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Basic Relationships of Well Log Interpretation

INTRODUCTION

This chapter provides a general introduction to well logging principles and methods that will be used throughout the book. Succeeding chapters (2 through 6) introduce the reader to specific log types. The text discusses how different log types measure various properties in the wellbore and surrounding formations, what factors affect these measurements, where on a standard log display a particular curve is recorded, and how interpreted information is obtained from the logs using both charts and mathematical formulas. Unlike many other logging texts, the logging tools are grouped according to their primary interpretation target, rather than their underlying measurement physics.

Spontaneous potential (SP) and gamma ray logs are discussed first, as their primary use is correlation and their primary interpretive target is gross lithology (the distinction between reservoir and nonreservoir). The porosity logs (i.e., sonic, density, and neutron logs) are covered next, then the resistivity logs. Nuclear magnetic-resonance logs, although they provide porosity (among other quantities of interest), are presented after resistivity logs. This is due in part to their recent arrival and to their relative absence in historical data archives.

The final four chapters again deal with interpretation of the data, this time in detail with example problems and their solutions. These chapters bring the introductory material of Chapter 1 together with the specific measurement information and are intended to provide a coherent view of the interpretation process. The reader is encouraged to work the examples to gain familiarity with the interpretation techniques and to begin to understand the limitations on interpretation that are present due to the nature of subsurface information.

The use of charts and simple calculations throughout the text, rather than the use of petrophysical computer software, is intentional. It is only through experience with such manual methods that the reader can gain an appreciation for the effects of parameters on the calculations, and gain a better understanding of the accuracy and precision of the techniques discussed here.

When the first edition of this book was published, virtually all well-logging data were acquired through the use of wireline-conveyed tools; that is, logging tools lowered in the borehole on a 7-conductor cable over which power, operating instructions, and data were sent. Since the mid-1980s, a second formation-evaluation technique, measurement while drilling (MWD) or logging while drilling (LWD), has developed. In this method, the logging sensors are imbedded in the thick-walled drill collars used at the bottom of the drill string (near the bit), and measurement of formation properties is done continuously during the drilling process (hence the name, MWD). Initially, MWD logging technology borrowed heavily from wireline technology, with the goal being to produce LWD measurements comparable to wireline measurements. As LWD technology has progressed, sensor design and other features of LWD have been incorporated back into wireline technology, for the improvement of those measurements.

Unless specifically noted in the text, the interpretation of borehole data is the same irrespective of the source of the data, either wireline or LWD sensors and measurement systems. The techniques shown here are applicable to both data sources and can even be extended to incorporate equivalent core measurements.

GENERAL

As logging tools and interpretive methods are developing in accuracy and sophistication, they are playing an expanded role in the geological decisionmaking process. Today, petrophysical log interpretation is one of the most useful and important tools available to a petroleum geologist.

Besides their traditional use in exploration to correlate zones and to assist with structure and isopach mapping, logs help define physical rock characteristics such as lithology, porosity, pore geometry, and permeability. Logging data are used to identify productive zones, to determine depth and thickness of zones, to distinguish between oil, gas, or water in a reservoir, and to estimate hydrocarbon reserves. Also, geologic maps developed from log interpretation help with determining facies relationships and drilling locations. Increasingly, the importance of petrophysics and well-log analysis is becoming more evident as more attention is being devoted to the ongoing management of reservoirs. The industry is realizing the importance of detailed petrophysical analyses, based on the details of the available data in monitoring, simulating, and enhancing reservoir performance to maximize the return on investment.

Of the various types of logs, the ones used most frequently in hydrocarbon exploration are called open-hole logs. The name open hole is applied because these logs are recorded in the uncased portion of the wellbore. All the different types of logs and their curves discussed in this text are of this type.

A geologist's first exposure to log interpretation can be a frustrating experience. This is not only because of its lengthy and unfamiliar terminology, but also because knowledge of many parameters, concepts, and measurements is needed before an understanding of the logging process is possible.

Perhaps the best way to begin a study of logging is by introducing the reader to some of the basic concepts of well log analysis. Remember that a borehole represents a dynamic system; that fluid used in the drilling of a well affects the rock surrounding the borehole and, therefore, log measurements. In addition, the rock surrounding the borehole has certain properties that affect the movement of fluids into and out of it.

The two primary parameters determined from well log measurements are porosity and the fraction of pore space filled with hydrocarbons (i.e., hydrocarbon saturation). The parameters of log interpretation are determined directly or inferred indirectly and are measured by one of three general types of logs:

- electrical
- nuclear
- acoustic or sonic logs

The names refer to the sources used to obtain the measurements. The different sources create records (*logs*), which contain one or more curves related to some property in the rock surrounding the wellbore (see Society of Professional Well Log Analysts, 1984). For the reader unfamiliar with petrophysical logging, some confusion may develop over the use of the word *log*. In common usage, the word log may refer to a particular curve, a suite or group of curves, the physical (paper) record of the measurements, a logging tool (sonde), or the process of logging.

Rock properties or characteristics that affect logging measurements are*: porosity, lithology, mineralogy, permeability,* and *water saturation*. Additionally, the *resistivity* of the rock is important because it is directly measured and is an essential part in the interpretation process. It is essential that the reader understand these properties and the concepts they represent before proceeding with a study of log interpretation.

Porosity

Porosity can be defined as the ratio of voids to the total volume of rock. It is represented as a decimal fraction or as a percentage and is usually represented by the Greek letter phi, ϕ.

$$\text{porosity}, \phi = \frac{\text{volume of pores}}{\text{total volume of rock}} \qquad 1.1$$

The amount of internal space or voids in a given volume of rock is a measure of the amount of fluid a rock will hold. This is illustrated by Equation 1.1 and is called the *total porosity.* The amount of void space that is interconnected, and thus able to transmit fluids, is called *effective porosity*. Isolated pores and pore volume occupied by adsorbed water are excluded from a definition of effective porosity but are included in the definition of total porosity.

Lithology and Mineralogy

In well-log analysis, the terms *lithology* and *mineralogy* are used with some ambiguity. *Lithology* is often used to describe the solid (*matrix*) portion of the rock, generally in the context of a description of the primary mineralogy of the rock (e.g., a *sandstone* as a description of a rock composed primarily of quartz grains, or a *limestone* composed primarily of calcium carbonate). In the early days of log interpretation (with limited measurements), this was usually a sufficient description. Probably the first instances of *lithologic effects* on the logs were observed in *shaly* or clay-containing sandstones. With the advent of multiple porosity measurements and the development of more detailed interpretive methods, it has become possible to estimate the primary solid constituents, normally as a mineral pair or triad.

The literature has tended to follow the improved understanding of the constitution of the solid part of the formations of interest, with most current literature referring to the determination of *mineralogy* instead of *lithology*. When one considers the physics of logging measurements, the ambiguity continues. Some measurements (primarily nuclear) are made as the result of molecular-level interactions between the formation and the logging tool. These might be considered as being affected by the formation's *mineralogy.* Others, especially the acoustic measurements, interact with the formation on a bulk or framework level, and could be considered to be more affected by *lithology* (S. L. Morriss, 1999, personal communication).

The ambiguity between lithology and mineralogy is best seen in porosity crossplots which, through time, have moved from estimating lithology to estimating mineralogy, while the underlying measurements and interpretive techniques have remained essentially the same.

As noted above, the first lithologic effects were probably due to the presence of clays and shales in formations of interest. One parameter that has been used consistently to account for these effects has been shale volume. As our understanding of geological processes matured, it became understood that *shale* and *clay* were different, and that *shaly sands* were usually not just sands with shales mixed in, but sands that contained clays — clays that could be very different from the clays present in the shales near those sands of interest. Again, the literature and our interpretive techniques often use the terms *shale volume* and *clay volume* interchangeably. In this text, *shale volume* will be used preferentially because most of the interpretive techniques in which the volumes are used derive those volumes from the properties of nearby shales.

Permeability

Permeability is the ability of a rock to transmit fluids. It is related to porosity but is not always dependent upon it. Permeability is controlled by the size of the connecting passages (pore throats or capillaries) between pores. It is measured in darcys or millidarcys (md) and is represented by the symbol K. The ability of a rock to transmit a single fluid, when it is completely saturated with that fluid, is called *absolute permeability*. *Effective permeability* refers to the ability of the rock to transmit one fluid in the presence of another fluid when the two fluids are immiscible.

Formation water (connate water in the formation) held by capillary pressure in the pores of a rock serves to inhibit the transmission of hydrocarbons. Stated differently, formation water takes up space both in pores and in the connecting passages between pores. As a consequence, it may block or otherwise reduce the ability of other fluids to move through the rock.

Relative permeability is the ratio between effective permeability of a fluid at partial saturation and the permeability at 100% saturation (absolute permeability). When relative permeability of a formation's water is zero, the formation produces water-free hydrocarbons (i.e., the relative permeability to hydrocarbons is 100%). *With increasing relative permeabilities to water, the formation produces increasing amounts of water relative to hydrocarbons*.

Water Saturation

Water saturation is the amount of pore volume in a rock that is occupied by formation water. It is represented as a decimal fraction or as a percentage and has the symbol S_w.

$$\text{water saturation, } S_w = \frac{\text{formation water occupying pores}}{\text{total pore space in the rock}} \qquad 1.2$$

Although hydrocarbon saturation is the quantity of interest, water saturation is usually used because of its direct calculation in equations such as Archie's equation, discussed in a later section in this chapter. Hydrocarbon saturation is usually determined by the difference between unity and water saturation:

$$S_h = 1 - S_w \qquad 1.3$$

Irreducible water saturation or $S_{w\ irr}$ is the term used to describe the water saturation at which all the water is adsorbed on the grains in a rock or is held in the capillaries by capillary pressure. At irreducible water saturation, water does not move and the relative permeability to water is zero.

Resistivity

Resistivity is the rock property on which the entire science of logging first developed. Resistivity is the inherent property of all materials, regardless of their shape and size, to resist the flow of an electric current. Different materials have different abilities to resist the flow of electricity.

While the resistance of a material depends on its shape and dimensions, the resistivity is an invariant property; the reciprocal of resistivity is conductivity. In log interpretation, the hydrocarbons, the rock, and the fresh water of the formation are all assumed to act as insulators and are, therefore, nonconductive (or at least very highly resistive) to electric current flow. Salt water, however, is a conductor and has a low resistivity. The measurement of resistivity is then a measurement, albeit indirect, of the amount (and salinity) of the formation water. The unit of measure used for the conductor is a cube of the formation, one meter on each edge. The measured units are ohm-meters^2/meter and are called ohm-meters.

$$R = \frac{r \times A}{L} \qquad 1.4$$

where:

R = resistivity (ohm-m)

r = resistance (ohms)

A = cross-sectional area of substance being measured (m^2)

L = length of substance being measured (m)

Resistivity is a basic measurement of a reservoir's fluid saturation and is a function of porosity, type of fluid (i.e., hydrocarbons, salt water, or fresh water), amount of fluid, and type of rock. Because both the rock and hydrocarbons act as insulators but salt water is conductive, resistivity measurements made by logging tools can be used to detect hydrocarbons and estimate the porosity of a reservoir. During the drilling of a well, fluids move into porous and permeable formations surrounding a borehole, so resistivity measurements recorded at different distances into a formation often have different values. Resistivity is measured by *electric logs*, commonly known (in the West) as laterologs and induction logs.

Conrad Schlumberger in 1912 began the first experiments which led, eventually, to the development of modern-day petrophysical logs. The first electric log was run September 5, 1927, by H. G. Doll in Alsace-Lorraine, France. In 1941, G. E. Archie with Shell Oil Company presented a paper to the AIME in Dallas, Texas, which set forth the concepts used as a basis for modern quantitative log interpretation (Archie, 1942).

Archie's experiments showed that the resistivity of a water-filled formation (R_o) could be related to the resistivity of the water (R_w) filling the formation through a constant called the formation resistivity factor (F):

$$R_o = F \times R_w \qquad 1.5$$

Archie's experiments also revealed that the formation factor (F) could be related to the porosity of the formation by the following formula:

$$F = \frac{a}{\phi^m} \qquad 1.6$$

where m is the cementation exponent whose value varies with grain size, grain-size distribution, and the complexity of the paths between pores (tortuosity), and a is the tortuosity factor. The higher the tortuosity of the formation, the higher the value of m. The tortuosity factor (a) is commonly set to 1.0, but is allowed to vary by some petrophysicists.

Water saturation (S_w) is determined from the water-filled resistivity (R_o) and the actual (*true*) formation resistivity (R_t) by the following relationship:

$$S_w = \left(\frac{R_o}{R_t}\right)^{\frac{1}{n}} \qquad 1.7$$

where n is the saturation exponent, whose value typically varies from 1.8 to 2.5 but is most commonly assumed to be 2.

By combining equations 1.6 and 1.7, the water-saturation formula can be rewritten in the following form:

$$S_w = \left(\frac{F \times R_w}{R_t}\right)^{\frac{1}{n}} \qquad 1.8$$

This is the formula that is most commonly referred to as the Archie equation for water saturation (S_w). All present methods of interpretation involving resistivity curves are derived from this equation. In its most general form, Archie's equation becomes:

$$S_w = \left(\frac{a \times R_w}{R_t \times \phi^m}\right)^{\frac{1}{n}} \qquad 1.9$$

Table 1.1 illustrates the range of values for a and m. In first-pass or reconnaissance-level interpretations, or where there is no knowledge of the local parameters, the following values can be used to achieve an initial estimate of water saturation:

$a = 1.0;\ m = n = 2.0$

Now that the reader is introduced to some of the basic concepts of well log interpretation, our discussion can continue in more detail about the factors that affect logging measurements.

BOREHOLE ENVIRONMENT

Where a hole is drilled into a formation, the rock plus the fluids in it (the rock-fluid system) are altered in the vicinity of the borehole. The borehole and the rock surrounding it are contaminated by the drilling mud, which affects logging measurements. Figure 1.1

Table 1.1. Different coefficients and exponents used to calculate formation factor (F). (Modified after Asquith, 1980.)

a: Tortousity factor	m: Cementation exponent	Comments
1.0	2.0	Carbonates[1]
0.81	2.0	Consolidated sandstones[1]
0.62	2.15	Unconsolidated sands (Humble formula)[1]
1.45	1.54	Average sands (after Carothers, 1968)
1.65	1.33	Shaly sands (after Carothers, 1968)
1.45	1.70	Calcareous sands (after Carothers, 1968)
0.85	2.14	Carbonates (after Carothers, 1968)
2.45	1.08	Pliocene sands, southern California (after Carothers and Porter, 1970)
1.97	1.29	Miocene sands, Texas–Louisiana Gulf Coast (after Carothers and Porter, 1970)
1.0	$\phi^{(2.05-\phi)}$	Clean granular formations (after Sethi, 1979)

[1]Most commonly used

is a schematic illustration of a porous and permeable formation that is penetrated by a borehole filled with drilling mud.

Some of the more important symbols shown in Figure 1.1 are:

Hole Diameter (d_h)

The borehole size is determined by the outside diameter of the drill bit. But, the diameter of the borehole may be

- larger than the bit size because of washout and/or collapse of shale and poorly cemented porous rocks, or
- smaller than the bit size because of a build up of mud cake on porous and permeable formations (Figure 1.1).

Common borehole sizes normally vary from 7-7/8 in. to 12 in., and modern logging tools are designed to operate within these size ranges. The size of the borehole is measured by a caliper log.

Drilling mud Resistivity (R_m)

Today, most wells are drilled with rotary bits and the use of a special fluid, called drilling mud, as a circulating fluid. The mud helps remove cuttings from the wellbore, lubricate and cool the drill bit, and maintain an excess of borehole pressure over formation pressure. The excess of borehole pressure over formation pressure prevents blowouts. The density of the mud is usually kept high enough so that hydrostatic pressure in the mud column is greater than formation pressure. This pressure difference forces some of the drilling fluid to invade porous and permeable formations. As invasion occurs, many of the solid particles (i.e., clay minerals from the drilling mud) are trapped on the side of the borehole and form mud cake (having a resistivity of R_{mc}; Figure 1.1). Fluid that filters into the formation during invasion is called mud filtrate (with a resistivity of R_{mf}; Figure 1.1). The resistivity values for drilling mud, mud cake, and mud filtrate are recorded on a log's header (Figure 1.2), and are used in interpretation.

Invaded Zone

The zone in which much of the original fluid is replaced by mud filtrate is called the invaded zone. It consists of a flushed zone (of resistivity R_{xo}) and a transition or annulus zone (of resistivity R_i). The flushed zone occurs close to the borehole (Figure 1.1) where the mud filtrate has almost completely flushed out a formation's hydrocarbons and/or water (R_w). The transition or annulus zone, where a formation's fluids and mud filtrate are mixed, occurs between the flushed zone and the uninvaded zone (of resistivity R_t). The uninvaded zone is defined as the area beyond the invaded zone where a formation's fluids are uncontaminated by mud filtrate.

The depth of mud-filtrate invasion into the invaded zone is referred to as diameter of invasion (d_i and d_j; Figure 1.1). The diameter of invasion is measured in inches or expressed as a ratio: d_j/d_h (where d_h represents the borehole diameter). The amount of invasion that takes place is dependent upon the permeability of the mud cake and not upon the porosity of the rock. In general, an equal volume of mud filtrate can invade low-porosity and high-porosity rocks if the drilling muds have equal amounts of solid particles. The solid particles in the drilling muds coalesce and form an impermeable mud cake. The mud cake then acts as a barrier to further invasion. Because an equal volume of fluid can be invaded before an impermeable mud-cake barrier forms, the diameter of invasion is greatest in low-porosity rocks. This occurs because low-porosity rocks have less storage capacity or pore volume to fill with the invading fluid, and, as a result, pores throughout a greater volume of rock are affected. General invasion diameters in permeable formations are

$d_j/d_h = 2$, for high-porosity rocks;

$d_j/d_h = 5$, for intermediate-porosity rocks; and

$d_j/d_h = 10$, for low-porosity rocks.

Flushed zone Resistivity (R_{xo})

The flushed zone extends only a few inches from the wellbore and is part of the invaded zone. If invasion is deep or moderate, most often the flushed zone is completely cleared of its formation water by mud filtrate (of resistivity R_{mf}). When oil is present in the flushed zone, the degree of flushing by mud filtrate can be determined from the difference between water saturations in the flushed (S_{xo}) zone and the uninvaded (S_w) zone (Figure 1.1). Usually, about 70% to 95% of the oil is flushed out; the remaining oil is called residual oil [$S_{ro} = (1.0 - S_{xo})$, where S_{ro} is the residual oil saturation, (ROS)].

Uninvaded zone Resistivity (R_t)

The uninvaded zone is located beyond the invaded zone (Figure 1.1). Pores in the uninvaded zone are uncontaminated by mud filtrate; instead, they are saturated with formation water (R_w), oil, and/or gas.

Even in hydrocarbon-bearing reservoirs, there is always a layer of formation water on grain surfaces. Water saturation (S_w; Figure 1.1) of the uninvaded zone is an important factor in reservoir evaluation because, *by using water saturation data, a geologist can determine a reservoir's hydrocarbon saturation*. Equation 1.3 expresses the calculation and is repeated here:

$$S_h = 1 - S_w$$

where:

S_h = hydrocarbon saturation (i.e., the fraction of pore volume filled with hydrocarbons).

S_w = water saturation of the uninvaded zone (i.e., the fraction of pore volume filled with water).

The ratio of the uninvaded zone's water saturation (S_w) to the flushed zone's water saturation (S_{xo}) is an index of hydrocarbon moveability.

INVASION AND RESISTIVITY PROFILES

Invasion and resistivity profiles are diagrammatic, theoretical, cross-sectional views of subsurface conditions moving away from the borehole and into a formation. They illustrate the horizontal distributions of the invaded and uninvaded zones and their corresponding relative resistivities. There are three commonly recognized invasion profiles:

- step
- transition
- annulus

These three invasion profiles are illustrated in Figure 1.3.

The step profile has a cylindrical geometry with an invasion diameter equal to d_j. Shallow-reading resistivity logging tools read the resistivity of the invaded zone (R_i), while deeper reading resistivity logging tools read true resistivity of the uninvaded zone (R_t).

The transition profile also has a cylindrical geometry with two invasion diameters: d_i (flushed zone) and d_j (transition zone). It is probably a more realistic model for true borehole conditions than is the step profile. At least three resistivity measurements, each sensitive to a different distance away from the borehole, are needed to measure a transitional profile. These three measure resistivities of the flushed (R_{xo}), transition (R_i), and uninvaded zones (R_t) (see Figure 1.3). By using these three resistivity measurements, the deep reading resistivity measurement can be corrected to a more accurate value of true resistivity (R_t), and the depth of invasion can be determined.

This ability to estimate the invasion in a formation arrived with the wide introduction of the dual induction and dual laterolog tools in the 1960s. As the names imply, each tool made two induction or two laterolog measurements. These two measurements investigate different distances into the formation and are referred to as *medium* and *deep* measurements. The word *dual* in the names of these logging tools can be confusing, because each tool also made a third measurement, which was shallower than the medium and deep measurements. In the 1980s, *array* resistivity tools made their appearance. Through the use of more sensors, they investigate more distances into the formation (usually 5 to 7), which provides for a more detailed picture of the formation and its invasion.

An annulus profile is only sometimes recorded on a log, because it rapidly dissipates in a well. The annulus profile is detected only by an induction log run soon after a well is drilled. However, it is very important to a geologist, because the profile can only occur in zones that bear hydrocarbons. As the mud filtrate invades the hydrocarbon-bearing zone, the hydrocarbons are moved out first. Next, formation water is pushed out in front of the mud filtrate, forming an annular (circular) ring at the edge of the invaded zone (Figure 1.3). The annulus effect is detected by a higher resistivity reading on a deep induction log than by one on a medium induction log.

Log resistivity profiles illustrate the resistivity values of the invaded and uninvaded zones in the formation being investigated. They are of particular interest because, by using them, a geologist can quickly scan a log and look for potential zones of interest such as hydrocarbon zones. Because of their importance, resistivity profiles for both water-bearing and hydrocarbon-bearing zones are discussed here. These profiles vary, depending on the relative resistivity values of R_w and R_{mf}. All the variations and their associated profiles are illustrated in Figures 1.4 and 1.5.

Water-bearing Zones

Figure 1.4 illustrates the borehole and resistivity profiles for water-bearing zones where the resistivity of the mud filtrate (R_{mf}) for a freshwater mud is much greater than the resistivity of the formation water (R_w), and where resistivity of the mud filtrate (R_{mf}) for a saltwater mud is approximately equal to the resistivity of the formation water (R_w). A freshwater mud (i.e., $R_{mf} > 3\ R_w$) results in a *wet* log profile where the shallow (R_{xo}), medium (R_i), and deep (R_t) resistivity measurements separate and record high (R_{xo}), intermediate (R_i), and low (R_t) resistivities (Figure 1.4). A saltwater mud (i.e., $R_w = R_{mf}$) results in a wet profile where the shallow (R_{xo}), medium (R_i), and deep (R_t) resistivity measurements all read low resistivity (Figure 1.4). Figures 1.6 and 1.7 illustrate the resistivity curves for wet zones invaded with either freshwater or saltwater mud.

Hydrocarbon-bearing Zones

Figure 1.5 illustrates the borehole and resistivity profiles for hydrocarbon-bearing zones where the resistivity of the mud filtrate (R_{mf}) for a freshwater mud is much greater than the resistivity of the formation water (R_w), and where R_{mf} of a saltwater mud is approximately equal to R_w. A hydrocarbon zone invaded with freshwater mud results in a resistivity profile where the shallow (R_{xo}), medium (R_i), and deep (R_t) resistivity measurements all record high resistivities (Figure 1.5). In some instances, the deep resistivity is higher than the medium resistivity. When this happens, it is called the annulus effect. A hydrocarbon zone invaded with saltwater mud results in a resistivity profile where the shallow (R_{xo}), medium (R_i), and deep (R_t) resistivity measurements separate and record low (R_{xo}), intermediate (R_i) and high (R_t) resistivities (Figure 1.5). Figures 1.8 and 1.9 illustrate the resistivity curves for hydrocarbon zones invaded with either freshwater or saltwater mud.

BASIC INFORMATION NEEDED IN LOG INTERPRETATION

Lithology

In quantitative log analysis, there are several reasons why it is important to know the lithology of a zone (i.e., sandstone, limestone, or dolomite). Porosity logs require a lithology or a matrix constant before the porosity (ϕ) of the zone can be calculated. The formation factor (F), a variable used in the Archie water-saturation equation, also varies with lithology. As a consequence, the calculated water saturation changes as F changes. Table 1.1 is a list of several different values for calculating formation factor and illustrates how lithology affects the formation factor.

Formation Temperature

Formation temperature (T_f) is also important in log analysis, because the resistivities of the drilling mud (R_m), the mud filtrate (R_{mf}), and the formation water (R_w) vary with temperature. The temperature of a formation is determined by knowing:

- formation depth
- bottom hole temperature (BHT)
- total depth of the well (TD)
- surface temperature

A reasonable value for the formation temperature can be determined by using these data and by assuming a linear geothermal gradient (Figure 1.10). The formation temperature is also calculated (Asquith, 1980) by using the linear regression equation:

$$y = mx + c \qquad 1.10$$

where:

x = depth

y = temperature

m = slope (In this example it is the geothermal gradient.)

c = a constant (In this example it is the mean annual surface temperature.)

An example of how to calculate formation temperature is illustrated here:

Temperature Gradient Calculation

Assume that:

y = bottom hole temperature (BHT) = 250°F

x = total depth (TD) = 15,000 ft

c = mean annual surface temperature = 70°F

Solve for m (i.e., slope or temperature gradient):

$$m = \frac{y - c}{x}$$

Therefore,

$$m = \frac{250° - 70°}{15{,}000 \text{ ft}}$$

$$m = 0.012°/\text{ ft or } 1.2°/100 \text{ ft}$$

Formation Temperature Calculation

Assume:

m = temperature gradient = 0.012°/ft

x = formation depth = 8,000 ft

c = surface temperature = 70°

Remember:

$y = mx + c$

Therefore:

$y = (0.012 \times 8{,}000) + 70$

y = 166° formation temperature at 8,000 ft

After a formation's temperature is determined either by chart (Figure 1.10) or by calculation, the resistivities of the different fluids (R_m, R_{mf}, or R_w) can be corrected to formation temperature. Figure 1.11 is a chart that is used for correcting fluid resistivities to the formation temperature. This chart is closely approximated by the Arp's formula:

$$R_{TF} = \frac{R_{temp}(Temp + 6.77)}{(T_f + 6.77)} \qquad 1.10$$

$$\left(= \frac{R_{temp}(Temp + 21.0)}{(T_f + 21.0)} \text{ for depth in meters} \right)$$

where:

R_{TF} = resistivity at formation temperature

R_{temp} = resistivity at a temperature other than formation temperature

$Temp$ = temperature at which resistivity was measured (usually Fahrenheit for depth in feet, Celsius for depth in meters)

T_f = formation temperature (usually Fahrenheit for depth in feet, Celsius for depth in meters)

Using a formation temperature of 166°F and assuming an R_w of 0.04 measured at 70°F, the R_w at 166°F is:

$R_{w166} = 0.04 \times (70 + 6.77) / (166 + 6.77)$

R_{w166} = 0.018 ohm-m

Resistivity values of the drilling mud (R_m), mud filtrate (R_{mf}), mud cake (R_{mc}), and the temperatures at which they are measured are recorded on a log's header (Figure 1.2). The resistivity of a formation's water (R_w) is obtained by analysis of water samples from a drill stem test, a water-producing well, or from a catalog of water resistivity values. Formation water resistivity (R_w) is also determined from the spontaneous-potential log (discussed in Chapter 2), or it can be calculated in water zones (i.e., where S_w =1) by the apparent water resistivity (R_{wa}) method (see Chapter 7).

COMMON EQUATIONS

Table 1.2 is a list of common equations that are used for the log evaluation of potential hydrocarbon reservoirs. These formulas are discussed in detail in subsequent chapters.

Table 1.2. Common equations of well-log interpretation

Porosity, ϕ:

$$\phi_{Sonic} = \frac{\Delta t_{\log} - \Delta t_{matrix}}{\Delta t_{fluid} - \Delta t_{matrix}}$$

Sonic log porosity (Wyllie time-average equation)

$$\phi_{Sonic} = \frac{5}{8} \times \left(\frac{\Delta t_{\log} - \Delta t_{matrix}}{\Delta t_{\log}} \right)$$

Sonic log porosity (Raymer-Hunt-Gardner equation)

$$\phi_{Density} = \frac{\rho_{matrix} - \rho_{bulk(\log)}}{\rho_{matrix} - \rho_{fluid}}$$

Density log porosity

$$\phi_{NDgas} = \sqrt{\frac{\phi_N^2 + \phi_D^2}{2}}$$

Porosity in a gas zone from neutron and density

Formation factor, F:

$$F = a / \phi^m$$

General form of the equation

$$F = 1.0 / \phi^{2.0}$$

Carbonates

$$F = 0.81 / \phi^{2.0}$$

Consolidated sandstones

$$F = 0.62 / \phi^{2.15}$$

Unconsolidated sands

Formation-water resistivity:

$$SSP = -K \times \log\left(R_{mf} / R_w\right)$$

Basic SP response equation

$$R_w = 10^{(K \times \log(R_{mf}) + SP)/K}$$

First-order approximation of R_w from the SP

Water saturation:

$$S_w = \left(\frac{a \times R_w}{R_t \times \phi^m} \right)^{\frac{1}{n}}$$

Water saturation in the uninvaded zone

$$S_{xo} = \left(\frac{a \times R_{mf}}{R_{xo} \times \phi^m} \right)^{\frac{1}{n}}$$

Water saturation in the flushed zone

$$S_w = \left(\frac{R_{xo} / R_t}{R_{mf} / R_w} \right)^{0.625}$$

Water saturation, ratio method

Bulk volume water:

$$BVW = \phi \times S_w$$

Permeability (estimated):

$$K_e = \left(250 \times \left(\frac{\phi^3}{S_{wirr}} \right) \right)^2$$

Permeability in millidarcys, oil reservoir

$$K_e = \left(79 \times \left(\frac{\phi^3}{S_{wirr}} \right) \right)^2$$

Permeability in millidarcys, gas reservoir

REVIEW

1. The four most fundamental rock properties used in petrophysical logging are:

- porosity
- permeability
- water saturation
- lithology

2. The Archie equation for water saturation is:

$$S_w = \left(\frac{a \times R_w}{R_t \times \phi^m} \right)^{\frac{1}{n}}$$

where:

S_w = water saturation of uninvaded zone
R_w = formation water resistivity
R_t = formation resistivity (uninvaded zone)
ϕ = porosity
a = tortousity factor
m = cementation exponent
n = saturation exponent

3. Where a porous and permeable formation is penetrated by the drill bit, the liquid part of the drilling mud invades the formation as mud filtrate. The mud filtrate resistivity is designated R_{mf}.

4. The invasion of a porous and permeable formation by mud filtrate creates invaded zones around the wellbore. Shallow-, medium-, and deep-reading resistivity measurements provide information about the invaded and uninvaded zones and about the depth of invasion of the drilling fluid.

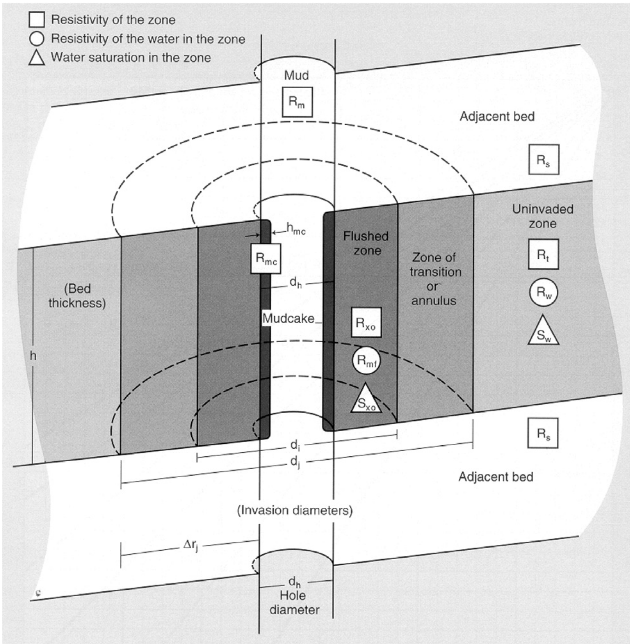
5. The lithology of a formation must be known because:

- A matrix value (usually sandstone, limestone, or dolomite) is needed to determine porosity from logs.
- The formation factor varies with lithology.
- The variation in the formation factor changes the water-saturation values.

6. The four fluids (and the symbols for their resistivity) that affect logging measurements are:

- drilling mud (R_m)
- mud filtrate (R_{mf})
- formation water (R_w)
- hydrocarbons (assumed infinite resistivity, no symbol)

7. The resistivities of the drilling mud (R_m), mud cake (R_{mc}), mud filtrate (R_{mf}) and formation water (R_w) all vary with changes in temperature. Consequently, a formation's temperature (T_f) must be determined and all resistivities corrected to T_f.



Courtesy Schlumberger Wireline & Testing, ©1998 Schlumberger

Figure 1.1. The borehole environment and symbols used in log interpretation.

This schematic diagram illustrates an idealized version of what happens when fluids from the borehole invade the surrounding rock. Dotted lines indicate the cylindrical nature of the invasion.

d_h = hole diameter
d_i = diameter of invaded zone (inner boundary of flushed zone)
d_j = diameter of invaded zone (outer boundary of invaded zone)
Δr_j = radius of invaded zone (outer boundary)
h_{mc} = thickness of mud cake
R_m = resistivity of the drilling mud
R_{mc} = resistivity of the mud cake
R_{mf} = resistivity of mud filtrate
R_s = resistivity of the overlying bed (commonly assumed to be shale)
R_t = resistivity of uninvaded zone (true formation resistivity)
R_w = resistivity of formation water
R_{xo} = resistivity of flushed zone
S_w = water saturation of uninvaded zone
S_{xo} = water saturation flushed zone

HALLIBURTON

HIGH RES INDUCTION
SPECTRAL DENSITY
DUAL SPACED NEUTRON

COMPANY GO FOR IT
WELL 1
FIELD TRAVIS
COUNTY TRAVIS STATE TEXAS

COMPANY GO FOR IT | WELL 1 | FIELD TRAVIS | COUNTY TRAVIS | STATE TEXAS

API No. 2222
Location 1350' FWL & 2560' FNL OF BALCONES "A" LEASE
Sect N/A Twp N/A Rge N/A

Other Services
SFT

Permanent Datum G.L. Elev 291.00
Log measured from T.K.B. , 26.000 ft. above perm. datum
Drilling measured from T.K.B.

Elev.: K.B. 317.00
D.F. 316.00
G.L. 291.00

Date	11–14–1999	11–21–1999	11–27–1999	02000
Run No.				
Depth – Driller	8000.00000	11900.0000	12910.0000	
Depth – Logger	7986.00000	11908.0000	12906.0000	
Bottom – Logged Interval	7977.00000	11899.0000	12897.0000	
Top – Logged Interval	2008.00000	8000.00000	11906.0000	
Casing – Driller	13.37 @ 2008.0	9.625 @ 8000.0	7.625 @ 11900.	@
Casing – Logger	2008.00000	8000.00000	11906.0000	
Bit Size	12.250000	8.500000	6.500000	
Type Fluid in Hole	WATER BASE MUD	OIL BASE MUD	OIL BASE MUD	
Dens. | Visc.	12.80 | 41.000	16.00 | 53.000	14.30 | 47.000	|
Ph | Fluid Loss	9.200 | 6.4000	| 4.0000	| 8.0000	|
Source of Sample	FLOW LINE	FLOW LINE	FLOW LINE	
Rm @ Meas. Temp.	1.670 @ 75.00	@	@	@
Rmf @ Meas. Temp.	1.200 @ 75.00	@	@	@
Rmc @ Meas. Temp.	2.080 @ 75.00	@	@	@
Source Rmf | Rmc	MEAS. | MEAS.	N/A | N/A	N/A | N/A	|
Rm @ BHT	0.630 @ 210.0	@	@	@
Time Since Circ.	8	10	8	
Time on Bottom	320	430	1914	
Max. Rec. Temp.	210.0 @	210.0 @	210.0 @	210.0 @
Equip. | Location	51561 | ALICE	51731 | ALICE	54261 | ALICE	
Recorded By	J. ZIMMER	VISHOK JAIN	AL PADILLA	
Witnessed By	DAN	PAUL		

Figure 1.2. Reproduction of a typical log heading.

This is the first page of a typical log heading. Following pages contain details of the logging equipment used, the scales used to display the data, general information about the borehole direction, remarks about the logging job, and a disclaimer which outlines the responsibilities of both the acquisition company and the client.

1. The title indicates the services that are associated with the data that appear on this log.
2. Basic well name and location information.
3. More detailed information about the physical surface location of the well.
4. Other services that were run at the same time (during the same trip to the well) as the services in this log.
5. Information about location and elevation from which the well depths are measured. K.B. = kelly bushing elevation, D.F. = drill floor elevation, G.L. = ground level elevation, T.K.B. = top of kelly bushing
6. Environmental information about the well. The drilling mud and borehole size values are especially important in applying the proper environmental corrections and interpretation parameters to the data.
7. General information about the logging equipment, the engineer, and any clients who witnessed the logging job. More detailed information about the specific logging tools is listed in the pages that usually follow this one and in tables that detail the calibration techniques and results.

Figure 1.3. Resistivity profiles for three idealized versions of fluid distributions in the vicinity of the borehole. As mud filtrate (R_{mf}) moves into a porous and permeable formation, it can invade the formation in several different ways. Various fluid distributions are represented by the step, transition, or annulus profiles. All three profiles illustrate the effect of a freshwater mud; for profiles using saltwater mud see figures 1.4 and 1.5. Mud cake thickness is indicated by h_{mc}.

Step profile:

This idealized model is the one inferred by the use of three resistivity logs to estimate invasion. Mud filtrate is distributed with a cylindrical shape around the borehole and creates an invaded zone. The cylindrical invaded zone is characterized by its abrupt contact with the uninvaded zone. The diameter of the cylinder is represented as d_j. In the invaded zone, pores are filled with mud filtrate (R_{mf}); pores in the uninvaded zone are filled with formation water (R_w) and hydrocarbons. In this example, the uninvaded zone is wet (water saturated and no hydrocarbons), thus the resistivity beyond the invaded zone is low. The resistivity of the invaded zone is R_{xo}, and the resistivity of the uninvaded zone is R_t (where R_t reduces to R_o when the formation is water bearing).

Transition profile:

This is the most realistic model of true borehole conditions. Here again invasion is cylindrical, but in this profile, the invasion of the mud filtrate (R_{mf}) diminishes gradually, rather than abruptly, through a transition zone toward the outer boundary of the invaded zone (see d_j on diagram for location of outer boundary).

In the flushed part (R_{xo}) of the invaded zone, pores are filled with mud filtrate (R_{mf}), giving a high resistivity reading. In the transition part of the invaded zone, pores are filled with mud filtrate (R_{mf}), formation water (R_w), and, if present, residual hydrocarbons. Beyond the outer boundary of the invaded zone, pores are filled with either formation water or formation water and hydrocarbons. In this diagram, hydrocarbons are not present, so resistivity of the uninvaded zone is low. The resistivity of the invaded zone is R_{xo}, and the resistivity of the uninvaded zone is R_t (where R_t reduces to R_o when the formation is water bearing).

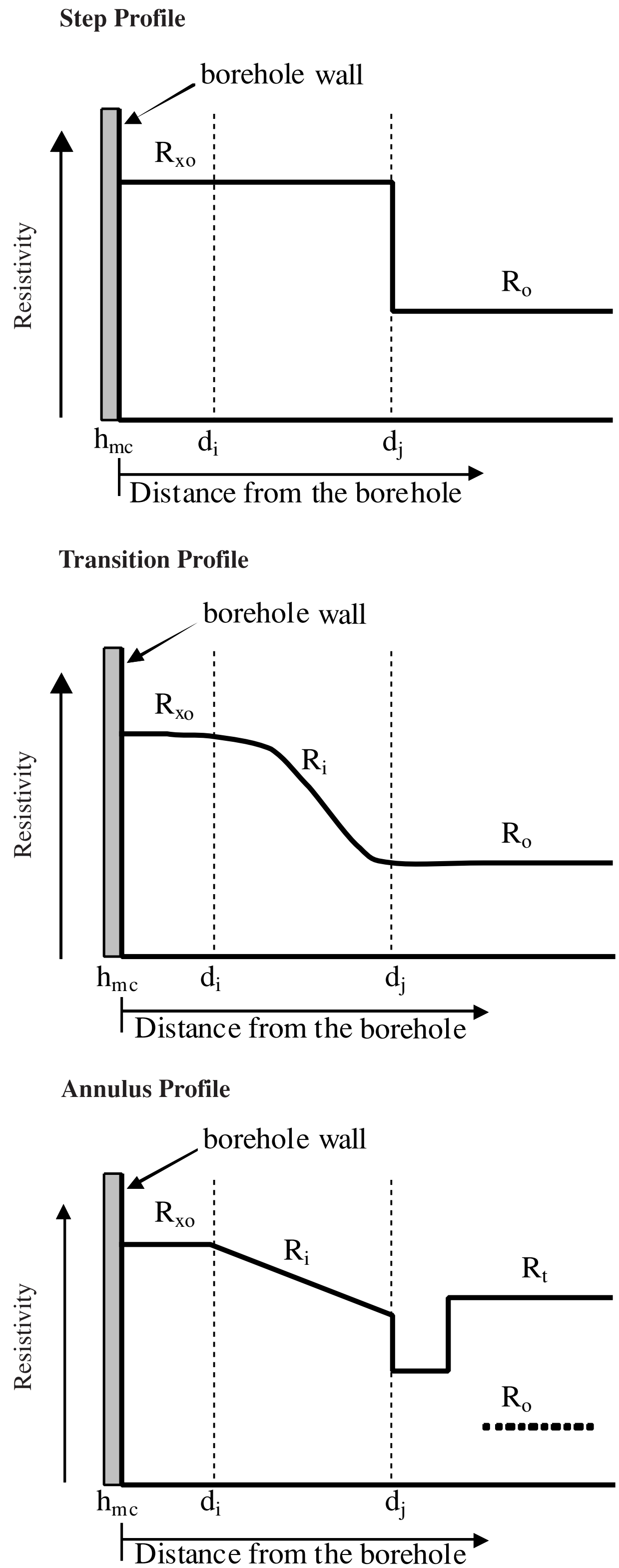
Annulus profile:

This reflects a temporary fluid distribution and is a condition that should disappear with time (if the logging operation is delayed, it might not be recorded on the logs at all). The annulus profile represents a fluid distribution that occurs between the invaded zone and the uninvaded zone and only exists in the presence of hydrocarbons.

In the flushed part (R_{xo}) of the invaded zone, pores are filled with both mud filtrate (R_{mf}) and residual hydrocarbons. Thus the resistivity reads high. Pores beyond the flushed part of the invaded zone (R_i) are filled with a mixture of mud filtrate (R_{mf}), formation water (R_w), and residual hydrocarbons.

Beyond the outer boundary of the invaded zone is the annulus zone, where pores are filled with formation water (R_w) and residual hydrocarbons. When an annulus profile is present, there is an abrupt drop in measured resistivity at the outer boundary of the invaded zone. The abrupt resistivity drop is due to the high concentration of formation water (R_w) in the annulus zone. Formation water has been pushed ahead by the invading mud filtrate into the annulus zone. This causes a temporary absence of hydrocarbons, which have been pushed ahead of the formation water.

Beyond the annulus is the uninvaded zone, where pores are filled with formation water (R_w) and hydrocarbons. The resistivity of the invaded zone is R_{xo}, and the resistivity of the uninvaded zone is R_t (where R_t reduces to R_o when the formation is water bearing).



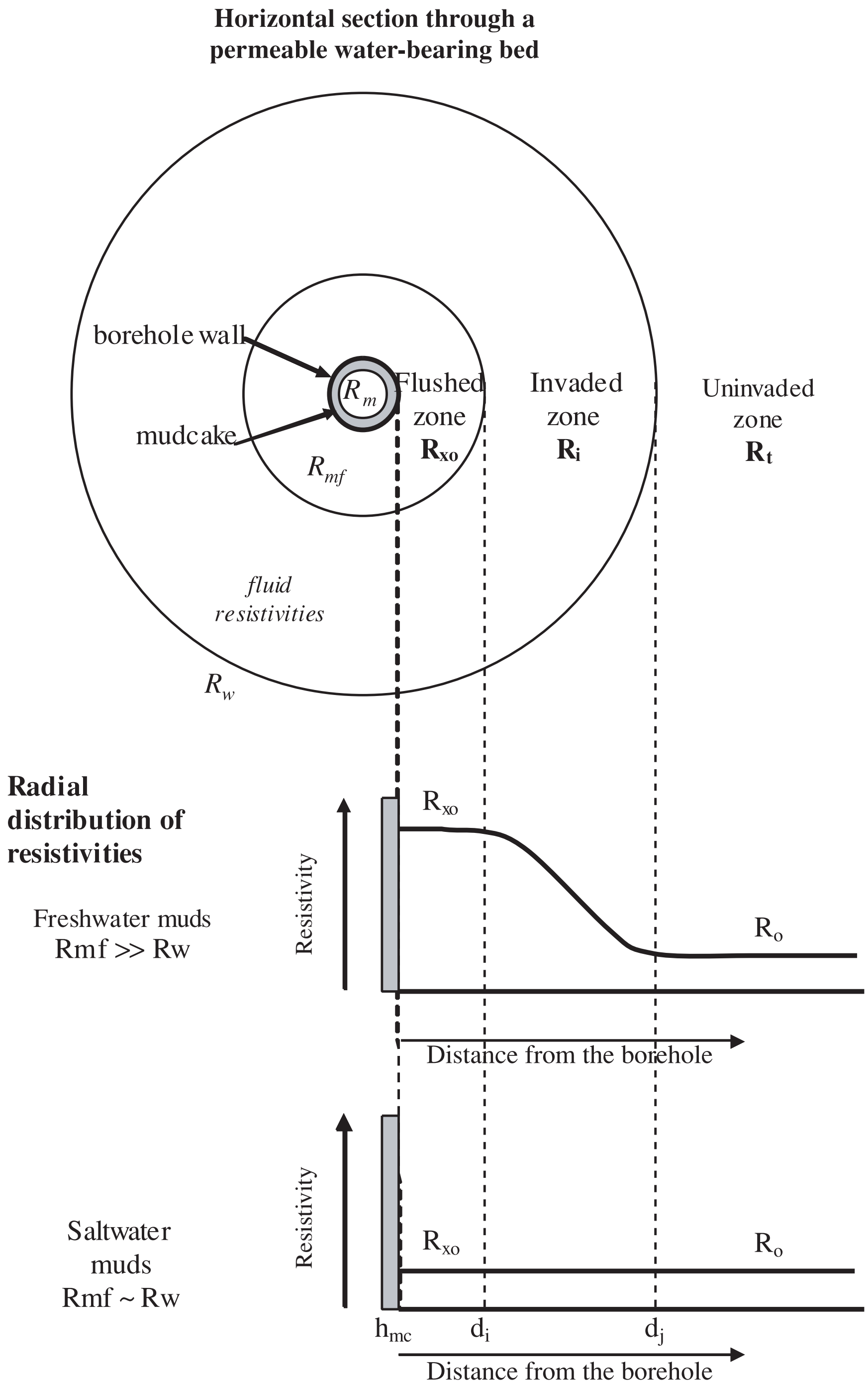


Figure 1.4. Resistivity profile for a transition-style invasion of a water-bearing formation.

Note: These examples are shown because freshwater muds and saltwater muds are used in different geographic regions, usually exclusively. The geologist needs to be aware that a difference exists. To find out which mud is used in your area, check the log heading of existing wells or ask your drilling engineer. The type of mud used affects the log package selected, as will be shown in later chapters.

Freshwater muds:

The resistivity of the mud filtrate (R_{mf}) is greater than the resistivity of the formation water (R_w) (remember, saltwater is conductive). A general rule when freshwater muds are used is: $R_{mf} > 3\ R_w$. The flushed zone (R_{xo}), which has a greater amount of mud filtrate, has higher resistivities. Away from the borehole, the resistivity of the invaded zone (R_i) decreases due to the decreasing amount of mud filtrate (R_{mf}) and the increasing amount of formation water (R_w).

With a water-bearing formation, the resistivity of the uninvaded zone is low because the pores are filled with formation water (R_w). In the uninvaded zone, true resistivity (R_t) is equal to wet resistivity (R_o) because the formation is completely saturated with formation water ($R_t = R_o$ where the formation is completely saturated with formation water).

To summarize: in a water-bearing zone, the resistivity of the flushed zone (R_{xo}) is greater than the resistivity of the invaded zone (R_i), which in turn has a greater resistivity than the uninvaded zone (R_t). Therefore: $R_{xo} > R_i > R_t$ in water-bearing zones.

Saltwater muds:

Because the resistivity of mud filtrate (R_{mf}) is approximately equal to the resistivity of formation water ($R_{mf} \sim R_w$), there is no appreciable difference in the resistivity from the flushed (R_{xo}) to the invaded zone (R_i) to the uninvaded zone ($R_{xo} = R_i = R_t$); all have low resistivities.

Both the above examples assume that the water saturation of the uninvaded zone is much greater than 60%.

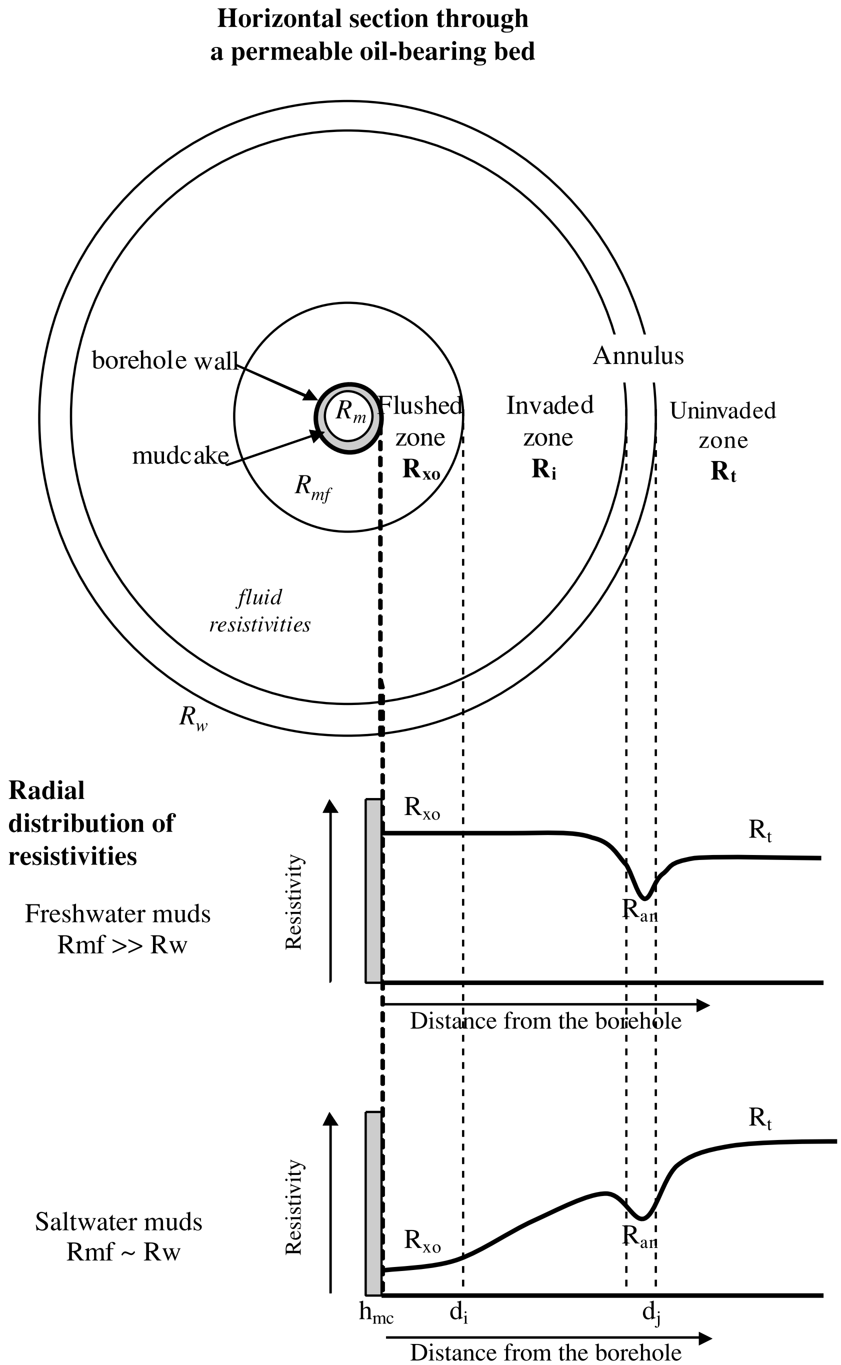


Figure 1.5. Resistivity profile for a transition-style invasion of a hydrocarbon-bearing formation.

Freshwater muds:

Because the resistivities of both the mud filtrate (R_{mf}) and residual hydrocarbons are much greater than formation water (R_w), the resistivity of the flushed zone (R_{xo}) is comparatively high (remember that the flushed zone has mud filtrate and some residual hydrocarbons).

Beyond its flushed part (R_{xo}), the invaded zone (R_i) has a mixture of mud filtrate (R_{mf}), formation water (R_w), and some residual hydrocarbons. Such a mixture causes high resistivities. In some cases, resistivity of the invaded zone (R_i) almost equals that of the flushed zone (R_{xo}).

The presence of hydrocarbons in the uninvaded zone causes higher resistivity than if the zone had only formation water (R_w), because hydrocarbons are more resistant than formation water. In such a case, $R_t > R_o$. The resistivity of the uninvaded zone (R_t) is normally somewhat less than the resistivity of the flushed and invaded zones (R_{xo} and R_i). However, sometimes when an annulus profile is present, the invaded zone's resistivity (R_i) can be slightly lower than the uninvaded zone's resistivity (R_t).

To summarize: $R_{xo} > R_i > R_t$ or $R_{xo} > R_i < R_t$ in hydrocarbon-bearing zones.

Saltwater muds:

Because the resistivity of the mud filtrate (R_{mf}) is approximately equal to the resistivity of formation water ($R_{mf} \sim R_w$), and the amount of residual hydrocarbons is low, the resistivity of the flushed zone (R_{xo}) is low.

Away from the borehole, as more hydrocarbons mix with mud filtrate in the invaded zone the resistivity of the invaded zone (R_i) increases.

Resistivity of the uninvaded zone (R_t) is much greater than if the formation were completely water saturated (R_o) because hydrocarbons are more resistant than saltwater. Resistivity of the uninvaded zone (R_t) is greater than the resistivity of the invaded (R_i) zone. So, $R_t > R_i > R_{xo}$. Both the above examples assume that the water saturation of the uninvaded zone is much less than 60%.

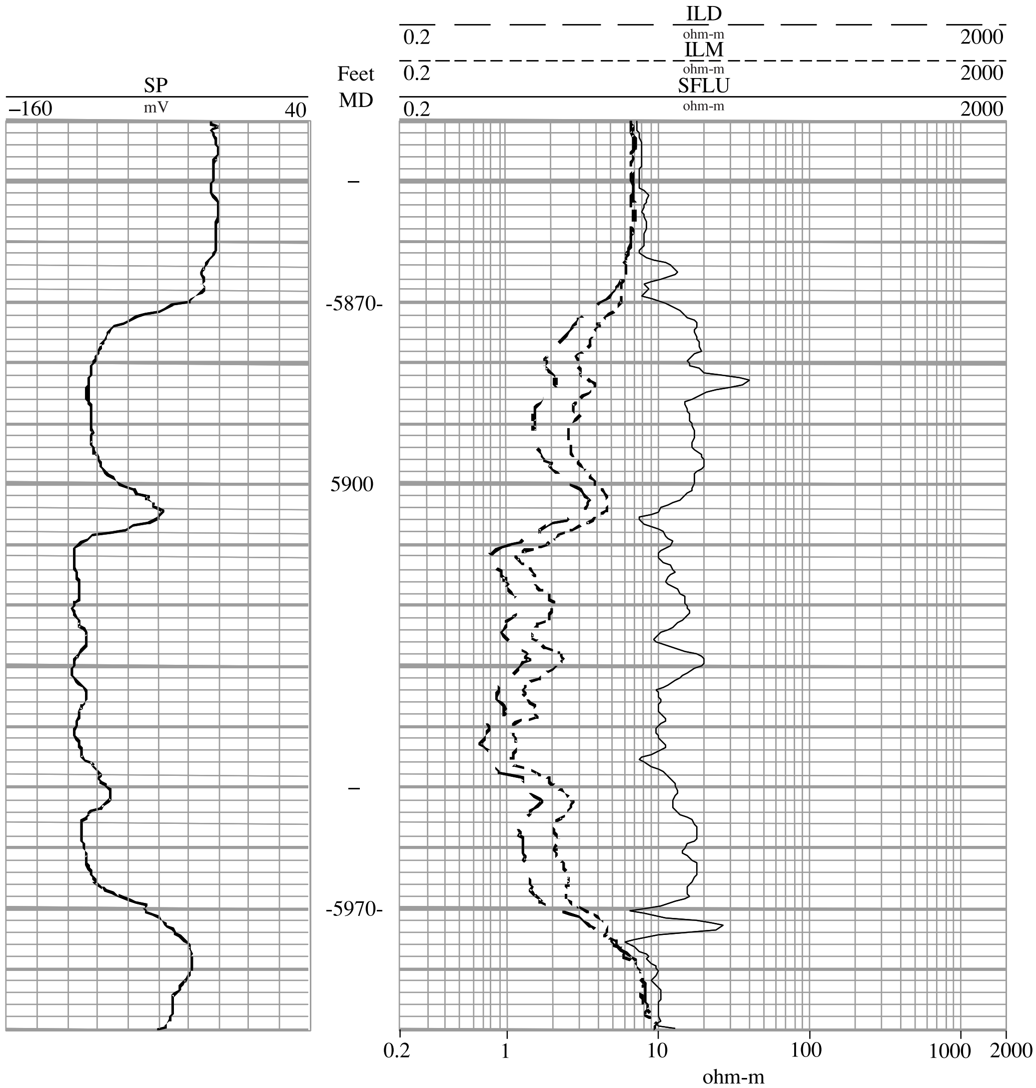


Figure 1.6. Example of dual induction log curves through a water-bearing zone.

Given: the drilling mud is freshwater based ($R_{mf} > 3R_w$).

Where freshwater drilling muds invade a water-bearing formation ($S_w > 60\%$), there is high resistivity in the flushed zone (R_{xo}), a lesser resistivity in the invaded zone (R_i), and a low resistivity in the uninvaded zone (R_t).

See Figure 1.4 for review. (Figure 1.8 shows the response of these resistivity curves in a hydrocarbon-bearing zone.)

Compare the three curves on the right side of the log (tracks 2 and 3). Resistivity increases from left to right. A key for reading this logarithmic resistivity scale is shown at the bottom of the log. Depth scale is in feet with each vertical increment equal to 2 ft.

Log curve ILD:

Deep induction log resistivity curves usually measure true formation resistivity (R_t), the resistivity of the formation beyond the outer boundary of the invaded zone. In water-bearing zones (in this case from 5870 to 5970 ft), the curve reads a low resistivity because the pores of the formation are saturated with low resistivity connate water (R_w).

Log curve ILM:

Medium induction log resistivity curves measure the resistivity of the invaded zone (R_i). In a water-bearing formation, the curve reads a resistivity between R_t and R_{xo} because the fluid in the formation is a mixture of formation water (R_w) and mud filtrate (R_{mf}).

Log curve SFLU:

Spherically focused log resistivity curves measure the resistivity of the flushed zone (R_{xo}). In a water-bearing zone, the curve reads a high resistivity because freshwater mud filtrate (R_{mf}) has a high resistivity. The SFL pictured here records a greater resistivity than either the deep (ILD) or medium (ILM) induction curves.

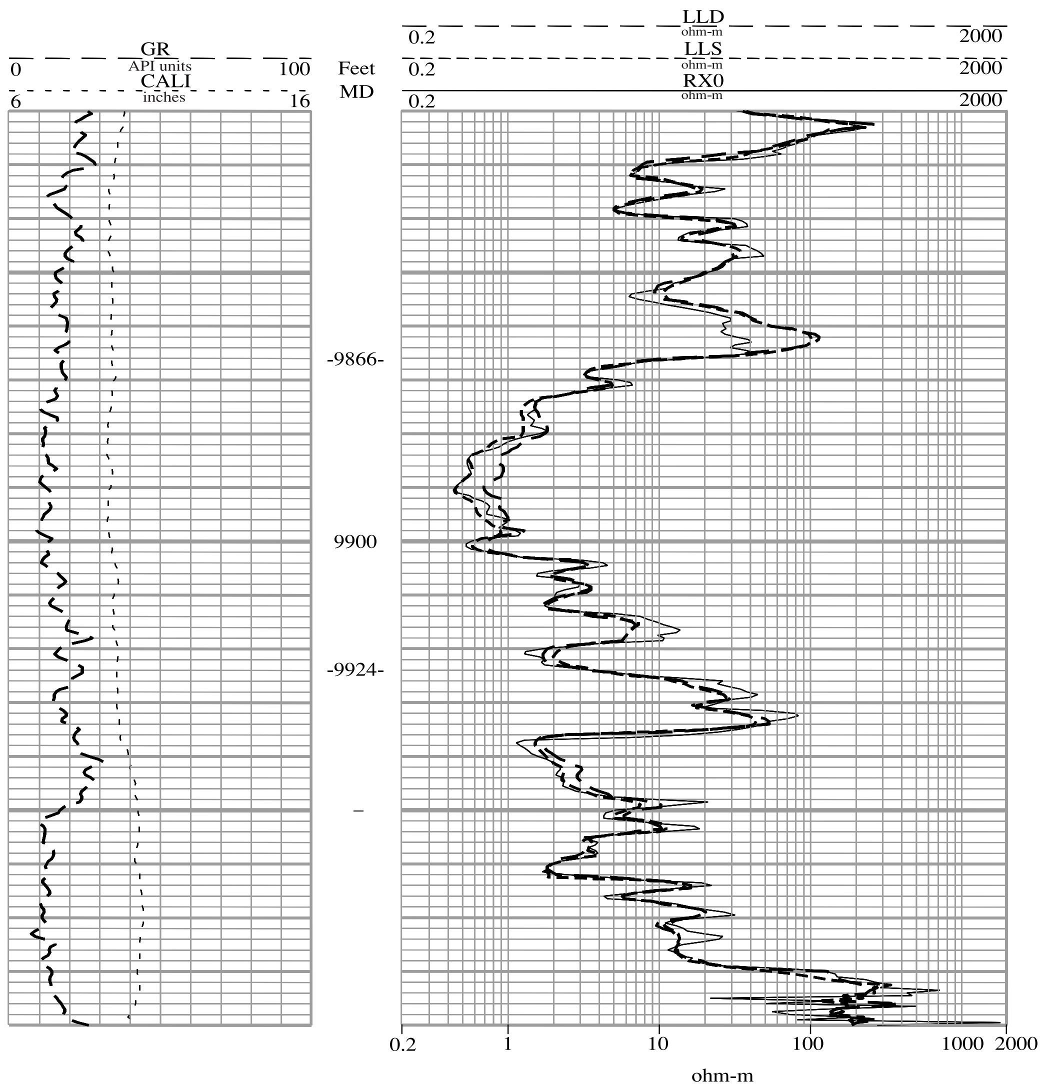


Figure 1.7. Example of dual laterolog curves through a water-bearing zone.

Given: The drilling mud is saltwater based ($R_{mf} \sim R_w$).

Where saltwater drilling muds invade a water-bearing formation ($S_w > 60\%$), there is low resistivity in the flushed zone (R_{xo}), a low resistivity in the invaded zone (R_i), and low resistivity in the uninvaded zone (R_t). Because R_{mf} is approximately equal to R_w, the pores in the flushed (R_{xo}), invaded (R_i), and uninvaded (R_t) zones are all filled with saline waters; the presence of salt results in low resistivity.

See Figure 1.4 for review. (Figure 1.9 shows the response of these resistivity curves in a hydrocarbon-bearing zone.)

Compare the three curves on the right side of the log (tracks 2 and 3). Resistivity increases from left to right. A key for reading this logarithmic resistivity scale is shown at the bottom of the log. Depth scale is in feet with each vertical increment equal to 2 ft.

Log curve LLD:

Deep laterolog resistivity curves usually measure true formation resistivity (R_t), the resistivity of the formation beyond the outer boundary of the invaded zone. In water-bearing zones (in this case from 9866 to 9924 ft), the curve reads a low resistivity because the pores of the formation are saturated with low resistivity connate water (R_w).

Log curve LLS:

Shallow laterolog resistivity curves measure the resistivity in the invaded zone (R_i). In a water-bearing zone, the shallow laterolog (LLS) records a low resistivity because R_{mf} is approximately equal to R_w.

Log curve RXO:

Microresistivity curves measure the resistivity of the flushed zone (R_{xo}). In water-bearing zones the curve records a low resistivity because saltwater mud filtrate has low resistivity. The resistivity recorded by the microresistivity log is low and approximately equal to the resistivities of the invaded and uninvaded zones.

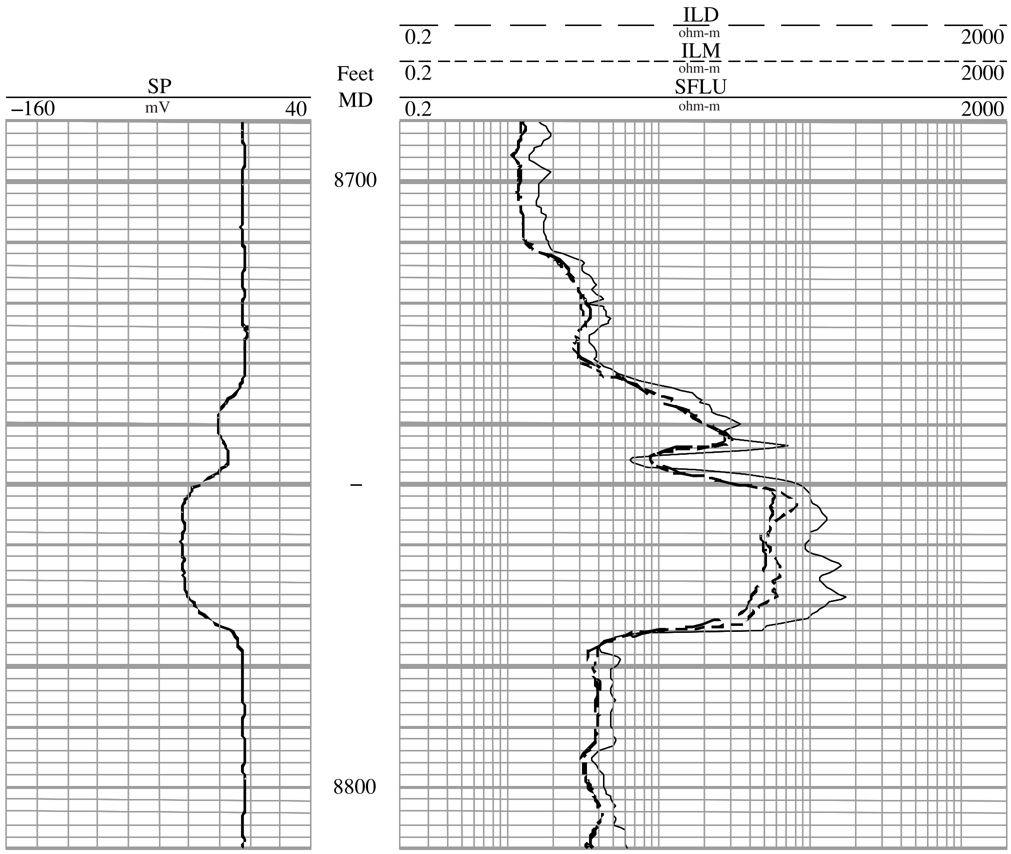


Figure 1.8. Example of dual induction log curves through a hydrocarbon-bearing zone.

Given: the drilling mud is freshwater based ($R_{mf} > 3R_w$).

Where freshwater drilling muds invade a hydrocarbon-bearing formation ($S_w < 60\%$), there is high resistivity in the flushed zone (R_{xo}), high resistivity in the invaded zone (R_i), and high resistivity in the uninvaded zone (R_t). Normally, the flushed zone has slightly higher resistivity than the uninvaded zone.

See Figure 1.5 for review. (Figure 1.6 shows the response of these resistivity curves in a water-bearing zone.)

Compare the three curves on the right side of the log (tracks 2 and 3). Resistivity increases from left to right.

Log curve ILD:

Deep induction log resistivity curves usually measure true formation resistivity (R_t), the resistivity of the formation beyond the outer boundary of the invaded zone. In hydrocarbon-bearing zones (in this case from 8748 to 8774 ft), the curve records a high resistivity because hydrocarbons are more resistant than saltwater in the formation ($R_t > R_o$).

Log curve ILM:

Medium induction log resistivity curves measure the resistivity of the invaded zone (R_i). In a hydrocarbon-bearing zone, because of a mixture of mud filtrate (R_{mf}), formation water (R_w), and residual hydrocarbons in the pores, the curve records a high resistivity. This resistivity is normally equal to or slightly more than the deep induction curve (ILD). But, in an annulus situation, the medium curve (ILM) can record a resistivity slightly less than the deep induction (ILD) curve.

Log curve SFLU:

Spherically focused log resistivity curves measure the resistivity of the flushed zone (R_{xo}). In a hydrocarbon-bearing zone, the curve reads a higher resistivity than the deep (ILD) or medium (ILM) induction curves because the flushed zone (R_{xo}) contains mud filtrate and residual hydrocarbons. The SFL pictured here records a greater resistivity than either the deep (ILD) or medium (ILM) induction curves.

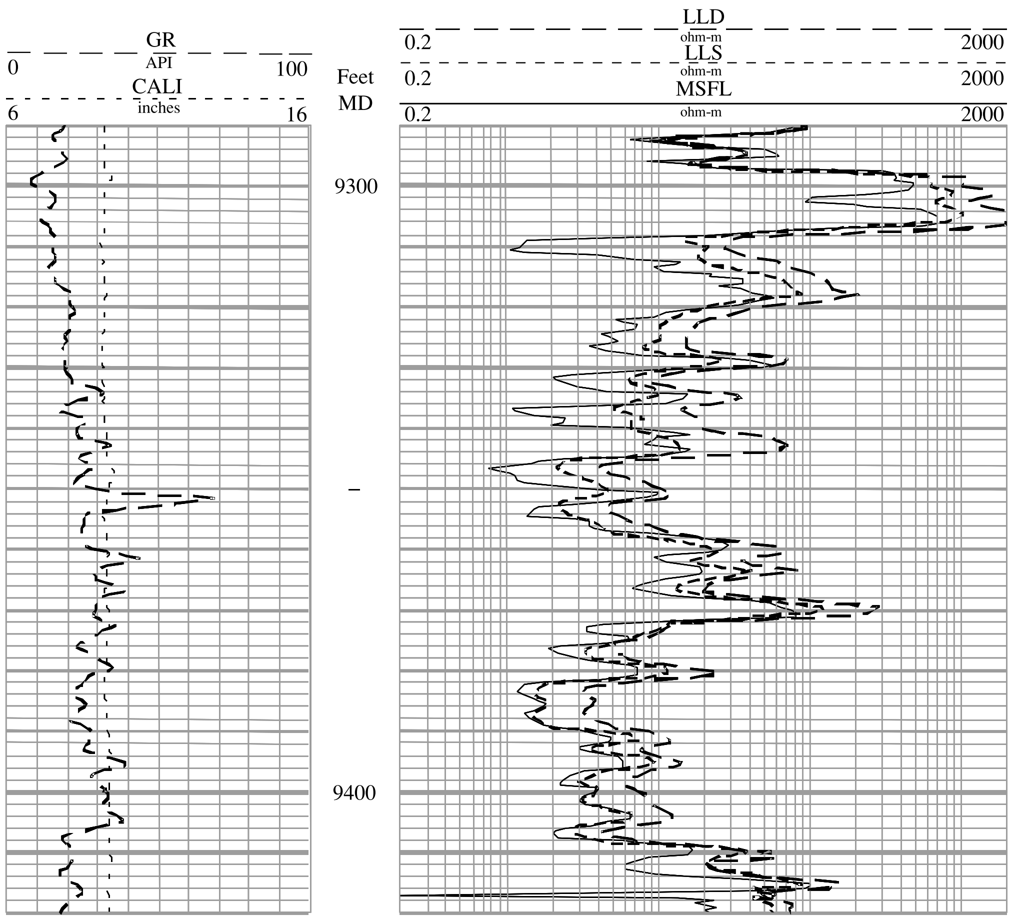


Figure 1.9. Example of dual laterolog curves through a hydrocarbon-bearing zone.

Given: The drilling mud is saltwater based ($R_{mf} \sim R_w$).

Where saltwater drilling muds invade a hydrocarbon-bearing formation ($S_w << 60\%$), there is low resistivity in the flushed zone (R_{xo}), an intermediate resistivity in the invaded zone (R_i), and high resistivity in the uninvaded zone (R_t). The reason for the increase in resistivities deeper into the formation is because of the increasing hydrocarbon saturation.

See Figure 1.5 for review. (Figure 1.7 shows the response of these resistivity curves in a water-bearing zone.)

Compare the three curves on the right side of the log (tracks 2 and 3). Resistivity increases from left to right.

Log curve LLD:

Deep laterolog resistivity curves usually measure true formation resistivity (R_t), the resistivity of the formation beyond the outer boundary of the invaded zone. In hydrocarbon-bearing zones (in this case from 9306 to 9409 ft), the curve reads a high resistivity because of high hydrocarbon saturation in the uninvaded zone (R_t).

Log curve LLS:

Shallow laterolog resistivity curves measure the resistivity in the invaded zone (R_i). In a hydrocarbon-bearing zone, the shallow laterolog (LLS) records a lower resistivity than the deep laterolog (LLD) because the invaded zone (R_i) has a lower hydrocarbon saturation than the uninvaded zone (R_t)

Log curve MSFL:

Microspherically focused log resistivity curves measure the resistivity of the flushed zone (R_{xo}). In hydrocarbon-bearing zones, the curve records a low resistivity because saltwater mud filtrate has low resistivity and the residual hydrocarbon saturation in the flushed zone (R_{xo}) is low. Therefore, in a hydrocarbon-bearing zone with saltwater-based drilling mud, the uninvaded zone (R_t) has high resistivity, the invaded zone (R_i) has a lower resistivity, and the flushed zone (R_{xo}) has the lowest resistivity.

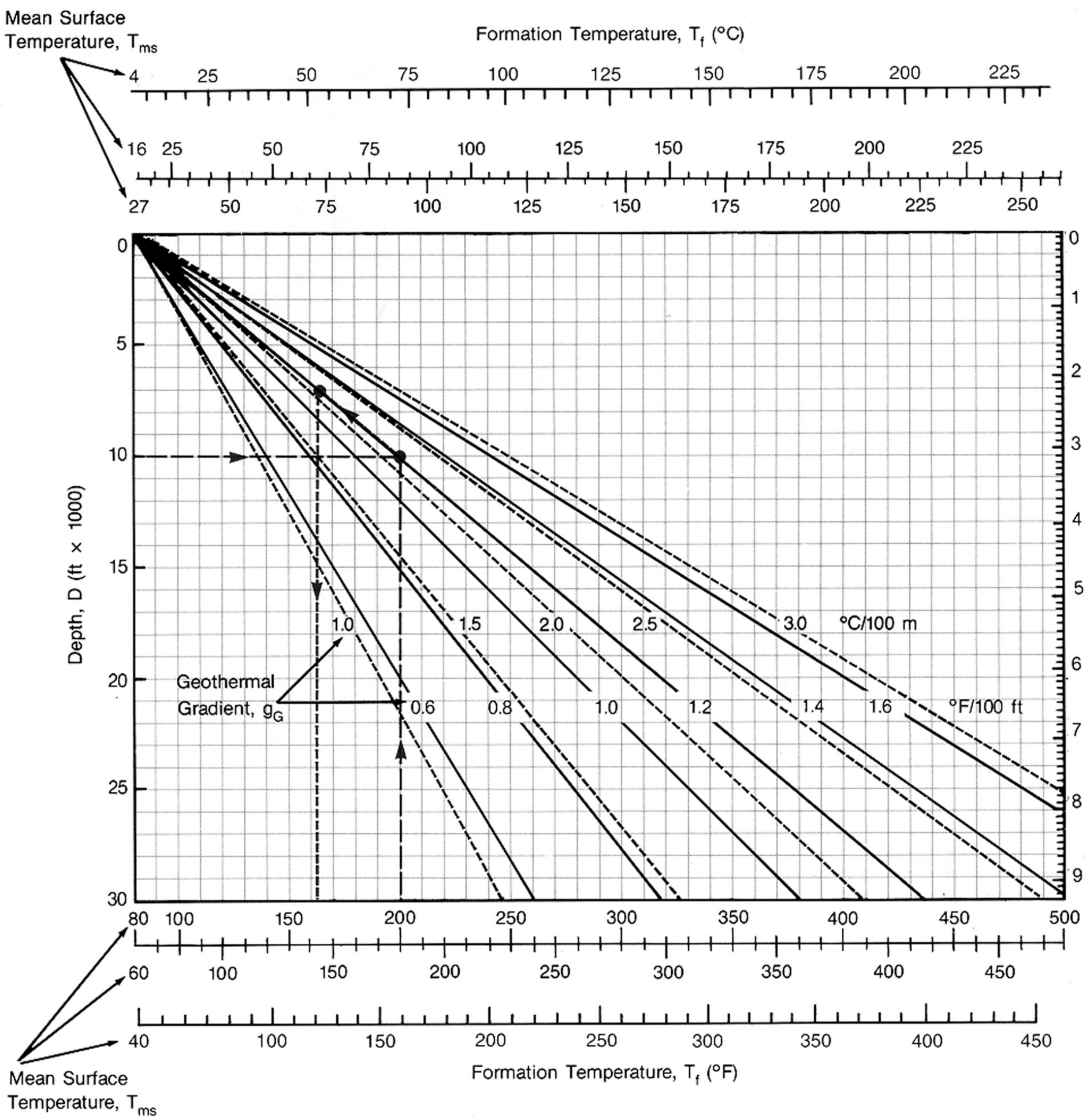


Figure 1.10. Chart for estimating formation temperature (T_f) with depth (linear gradient assumed). (Western Atlas International, Inc., 1995, Figure 2-1)

Given:

Surface temperature = 80°F
Bottom hole temperature (BHT) = 200°F
Total depth (TD) = 10,000 ft
Formation depth = 7000 feet

Procedure:

1. Locate BHT (200°F) on the 80 scale (bottom of the chart; mean surface temperature = 80°F).
2. Follow BHT (200°F) vertically up until it intersects the 10,000 ft (TD) line. This intersection defines the temperature gradient.
3. Move parallel to the (diagonal) temperature gradient line up to 7000 ft (formation depth).
4. Formation temperature (164°F) is read on the bottom scale (i.e., 80 scale) vertically down from the point where the 7000 ft line intersects the temperature gradient.

NOTE: In the United States (as an example), 80°F is used commonly as the mean surface temperature in the southern states, and 60°F is used commonly in the northern states. However, a specific mean surface temperature can be calculated if such precision is desired. Another source for mean surface-temperature gradients is any world atlas with such listings.

Figure 1.11. Chart for adjusting fluid resistivities for temperature. (Schlumberger, 1998, Figure Gen-9.)

Given:

> Resistivity of drilling mud (R_m) equals 1.2 ohm-m at 75°F. Formation temperature (T_f) = 160°F.

Procedure:

1. Locate the resistivity value, 1.2 ohm-m, on the scale at the left of the chart.
2. Move to the right horizontally along the 1.2 ohm-m line until the vertical line representing a temperature of 75°F (from the bottom of the chart) is encountered (point A on the chart).
3. Move parallel to the (diagonal) constant salinity line to where it intersects the vertical line representing a temperature value of 160°F (point B on the chart).
4. From point B, follow the horizontal line to the left to determine the resistivity of the fluid at the desired temperature (0.58 ohm-m at 160°F).

Each diagonal line on the chart shows the resistivity of a solution of fixed concentration over a range of temperatures. The diagonal lines at the bottom of the chart indicate that an NaCl solution can hold no more than 250,000 to 300,000 ppm NaCl depending on temperature (i.e., the solution is completely salt saturated).