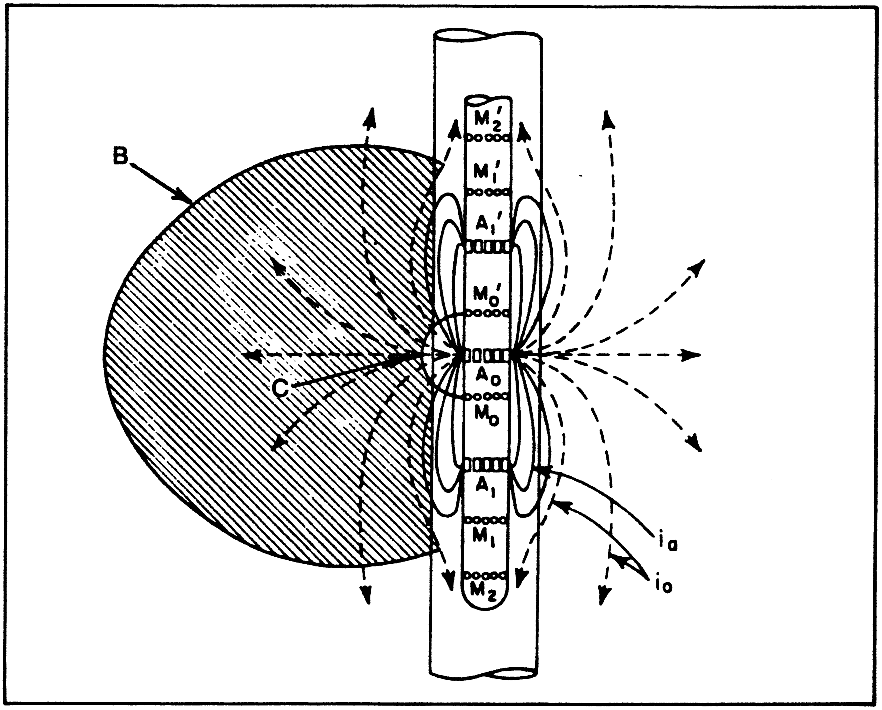

Fig. 4–8 Principle of the spherically focused log (courtesy Schlumberger)