Basic Relationships of Well Log Interpretation

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 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:

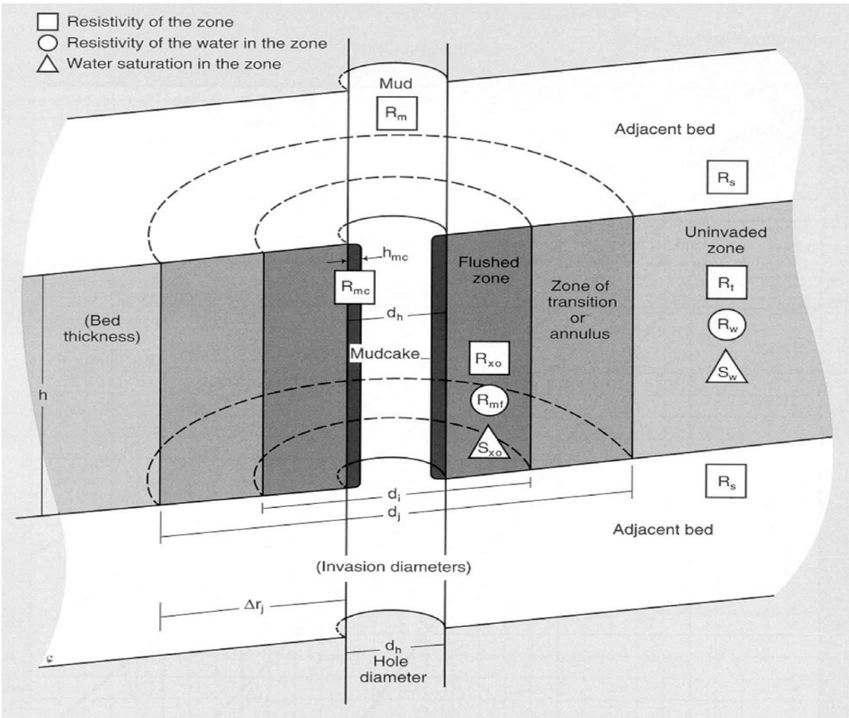


Figure 1.1. The borehole environment and symbols used in log interpretation.

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.

dh = hole diameter

di = diameter of invaded zone (inner boundary of flushed zone)

dj = diameter of invaded zone (outer boundary of invaded zone)

Δrj = radius of invaded zone (outer boundary)

hmc = thickness of mud cake

Rm = resistivity of the drilling mud

Rmc = resistivity of the mud cake

Rmf = resistivity of mud filtrate
Rs = resistivity of the overlying bed (commonly assumed to be shale)
Rt = resistivity of uninvaded zone (true formation resistivity)
Rw = resistivity of formation water
Rxo = resistivity of flushed zone
Sw = water saturation of uninvaded zone
Sxo = water saturation flushed zone

Hole Diameter (dh)

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 (Rm)

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 *Rmc*; Figure 1.1). Fluid that filters into the formation during invasion is called mud filtrate (with a resistivity of *Rmf*; 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 *Rxo*) and a transition or annulus zone (of resistivity *Ri*).

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 (*Rw*). 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 *Rt*).

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 (*di* and *dj*). The diameter of invasion is measured in inches or expressed as a ratio: *dj*/*dh* (where *dh* 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.

General invasion diameters in permeable formations are

dj/*dh* = 2, for high-porosity rocks;
dj/*dh* = 5, for intermediate-porosity rocks; and
dj/*dh* = 10, for low-porosity rocks.

Flushed zone Resistivity (Rxo)

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 *Rmf*).

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 (*Sxo*) zone and the uninvaded (*Sw*) zone.

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 (Rt)

The uninvaded zone is located beyond the invaded zone. 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.

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).

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: *di* (flushed zone) and *dj* (transition zone). It is probably a more realistic model for true borehole conditions than is the step profile.

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.

Water-bearing Zones

Figure 1.4 illustrates the borehole and resistivity profiles for water-bearing zones where the resistivity of the mud filtrate (*Rmf*) for a **freshwater mud** is much greater than the resistivity of the formation water (*Rw*), and where resistivity of the mud filtrate (*Rmf*) for a **saltwater mud** is approximately equal to the resistivity of the formation water (*Rw*).

A freshwater mud (i.e., *Rmf* > 3 Rw) results in a *wet* log profile where the shallow (*Rxo*), medium (*Ri*), and deep (*Rt*) resistivity measurements **separate** and record high (*Rxo*), intermediate (*Ri*), and low (*Rt*) resistivities.

A saltwater mud (i.e., *Rw* = *Rmf*) results in a wet profile where the shallow (*Rxo*), medium (*Ri*), and deep (*Rt*) resistivity measurements all read low resistivity.

Hydrocarbon-bearing Zones

Figure 1.5 illustrates the borehole and resistivity profiles for hydrocarbon-bearing zones where the resistivity of the mud filtrate (*Rmf*) for a **freshwater** mud is much greater than the resistivity of the formation water (*Rw*), and where *Rmf* of a **saltwater** mud is approximately equal to *Rw*.

A hydrocarbon zone invaded with **freshwater** mud results in a resistivity profile where the shallow (*Rxo*), medium (*Ri*), and deep (*Rt*) 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 (*Rxo*), medium (*Ri*), and deep (*Rt*) resistivity measurements **separate** and record low (*Rxo*), intermediate (*Ri*) and high (*Rt*) resistivities.

Basic Information Needed In Log Interoretation

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.

Formation Temperature

Formation temperature (Tf) is also important in log analysis, because the resistivities of the drilling mud (Rm), the mud filtrate (Rmf), and the formation water (Rw) 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 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 X 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 (*Rm*, *Rmf*, or *Rw*) 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:

$$R_{TF} = \frac{R_{temp}(Temp + 6.77)}{(T_f + 6.77)} \quad \left(= \frac{R_{temp}(Temp + 21.0)}{(T_f + 21.0)} \text{ for depth in meters} \right) \qquad 1.10$$

where:
RTF = resistivity at formation temperature
Rtemp = 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)

Tf = formation temperature

(usually Fahrenheit for depth in feet, Celsius for depth in meters)

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

R*w*166 = 0.04 X (70 + 6.77) / (166 + 6.77)

R*w*166 = 0.018 ohm-m

Resistivity values of the drilling mud (*Rm*), mud filtrate (*Rmf*), mud cake (*Rmc*), 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 (*Rw*) 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 (*Rw*) is also determined from the spontaneous potential log, or it can be calculated in water zones (i.e., where *Sw* =1) by the apparent water resistivity (*Rwa*) method.

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 :

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

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

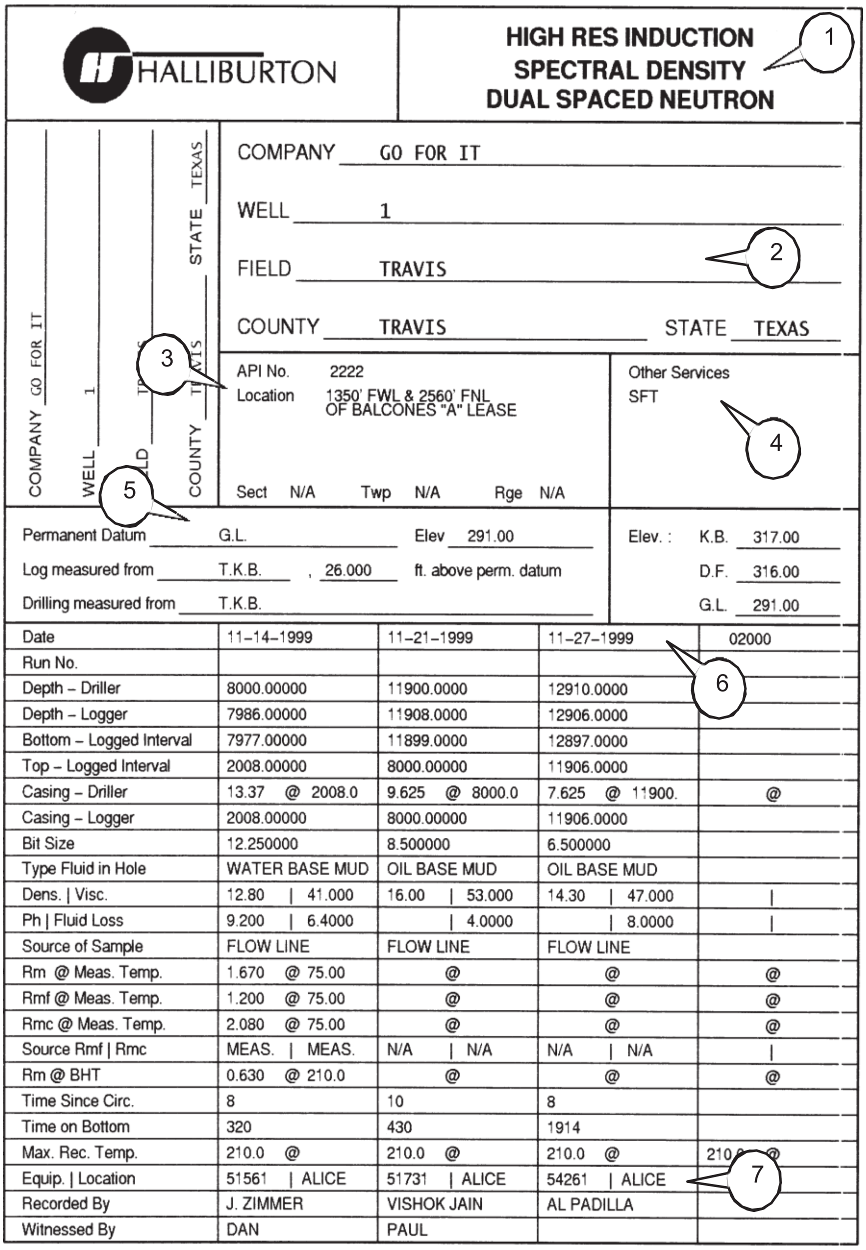
Bulk volume water:

$$BVW = \phi \times S_w$$

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



HALLIBURTON

HIGH RES INDUCTION
SPECTRAL DENSITY
DUAL SPACED NEUTRON

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

<table>
<tr><td>Date</td><td>11–14–1999</td><td>11–21–1999</td><td>11–27–1999</td><td>02000</td></tr>
<tr><td>Run No.</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Depth – Driller</td><td>8000.00000</td><td>11900.0000</td><td>12910.0000</td><td></td></tr>
<tr><td>Depth – Logger</td><td>7986.00000</td><td>11908.0000</td><td>12906.0000</td><td></td></tr>
<tr><td>Bottom – Logged Interval</td><td>7977.00000</td><td>11899.0000</td><td>12897.0000</td><td></td></tr>
<tr><td>Top – Logged Interval</td><td>2008.00000</td><td>8000.00000</td><td>11906.0000</td><td></td></tr>
<tr><td>Casing – Driller</td><td>13.37 @ 2008.0</td><td>9.625 @ 8000.0</td><td>7.625 @ 11900.</td><td>@</td></tr>
<tr><td>Casing – Logger</td><td>2008.00000</td><td>8000.00000</td><td>11906.0000</td><td></td></tr>
<tr><td>Bit Size</td><td>12.250000</td><td>8.500000</td><td>6.500000</td><td></td></tr>
<tr><td>Type Fluid in Hole</td><td>WATER BASE MUD</td><td>OIL BASE MUD</td><td>OIL BASE MUD</td><td></td></tr>
<tr><td>Dens. | Visc.</td><td>12.80 | 41.000</td><td>16.00 | 53.000</td><td>14.30 | 47.000</td><td>|</td></tr>
<tr><td>Ph | Fluid Loss</td><td>9.200 | 6.4000</td><td>| 4.0000</td><td>| 8.0000</td><td>|</td></tr>
<tr><td>Source of Sample</td><td>FLOW LINE</td><td>FLOW LINE</td><td>FLOW LINE</td><td></td></tr>
<tr><td>Rm @ Meas. Temp.</td><td>1.670 @ 75.00</td><td>@</td><td>@</td><td>@</td></tr>
<tr><td>Rmf @ Meas. Temp.</td><td>1.200 @ 75.00</td><td>@</td><td>@</td><td>@</td></tr>
<tr><td>Rmc @ Meas. Temp.</td><td>2.080 @ 75.00</td><td>@</td><td>@</td><td>@</td></tr>
<tr><td>Source Rmf | Rmc</td><td>MEAS. | MEAS.</td><td>N/A | N/A</td><td>N/A | N/A</td><td>|</td></tr>
<tr><td>Rm @ BHT</td><td>0.630 @ 210.0</td><td>@</td><td>@</td><td>@</td></tr>
<tr><td>Time Since Circ.</td><td>8</td><td>10</td><td>8</td><td></td></tr>
<tr><td>Time on Bottom</td><td>320</td><td>430</td><td>1914</td><td></td></tr>
<tr><td>Max. Rec. Temp.</td><td>210.0 @</td><td>210.0 @</td><td>210.0 @</td><td>210.0 @</td></tr>
<tr><td>Equip. | Location</td><td>51561 | ALICE</td><td>51731 | ALICE</td><td>54261 | ALICE</td><td></td></tr>
<tr><td>Recorded By</td><td>J. ZIMMER</td><td>VISHOK JAIN</td><td>AL PADILLA</td><td></td></tr>
<tr><td>Witnessed By</td><td>DAN</td><td>PAUL</td><td></td><td></td></tr>
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Figure 1.2. Reproduction of a typical log heading.

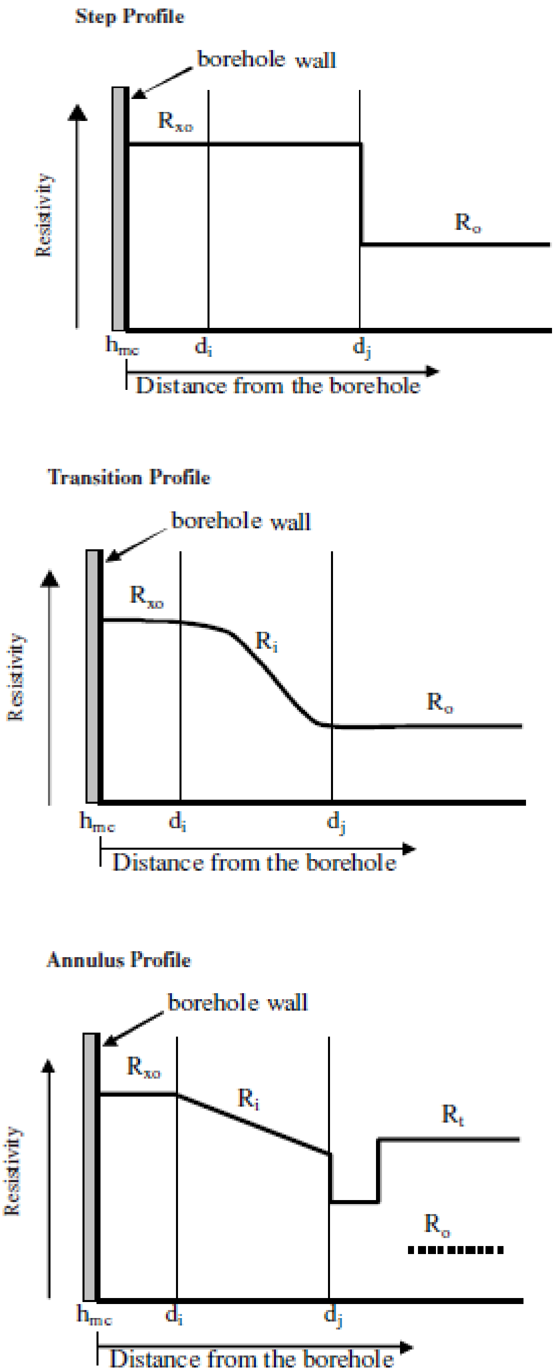

Figure 1.3. Resistivity profiles for three idealized versions of fluid distributions in the vicinity of the borehol.

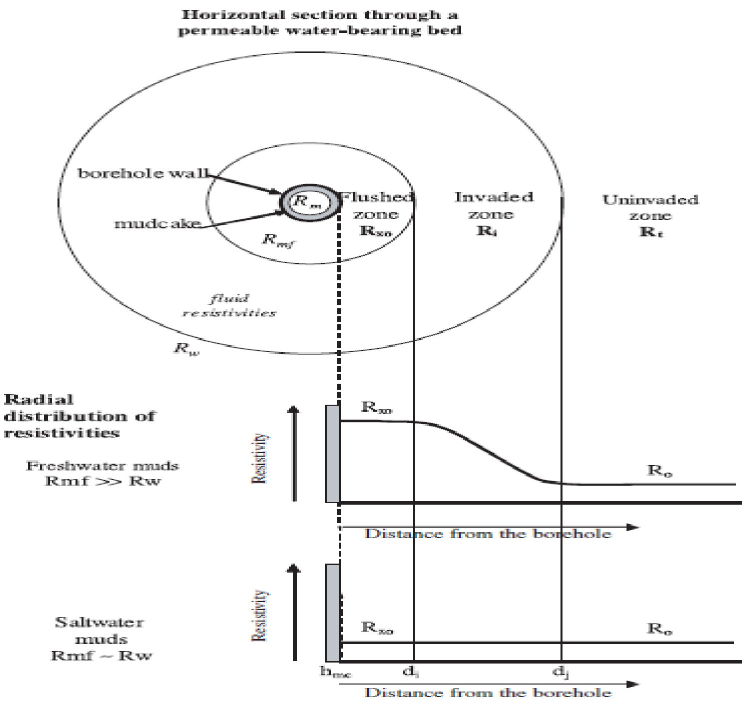

Figure 1.4. Resistivity profile for a transition-style invasion of a water-bearing formation.

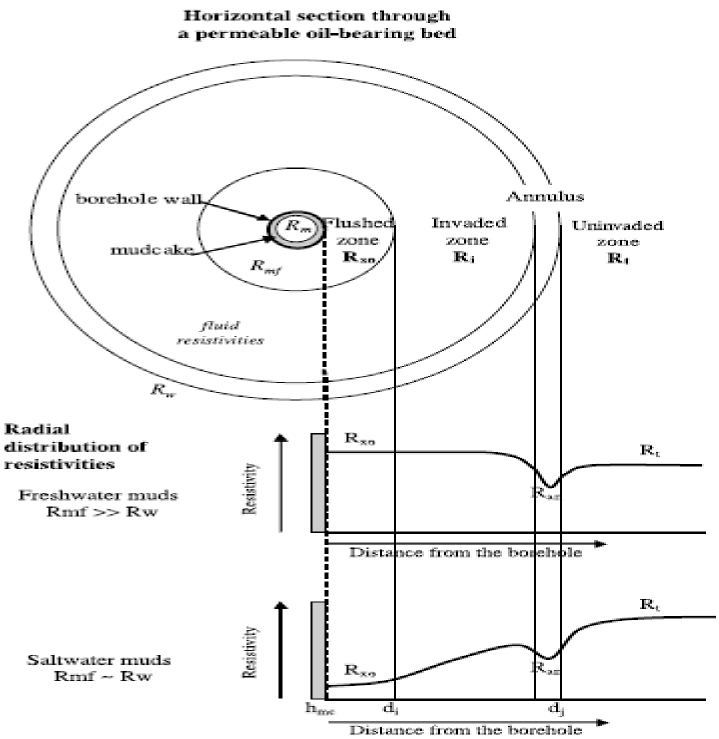

Figure 1.5. Resistivity profile for a transition-style invasion of a hydrocarbon-bearing formation.