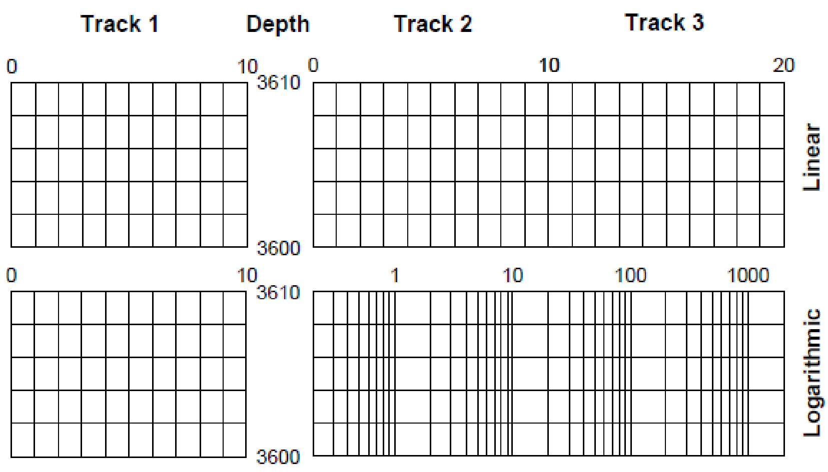
RESISTIVITY LOGS

- Resistivity is ability to impede the flow of an electric current through a substance.
- **Resistivity logs** measure the ability of rocks to conduct electrical current and are scaled in units of ohm- meters.
- Resistivity is the inverse of conductivity. The ability to conduct electric current depends upon:
  - The **Volume** of water.
  - The **Temperature** of the formation.
  - The **Salinity** of the formation
- Resistivity logs are electrical logs used to:
  - ✓ determine hydrocarbon-bearing versus water bearing zones.
  - ✓ indicate permeable zones.
  - ✓ determine water saturation.
- Typical formation resistivity are usually from 0.2 to 1000 ohm-m.
- Resistivity higher than 1000 ohm-m are uncommon in permeable formations but are observed in Evaporates impermeable formation(salt, anhydrites).
- Resistivity of soft formations i.e. shaly sands range from 0.5 Ω-m to about 50 Ω-m and 10Ω-m to 100 Ω-m for hard formations (carbonates).



- Because resistivity cannot be read correctly over the entire measurement range when displayed on a linear scale, all resistivity logs are presented on logarithmic scale, usually in 4 cycle across two log tracks. This allows the display of readings from 0.2 to 2000 ohm.m.

❖ Resistivity Log Tools Types

- In general, resistivity logs are classified into four groups;

A. **Conventional Electrical Surveys (ES)**

  - Short Normal devices 16"N
  - Long Normal devices 64"N
  - Lateral devices, (18'8")

B. Focusing Electrode Logs

  - Laterologs (LL)
    - ✓ Basic laterologs, (LL3 , LL7 , LL8)
    - ✓ Dual laterologs DLL (LLd + LLs)
  - Spherically Focussed Log SFL

C. Micro-Resistivity Logs

  - Microlog ML
  - Microlatero log MLL
  - Proximity Log PL
  - Micro Spherically Focussed Log MSFL

D. Induction logs

  - The Dual Induction Laterolog DIL (ILD + ILM).
  - The Induction Spherically Focussed Log ISF, combines; 6FF40, SFL and SP.

❖ Resistivity Log Tools Uses

- Measuring the resistivity of formations is complicated by the invasion of drilling fluids into permeable rocks. In wireline logging we make all measurement through the borehole. There are three main regions surrounding the wellbore:
  - ✓ The flushed zone.
  - ✓ The transition zone.
  - ✓ The undisturbed (un-invaded) zone.
- The purpose of all resistivity devices is to measure True Resistivity (R_t) or the resistivity of the flushed zone (R_{xo}).

	Flushed Zone	Transition Zone	Un-invaded Zone
Rock resistivity	R_{xo}	R_i	R_t
Water resistivity	R_{mf}	R_z	R_w
Water saturation	S_{xo}	S_{xi}	S_w

- The resistivity devices (tools) used in these regions are:
  - ✓ Deep Resistivity Tool….(measures Rt in un-invaded zone).
  - ✓ Medium/ Shallow Resistivity Tool.. (measures Ri, in transition zone).
  - ✓ Micro Resistivity Tool….{ measures Rxo in flushed zone}.

Tools	Flushed Zone R_{xo}	Transition(invaded) Zone R_i	Un-invaded Zone R_t
	0.084-0.5 ft	0.5 – 3 ft	+ 3 ft
Laterolog3 *LL3*			●
Laterolog shallow *LLS*		●	
Spherically Focussed Log SFL		●	
Laterolog7 *LL7*			●
Laterolog8 *LL8*		●	
Laterolog deep *LLD*			●
Microlog ML	●		
Microlaterolog MLL	●		
Proximity Log PL	●		
Micro Spherically Focussed Log MSFL	●		
Induction Log deep ILD			●
Induction Log medium ILM		●	
Induction Log 6FF40			●
Lateral 18'8"			●
Long Normal (64"N)			●
Short Normal (16"N)		●	

A) Conventional Electric Logs/ Electrical Survey Log (ES)

- ES logs were the first wireline logs, and are no longer used.
- These logs used 4-electrode system;
    - current electrode A and current electrode B to create currents.
    - potential electrode M and potential electrode N to measure potential difference.
- A surface current electrode (B) send an electrical current to an electrode (A) on the tool through formation. The potential difference is measured between potential electrode (M) on the tool and potential electrode (N) at the surface.
- The surface detector will measure the formation's resistance to the current.

  {The current(***I)*** flowing in a conductor is proportional to the *electrical potential difference* ***(ΔE)*** }.
- The potential difference is proportional to the resistivity of formation**.**

$$\Delta E \propto R$$

- Many factors affect the reading of a conventional electric log.
    - ✓ Hole diameter (d_h).
    - ✓ Diameter of invaded zone (di).
    - ✓ Mud resistivity Rm.
    - ✓ Bed thickness.
- Since the material surrounding the electrode system is not uniform, the logs read only an <u>*apparent resistivity (Ra)*</u>.

- There must be conductive fluid in the borehole for the tool to function properly. So this tool does not work in oil or air-filled holes.

- The conventional **electrical survey (ES)** usually consisted of;
  - ✓ Short Normal devices 16"N {16"N = 16 inch normal}
  - ✓ Long Normal devices 64"N { 64"N = 64-inch normal}
  - ✓ Lateral devices, (18'8") {18'8" = 18 foot 8 inch lateral}

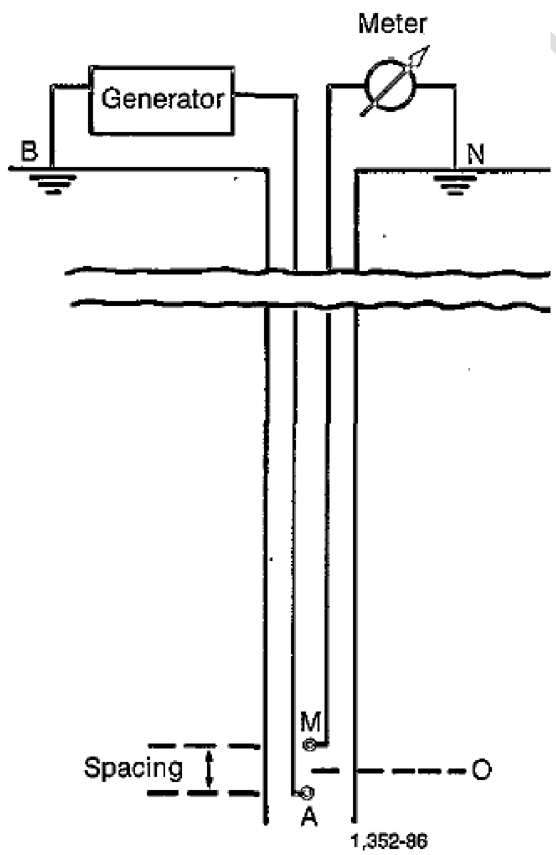
A. **Normal Device**

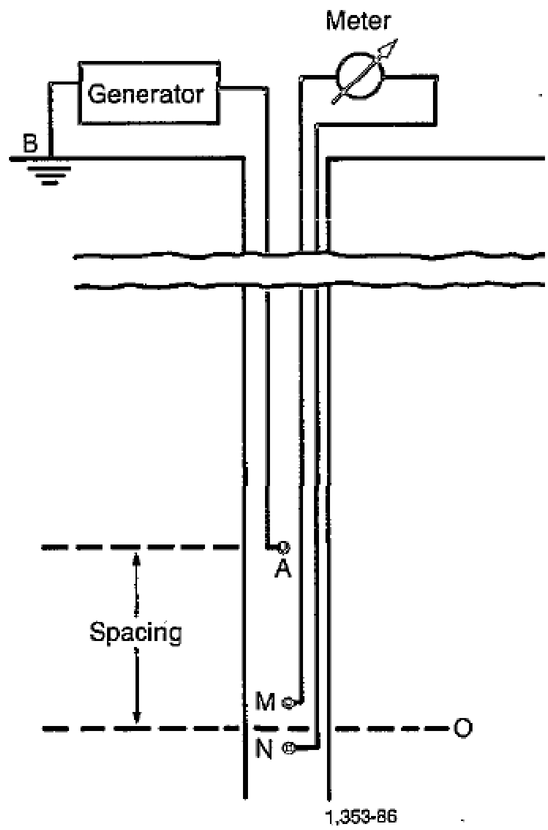
- The electrode spacing of a short normal is usually 16 inches (16"N) and the long normal is 64 inches (64"N).

B. Lateral Device

Here the electrode spacing is defined as the distance between the electrode (A) and the midpoint between the two potential electrodes (O).

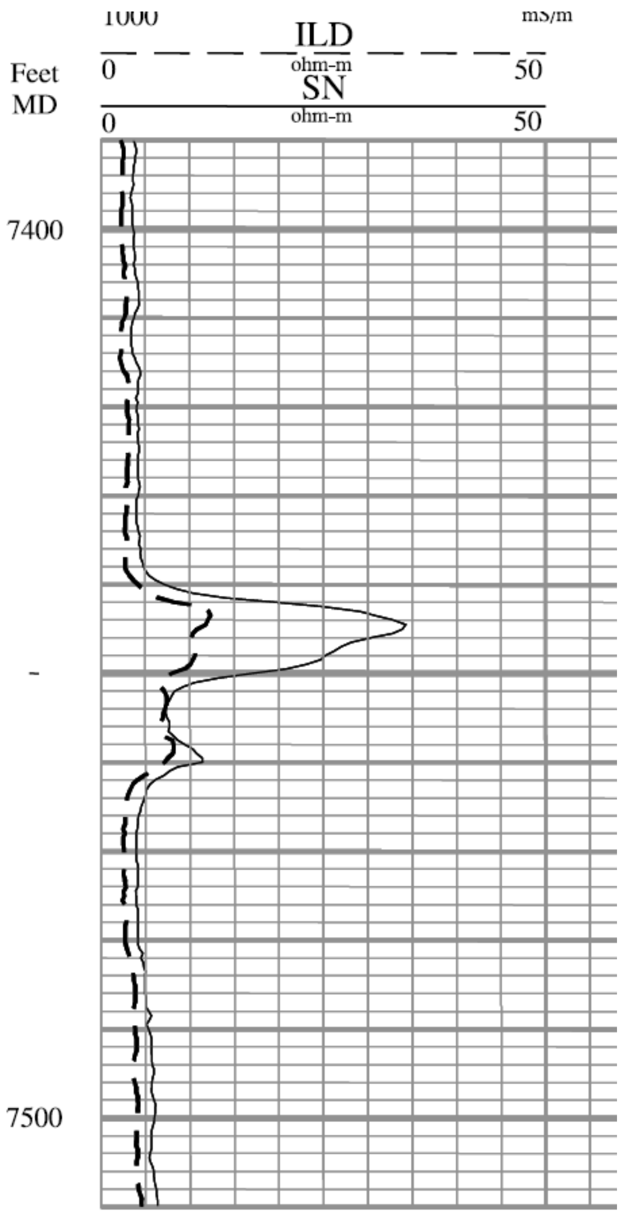
- Generally, the large the spacing, the deeper the device investigates into the formation and measurement . Thus, in the ES resistivity logs, the lateral log has the deepest investigation from the normal log.
- ES logs are rarely used today since these logs has largely been replaced by Induction- Electrical logs





❖ Conventional Electric Log Presentation

The log is presented starting with the third track. The scale is **linear** and often goes from 0 to 10 and then 0-100. The units for resistivity is ohm-meter (Ω - m). Typically speaking, the deep dashed line, if present, is the deepest reading curve. Sometimes there is an expanded scale for the short normal. This is used to help pick bed boundaries.

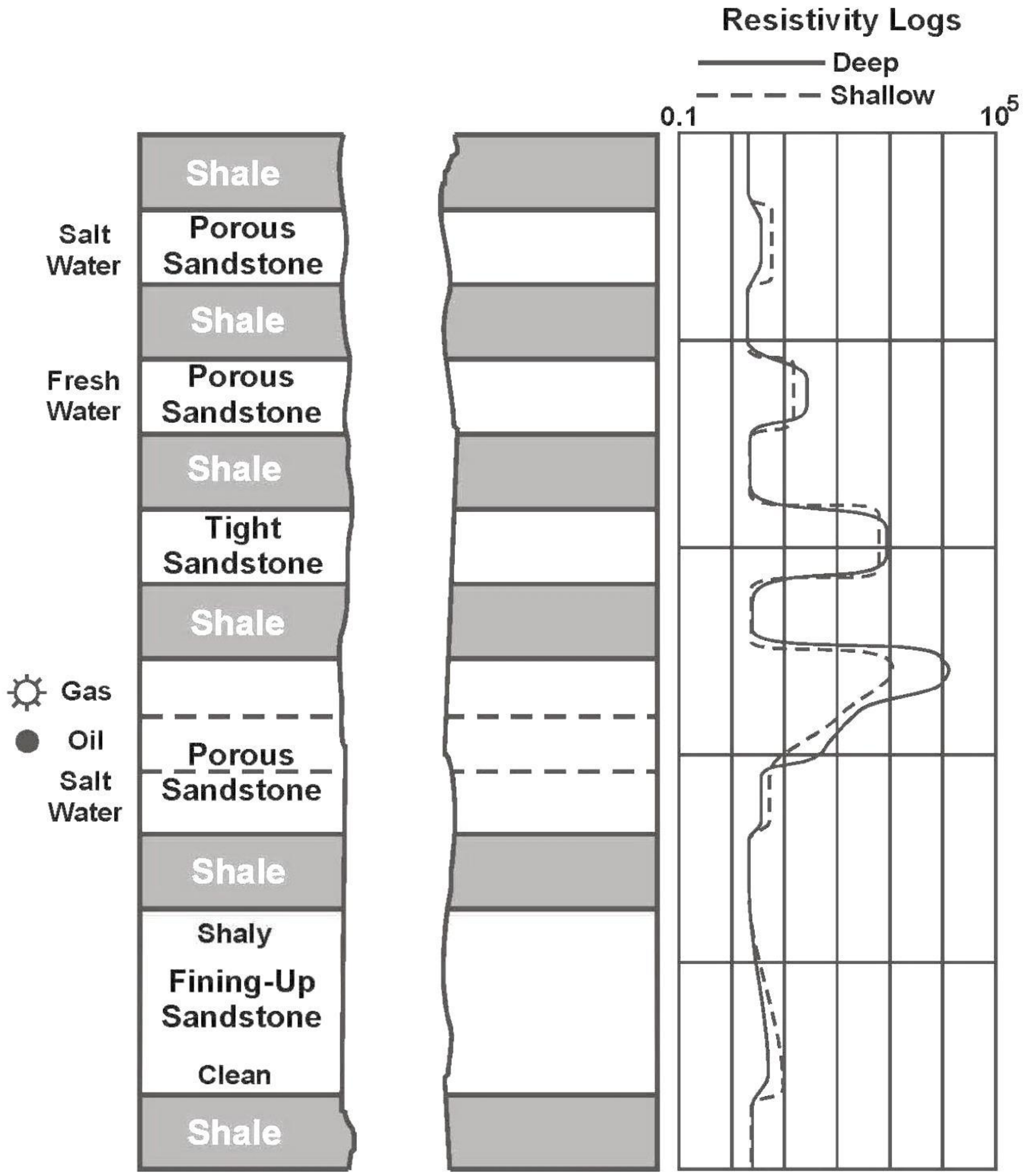


Typical Resistivity

- 0.5Ω-m to 1000 Ω-m for typical formations.
- Soft formations i.e. shaly sands range from 0.5 Ω-m to about 50 Ω-m
- 10Ω-m to 100 Ω-m for hard formations (carbonates)
- Evaporites (salt, anhydrites) may have several thousand Ω-m
- Formation water will range from 0.015 Ω-m (very salty brines)
- Several Ω-m, fresh water reservoirs
- Sea water has a resistivity of 0.35 Ω-m at 75 degrees Fahrenheit

❖ Typical Responses of an Resistivity Tool

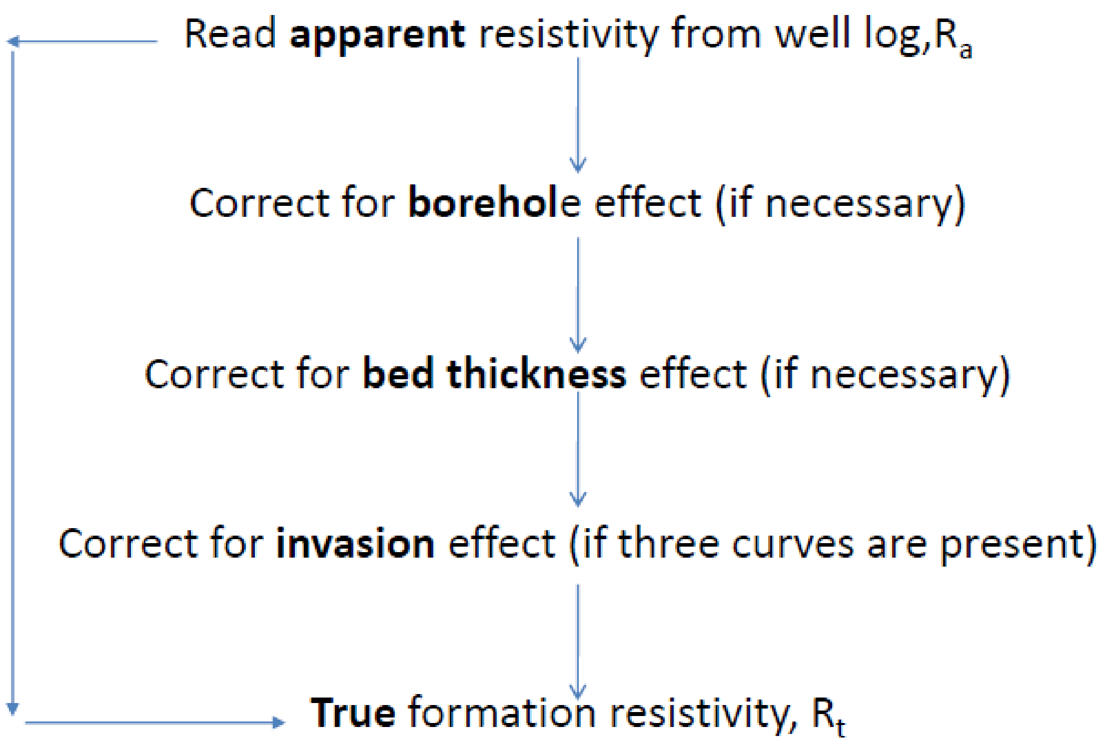
Figure below shows the typical response of an electrical tool in a sand/shale sequence. Note the lower resistivity in shales, which is due to the presence of bound water in clays that undergo surface conduction. The degree to which the sandstones have higher resistivities depends upon (i) their porosity, (ii) their pore geometries, (iii) the resistivity of the formation water, (iv) the water, oil and gas saturations (oil and gas are taken to have infinite resistivity).



Note: Assume Deep Resistivity Reads Rt If;

1) Rt/Rm is greater than about 10.
2) Rt/Rs is greater than about 10.
3) Hole diameter (dh) is greater than about 12 inches.
4) The bed is thinner than about 15 ft.
5) Invasion diameter (di) is greater than about 40 inches

- dh – hole diameter
- di – diameter of invaded zone (inner boundary; flushed zone)
- R_m – resistivity of the drilling mud
- R_s – Resistivity of surrounding bed
- R_t – resistivity of un-invaded zone (true resistivity)



B. Focused Resistivity Logs / Laterologs

- To overcome the limitations of the original electrode logs **(Electrical Survey Log**) the *laterolog* device was developed.
- Laterologs are electrode logs designed to measure formation resistivity in boreholes filled with saltwater muds (where *Rmf* ~ *Rw*) and resistivity > 200 Ω.m.
- Focused resistivity devices use "guard electrodes" to force current deeper into the formation (but they can have deep, medium and shallow depths of investigation).
- Focused devices were developed due to problems with;
  - i) conductive muds.
  - ii) large Rt (true resistivities of the formation)
  - iii) deep invasion of borehole fluid
  - iv) thin beds (but may be used in moderately thick beds).
- In focused devices Ra (apparent Resistivity) is within 10% of the Rt (true Resistivity).
- **Utility and Limitations of Focused Resistivity Devices**
  - Good Points - best in resistive, thin, interbedded sequences with a low borehole fluid resistivity (Rm) (therefore focused resistivity devices are well suited for salt-mud, carbonate logging programs.
  - Limitations - affected by invasion of borehole fluid and tough to run properly in the field.
- Invasion can influence the laterolog, 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.

- 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*.

EXAMPLE of a laterolog and microlatero log.

- ✓ This log illustrates the curves and provides an example for picking log values. These logs are used when *Rmf* ~ *Rw*.
- ✓ **Track 1**: The log track on the far left contains gamma ray (GR) and caliper (CALI) curves, shown as solid and dashed lines respectively. Gamma ray logs commonly accompany laterologs. This one is recorded in units that predate API units, microgram-Radium equivalents per ton (µgRa-eq/ton).
- ✓ **Track 2**: This displays the laterolog (LL3), which measures the deep resistivity or true resistivity (*Rt*) of the formation. Note that the scale increases linearly from left to right in increments of 5 ohm-m from 0 to 50. At the depth of **3948 ft**, the laterolog value reads **21 ohm-m**.
- ✓ **Track 3**: The microlaterolog (MLL) measures the resistivity of the flushed zone (*Rxo*). Note that the scale starts with zero at the left edge of track 3. The scale ranges from 0 to 50 ohm-m in increments of 5 ohm-m. At the depth of **3948 ft** the microlaterolog reads 8 ohm-m.

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

$$R_t = 1.67\ (R_{LL}) - 0.67\ (R_{xo})\quad R_t = 1.67\ (21) - 0.67\ (8)$$

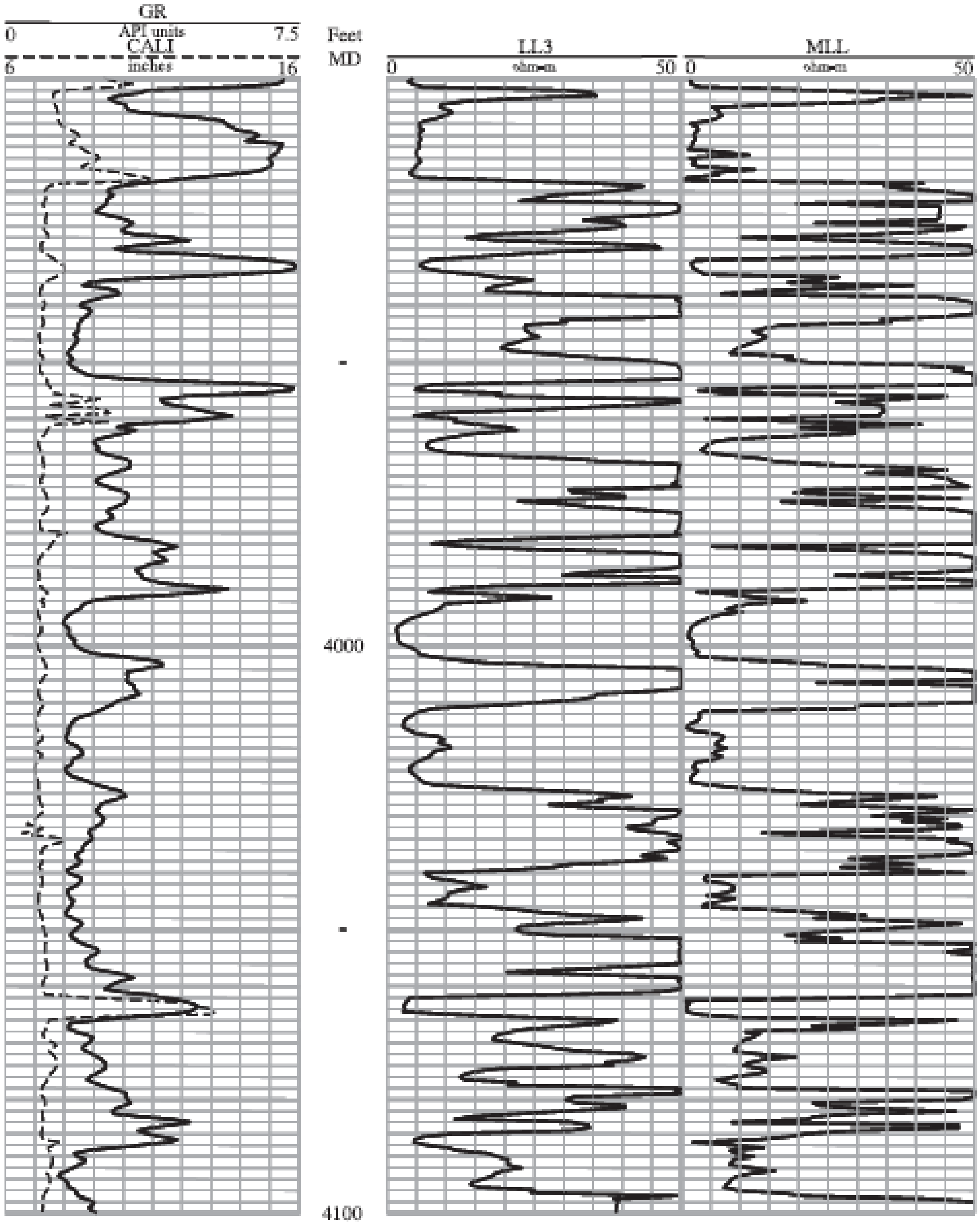
$$R_t = 29.7 \text{ ohm-m}$$

where:

R_t = resistivity of the uninvaded zone

R_{LL} = laterolog resistivity (21 ohm-m at 3948 ft)

R_{xo} = microlaterolog resistivity (8 ohm-m at 3948 ft)


GR
0 API units 7.5
CALI
6 inches 16
Feet
MD
LL3
0 ohm-m 50
MLL
0 ohm-m 50
4000
4100

❖ Dual Laterolog

- The dual laterolog 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 track 1.
- The third resistivity measurement is the microspherically focused resistivity (*RMSFL*), a 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.

EXAMPLE of dual laterolog with microspherically focused log.

- These logs are used when *Rmf* ~ *Rw* and invasion is deep.
- The resistivity scale in tracks 2 and 3 is a four-cycle logarithmic scale ranging from 0.2 to 2000 ohm-m; the values increase from left to right.

Deep laterolog resistivity:

- The LLD (long-dashed line) measures the deep resistivity of the formation, If invasion is not deep and the bed of interest is thick **(>2 ft),** the deep reading commonly approximates true formation resistivity (*Rt*).
- At the depth of **9324 ft**, the deep laterolog resistivity (*RLLD*) is **16 ohm-m**.

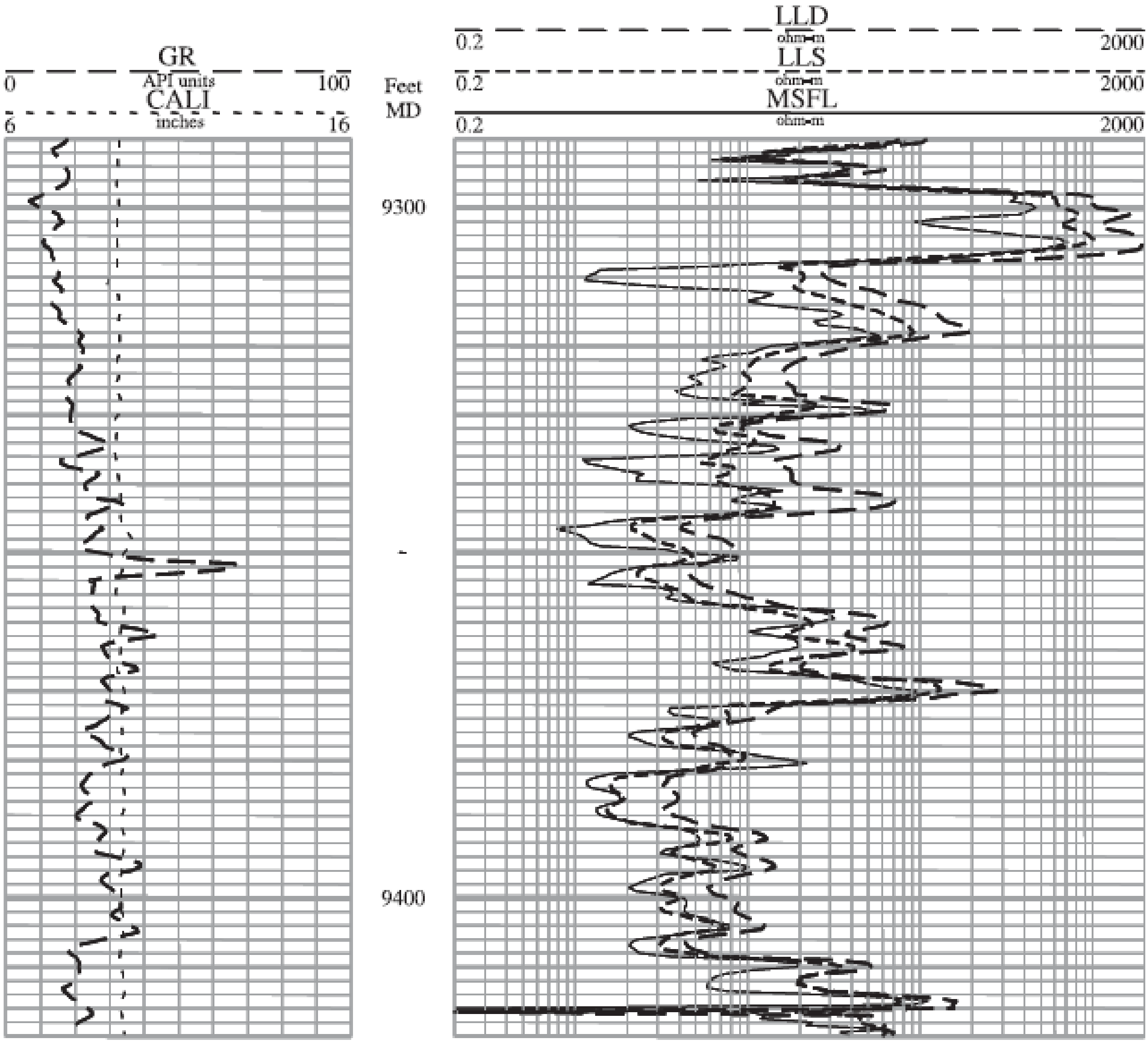
Shallow laterolog resistivity:

- The LLS (short-dashed line) measures the shallow resistivity of the formation or the resistivity of the invaded zone (*Ri*).
- At **9324 ft**, the shallow laterolog resistivity (*RLLS*) is **10 ohm-m**.

Microspherically focused log (MSFL) resistivity:

- The MSFL (solid line) measures the resistivity of the flushed zone (*Rxo*).
- At **9324 ft**, the MSFL resistivity (*RMSFL*) is **4.5 ohm-m**.

- 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*.
- A ***tornado chart*** (**CHART Rint-9b**) is used to graphically correct *RLLD* to *Rt* and to determine the diameter of invasion (*di*) and the *Rxo*.



- The following ratios are needed for work on the **tornado chart** (Figure 6), and the values represented are picked from the log as shown above:

LLD/MSFL = *RLLD*/*RMSFL* = 16/4.5 = 3.6

LLD/LLS = *RLLD*/*RLSS* = 16/10 = 1.6

- **EXAMPLE;** Dual laterolog-*Rxo* tornado chart for correcting deep resistivity to *Rt*. Log values in this exercise are picked from the example dual laterolog-MSFL in previous example.

- **TORNADO CHART Rint-9b (Fig.6)** consists of from the following parameters**;**

✓ RLLD/Rxo vertical axis of chart

✓ RLLD/RLLS horizontal axis of chart.

✓ Rt/RLLD ratio: The scale for this value is represented by the solid red lines. The scale values are in red and range from 1.1 to 1.8.

✓ di: The diameter of invasion around the borehole is picked from the chart by following the dashed, blue lines to the scales at the top of the chart. The scale from 20 to 120 gives di in inches, and the scale from 0.50 to 3.04 gives di in meters.

✓ *Rt*/*Rxo* ratio: The scale for this ratio value is represented by the heavy, blue, solid lines. The scale values are in black, increase from bottom to top, and range from 1.5 to 100.

- Given:

LLD = *RLLD* = 16.0 ohm-m

LLS = *RLLS* = 10.0 ohm-m

MSFL = *RMSFL* = 4.5 ohm-m

RLLD/*RMSFL* = *RLLD*/*Rxo* = 3.6

RLLD/*RLLS* = 1.6

Procedure:

1. Plot *RLLD*/*Rxo* (= 3.6) on the vertical axis and *RLLD*/*RLLS* (= 1.6) on the horizontal axis. Plot the intersection of these values on the tornado chart, and determine *Rt/RLLD*, Ri and *Rt*/*Rxo* values.
   - ***Rt/RLLD** value falls between the scale values 1.3 and 1.4, so we assign a value of **1.32**.*
   - **di** value falls between the scale values of 40 and 50 inches, so we assign a value of **43 inches**.
   - ***Rt/Rxo*** value falls between the scale values 3 and 5 (much closer to 5), so we assign a value of **4.8**.
2. Finally, corrected values for true resistivity of the formation (*Rt*) and resistivity of the flushed zone (*Rxo*) are determined using these ratios.

$$(Rt/RLLD) \times (RLLD)_{log} = Rt\ (corrected)$$

1.32 x 16.0 ohm-m = 21.1 ohm-m = *Rt*, true formation resistivity.

$$Rt\ (corrected)/(Rt/Rxo)_{chart} = Rxo$$

21.1 ohm-m/4.8 = 4.4 ohm-m = *Rxo*, resistivity of flushed zone.

When the deep laterolog log reading is corrected for invasion via the tornado chart, the resulting estimate of true formation resistivity is always greater than the deep laterolog reading.

C. **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;

$$C = \frac{1000}{R}$$

where:

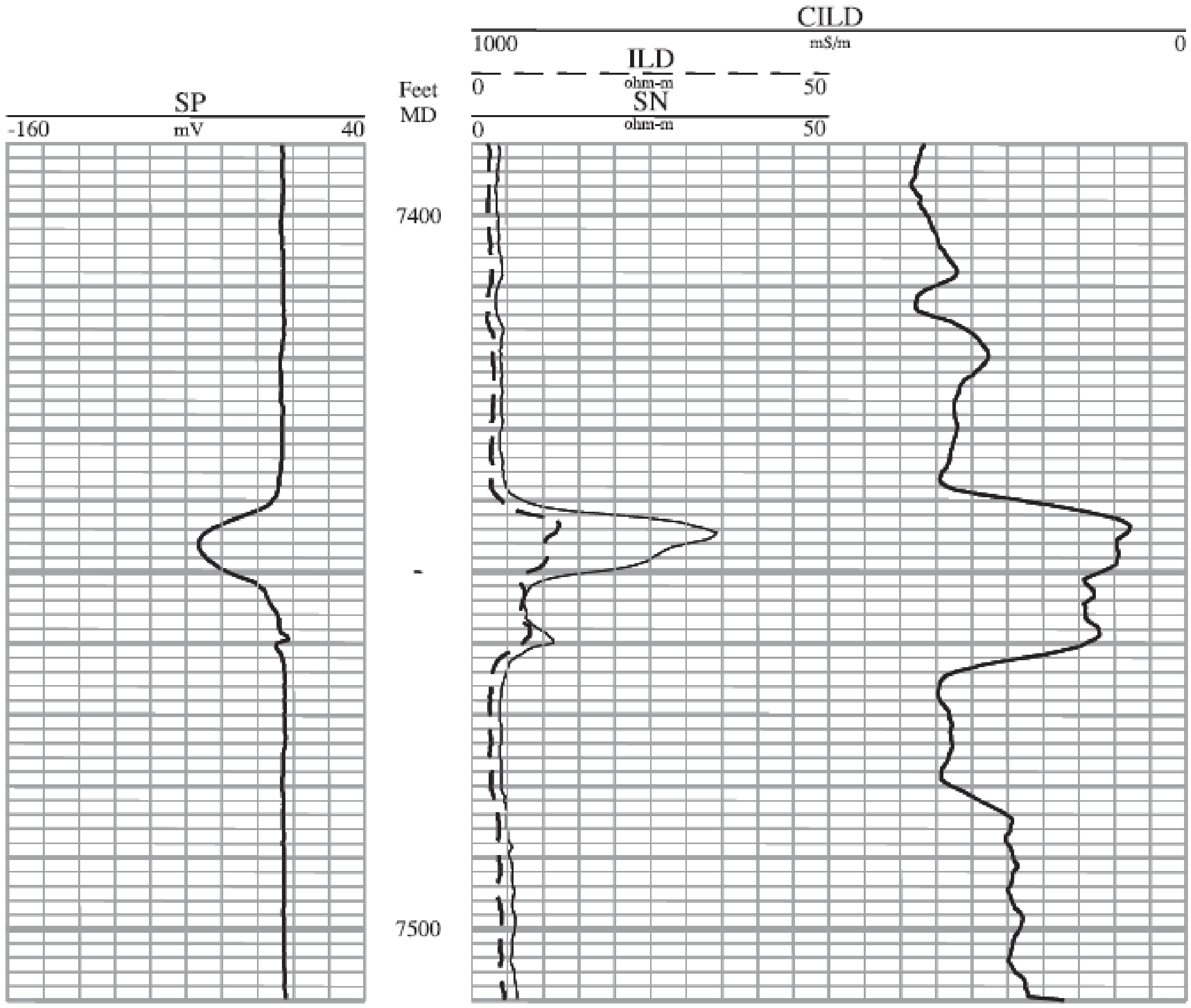
C = conductivity in milli mho/m (= milli Siemens)

R = resistivity in ohm-m

- By design, induction logs work well in wells containing non-conducting fluids in the borehole (such as air and oil-based mud) or in freshwater muds (where $Rmf > 3\ Rw$).
- They are most affected by salty muds. Induction logs work best in low to moderate formation resistivities.
- The uncertainty in the measurement increases at high formation resistivities, making induction logs less desirable than the laterolog for highly resistive formations (resistivities greater than about 100 ohm-m).
- Like the laterolog, the first version of the induction log, the induction electric log, had a single deep induction measurement (*RIL*). It, however, was combined with the earlier (electrode-type) short-normal measurement (*RSN*) to 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.

EXAMPLE of Induction Electric Log.

- The Induction Electric Log is normally used when *Rmf* > *Rw*.
- **Track 1:** The log track on the far left contains the spontaneous potential (SP) log. The SP scale increases from -160 mV on the left to +40 mV log on the right and has 10 increments of 20 mV. The value at the depth of 7446 ft is about -50 mV. The value of the SP in is measured from the shale baseline (i.e., the SP value in the shales where the SP value is zero), and the deflection from the baseline is negative.
- **Track 2:** The middle log track contains two resistivity curves. The short normal (SN, also called the 16-inch normal) represented by the solid line, measures the invaded zone resistivity (*Ri*). The induction log (ILD), represented by the dashed line, measures the uninvaded zone resistivity (*Rt*). At 7446 ft, the short normal has a value of 30 ohm-m. The induction value at the same depth is 10 ohm-m.
- **Tracks 2 and 3**: These tracks contain the conductivity curve (CILD) which is the basic induction-log measurement. The conductivity curve can be used to convert values to resistivity. In this way, track 2 resistivity values can be checked for accuracy, or values can be derived more accurately at low resistivities. For example, to convert track 3 values to resistivity the procedure is as follows:
  - ✓ The values on the conductivity scale increase from right to left, from 0 to 1000 are marked in 50 mmhos/meter increments. At a depth of 7446 ft, the curve in track 3 is nearly 2 increments from the right and shows a value of 97 mmhos/meter. Because resistivity equals 1000/conductivity, the resistivity = 1000/97 = 10.3 ohm-m. When the logs are displayed on linear scales, as in this example, resistivity can determined more accurately from conversion of the conductivity curve than from reading the resistivity curve itself.



❖ Utility and Limitations

- induction logs are used most effectively in holes filled with moderately- to non-conductive drilling muds, or in empty holes

- operates to advantage when the borehole fluid is an insulator (oil or gas), but also works well when the borehole contains conductive mud (if the mud is not too salty, the formations are not too resistive, and the borehole diameter is not too large)

- vertical focusing is good (down to approximately 5 feet thick)

- **Problems** - for resistive thin beds (less than 5 ft thick), an induction log may not be reliable for determining True Resistivity

- Induction logs are conductivity devices, and perform best in higher conductivities (lower resistivities); therefore if the resistivities of the bed are greater than 100 ohm-meters the use of induction logs is questionable.

❖ ***Dual Induction Log***

- The second-generation induction log is called the dual induction. This log consists of a deep-reading induction device, which attempts to measure *Rt*, and a medium-reading induction device which measures *Ri*.
- The dual induction log also has a third resistivity curve, a shallow-reading, focused, laterolog-type measurement which 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*).
- 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 (Rint-2b*** *and* ***Rint-2c)*** **(Fig.7-8)**. This tornado chart can also help determine the diameter of invasion (*di*) and the ratio of *Rxo*/*Rt*.

- **EXAMPLE** of a dual induction log. The dual induction log is normally used when *Rmf* is much greater than *Rw* and also where invasion is deep.

Track 1 in this log suite contains gamma ray and SP curves. The resistivity scale in tracks 2 and 3 is a logarithmic scale from 0.2 to 2000 ohm-m, increasing from left to right. Note the following logs.

Deep induction log resistivity:

The dashed ILD curve measures the deep resistivity of the formation, or close to true resistivity (*Rt*). At the depth of **13591 ft**, the deep resistivity (ILD) is **70 ohm-m**.

Medium induction log resistivity:

The dotted ILM curve measures the medium resistivity of the formation or resistivity of the invaded zone (*Ri*). At **13,591 ft**, the medium resistivity (ILM) is **105 ohm-m**.

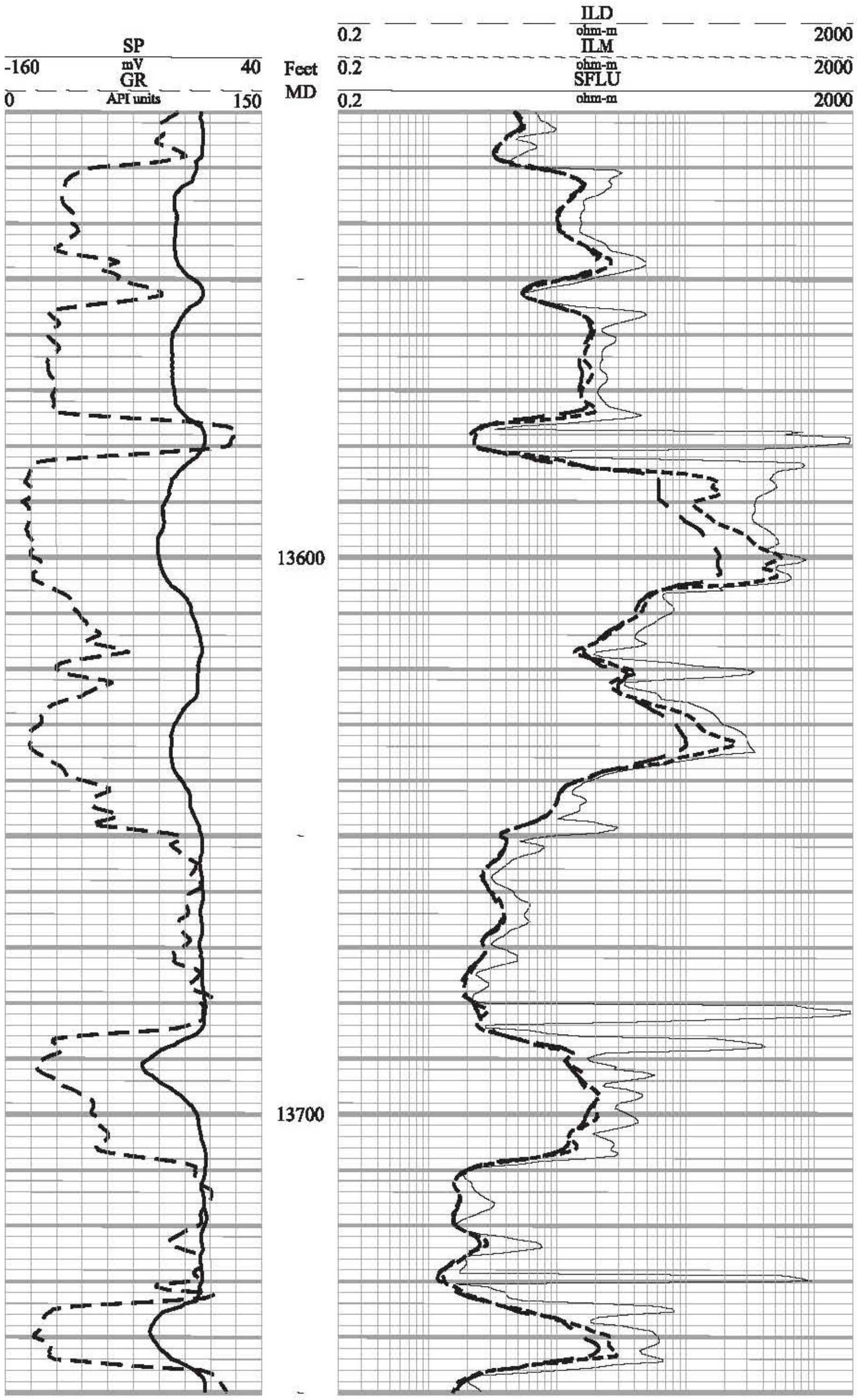
Spherically focused log resistivity:

The solid SFLU curve measures the shallow resistivity of the formation or resistivity of the flushed zone (*Rxo*). At **13,591 ft**, the resistivity of the flushed zone is **320 ohm-m**.

The following ratios are needed for work on the tornado chart, and the values are picked from the example log:

SFLU/ILD = *RSFLU*/*RILD* = 320 ohm-m/70 ohm-m = 4.6

ILM/ILD = *RILM*/*RILD* = 105 ohm-m/70 ohm-m = 1.5


SP
-160 mV 40
GR
0 API units 150
Feet
MD
13600
13700
ILD
0.2 ohm-m 2000
ILM
0.2 ohm-m 2000
SFLU
0.2 ohm-m 2000

EXAMPLE; Dual Introduction-SFL tornado chart used for correcting *RILD* values to *Rt*, true formation resistivity. Log values in this exercise are picked from the example dual laterolog-MSFL in previous example.

- **TORNADO CHART Rint-2c** consists of the following from the parameters**;**

✓ **RSFL/RID ratio** vertical axis of chart

✓ **RIM/RID ratio** horizontal axis of chart.

✓ **Rt/RID ratio**: The scale for this value is represented by the solid red lines. The scale values are in red and range from 1.0 to 0.8, decreasing from left to right.

✓ di: The diameter of invasion around the borehole is picked from the chart by following the dashed, blue lines to the appropriate scale. Note that the *di* scale is in inches across the top of the tornado and is in meters through the middle part of the tornado chart; both scales increase from left to right.

✓ ***Rt/Rxo ratio***: This is the ratio of resistivity of the flushed zone (*Rxo*) over the true resistivity of the formation (corrected *Rt*). This ratio, derived from the chart, is used in later calculations. The scale is represented by the heavy, blue, solid lines, and the scale values are shown as whole numbers midway across the lines.

- Given:

ILD = *RILD* = 70 ohm-m

ILM = *RILM* = 105 ohm-m

SFLU = *RSFL* = 320 ohm-m

RSFL/*RILD* = 4.6

RILM/*RILD* = 1.5

Procedure:

1. Plot the *RSFL*/*RILD* ratio (= 4.6) on the vertical axis) and the *RILM*/*RILD* ratio (=1.5) on the horizontal axis. Plot the intersection of these values on the tornado chart, and pick the following values:
   - ✓ *Rt*/*RILD* value; falls on the 0.80 line.
   - ✓ *di*: the value is between the 60-inch and 70-inch lines, and *di* is about 68 inches.
   - ✓ Rxo/Rt: the plotted sample falls on the line with a value of 7.0.
2. Finally, with values taken from the chart, calculate corrected values for *Rt* and *Rxo*.

(*Rt/RILD*)$_{chart}$ X *(RILD)$_{log}$* = *Rt* (corrected)

0.80 X 70 = 56 ohm-m (*Rt* corrected, or true formation resistivity)

(*Rxo/Rt*)$_{chart}$ X *Rt* (corrected) = *Rxo* (corrected)

7 X 56 = 392 ohm-m (*Rxo*, corrected resistivity of the flushed zone).

When the deep induction log reading is corrected for invasion via the tornado chart, the resulting estimate of true formation resistivity is always less than the deep induction reading.

- 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:

$$Rt_{min} = R_i x \frac{R_w}{R_{mf}}$$

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 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 (Schlumberger) or forward modeling algorithms are available to correct the deep induction log resistivity to *Rt*.

❖ MICRORESISTIVITY LOGS

- These tools are designed to;
  - ✓ define permeable beds by detecting presence of a mud cake.
  - ✓ obtain the resistivity of the flushed zone (Rxo).
- Rxo (Resistivity of "Flushed Zone") is used to;
  - ✓ Calculate residual oil saturation left after flushing the flushed zone

$$\text{residual oil saturation} = \text{Sor} = \{\varphi * (1 - \text{Sxo})\}$$

$$S_{xo}^{n} = \frac{F\,R_{mf}}{R_{xo}} = \frac{a\,R_{mf}}{\varphi^{m}\,R_{xo}}$$

F = formation resistivity factor (no units).

m = cementation factor (no units).

a = tortuosity factor (no units).

n = saturation exponent (no units).

R_{mf} – resistivity of mud filtrate. Ω m

S_{xo} – water saturation of flushed zone. Ω m

R_{xo} – resistivity of flushed zone. Ω m (from Micro resistivity log)

✓ Calculate formation porosity.

$$\frac{Rxo}{Rmf} = F = \frac{a}{\varphi^{m}}$$

Note: The following conditions must be exists when calculating porosity from Rxo tools;

☒ Rxo/Rmc > 15

☒ Mud cake thickness > 0.5 inch

$$mud\ cake\ thickness = \frac{bit\ size - hole\ size}{2}$$

☒ Invasion diameter > 4 inch

✓ Recognize (by comparing Rxo with Rt) which zones have sufficient permeability to be invaded by mud filtrate

✓ Calculate *movable hydrocarbon saturation*.

$$\text{movable hydrocarbon saturation} = \text{Shr} = \{\varphi * (\text{Sxo} - \text{Sw})\}$$

◈ *Microlog (ML)*

- The microlog is a micro resistivity device that detects mudcake.
- Two resistivity measurements are made; the micro-normal (R_2) and the micro-inverse (R_{1x1}).
- The micro-normal device investigates 3 to 4 inches into the formation (measuring *Rxo*) and the micro-inverse investigates approximately 1 to 2 inches into the formation and is significantly affected by the resistivity of the mud cake (R_{mc}).
- The detection of mud cake by the microlog indicates that invasion has occurred and the formation is permeable.

Case 1: permeable zones / *hydrocarbon zone*

micro-normal curve R_2 > micro-inverse curve R_{1x1}

positive separation (occur when $R_{mc} > R_m > R_{mf}$)

Case 2: Shale zones

micro-normal curve R_2 < micro-inverse curve R_{1x1}

negative separation

micro-normal curve R_2 ≈ micro-inverse curve R_{1x1}

no separation

Case 3: permeable zones / *water zone*

micro-normal curve R_2 < micro-inverse curve R_{1x1}

negative separation

Case 4: permeable zones / *no invasion*

micro-normal curve R_2 ≈ micro-inverse curve R_{1x1}

no separation

note: Resistivity values of the mud cake Rmc , drilling mud Rm, and mud filtrate Rmf are obtained from log heading information .

- The microlog tool also has a caliper log that measures the borehole diameter.
- A decrease in borehole diameter can indicate mud cake and support the interpretation of permeability.

Caliper log curve < Bit Size (BS)

borehole size smaller than the diameter of the drill bit used to drill the hole.

Indicated mud cake (permeable formation)

- **Remember that** even though the resistivity of the mud filtrate (*Rmf*) is less than the resistivity of the mud cake (*Rmc*), the micronormal curve reads a higher resistivity in a permeable zone than the shallower reading micro-inverse curve.??? why
- 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.
- In enlarged boreholes, a shale zone can exhibit as positive separation. To detect zones of erroneous positive separation, a microcaliper log is run in track 1, so that borehole irregularities are detected.
- Nonporous and impermeable zones have high resistivity values on both the micronormal and microinverse curves.
- Hilchie (1978) states that resistivities of approximately ten times the resistivity of the drilling mud (R_m) at formation temperature indicate an impermeable zone.

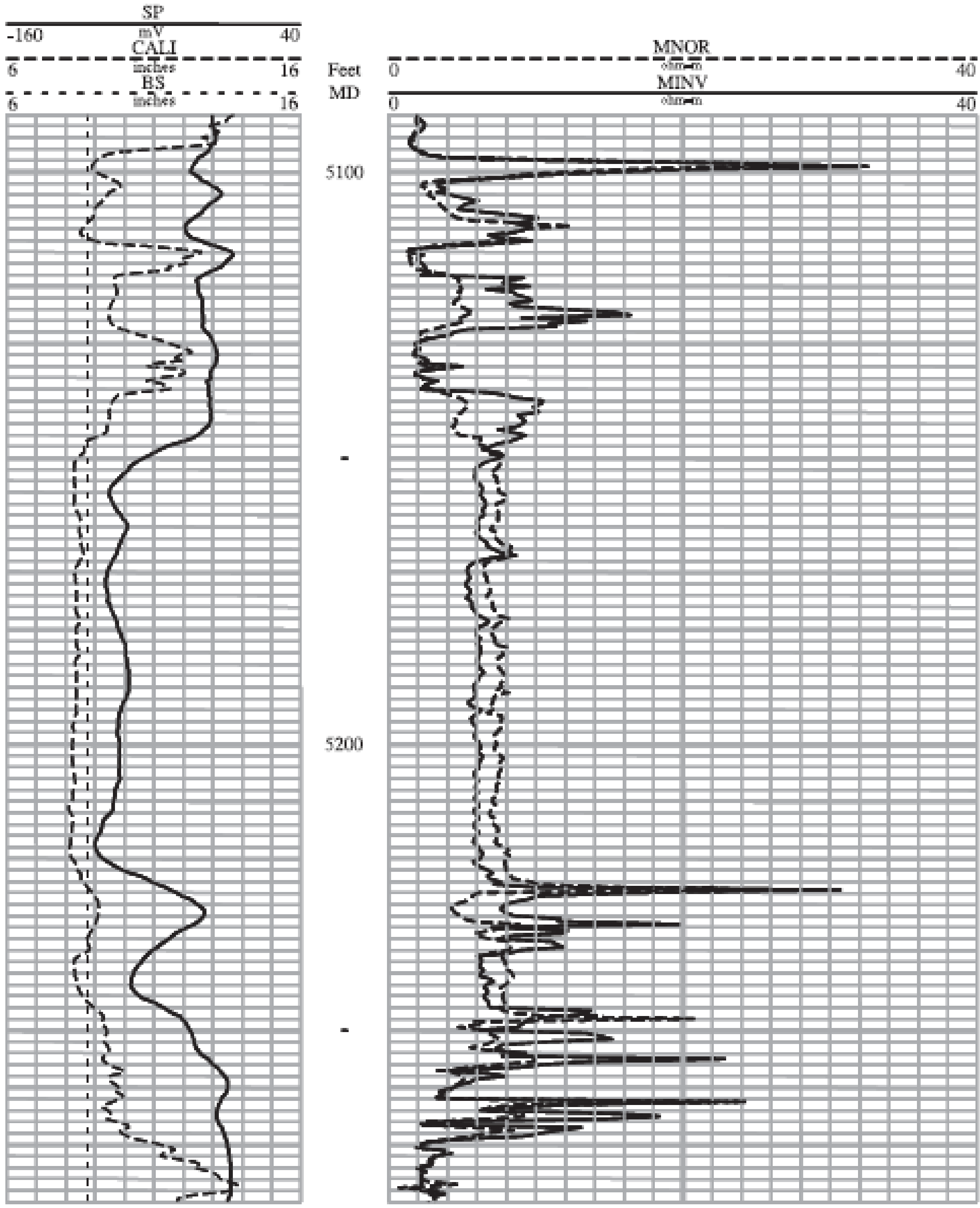
EXAMPLE; Microlog with SP log and caliper.

- This log demonstrates permeability two ways: by *positive separation* between the micronormal and microinverse logs (MNOR > MINV) in tracks 2 and 3 and by decreased borehole diameter due to mudcake, detected by the caliper log in track 1.
- Examine the interval from 5147 to 5246 ft.
- **Track 1**: The caliper measurement is shown by the long-dashed line in track 1. The short-dashed line shows the bit size (BS), which is 8.75 inches. Just above 5147 ft, the caliper shows a borehole diameter of approximately 11 inches, but the hole size decreases to about 8.5 inches from 5147 to 5224 ft, indicating the presence of mud cake and a permeable zone. Mudcake is also present at 5237 to 5245 ft. Note how the SP corresponds with these two mudcake intervals.
- **Tracks 2 and 3**: The micro-normal log (MNOR, shown by the dashed line) measures the resistivity of the flushed zone, and the micro-inverse (MINV, shown by the solid line) measures the resistivity of any mud cake that might be present.
- Mud cake and permeability are indicated by *positive separation*, which occurs where micro-normal log shows a higher resistivity than the micro-inverse log.

  Note the **positive separation** from **5150 to 5224 ft** and from **5237 to 5246 ft**.
- The separation is about 0.5 ohm-m.
- The fluid in the flushed zone is a combination of mud filtrate, formation water, and possibly residual hydrocarbons. The fluid in the mud cake is just mud filtrate, which has a higher resistivity than the fluids in the flushed zone. Based on this alone, we might expect the micro-inverse to show a higher resistivity than the micro-normal over intervals of mud cake.
- Remember, however, that rock generally has a higher resistivity than the fluids in it or around it. The rock in the flushed zone is compacted

and cemented, but the rock part of the mud cake (cuttings and mud solids) is not compacted or cemented.

- Mud cake contains much more fluid and much less rock than an equal volume of the formation in the flushed zone. The higher concentration of fluid in the mud cake gives the mud cake a lower resistivity than the flushed zone.

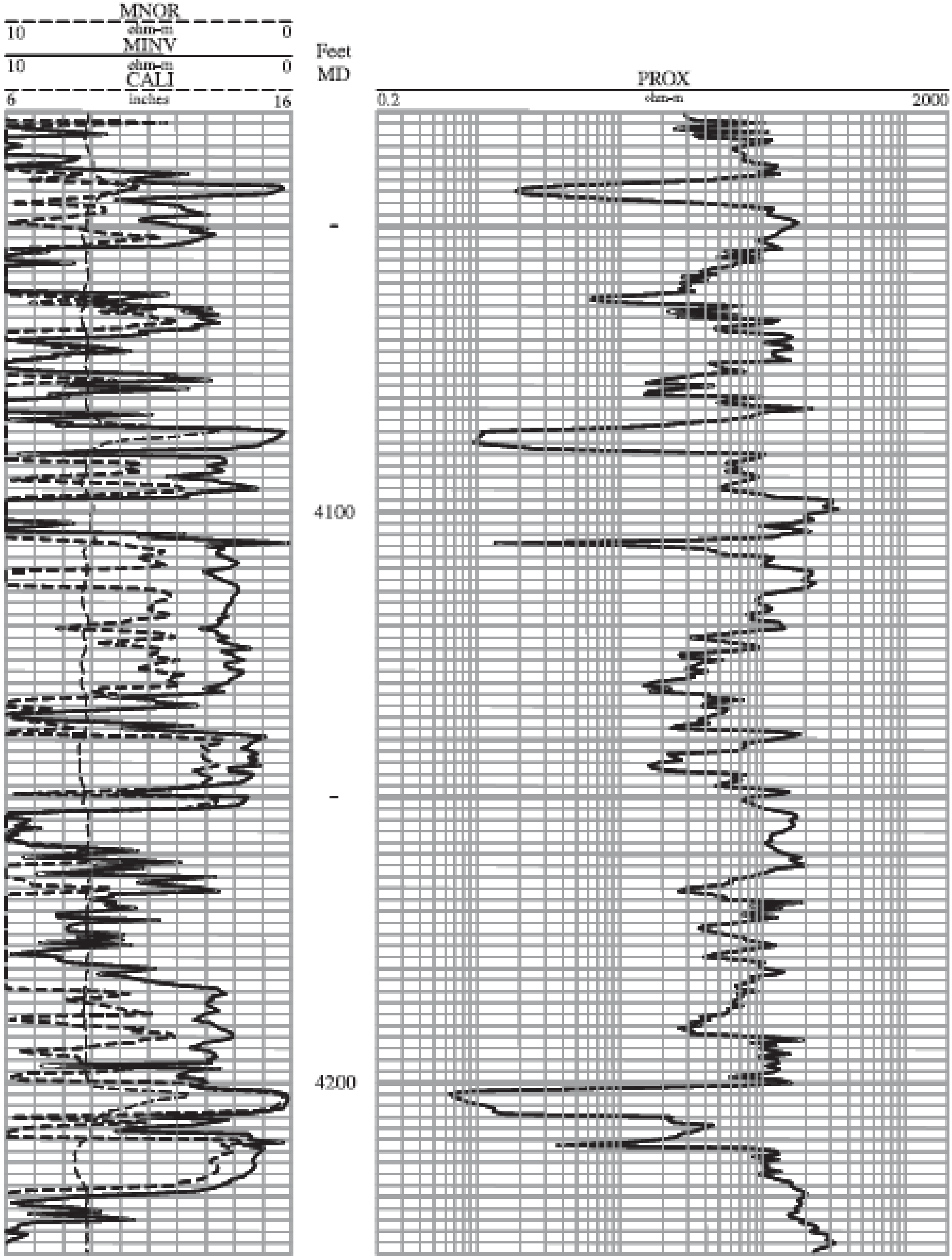


❖ Other Microresistivity Logs

- The microlaterolog (MLL), the proximity log (PL), and the microspherically focused log (MSFL) are 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 mud cake 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 mud cake 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*).

- **Example** of a proximity log with a microlog and caliper.
- The proximity log is designed to read the resistivity of the flushed zone (*Rxo*). This particular log package includes a proximity log to read Rxo, a microlog to determine permeable zones, and a caliper to determine the size of the borehole.
- Examine the log curves at 4144 ft.
- **Track 1**: Track 1 shows both a microlog and a caliper log. On this example, the resistivity values for micronormal and microinverse increase from right to left, so that the positive separation shows the same pattern with respect to the depth track as it does when displayed in track 2. At the depth of 4144 ft, the micronormal (MNOR, shown by the dashed line) shows higher resistivity than microinverse (MINV, shown by the solid line). The microinverse has a value of about

1.5 ohm-m, and the micronormal has a value of about 3.0 ohm-m. The microlog indicates a permeable zone.



- The caliper log indicates a borehole slightly less than 9 inches.
- **Tracks 2 and 3**: The proximity log measures resistivity of the flushed zone (*Rxo*). In this example the scale is logarithmic, reading from left to right. At 4144 ft, we read a proximity curve value (*Rxo*) of 18 ohm-m.