Resistivity Logs

General

Resistivity logs are used to:

• determine hydrocarbon-bearing versus water bearing zones
• indicate permeable zones
• determine porosity

By far the most important use of resistivity logs is the determination of hydrocarbon-bearing versus water-bearing zones. Because the rock's matrix or grains are nonconductive and any hydrocarbons in the pores are also nonconductive, the ability of the rock to transmit a current is almost entirely a function of water in the pores. As the hydrocarbon saturation of the pores increases (as the water saturation decreases), the formation's resistivity increases.

The current can be produced and measured by either of two methods. Electrode tools (also called galvanic devices) have electrodes on the surface of the tool to emit current and measure the resistivity of the formation. Induction tools use coils to induce a current and measure the formation's conductivity.

The lateral has an asymmetric electrode pattern (with respect to the axis of the tool) and is very different in its interpretation than the normal curves or the measurements available today.
The normal log was developed in two configurations, each with its own electrode spacing. The 16- inch spacing was called the *short normal* and a 64- inch spacing was called the *long normal*. These older measurements were unfocused electrode devices and were ineffective in high borehole salinities (low resistivities) and in thin beds.

Table 3.1. Classification of Resistivity Logs.

<table>
<tr><td colspan="3">Induction Logs [coil logs] (measure formation conductivity)</td></tr>
<tr><td colspan="3">Induction (deep and medium)</td></tr>
<tr><td colspan="3">Galvanic devices [electrode logs and laterologs] (measure formation resistivity)</td></tr>
<tr><td colspan="2">Normal</td><td>Microlaterolog (MLL)</td></tr>
<tr><td colspan="2">Lateral</td><td>Microlog (ML)</td></tr>
<tr><td colspan="2">Laterolog (deep and shallow)</td><td>Proximity Log (PL)</td></tr>
<tr><td colspan="2">Spherically Focused Log (SFL)</td><td>MicroSpherically Focused Log (MSFL)</td></tr>
<tr><td colspan="3">Resistivity Log Depth of Investigation</td></tr>
<tr><td>Flushed Zone (Rxo)</td><td>Invaded Zone (Ri)</td><td>Uninvaded Zone (Rt)</td></tr>
<tr><td>MicroLog (ML)</td><td>Short Normal (SN)</td><td>Long Normal (LN)</td></tr>
<tr><td>Microlaterolog (MLL)</td><td>Laterolog-8 (LL8)</td><td>Lateral Log</td></tr>
<tr><td>Proximity Log (PL)</td><td>Spherically Focused Log (SFL)</td><td>Deep Induction Log (ILd)</td></tr>
<tr><td>MicroSpherically Focused Log (MSFL)</td><td>Medium Induction Log (ILm)</td><td>Deep Laterolog (LLd)</td></tr>
<tr><td></td><td>Shallow Laterolog (LLs)</td><td>Laterolog-3 (LL3)</td></tr>
<tr><td></td><td></td><td>Laterolog-7 (LL7)</td></tr>
</table>

Laterologs

The *laterolog* are designed to measure formation resistivity in boreholes filled with saltwater muds (where *Rmf* ~ *Rw*).

A current from the surveying electrode is forced into the formation by focusing electrodes. Focusing electrodes emit current of the same polarity as the surveying electrode but are located above and below it. The focusing electrodes (sometimes called guard electrodes) prevent the surveying current from flowing up the borehole filled with saltwater mud (Figure 3.1).

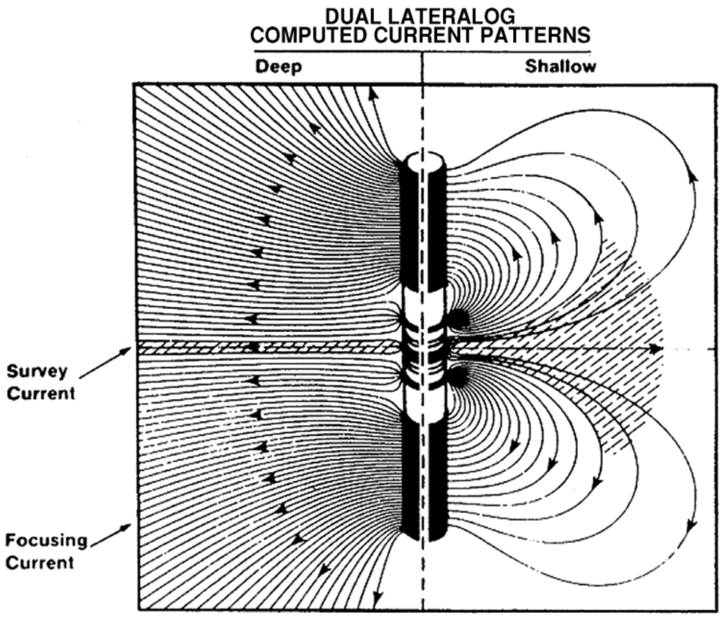

Figure 3.1. Schematic illustration of a focused laterolog illustrating current flow.

The effective depth of laterolog investigation is controlled by the extent to which the surveying current is focused. Deep-reading laterologs are therefore more strongly focused than shallow-reading laterologs.

Invasion can influence the laterolog. However because the resistivity of the mud filtrate is approximately equal to the resistivity of formation water (*Rmf* ~ *Rw*) when a well is drilled with saltwater muds, invasion does not strongly affect *Rt* values derived from a laterolog. But, when a well is drilled with freshwater muds (where *Rmf* > 3 *Rw*), the laterolog can be strongly affected by invasion. Under these conditions, a laterolog should not be used (see Figure 3.2). The borehole size and formation thickness affect the laterolog, but normally the effect is small enough so that laterolog resistivity can be taken as *Rt*.

Laterolog consisted of a single laterolog measurement and sometimes a microlaterolog measurement. The laterolog curve (Figure 3.3) appears in track 2 of the log and has a linear scale. Because saltwater mud (where

Rmf ~ *Rw*) gives a very poor SP response, a natural gamma-ray log was often run in track1 as a lithology and correlation curve. The microlaterolog, if run, was recorded in track 3.

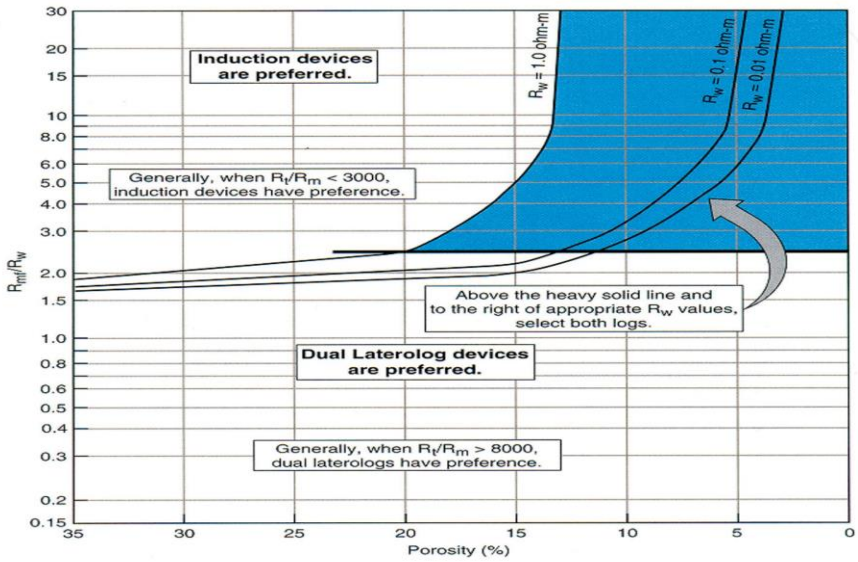

Figure 3.2. Chart for quick determination of preferred conditions for using an induction log versus a laterolog.

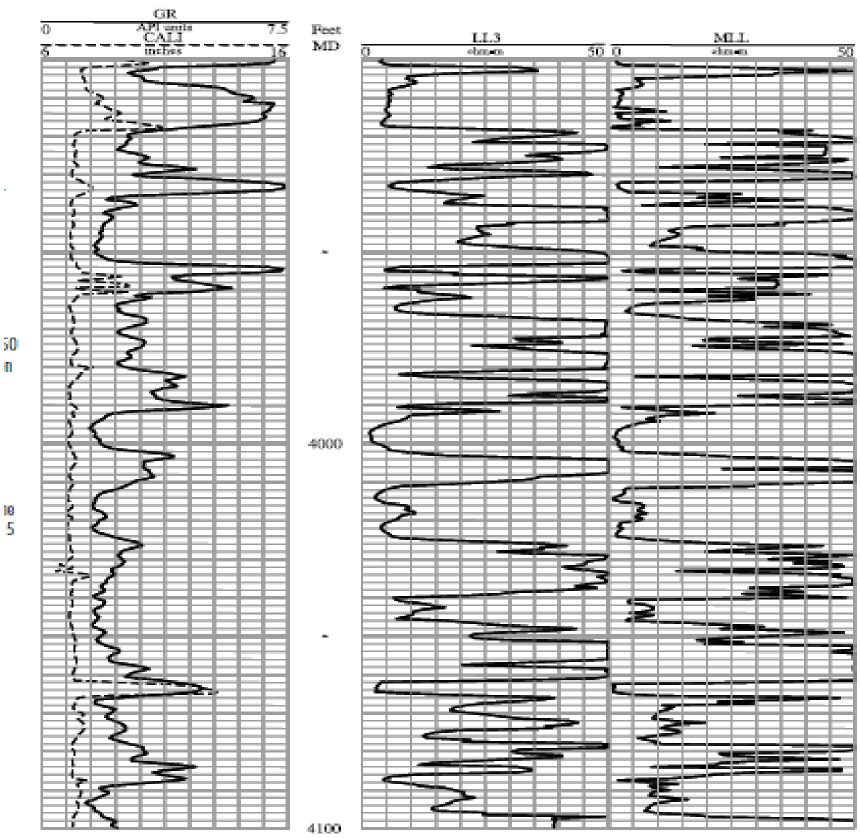

Figure 3.3. Example of a laterolog and microlaterolog. This log illustrates the curves and provides an example for picking log values. These logs are used when Rmf ~ Rw.

Note: To correct the laterolog (for invasion) to true resistivity (*Rt*), use the following formula from (Hilchie, 1979). Using the example at 3948 ft:

Rt = 1.67 (*RLL*) – 0.67 (*Rxo*) *Rt* = 1.67 (21) – 0.67 (8)

Rt = 29.7 ohm-m

where:

Rt = resistivity of the uninvaded zone

RLL = laterolog resistivity (21 ohm-m at 3948 ft)

Rxo = microlaterolog resistivity (8 ohm-m at 3948 ft)

Dual Laterolog

The dual laterolog (Figure 3.4) was introduced in the early 1970s and is still in use today. It consists of a deep-reading measurement (*RLLD*) and a shallow-reading measurement (*RLLS*). Both curves are displayed in tracks 2 and 3 of the log, usually on a four-cycle logarithmic scale ranging from 0.2 to 2000 ohm-m. A natural gamma ray log is often displayed in track1. The third resistivity measurement is the microspherically focused resistivity (*RMSFL*), a pad-type, focused electrode log that has a very shallow depth of investigation and measures the formation resistivity very close (within a few inches) of the wellbore. When this three resistivity-curve combination (i.e., deep, shallow, and very shallow) is used, the deep laterolog curve can be corrected for invasion effects to produce *Rt*.

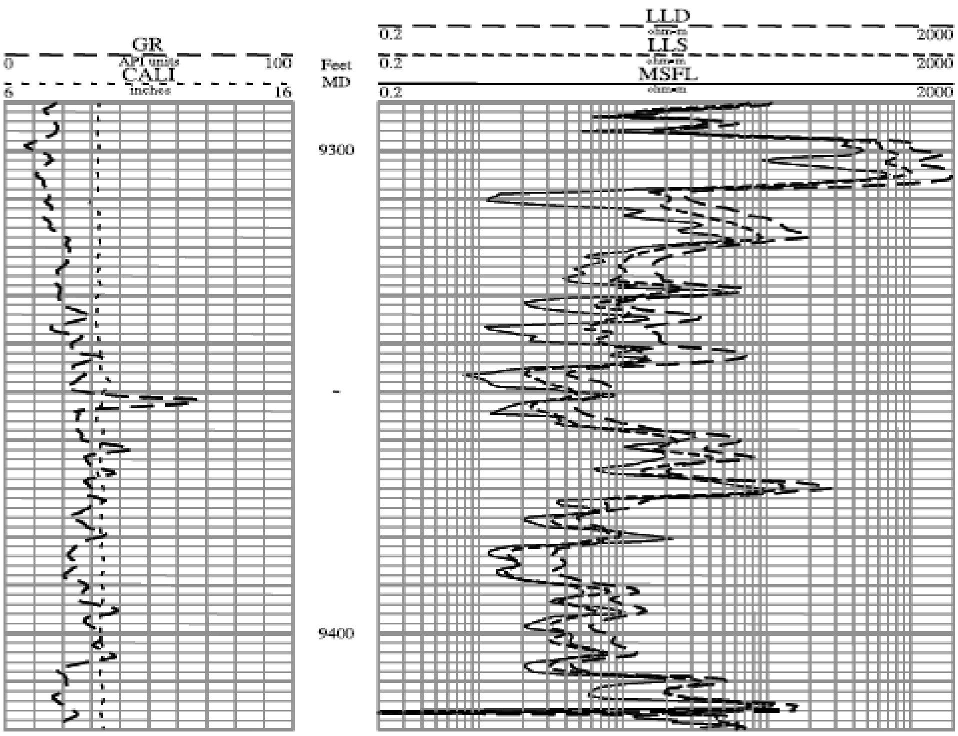

Figure 3.4. Example of dual laterolog with microspherically focused log.

A ***tornado chart*** (Figure 3.5) is used to graphically correct *RLLD* to *Rt* and to determine the diameter of invasion (*di*) and the ratio *Rt*/*Rxo*, from which *Rxo* can be determined. The correction procedure is illustrated in Figure 3.5.

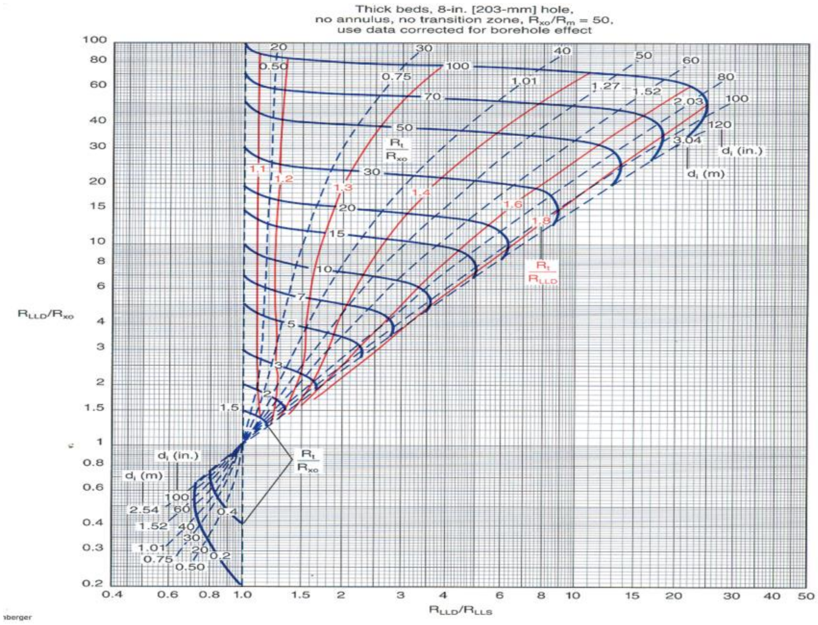

Figure 3.5. Dual laterolog-*Rxo* tornado chart for correcting deep resistivity to *Rt*.

Induction Logs

Unlike the original (unfocused) electrode logs and laterologs, induction logs measure formation conductivity rather than resistivity. Formation conductivity is related to formation resistivity through the following equation:

$$C = 1000/R \qquad 3.1$$

where:
C = conductivity in millimho/m (= milliSiemens)
R = resistivity in ohm-m

An induction tool consists of several transmitting coils that emit a high-frequency alternating current of constant intensity. The alternating electromagnetic field that is created induces currents in the formation.
These currents flow as ground-loop currents perpendicular to the axis of the logging tool and create electromagnetic fields which induce signals in the receiver coils. The receiver signals are essentially proportional to conductivity. The responses of the individual coils are combined in such a way as to minimize the effect of materials in the borehole, the invaded zone, and other nearby formations (Figure 3.6).
While the older generation of the tools, which are still in use, relied on electronic circuitry to properly mix the receiver signals to minimize the

various nearborehole effects, newer *array tools* usually have more receivers and process the received signals with computer- based algorithms which model the response of the tool to formation properties.

Induction logs have evolved from a single induction measurement run in combination with the older short-normal measurement, to the dual induction, which makes two different induction measurements simultaneously, to the array measurements, which measure formation resistivity at different frequencies and distances away from the borehole.

Induction Electric Log

Like the laterolog, the first version of the induction log, the induction electric log (Figure 3.7), had a single deep induction measurement (*RIL*). It, however, was combined with the earlier (electrode-type) short-normal measurement (*RSN*) to simultaneously measure the resistivity of the formation at two distances from the borehole. The SP measurement was a common correlation measurement in this suite.

The short-normal measurement interrogated the formation at a shallow distance from the wellbore, and comparison of the two measurement values, *RSN* and *RIL*, was an indication of invasion and, thus, formation permeability.

The short-normal tool can record a reliable value for resistivity from a bed thickness of four feet or greater. The short-normal curve is usually recorded in track 2 on a linear scale. The short-normal tool works best in freshwater muds (where *Rmf* > 3 *Rw*), so saltwater muds (where *Rmf* ~ *Rw*) are not a good environment for its use. In addition to providing a value for *Ri*, the short-normal curve can be used to calculate a value for resistivity-derived porosity if a correction is made for unflushed oil in the invaded zone.

To obtain a more accurate reading of *Ri* from the short-normal curve, an amplified short-normal curve (the same data displayed on a more sensitive scale) is sometimes displayed in track 2 along with the short-normal curve.

The induction log has a transmitter-receiver spacing of 40 inches and can measure a reliable value for resistivity down to a bed thickness of about five feet.

The induction curve on the induction electric log appears in track2 (Figure 3.7). Because the induction device is a conductivity measuring tool, a conductivity curve is presented in track 3. The track 3 conductivity curve is useful to more accurately determine the resistivity value in low-resistivity formations and to eliminate possible errors in the acquisition system's derivation of resistivity from conductivity. Because the induction log does not require the transmission of electrical current through drilling fluid, it can be run in nonconducting borehole fluids such as air, oil, or foam.

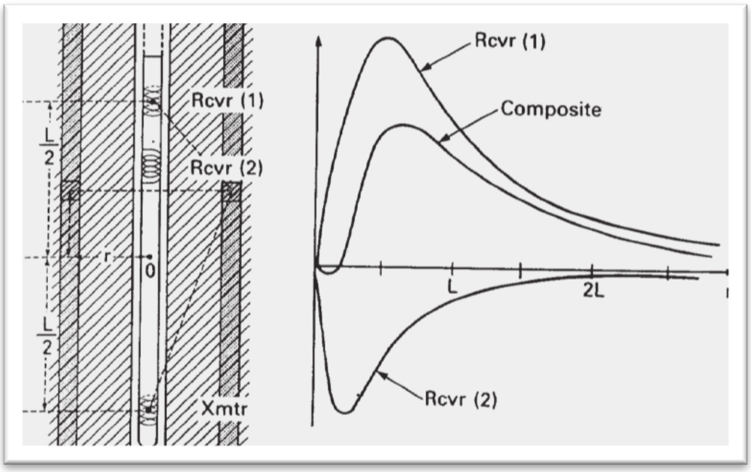

Figure 3.6. Schematic illustration of a basic three-coil induction system.

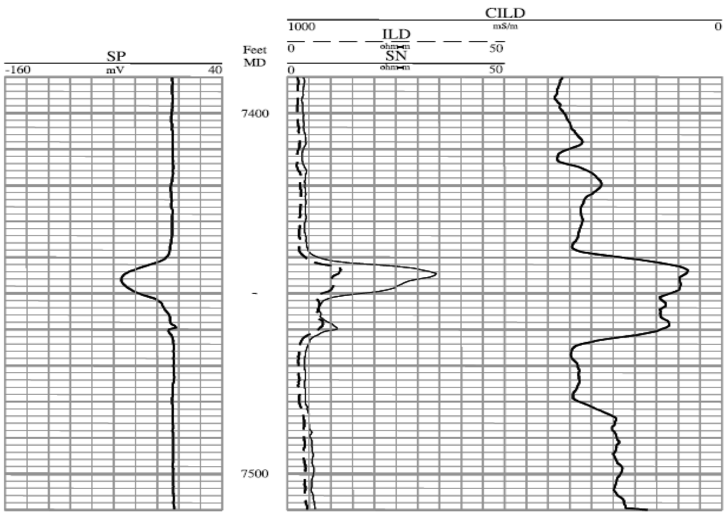

Figure 5.7. Induction Electric Log. The Induction Electric Log is normally used when *Rmf* > *Rw*.

Dual Induction Log

The second-generation induction log is called the dual induction and was introduced in the mid-1960s. This log (Figure 3.8) consists of a deep-reading induction device, which attempts to measure *Rt*, and a medium-reading induction device which measures *Ri*. The deep-reading measurement is similar to the induction curve from an induction electric log. The dual induction log also has a third resistivity curve, a shallow-reading, focused, laterolog-type measurement that is similar in depth of investigation to the short normal. The shallow-reading laterolog may be either a laterolog-8 (LL8) or a spherically focused log (SFL). The dual induction log is useful in formations that are deeply invaded by mud filtrate. Because of deep invasion, the deep reading induction may not accurately measure the true resistivity of the formation (*Rt*).

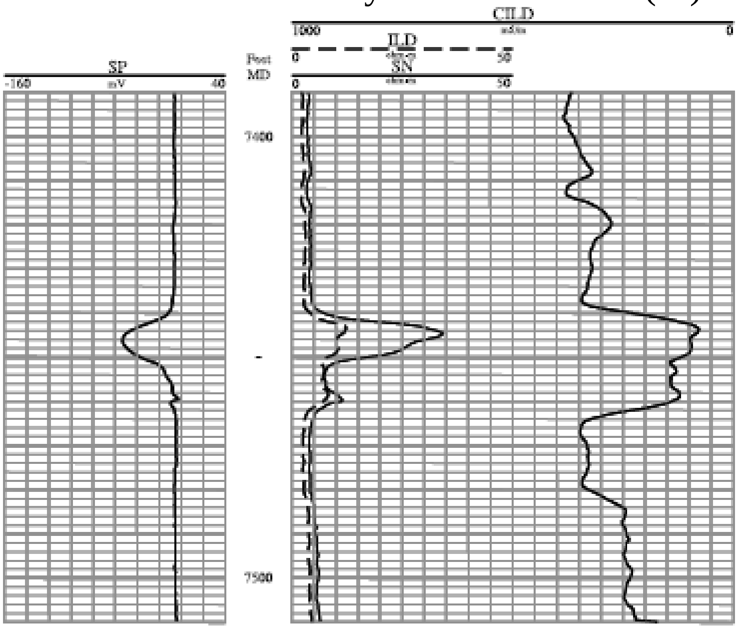

Figure 3.8. Example of a dual induction log.

Resistivity values obtained from the three curves on a dual induction log are used to correct deep resistivity to true resistivity (*Rt*) from a *tornado chart* (Figure 3.9). This tornado chart can also help determine the diameter of invasion (*di*) and the ratio of *Rxo*/*Rt.*

The three resistivity curves on the dual induction log are usually recorded on a four-cycle logarithmic scale ranging from 0.2 to 2000 ohm/m (Figure 3.8) and correspond to tracks 2 and 3 on the induction electric log. Usually, a spontaneous potential or a gamma ray curve is placed in track1.

The deep induction log does not always record an accurate value for deep resistivity in thin, resistive zones (where $Rt > 100$ ohm-m). Therefore, an alternate method to determine true resistivity (*Rt*) should be used. The technique is called *Rt minimum* (*Rt min*) and is calculated by the following formula:

$$Rt\ min = Ri \times Rw / Rmf \qquad 3.2$$

where:

Rt min = true resistivity (also called *Rt minimum*)

Rmf = resistivity of mud filtrate at formation temperature
Rw = resistivity of formation water at formation temperature
Ri = resistivity tool measuring in the invaded zone, usually laterolog-8 or spherically focused log

The rule for applying *Rt min* is to determine *Rt* from both the dual induction log tornado chart (Figure 3.9) and from the *Rt min* formula, and use whichever value of *Rt* is the greater. In addition to the Rt min method for determining *Rt* in thin resistive zones, correction curves or forward modeling algorithms are available to correct the deep induction log resistivity to *Rt*.

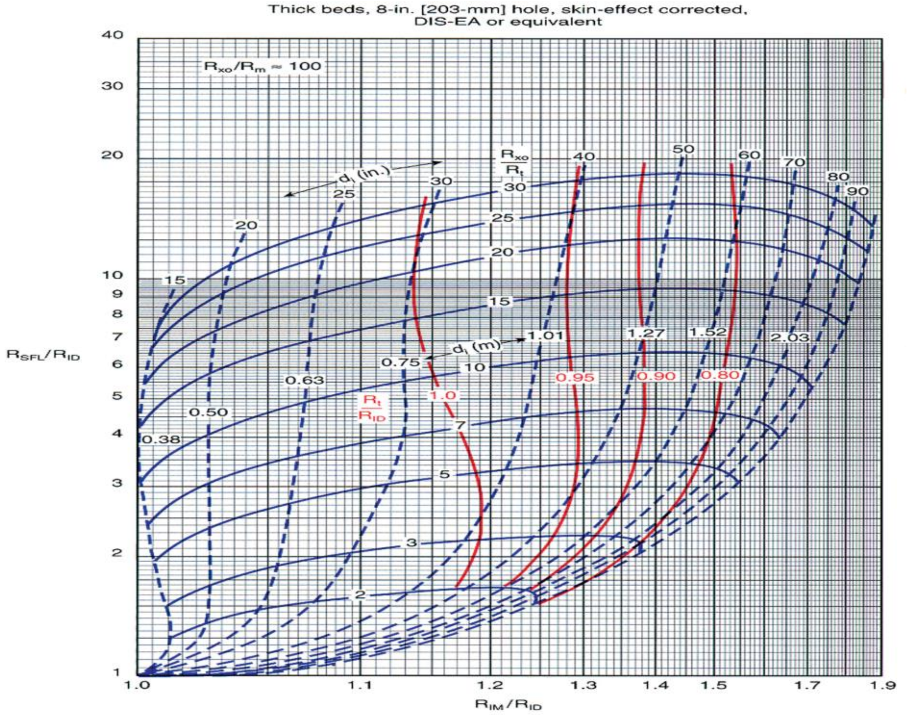

Figure 3.9. Dual Introduction-SFL tornado chart used for correcting *RILD* values to *Rt*, true formation resistivity.

Flushed Zone Resistivity Logs

At the same time that resistivity tools were being designed to interrogate the undisturbed region of the formation, another class of tools, based on the same physical principles, was being designed expressly to interrogate the region very close to the borehole. This region is usually flushed of original formation fluids by the drilling mud. By knowing the resistivity of the flushing fluid (the resistivity of the mud filtrate, *Rmf*) and making some assumptions about the fluid saturation of the flushed zone, formation porosities and saturations could be better estimated.

These ***microresistivity*** devices are either unfocused electrode or focused electrode (laterolog) devices. Because of their very shallow depths of investigation (on the order of a few inches), the electrodes are mounted on pads that are pressed against the borehole wall. Figure 3.11 is a schematic of two such tools. The tool must make good contact with the borehole wall for a valid measurement, and a thick mud cake or a rough hole adversely affects the measurement.

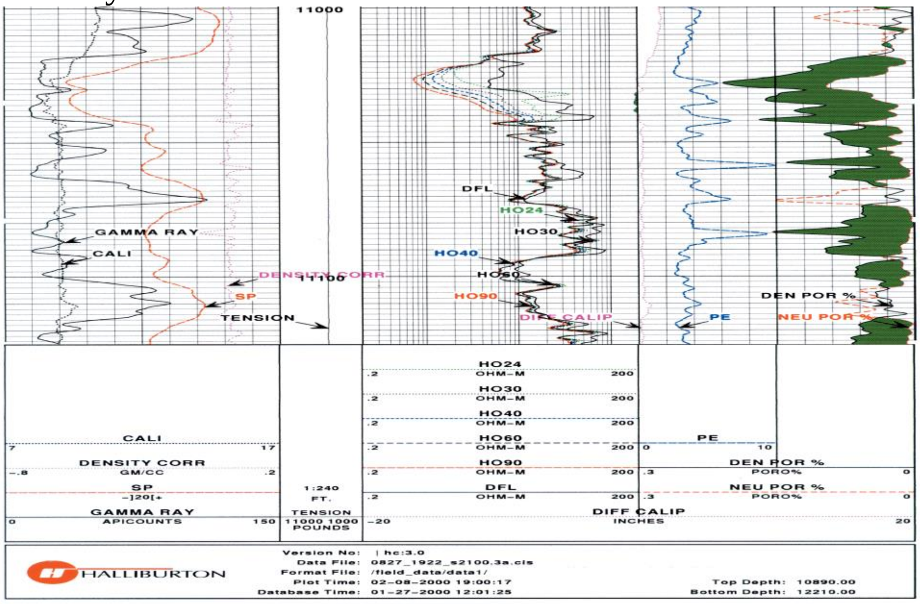

Figure 3.10. Example of an array induction log.

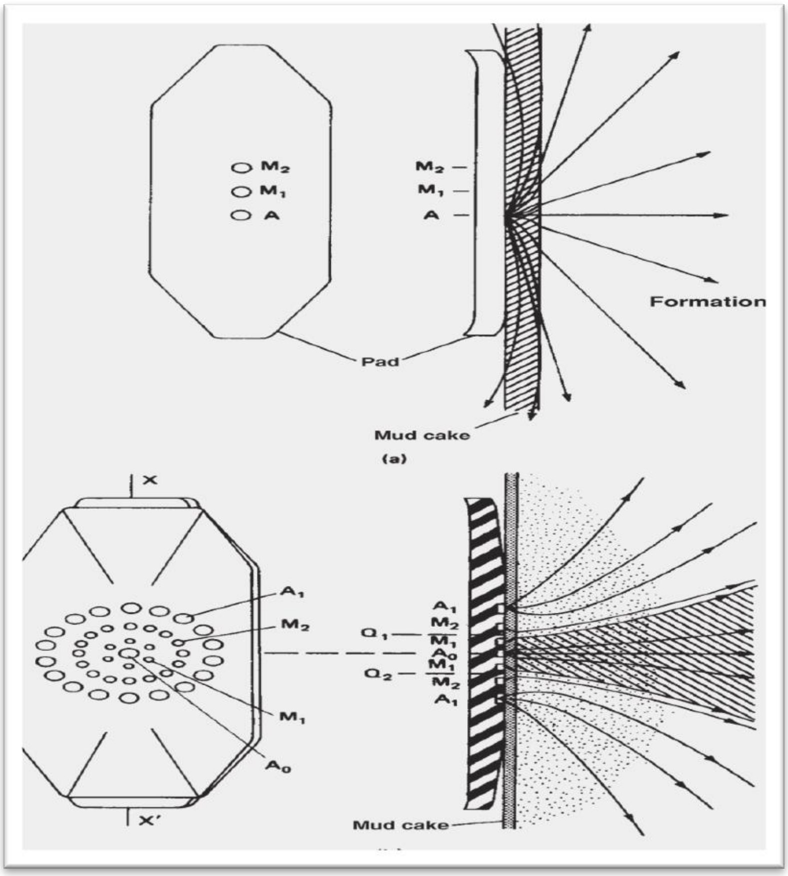

Figure 3.11. Microresistivity tools

Microlog (ML)

The microlog (Figure 3.12) is a pad-type resistivity device that primarily detects mudcake. The pad is in contact with the borehole and consists of three electrodes spaced one inch apart.

Two resistivity measurements are made; the micronormal (*R2*) and the microinverse (*R1x1*). The micronormal device investigates three to four inches into the formation (measuring *Rxo*) and the microinverse investigates approximately one to two inches into the formation and is significantly affected by the resistivity of the mudcake (*Rmc*).

The detection of mudcake by the microlog indicates that invasion has occurred and the formation is permeable. On the microlog, permeable zones show up when the micronormal curve reads higher resistivity than the microinverse curve (*R2* > *R1x1*). This is known as *positive separation* (Figure 3.12).

The microlog tool also has a caliper that measures the borehole diameter. A decrease in borehole diameter can indicate mudcake and support the interpretation of permeability. In Figure 3.12, mudcake is indicated where the caliper shows a borehole size smaller than the diameter of the drill bit used to drill the hole. Shale zones are indicated by no separation or *negative separation* (i.e., micronormal < microinverse).

Positive separation can only occur when *Rmc* > *Rm* > *Rmf*. If there is any doubt, check the log heading for resistivity values of the mudcake, drilling mud, and mud filtrate.

Remember that even though the resistivity of the mud filtrate (*Rmf*) is less than the resistivity of the mudcake (*Rmc*), the micronormal curve reads a higher resistivity in a permeable zone than the shallower reading microinverse curve. This is because the filtrate has invaded the formation, and part of the resistivity measured by the micronormal curve is read from the rock matrix, whereas the microinverse curve measures only the mudcake (*Rmc*) which has a lower resistivity than rock.

However, in enlarged boreholes, a shale zone can exhibit minor, positive separation. To detect zones of erroneous positive separation, a microcaliper log is run in track 1 (Figure 3.12), so that borehole irregularities are detected. Nonporous and impermeable zones have high resistivity values on both the micronormal and microinverse curves (Figure 3.12). Hilchie (1978) states that resistivities of approximately ten times the resistivity of the drilling mud (*Rm*) at formation temperature indicate an impermeable zone.

The microlog does not work well in saltwater muds (where *Rmf* ~ *Rw*) or gypsum-based muds because the mudcake may not be strong enough to keep the pad away from the formation. Where the pad is in contact with the formation, positive separation cannot occur.
Because the microlog is so greatly affected by borehole conditions, it generally does not provide a good estimate of flushed-zone resistivity (*Rxo*).

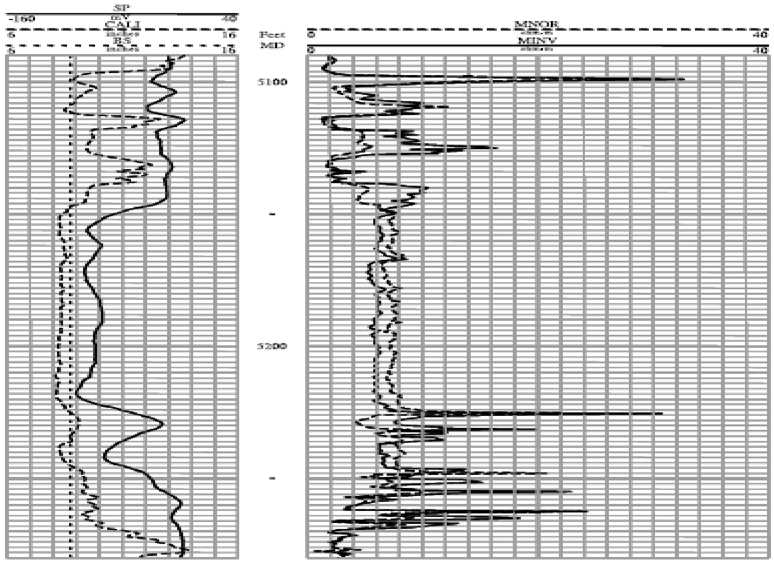

Figure 3.12. Microlog with SP log and caliper.

Other Microresistivity Logs

The microlaterolog (MLL), the proximity log (PL) (Figure 3.13), and the microspherically focused log (MSFL) are pad-type, focused, electrode logs designed to measure the resistivity in the flushed zone (*Rxo*). Unlike the microlog, all produce a single resistivity curve, but because of their focused design they are more accurate predictors of flushed-zone resistivity.

Because the microlaterolog is strongly influenced by mudcake thicknesses greater than 1/4 inch , the microlaterolog should be run only with saltwater muds. The proximity log, which is more strongly focused than the microlaterolog, is designed to investigate deeper so it can be used with freshwater muds where mudcake is thicker, but with low invasion it might measure beyond the invaded zones.

The microspherically focused log, introduced by Schlumberger in 1972, and other tools of similar design seem to generally be very good at determining flushed-zone resistivity (*Rxo*).

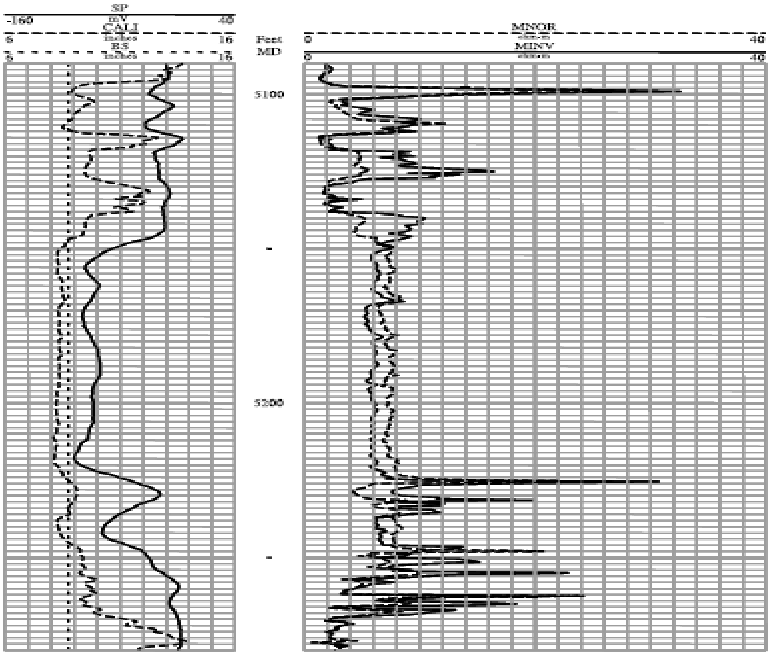

Figure 3.13. Example of a proximity log with a microlog and caliper.

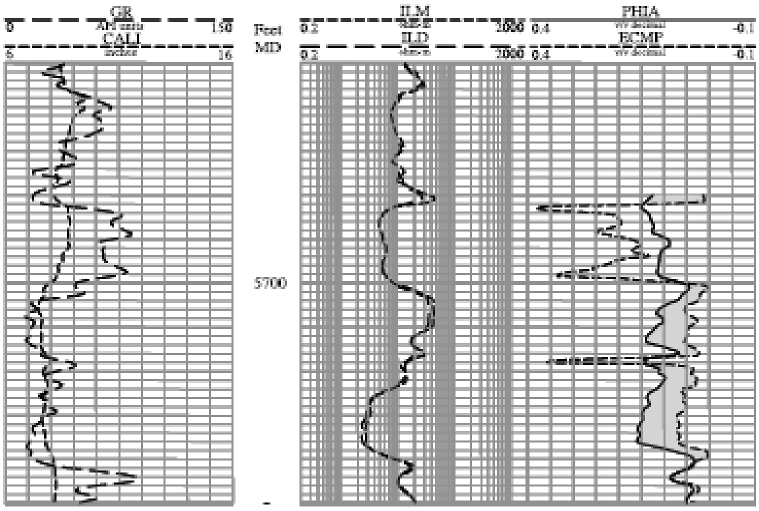

Figure 3.14. Computer-generated neutron-density porosity (PHIA) and EPT porosity (ECMP) log.