Basics of
Geophysical Well Logs:
Lithology & Resistivity

Spontaneous Potential

When the well bore is filled by a water based mud and in presence of an alternation of permeable and impermeable layers, due to electrochemical phenomena, electrical currents are spontaneously generated at the interfaces between mud and formation and between impermeable shales and reservoir sands.

The **SP** log is the measurement of the potential of a down hole electrode with respect to a surface reference electrode which is proportional to the intensity of the currents generated.

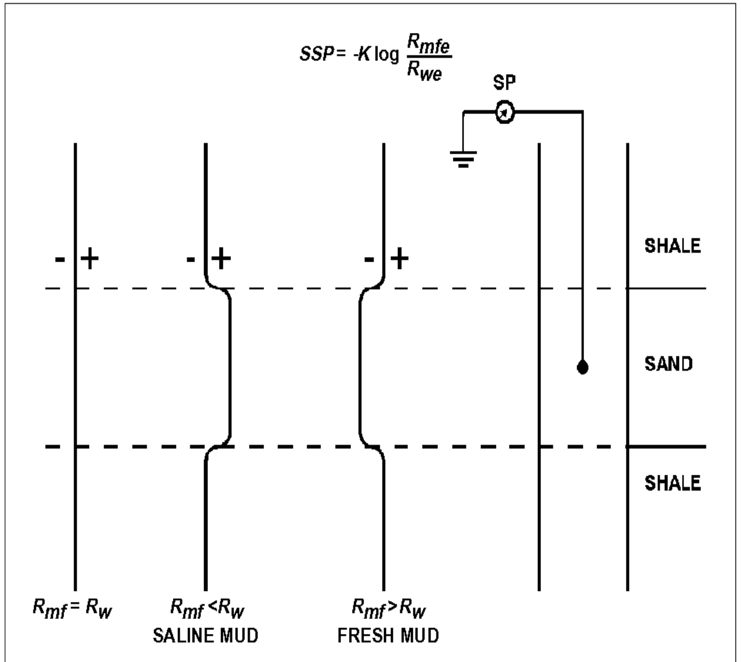


Figure B10: The SP Deflection and its R_{mf}-R_w Dependency

Spontaneous Potential

The SP log is recorded on the left hand track (track #1) and is used:

1. To detect permeable beds
2. To detect boundaries of permeable beds
3. To determine the formation water resistivity (Rw)
4. To determine the volume of shale (Vsh) in permeable beds

Determination of Rw from SP log

The Static Spontaneous Potential (SSP) is the **maximum** SP that a thick, shale-free, porous and permeable formation can have for a given ratio between R_{mf}/R_w:

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

(where $K=(.133xT_f)+60$

Or can be determined by a chart

IMPORTANT: THE SP LOG IS USED ONLY WITH CONDUCTIVE (SALT-WATER BASED) DRILLING MUDS

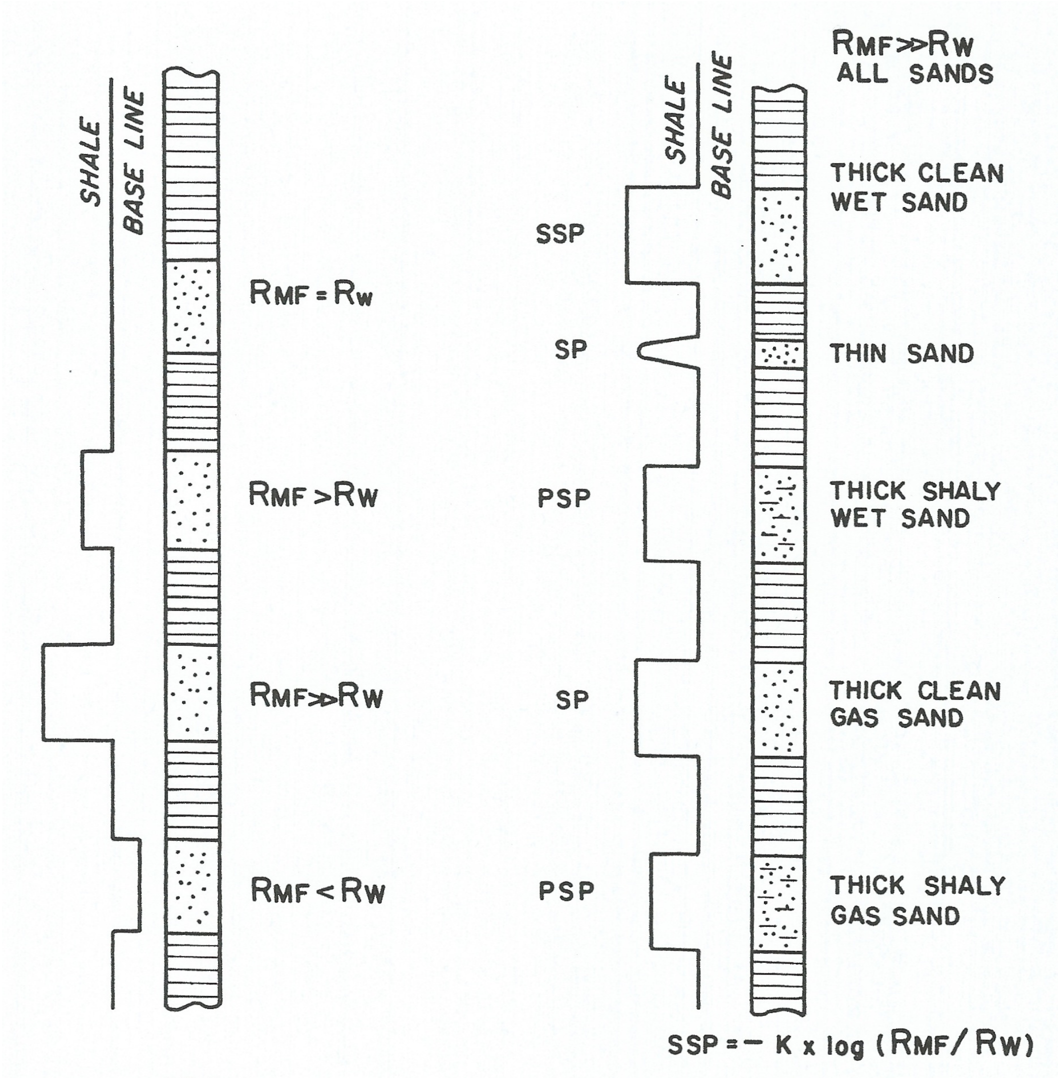
Shale baseline

The SP response of shales is relatively constant and follows a straight line called a shale baseline.

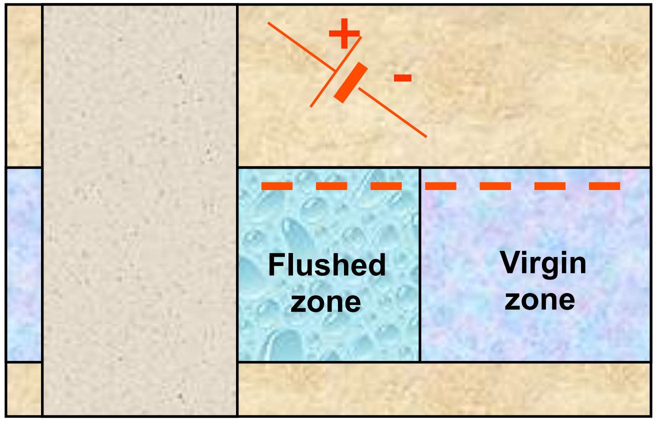
SP deflections are measured from this shale baseline.

- PERMEABLE ZONES ARE LOCATED WHERE THERE IS A SP DEFLECTION FROM THE SHALE BASELINE
- THE MAGNITUDE OF SP DEFLECTION IS **DUE TO THE DIFFERENCE BETWEEN R_{MF} AND R_W AND NOT TO THE AMOUNT OF PERMEABILITY**

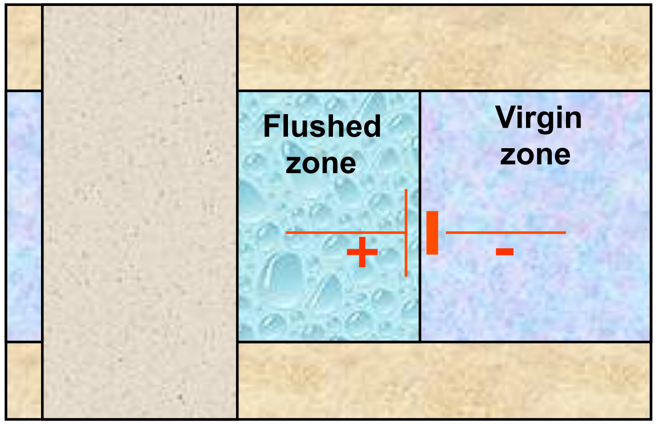
Examples of SP deflection from the Shale baseline



Spontaneous Potential



Membrane potential

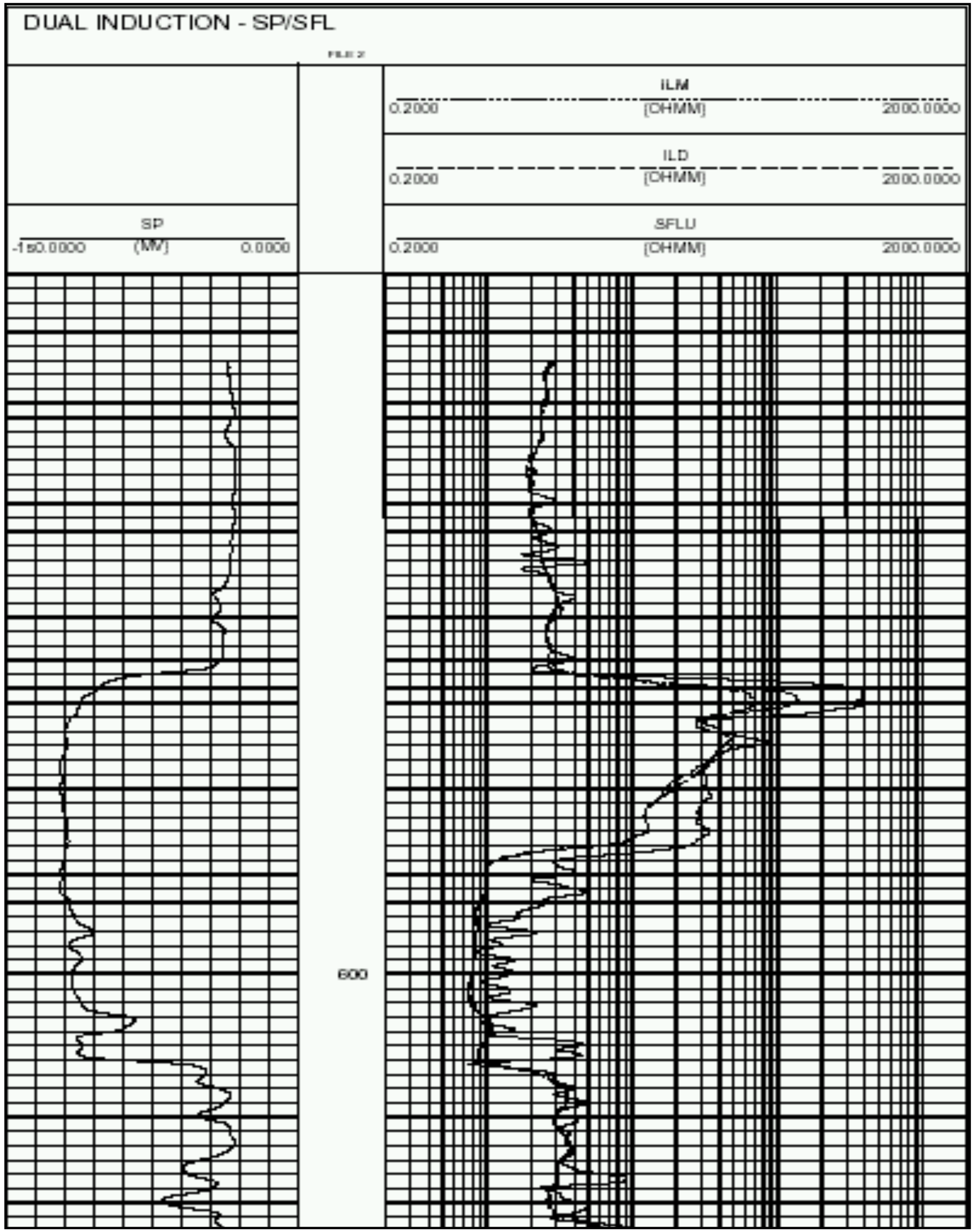


Liquid-junction potential

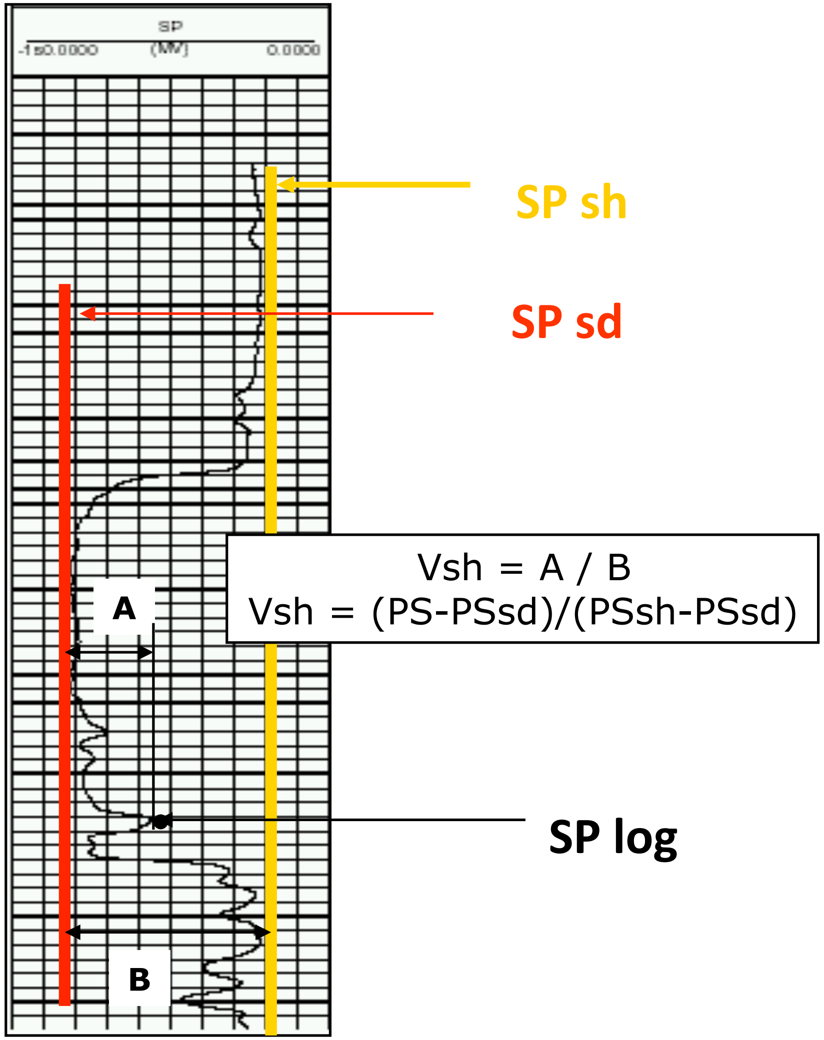
The magnitude of the SP generated is a function of the salinity contrast between mud and formation water.
Two are the main SP generation mechanisms:

- membrane potential,
- liquid-junction potential.

The SP log is primarily a permeability contrast indicator as well as a fundamental lithology log especially in shaly sand sequences



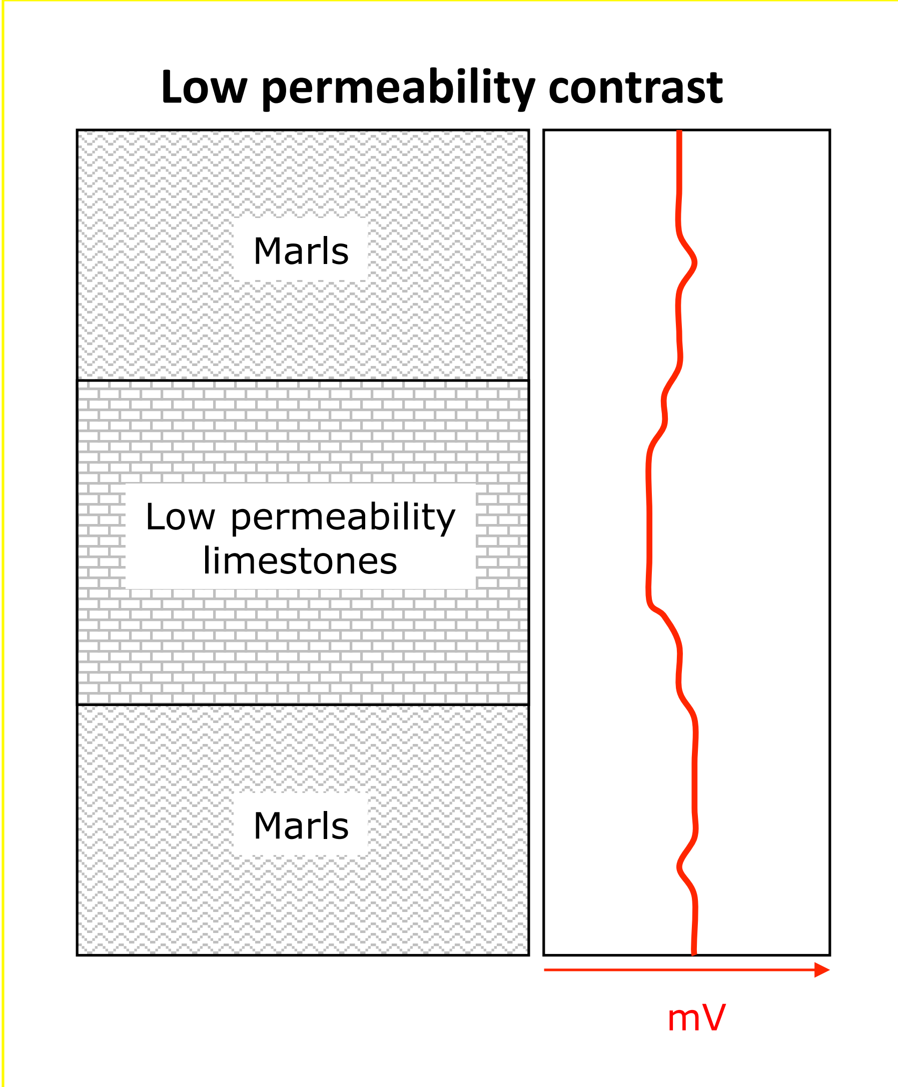
Spontaneous Potential (fresh mud and salty formation water)



SP log interpretation problems

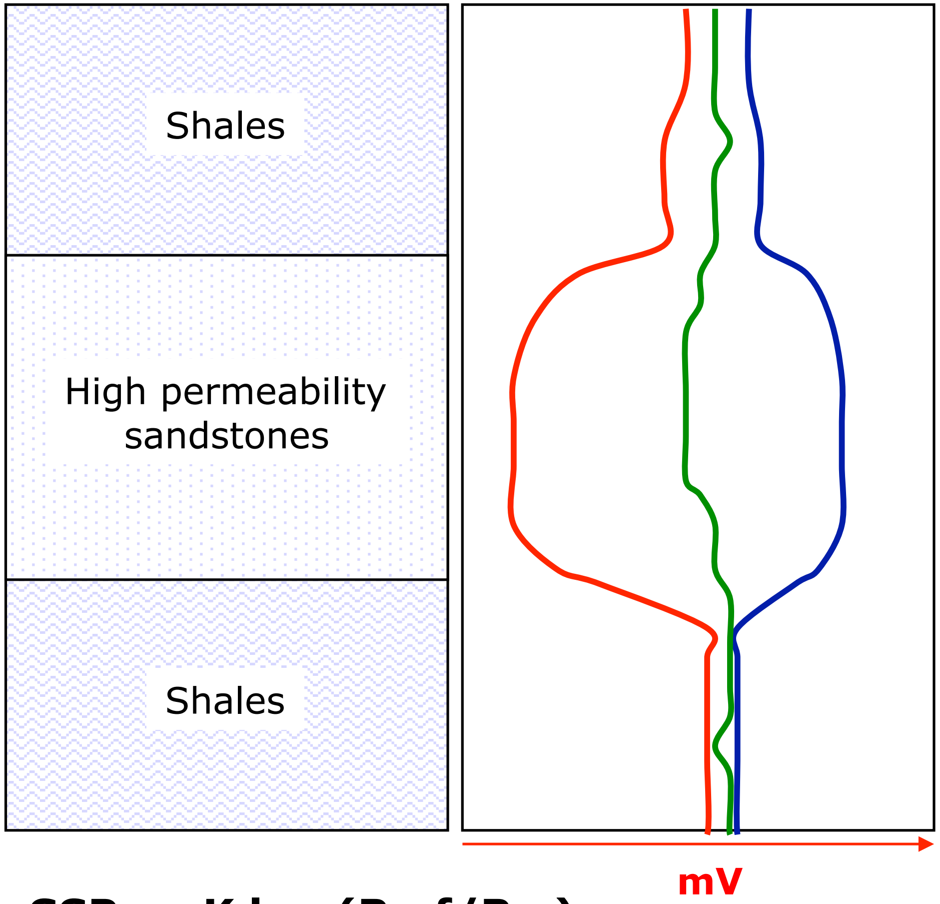
Main problems of SP log interpretation are mostly linked to:

- lack of permeability contrast
- lack of mud/formation water salinity contrast
- thin beds
- hydrocarbon occurrence



SP log interpretation problems

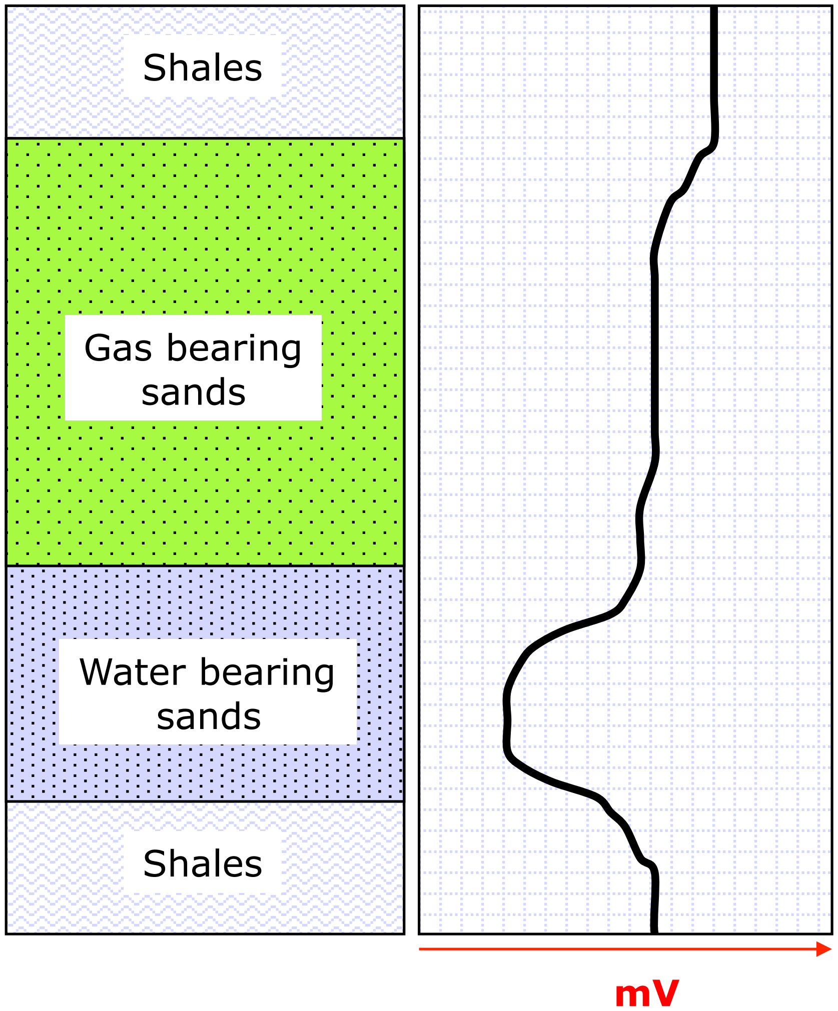
SP log behavior as a function of mud/formation water salinity contrast

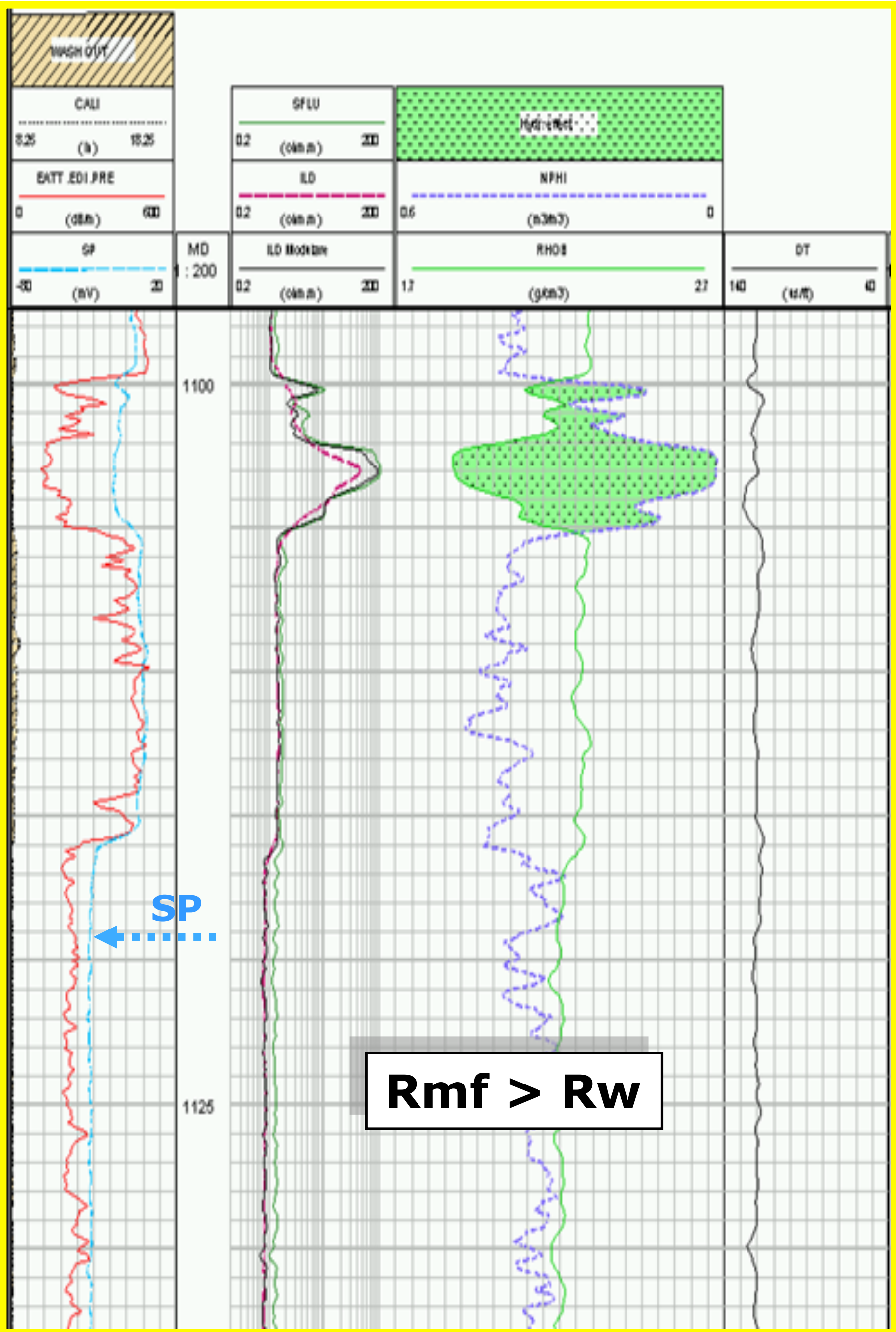
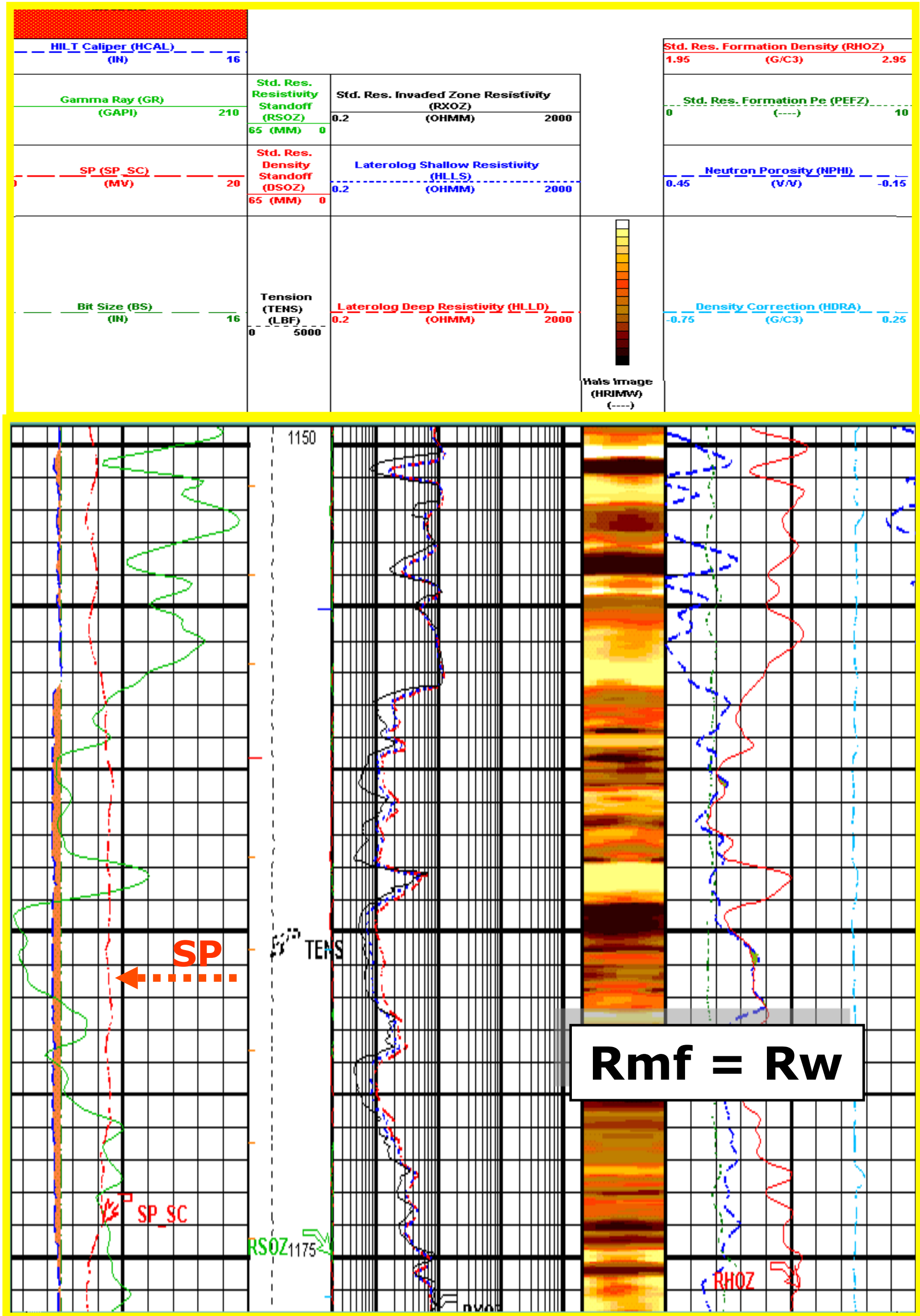


SSP = -K log (Rmf/Rw)

Rm > Rw (red) | Rm = Rw (green) | Rm < Rw (blue)

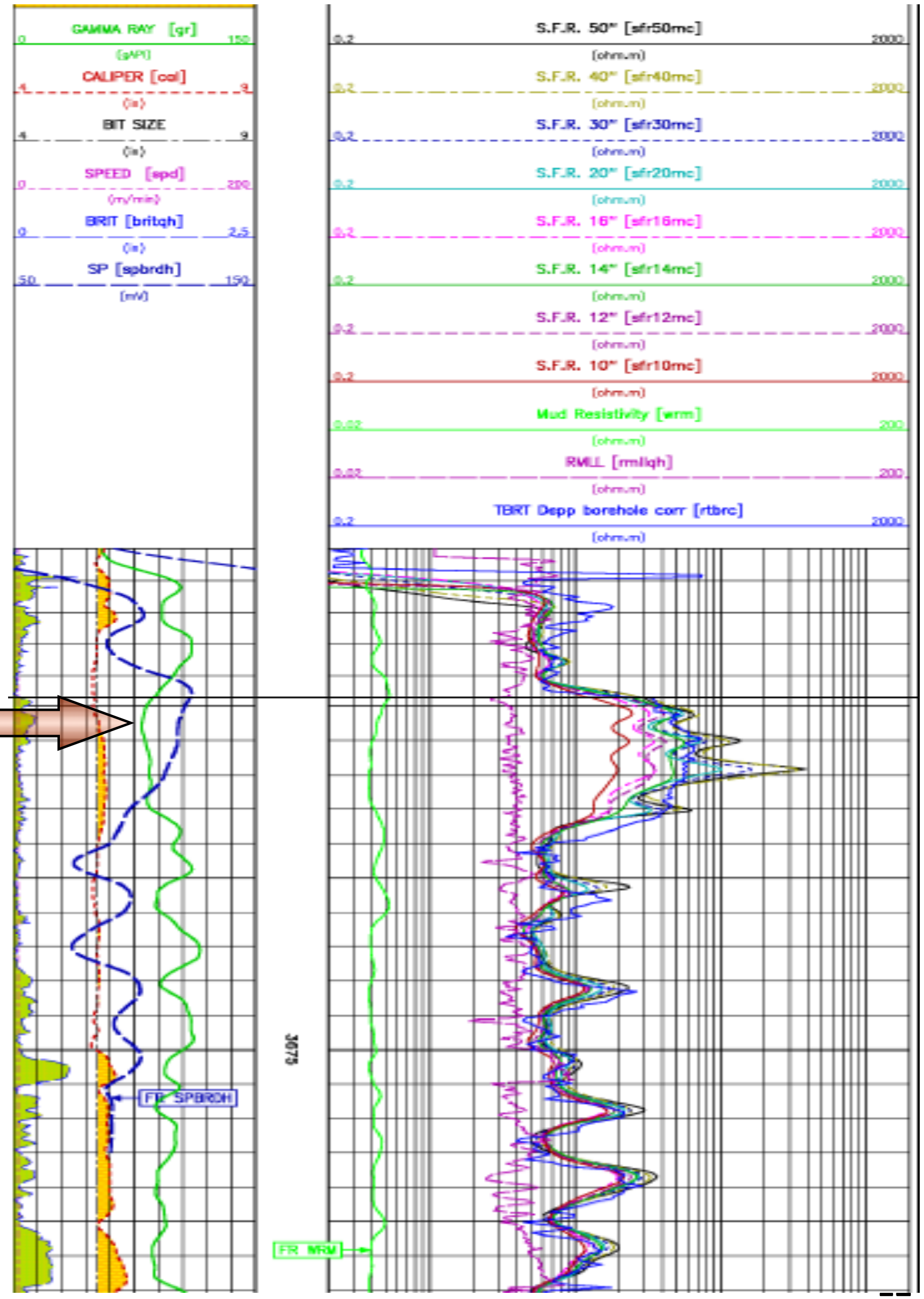
Hydrocarbon effect on the SP log




CALI
SFLU
ILD
NPHI
SP
MD
1 : 200
RHOB
DT
1100
1125
SP
Rmf > Rw

HILT Caliper (HCAL)
Gamma Ray (GR)
SP (SP_SC)
Bit Size (BS)
Std. Res. Resistivity Standoff (RSOZ)
Std. Res. Density Standoff (DSOZ)
Tension (TENS)
Std. Res. Invaded Zone Resistivity (RXOZ)
Laterolog Shallow Resistivity (HLLS)
Laterolog Deep Resistivity (HLLD)
Hals Image (HRIMW)
Std. Res. Formation Density (RHOZ)
Std. Res. Formation Pe (PEFZ)
Neutron Porosity (NPHI)
Density Correction (HDRA)
1150
1175
TENS
SP_SC
RSOZ
RHOZ
SP
Rmf = Rw

Inverted SP:

Rmf << Rw



SP log interpretation problems

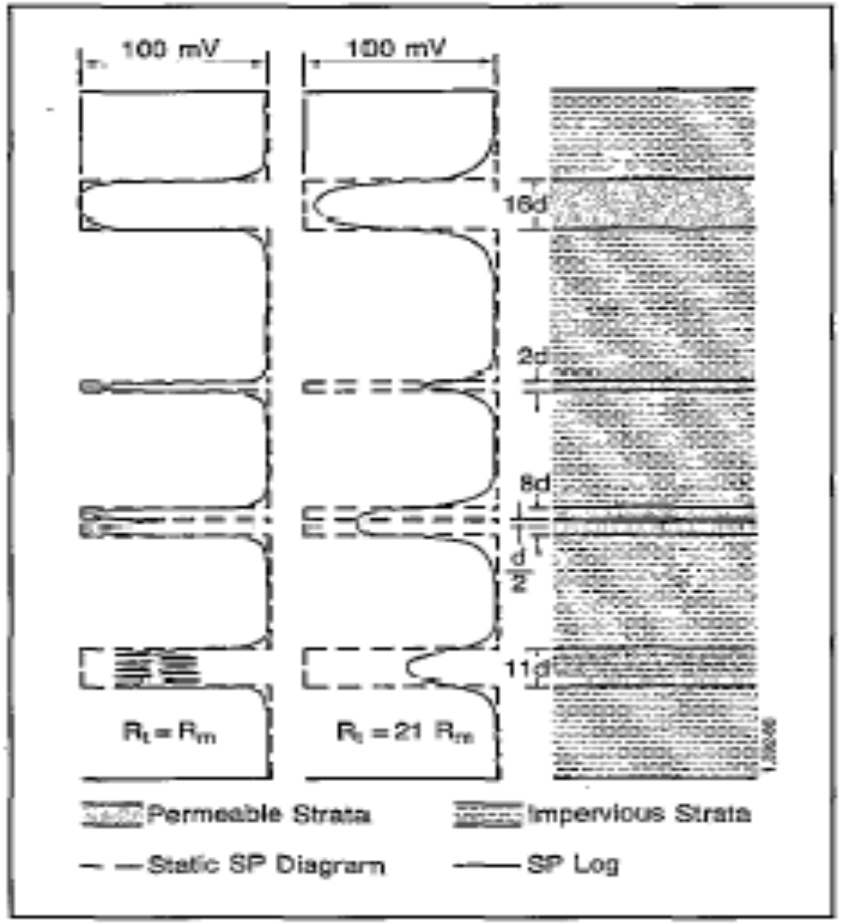
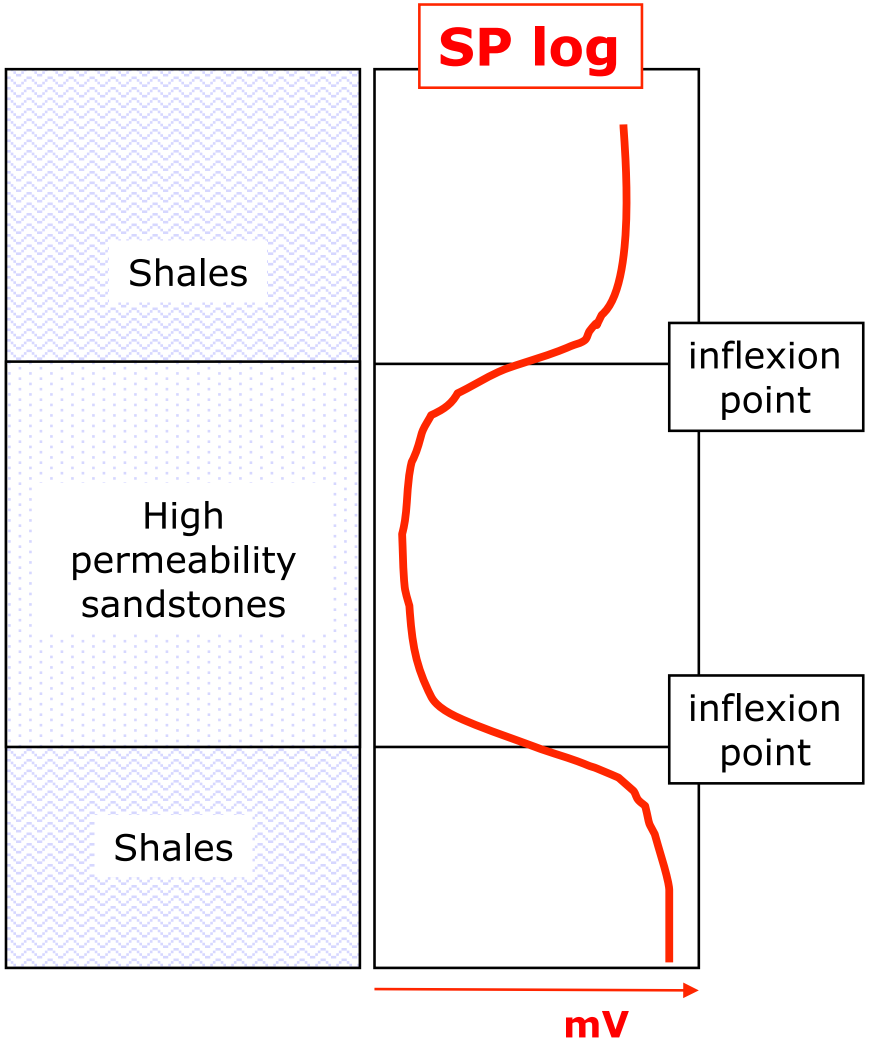


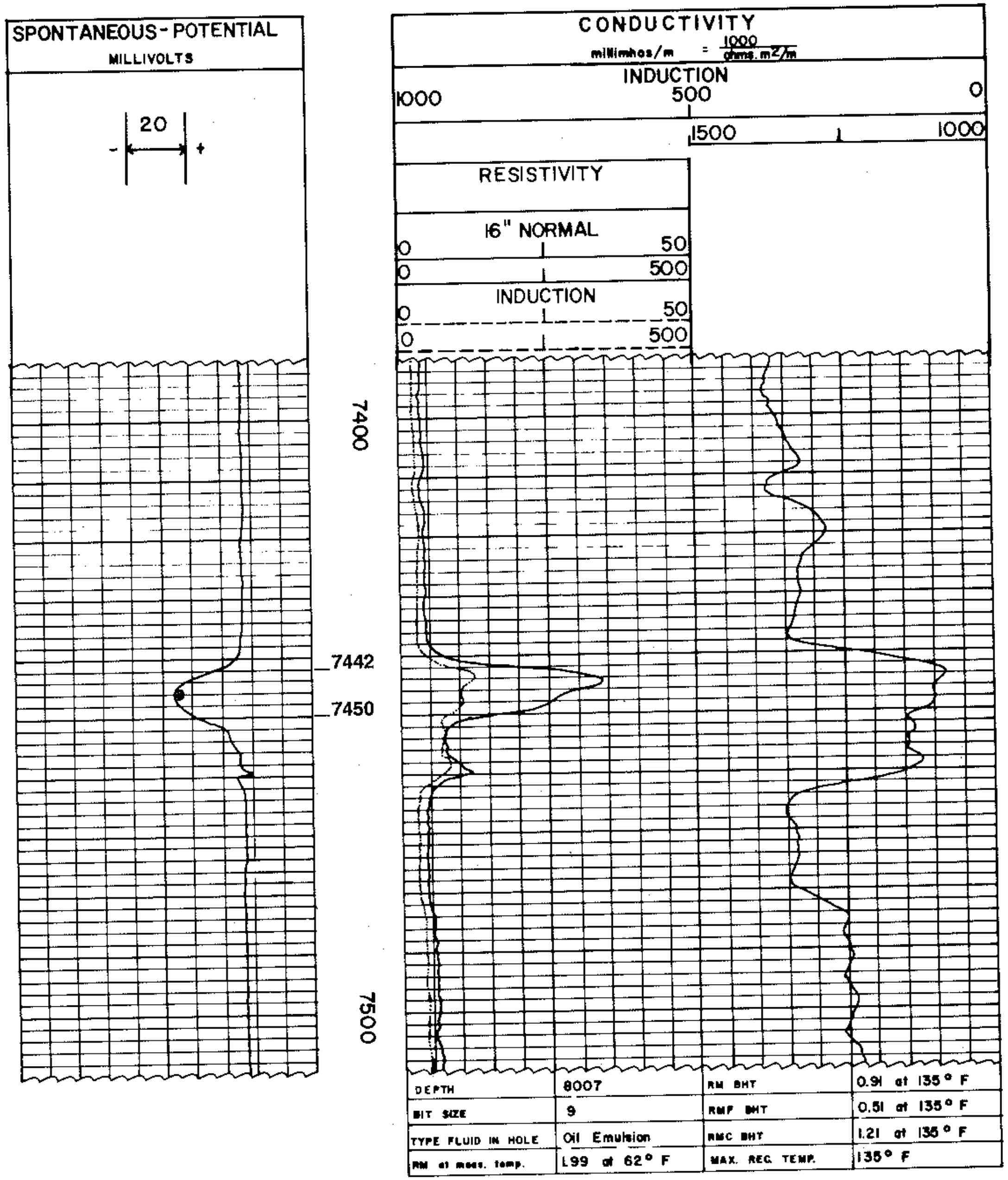
Fig. 3-3—SP curve in beds of different thickness for $R_t = R_m$ (left) and $R_t = 21\ R_m$ (center).

Vertical resolution of the SP log



Boundary location by means of the SP log

Exercise: Rw determination from SP log



Exercise: Rw determination from SP log: the data

Given data:

Rmf= 0.51 @ 135° (BHT)

Rm= 0.91 @ 135° (BHT)

Surface temperature= 60°F

Total depth= 8007 ft

BHT= 135°F

From log track:

SP= -40 mV

Bed thickness= 8 ft

Resistivity short normal= 28 ohm-m

Formation depth= 7446 ft

Exercise: Rw determination from SP log: procedure

Step 1:
Determine Tf by using chart 1
(Ans. Tf= 130°F)

Step 2:
Correct Rm and Rmf to Tf using chart 2:
Use Tf= 130°F from step1, Rm= 0.91 @ 135°F and Rmf= 0.51 @ 135°F
(Ans. Rm= 0.94 @ 130°F and
Rmf= 0.53 @ 130°F)

Exercise:
Rw determination from SP log: procedure

Step 3:
Correct SP to SSP (thin bed effect)
Use chart 3
(Ans. SSP=-52mV)

Step 4:
Determine Rmf/Rwe
Use chart 4:
(Ans. Rmf/Rwe=5.0)

Exercise: Rw determination from SP log: procedure

Step 5:

Determine Rwe

Rwe= Rmf/(Rmf/Rwe)=

= 0.53/5.0

Rwe= 0.106

Exercise: Rw determination from SP log: procedure

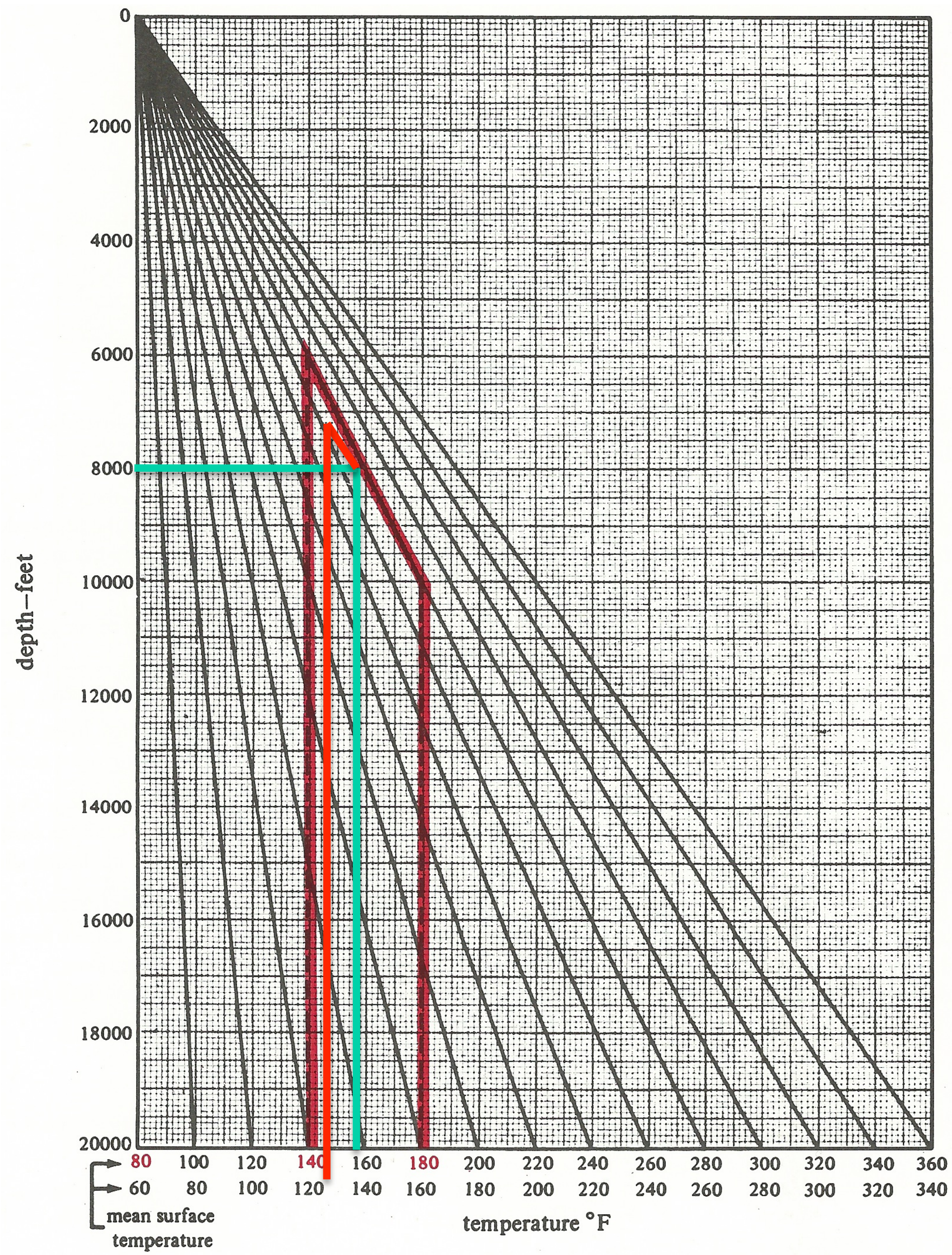
Step 6 (end):

Correct Rwe to Rw

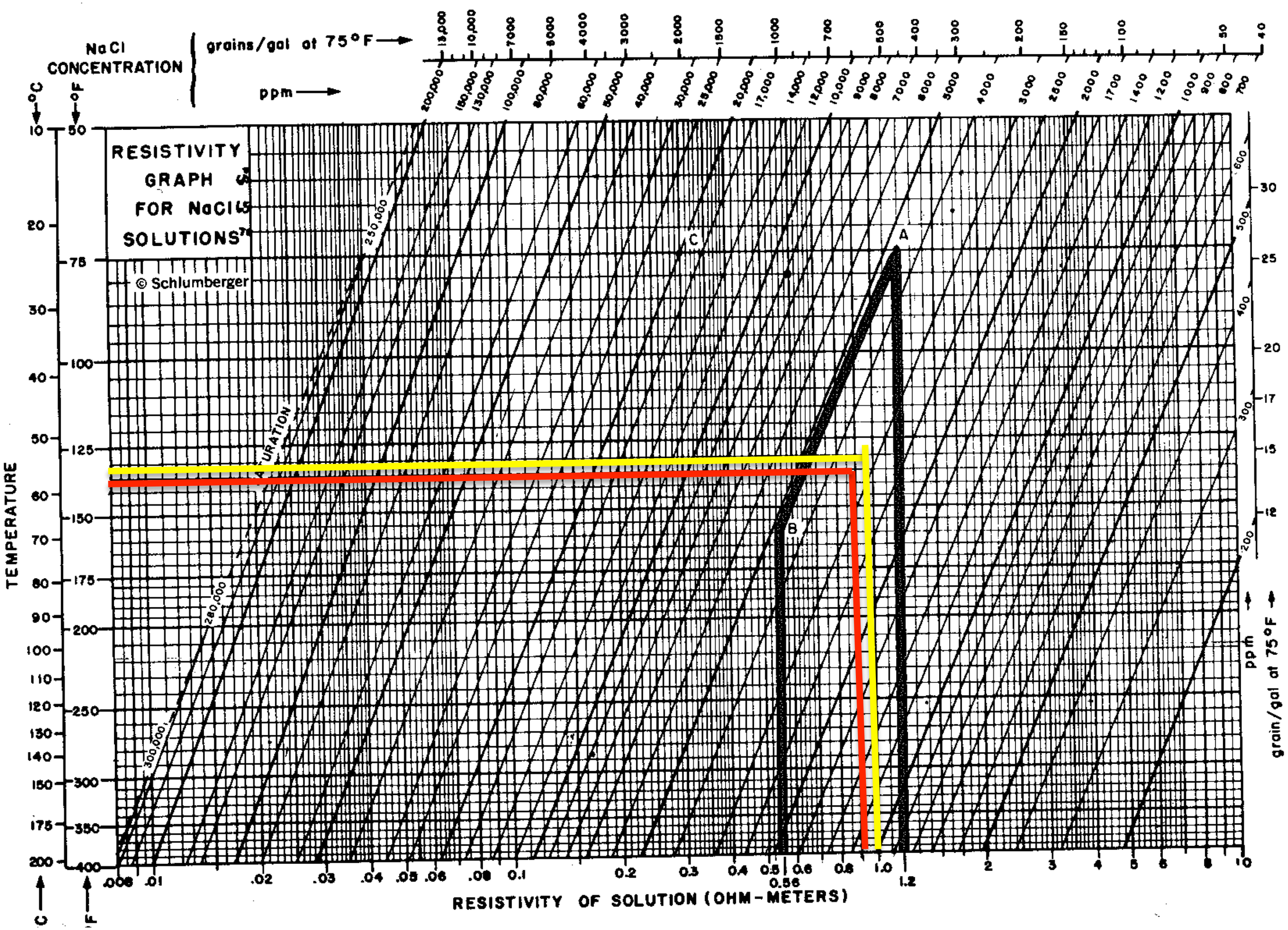
Use chart 5

(ans. Rw=0.11 ohm-m @ Tf)

Formation temperature determination: chart 1



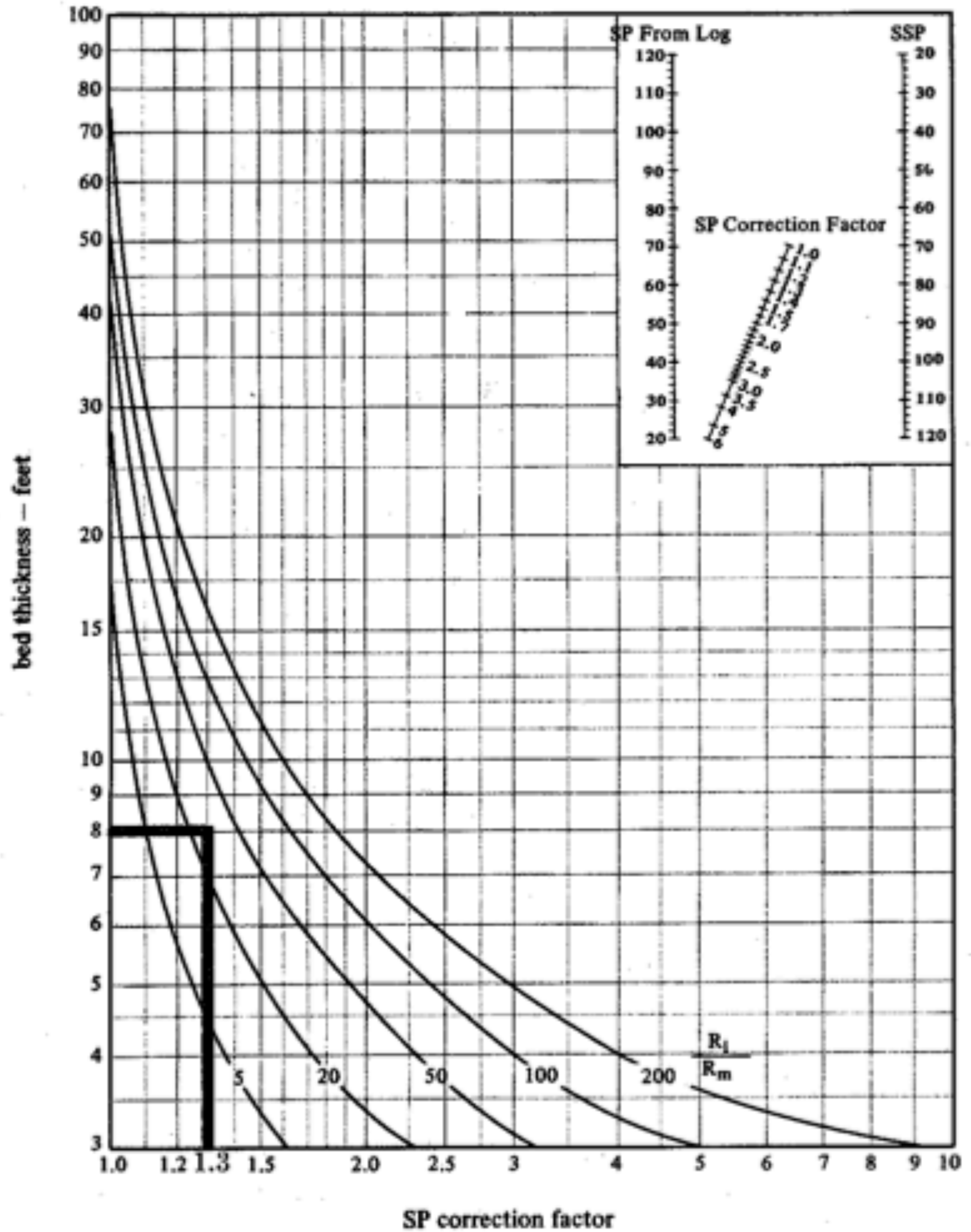
Correction of Rm and Rmf @ Tf: chart 2



Correction of SP to SSP: chart 3

Ri/Rm= 28/0.94

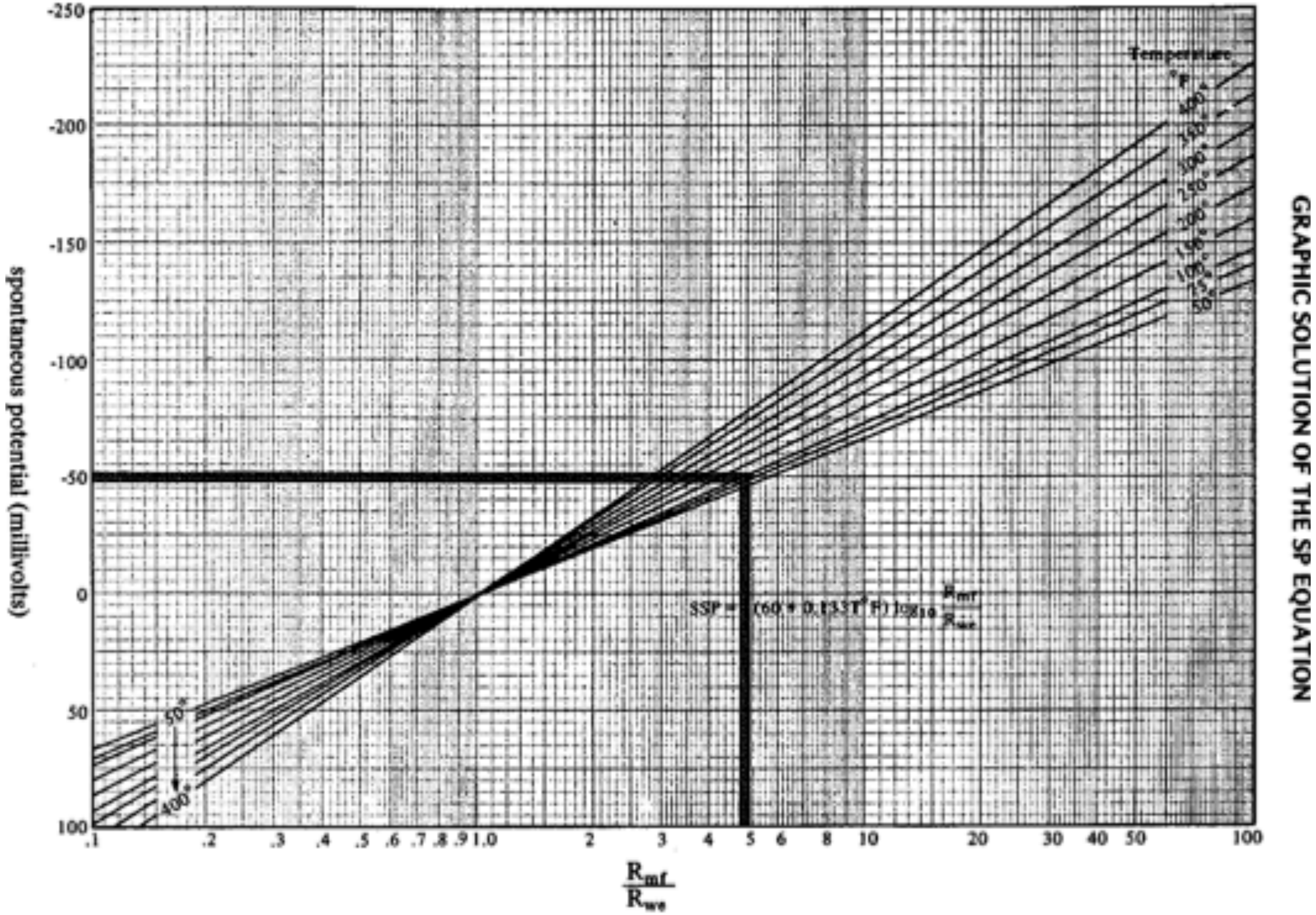
Thickness= 8 ft



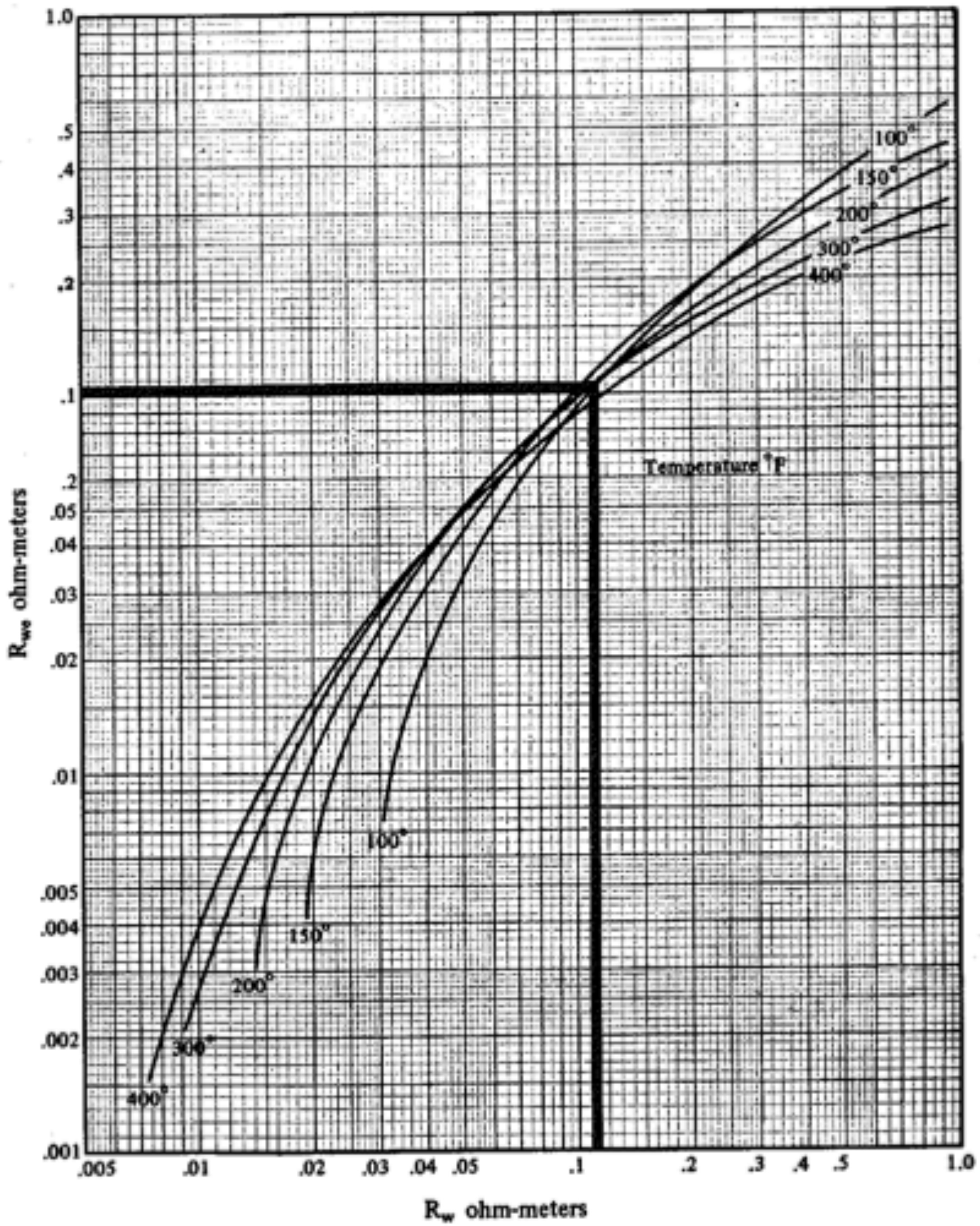
Determine Rmf/Rwe: chart 4

SSP=-52mV

Tf=130°F



Correction of Rwe to Rw @ Tf: chart 5



Volume of Shale (Vsh) Calculation in permeable layers

$$\textbf{Vsh (in \%)} = 1.0 - (PSP/SSP)$$

where

Vsh = volume of shale

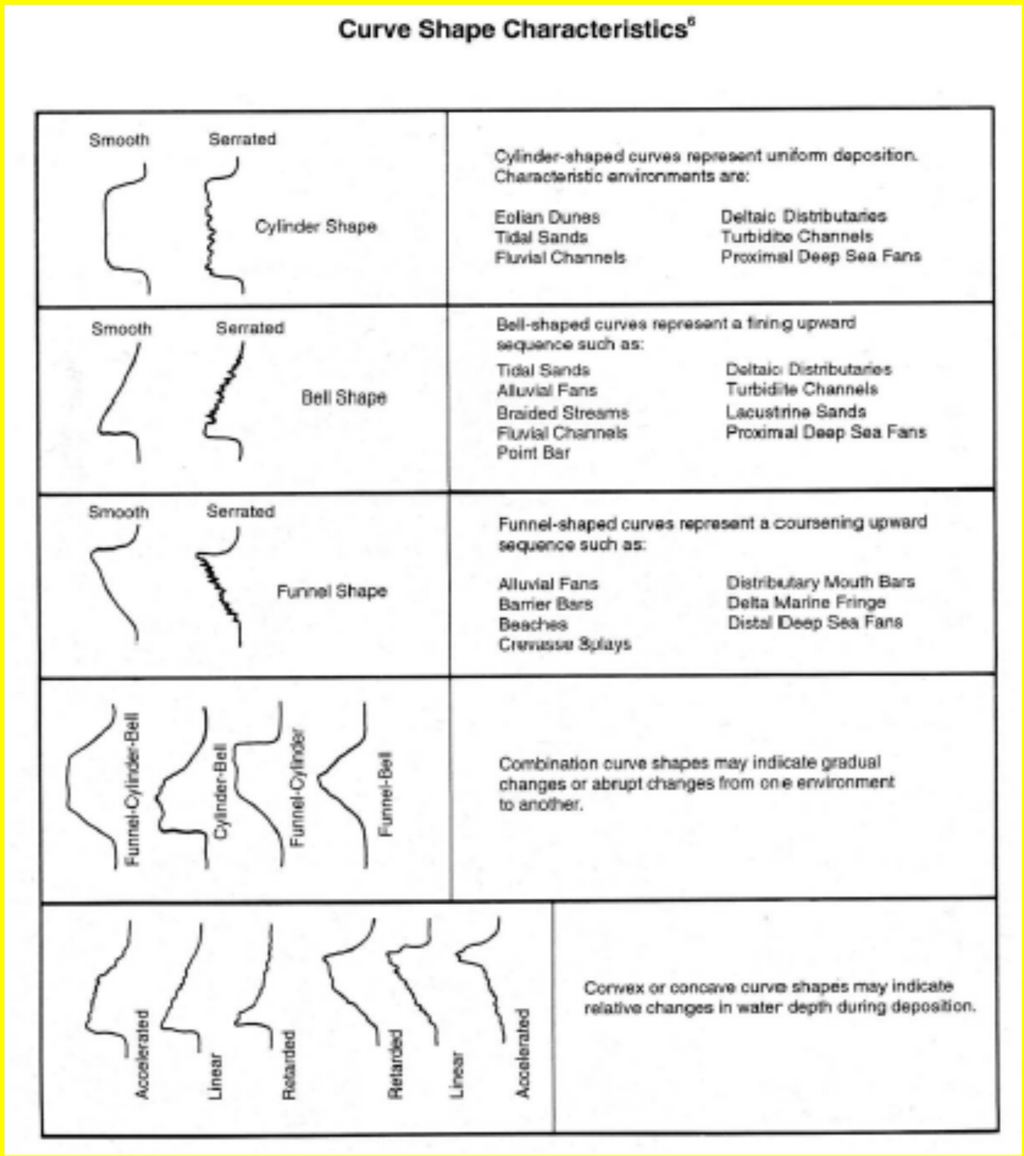
PSP= pseudo static potential (SP of shaly formation)

SSP= static SP of thick clean sand or carbonate

$$SSP = -K \times \log (Rmf/Rw)$$

$$K = 60 + (0.133 \times Tf)$$

Geological application of the SP log



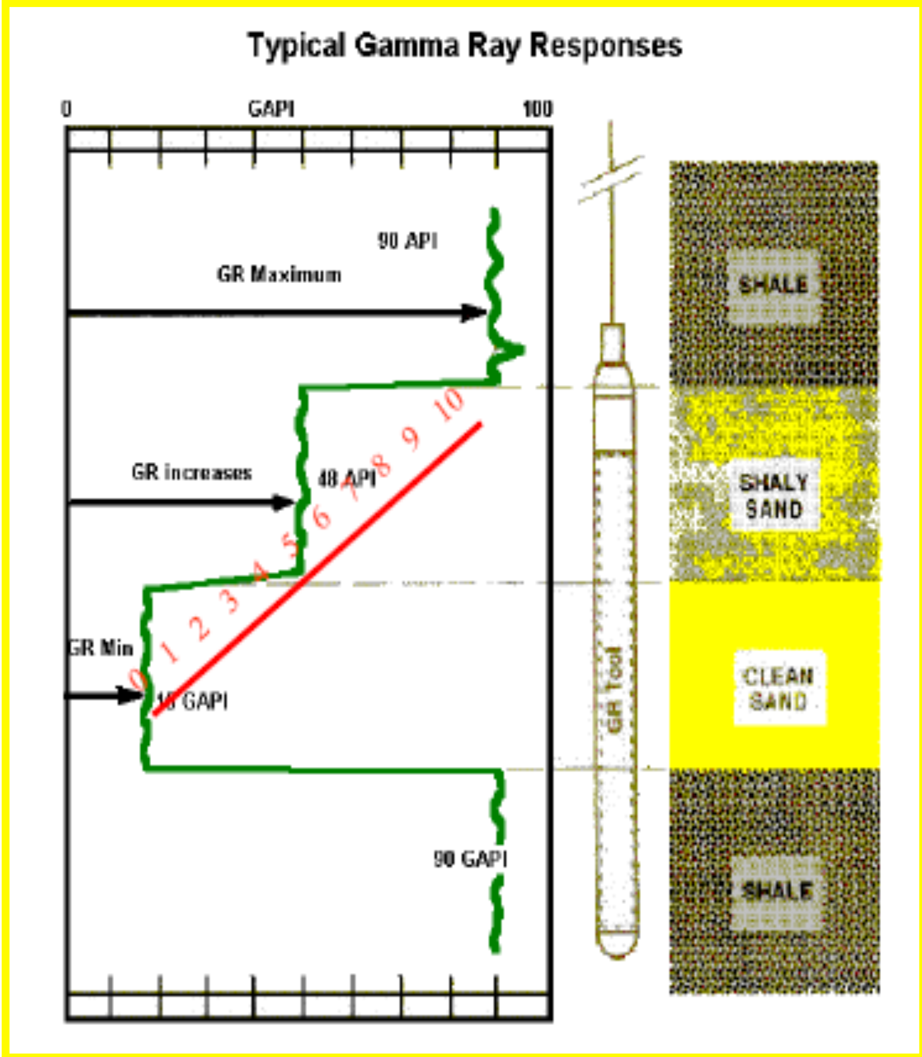
In absence of SP anomalies, when dealing with water saturated formations and with muds of constant salinity in all the wells under evaluation, the SP log may be used for geological correlation among wells and to define the different sedimentary facies (in order to define lateral and vertical evolution of the sedimentary environments).

Gamma Ray log

The natural radioactivity of geological formations is due to the presence in rock forming minerals of the radioactive isotopes of elements such as Uranium (U), Thorium (Th) and Potassium (K).

These isotopes are mostly related to clay minerals whose content in Th and K is generally higher than associated sand and sandstones.

In carbonate formations the radioactivity is mostly due to the presence of U and the Gamma Ray level is not directly related to formation shalyness.



Gamma Ray log

Clean sandstones may also produce high gamma ray readings if it contains

Potassium feldspars

Micas

Glauconite

Uranium rich water

IF the potential presence of such components is known from geology,

A **SPECTRALOG** should be run in parallel with the gamma ray log:

The spectralog breaks the natural radioactivity into the different types of radioactive materials: (1) Thorium (2) Potassium (3) Uranium

Volume of Shale calculation from Gamma Ray log

1. Calculate gamma ray index I_{gr}:

   $I_{gr}=(GR_{log}-GR_{min})/(GR_{max}-GR_{min})$

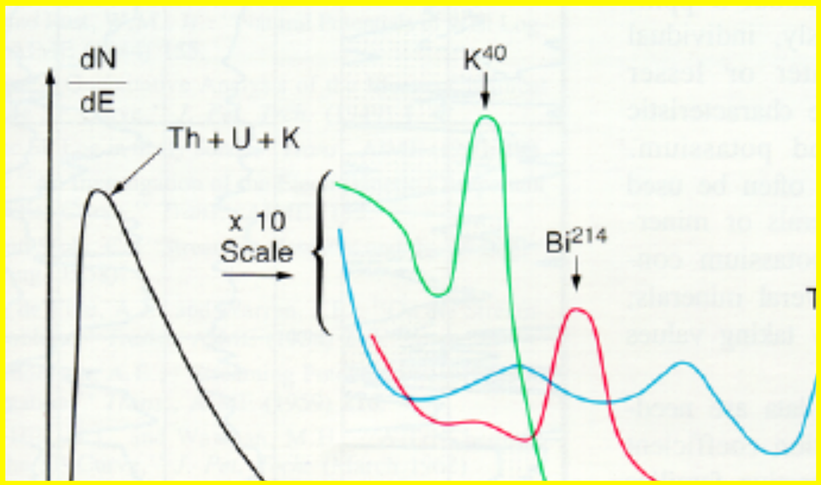
2. Older consolidated rocks:

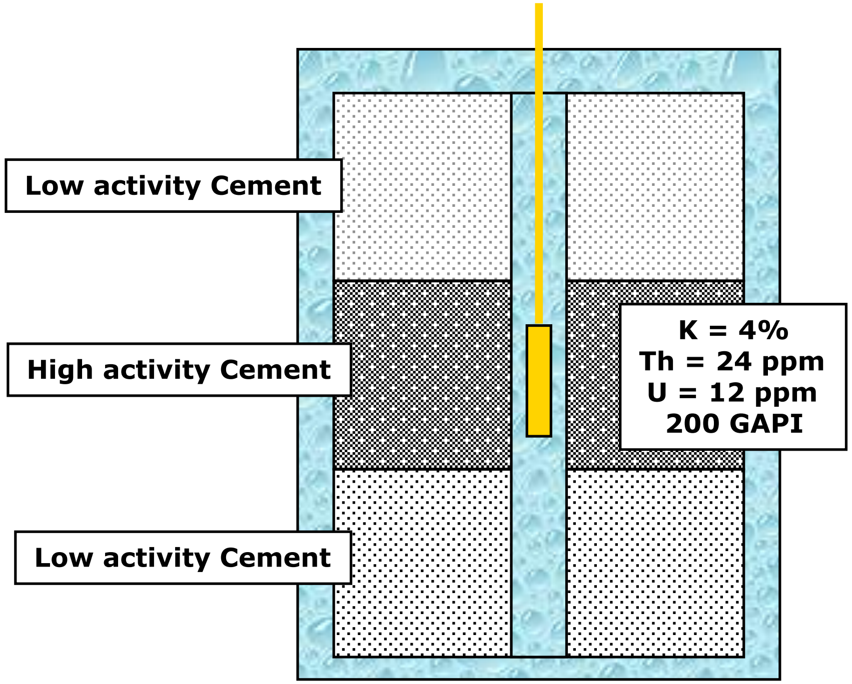
   $Vsh= 0.33[2^{(2xIgr)}- 1.0]$

3. Tertiary unconsolidated rocks:

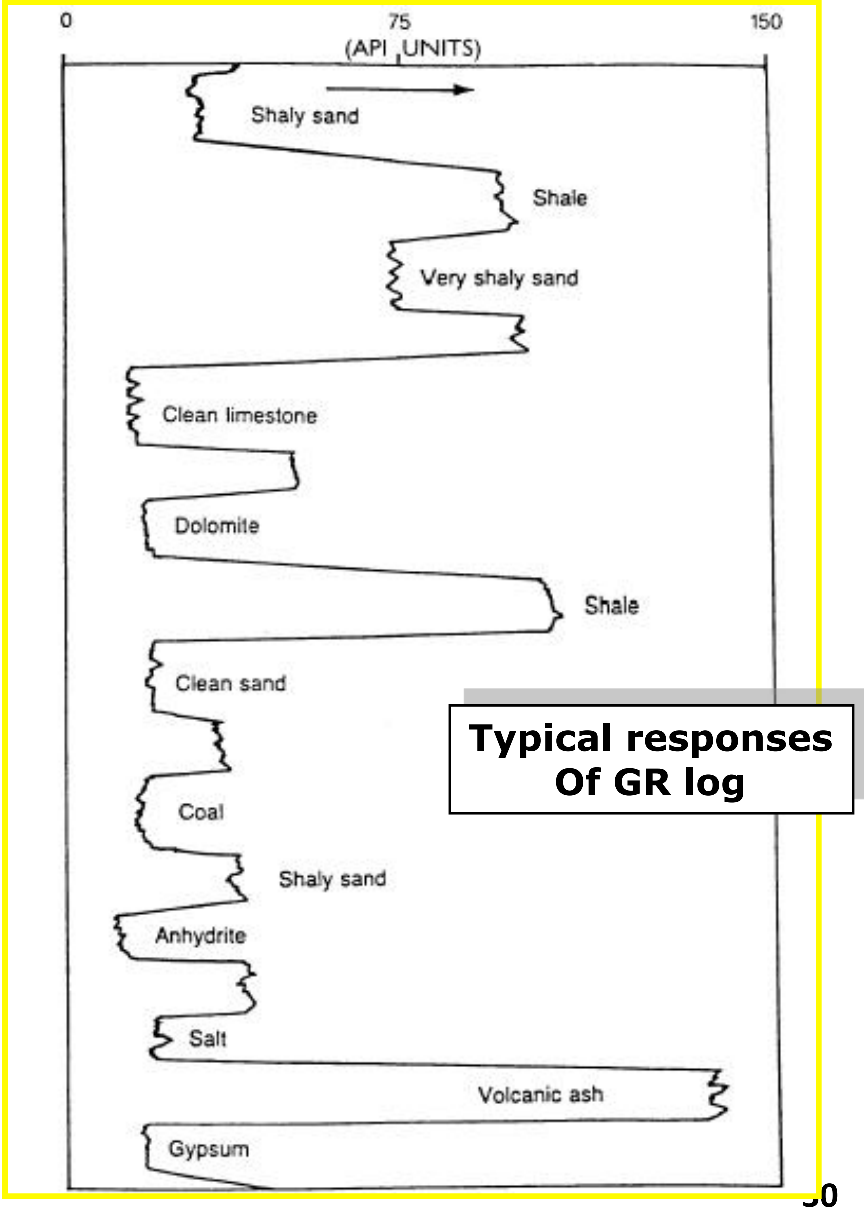
   $Vsh= 0.083[2^{(3.7xIgr)}- 1.0]$

Gamma Ray log

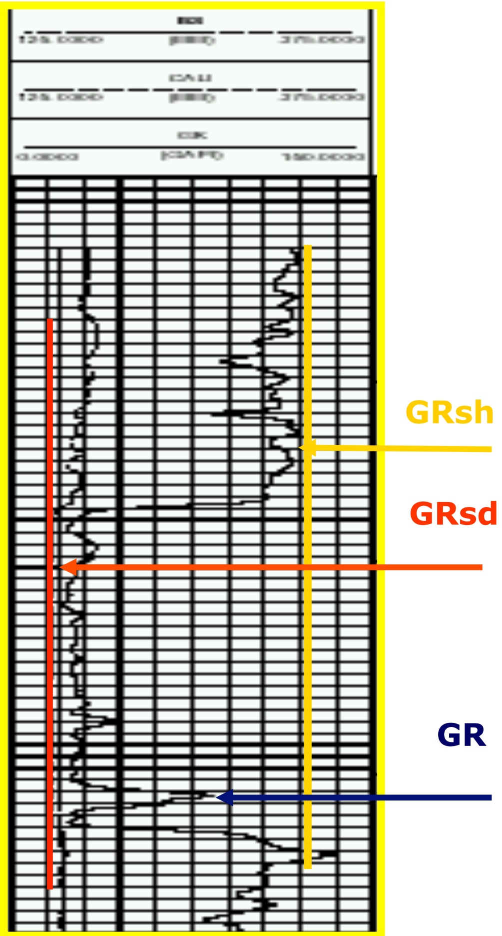


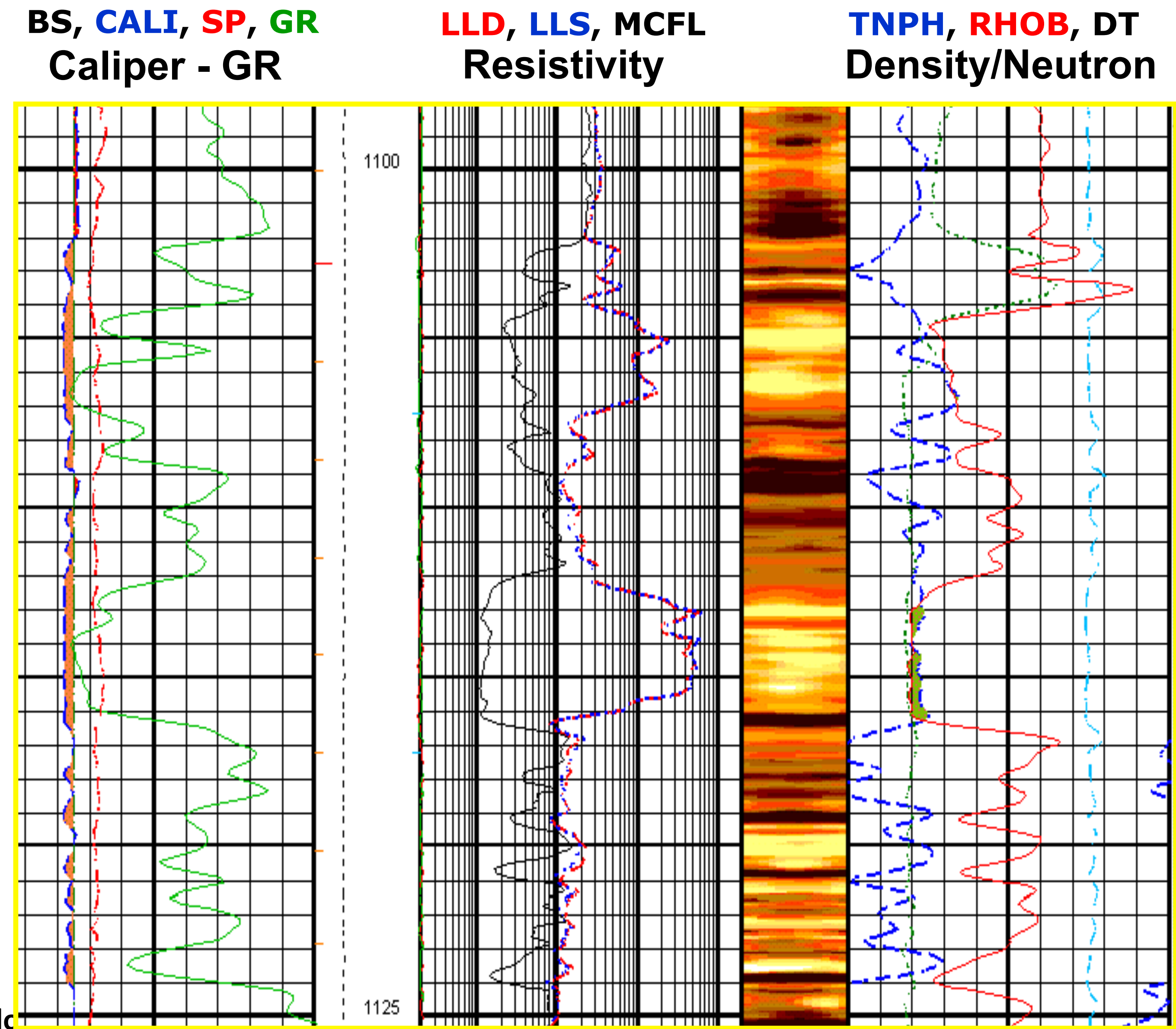


Gamma Ray American Institute Test Pit



Shale volume from GR log



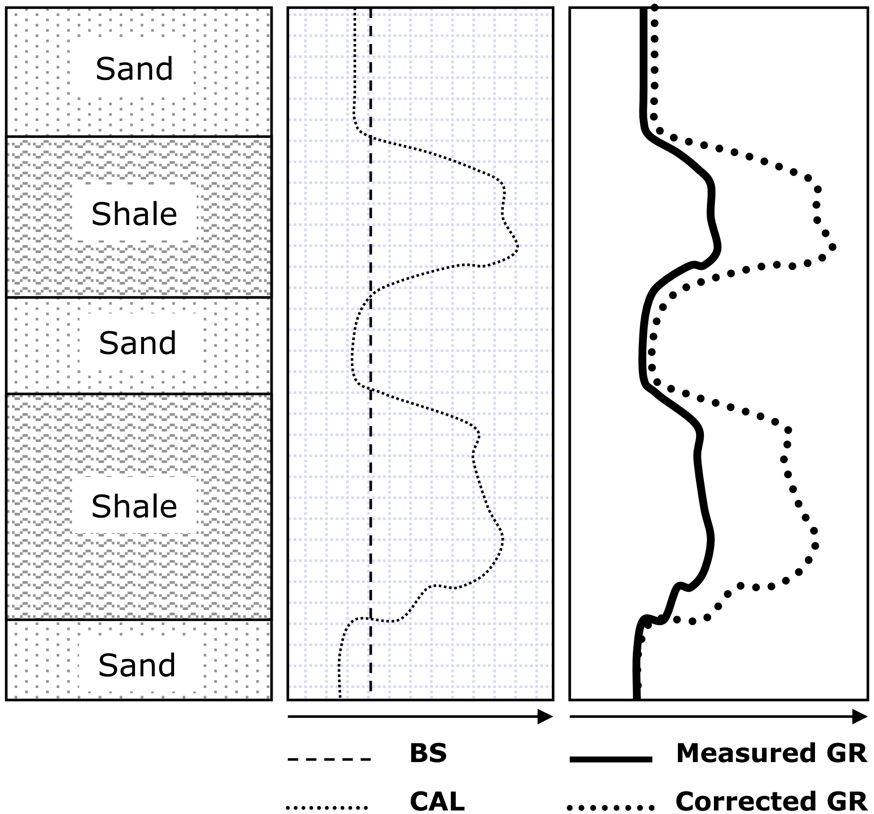


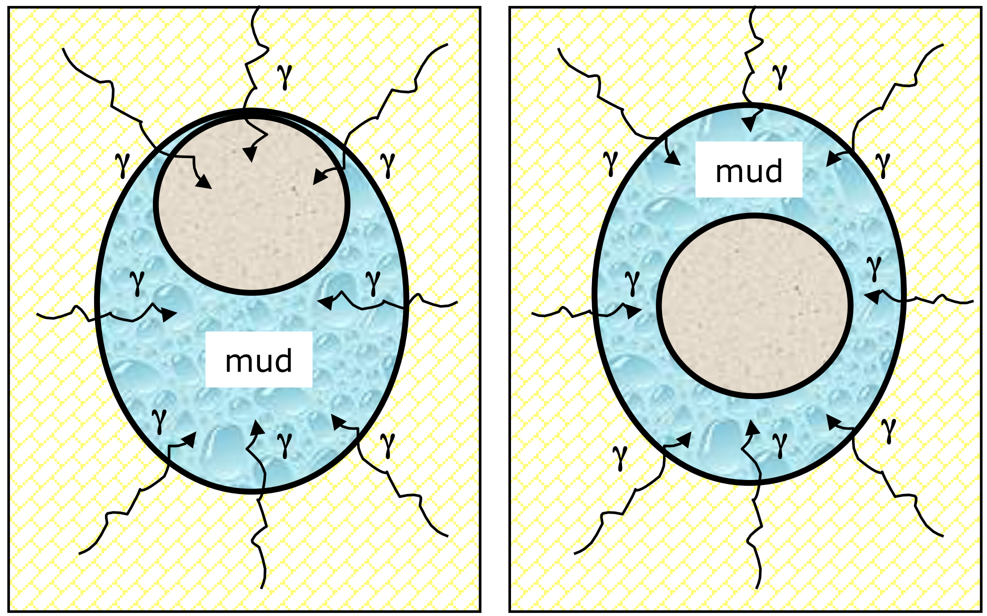
$$Vsh = \frac{(GR-GRsd)}{(GRsh-GRsd)}$$

Gamma Ray: environmental corrections

Main factors affecting GR measurements are:

- hole diameter
- sonde position in the well
- mud loaded with radioactive material



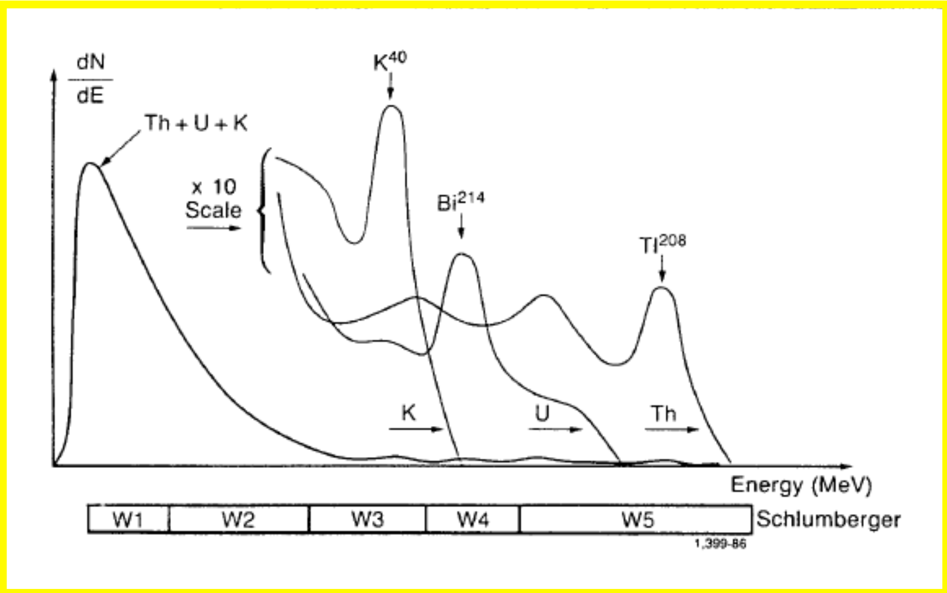


Tool eccentered **Tool centered**

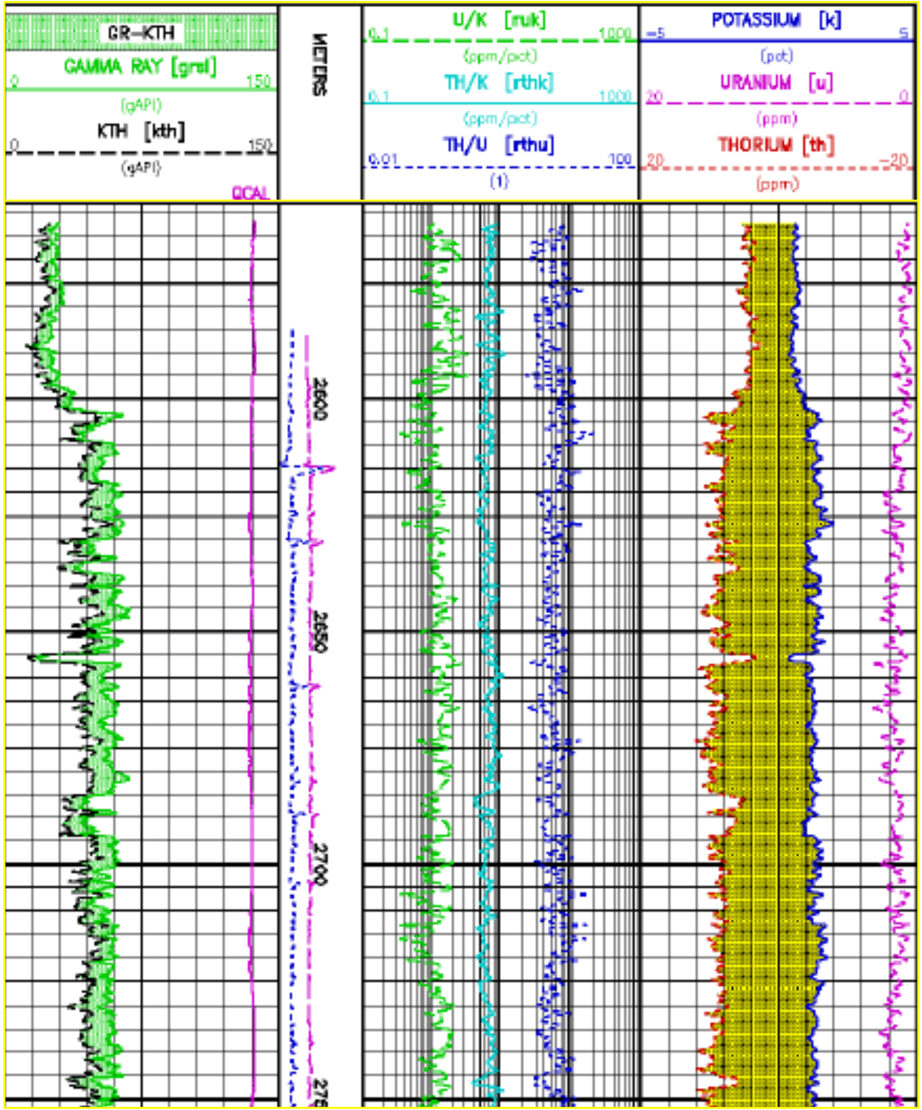
Gamma Ray: environmental corrections

$$t = \frac{W_{mud}}{8.345}\left(\frac{2.54\,(d_{hole})}{2} - \frac{2.54\,(d_{sonde})}{2}\right).$$

Gamma Ray Spectrometry

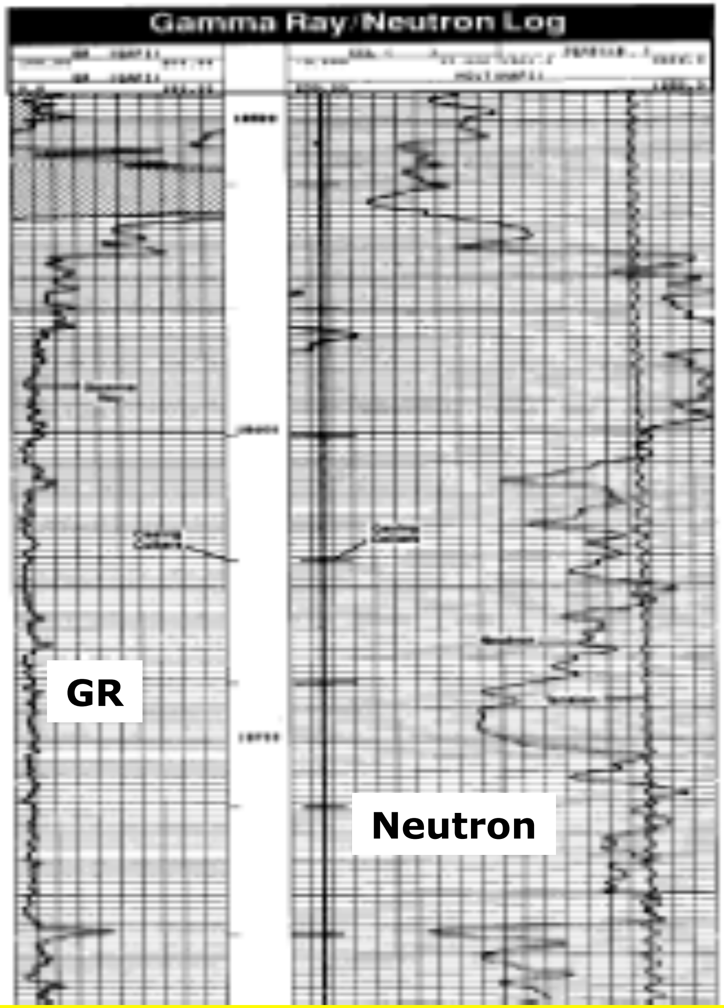


Gamma Ray emission spectra

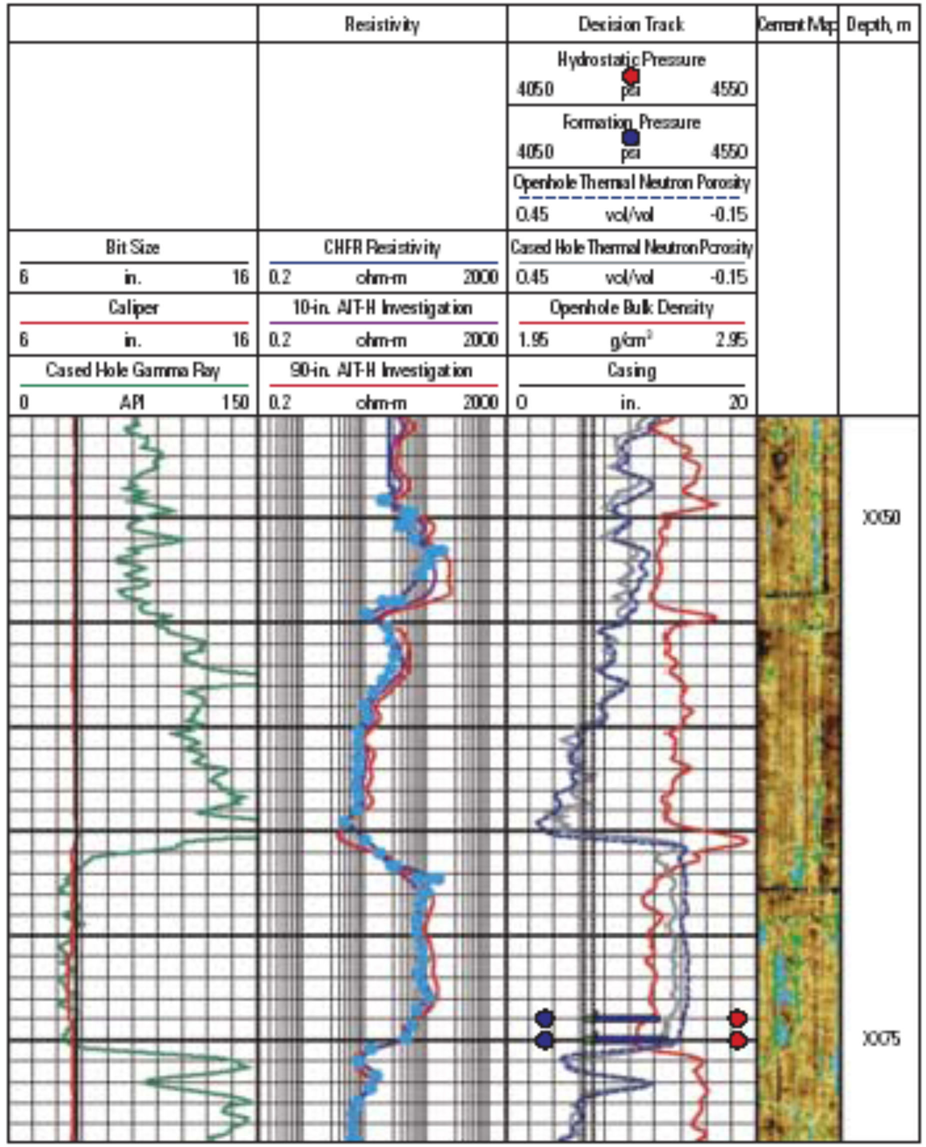


	WLL Services
SLB	NGS
SLB	HNGS (PEX)
BA	SL

GR in cased hole

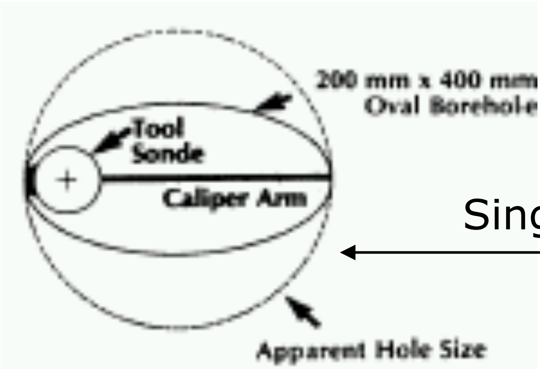


GR correlation Log in cased hole

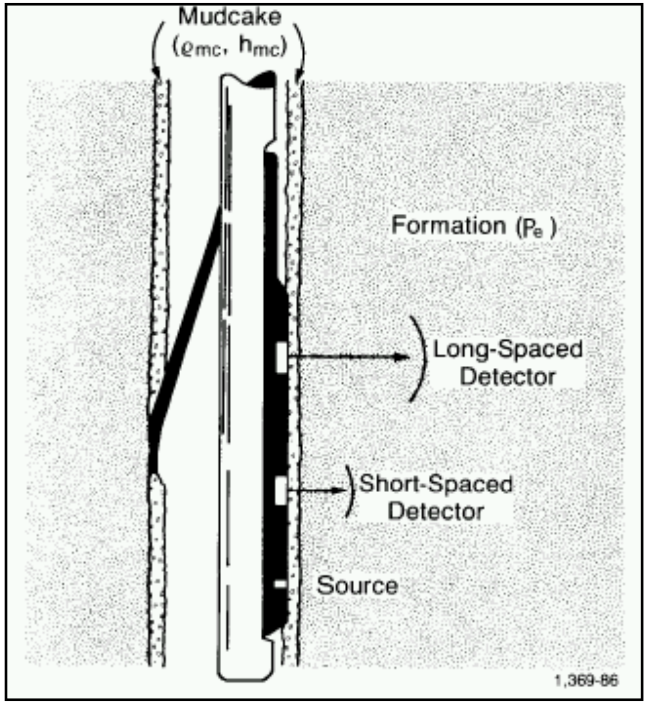


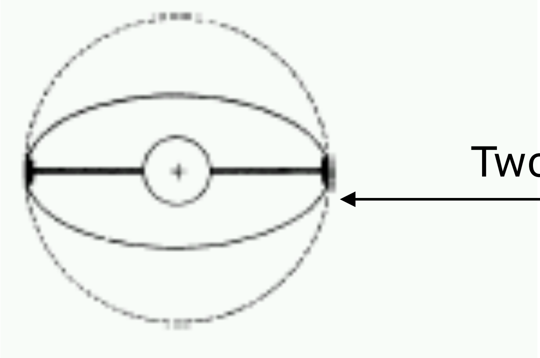
Formation Evaluation logging in CH

Caliper log

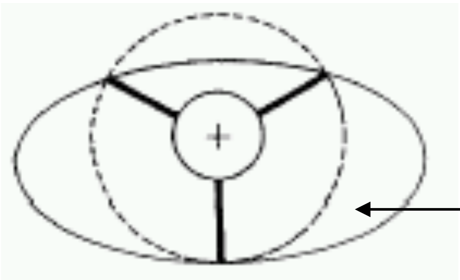


Single arm caliper

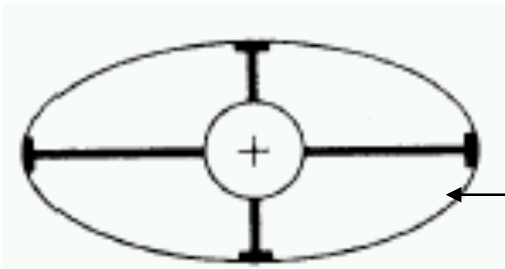




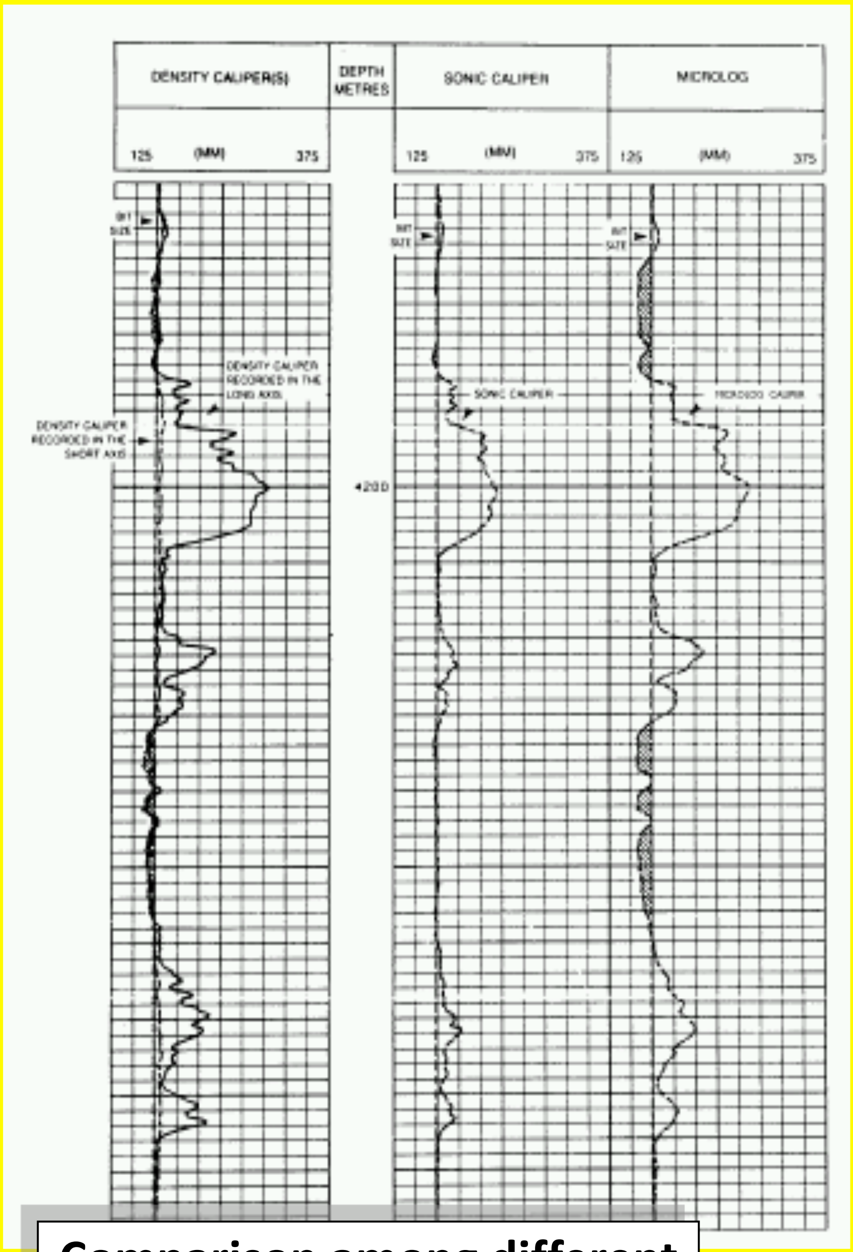
Two arm caliper

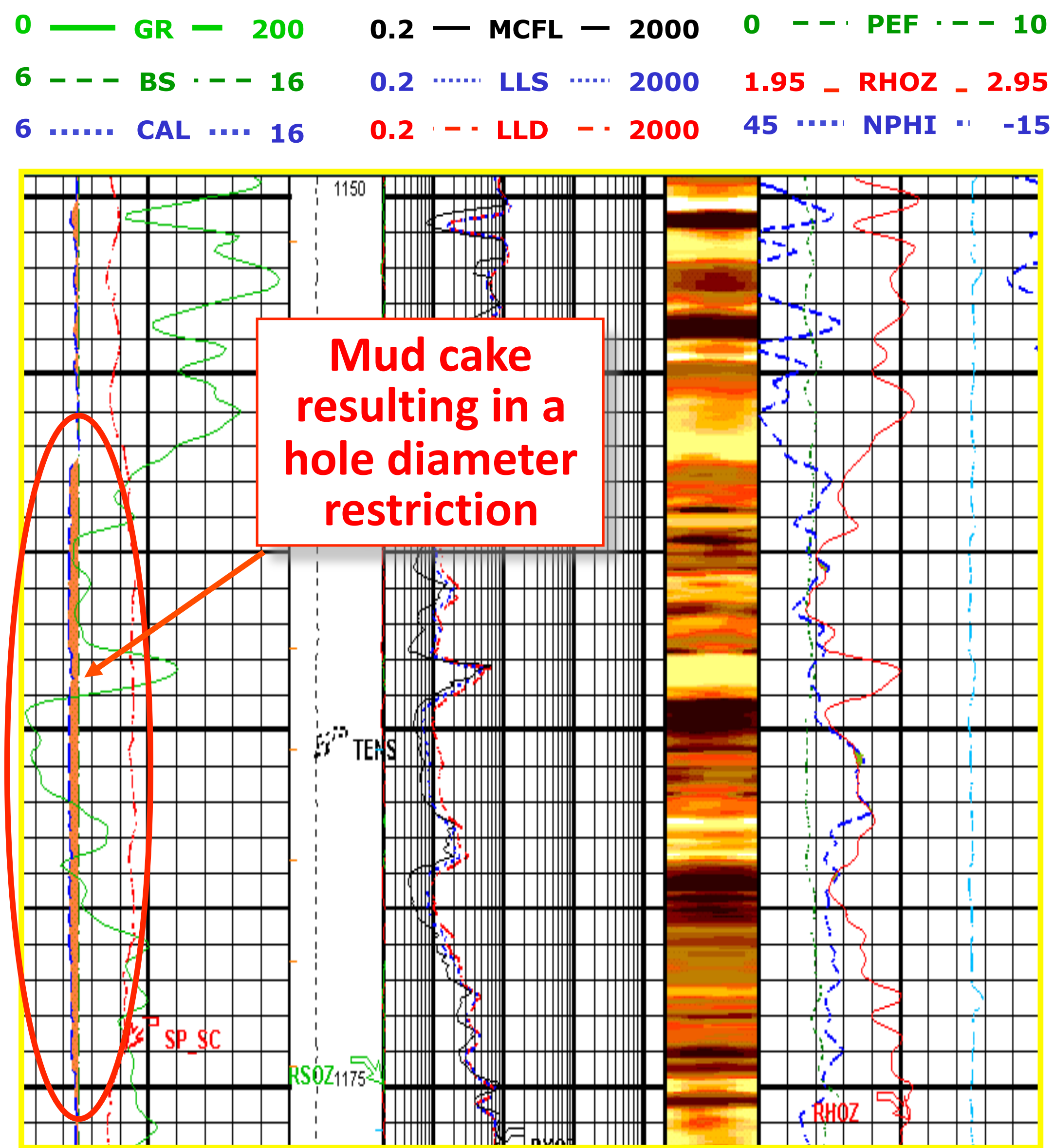


Three arm caliper



Four arm caliper

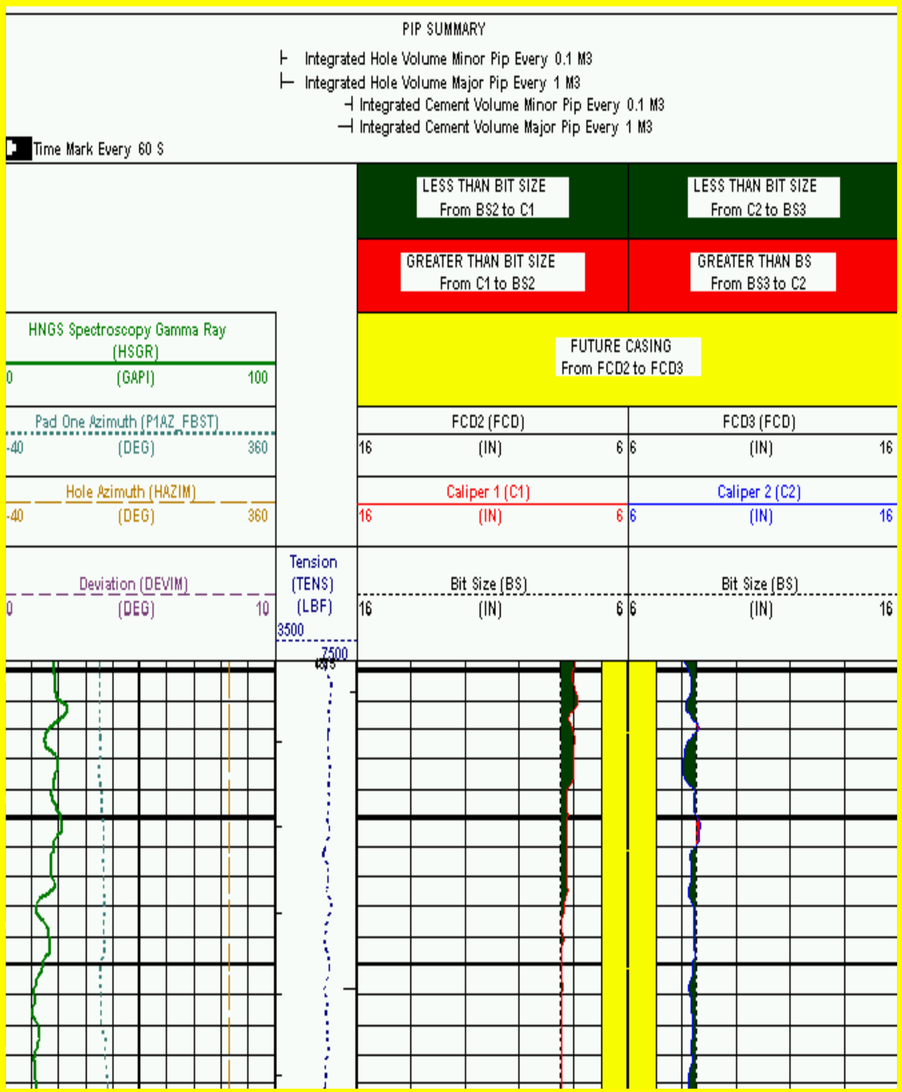


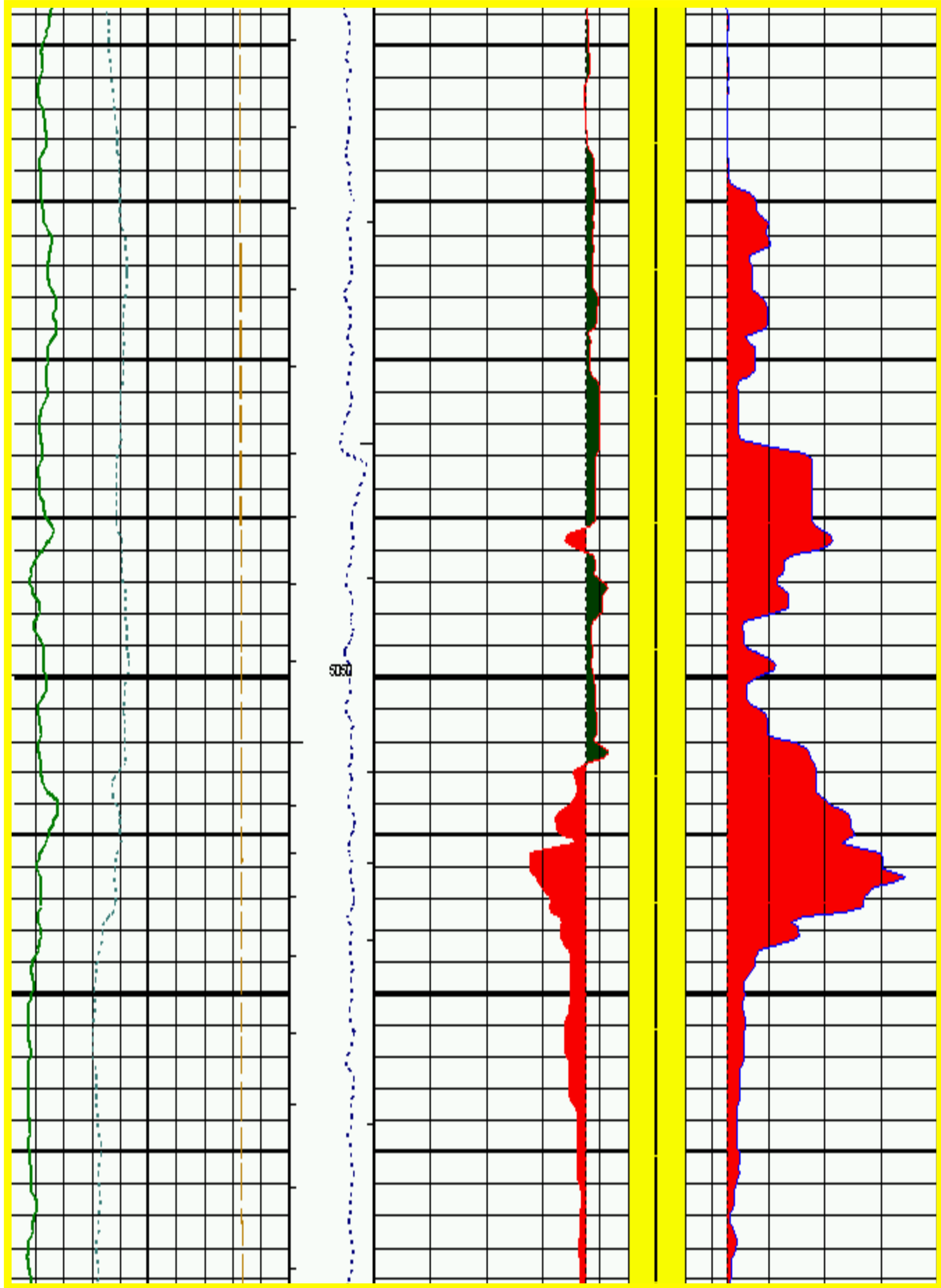


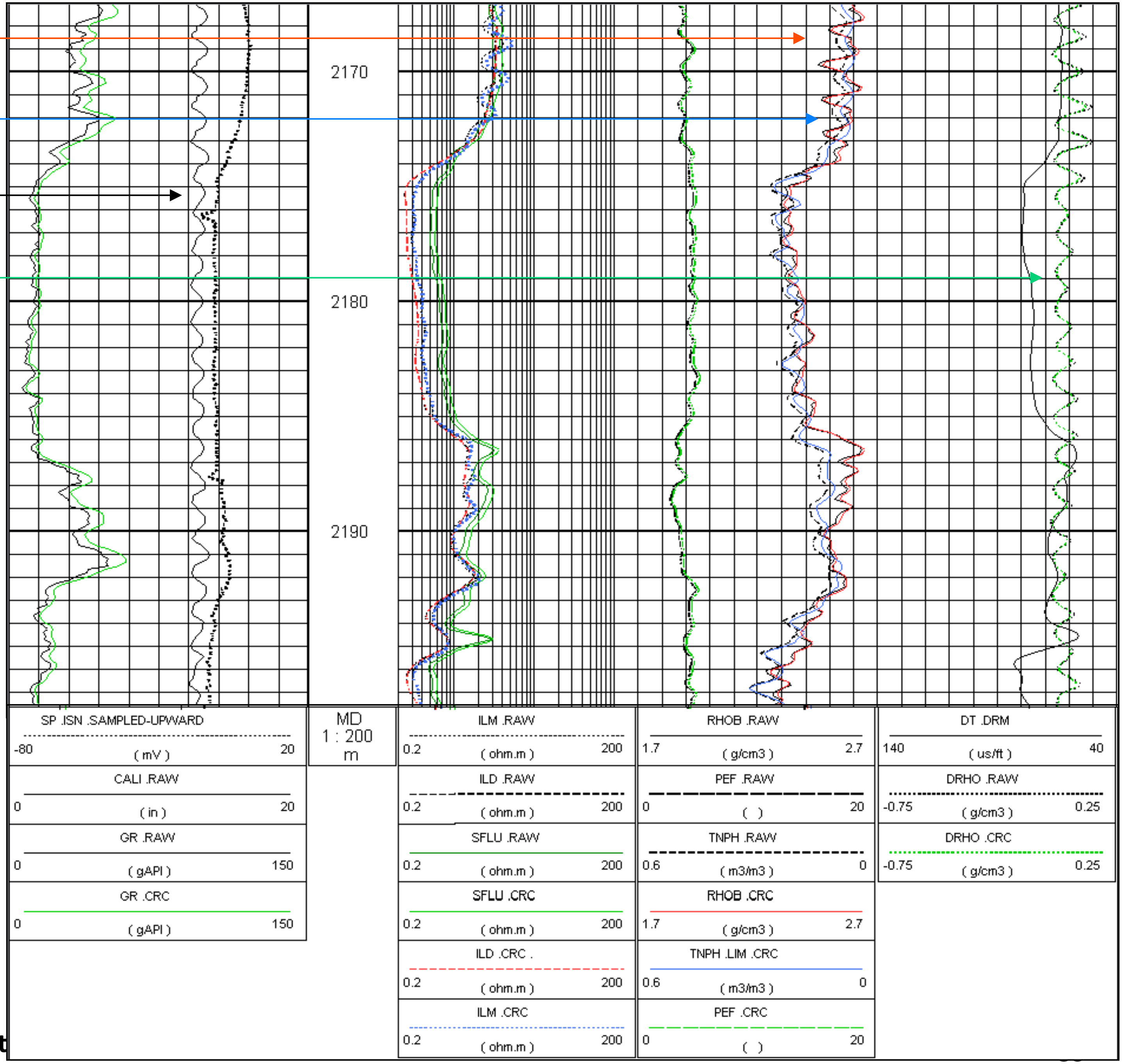
Comparison among different caliper measurements

esistivity

Borehole Geometry Tool (BGT)







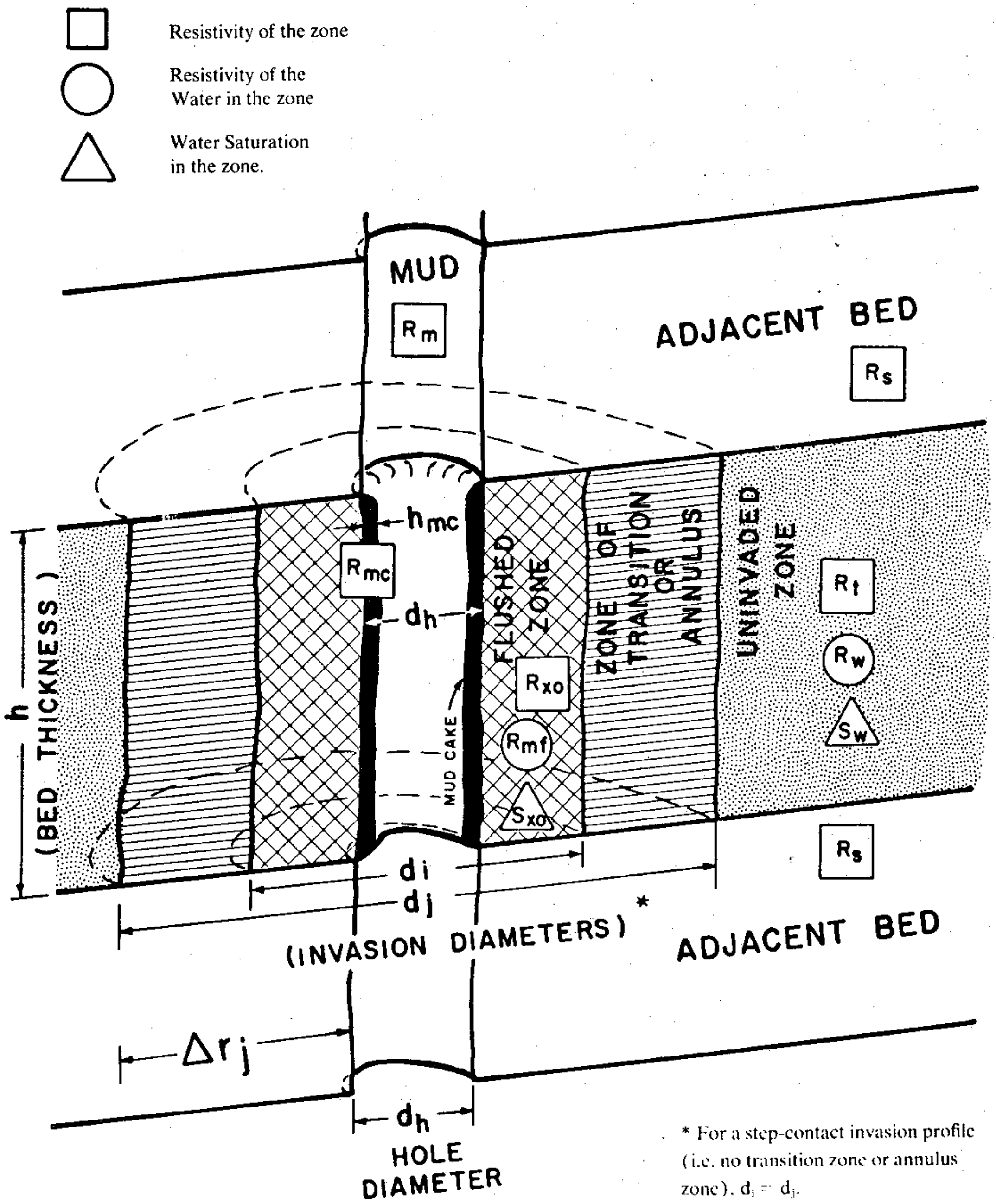
"Noisy" logs due to poor borehole wall quality.

Resistivity logs

Resistivity logs are used to:

- Determine **hydrocarbon vs. water-bearing** zones (most important)
- Indicate permeable zones
- Determine resistivity derived porosity

Resistivity logs



Resistivity logs: Archie's law

Definitions:

- ρ_o=resistivity of a water-filled formation
- ρ_w=resistivity of formation water
- F= formation resistivity factor
- m=cementation exponent (function of grain size, grain distribution, tortuosity>> high tortuosity $\equiv$ high m
- S_w= water saturation
- ρ_t= formation resistivity

Resistivity logs: Archie's law

- $\rho_o = F \times \rho_w$
- $F = \Phi^{-m}$

$$S_w = \left(\frac{\rho_0}{\rho_t} \right)^{\frac{1}{n}}$$

- n= saturation exponent (between 1.85 and 2.5: most commonly 2.0)

$$S_w = \left(\frac{F \times \rho_w}{\rho_t} \right)^{\frac{1}{n}}$$

Classification of Resistivity logs

In relation to depth of investigation

- Macro-devices to measure ρ_t
- Micro-devices to measure ρ_{xo}

Classification of tools

a. **Induction based > conductivity measurement**

   when $R_{mf} > 3\ R_w$ (non-salt-saturated drilling mud)

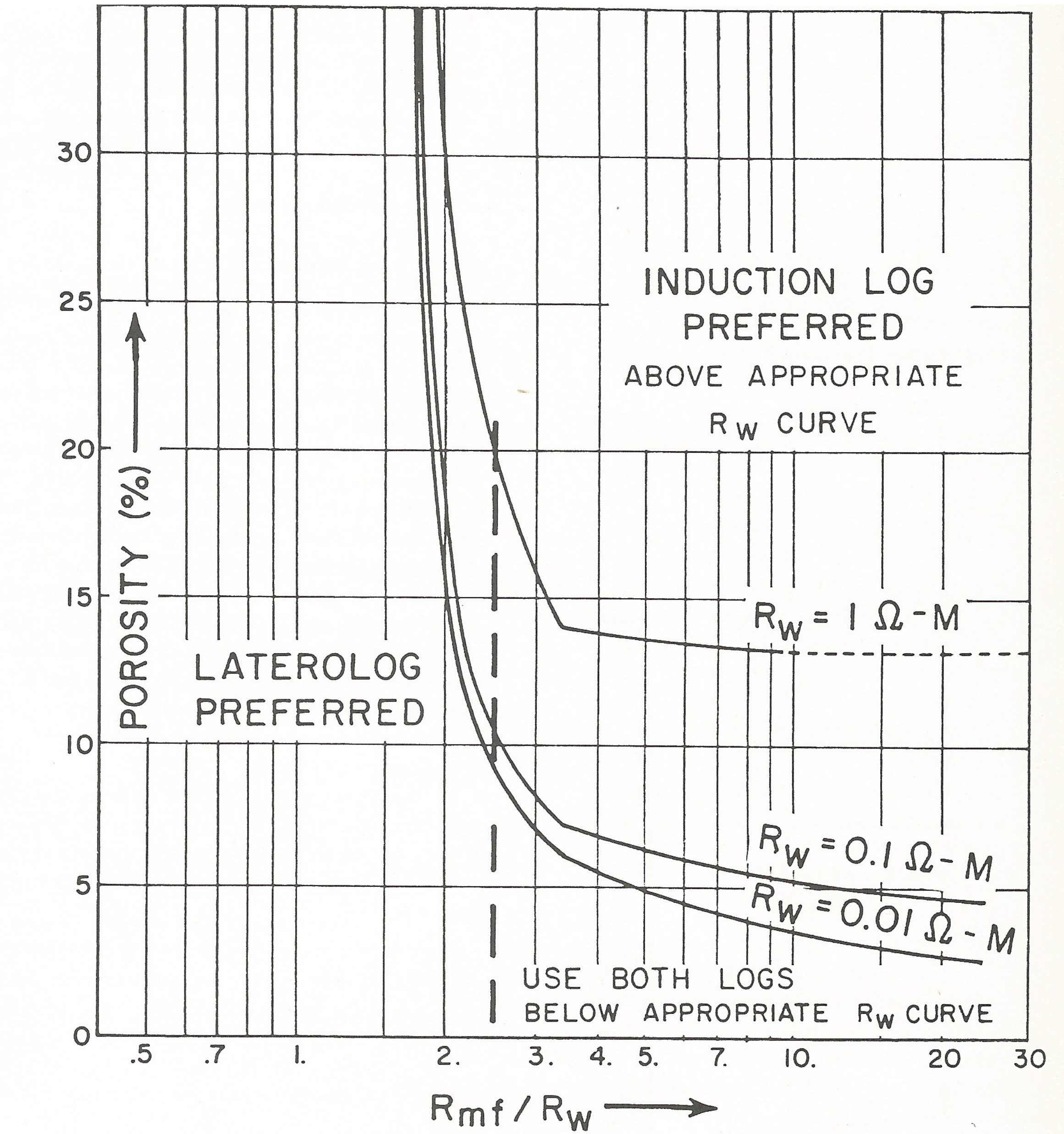
b. **Electrode > resistivity**

   when $R_{mf} \approx 3\ R_w$

In relation to tool physics

- Non focused, galvanic devices (WLL)
- Focused, galvanic devices (WLL e LWD)
- Low frequency induction devices (WLL)
- EM wave propagation devices (LWD)

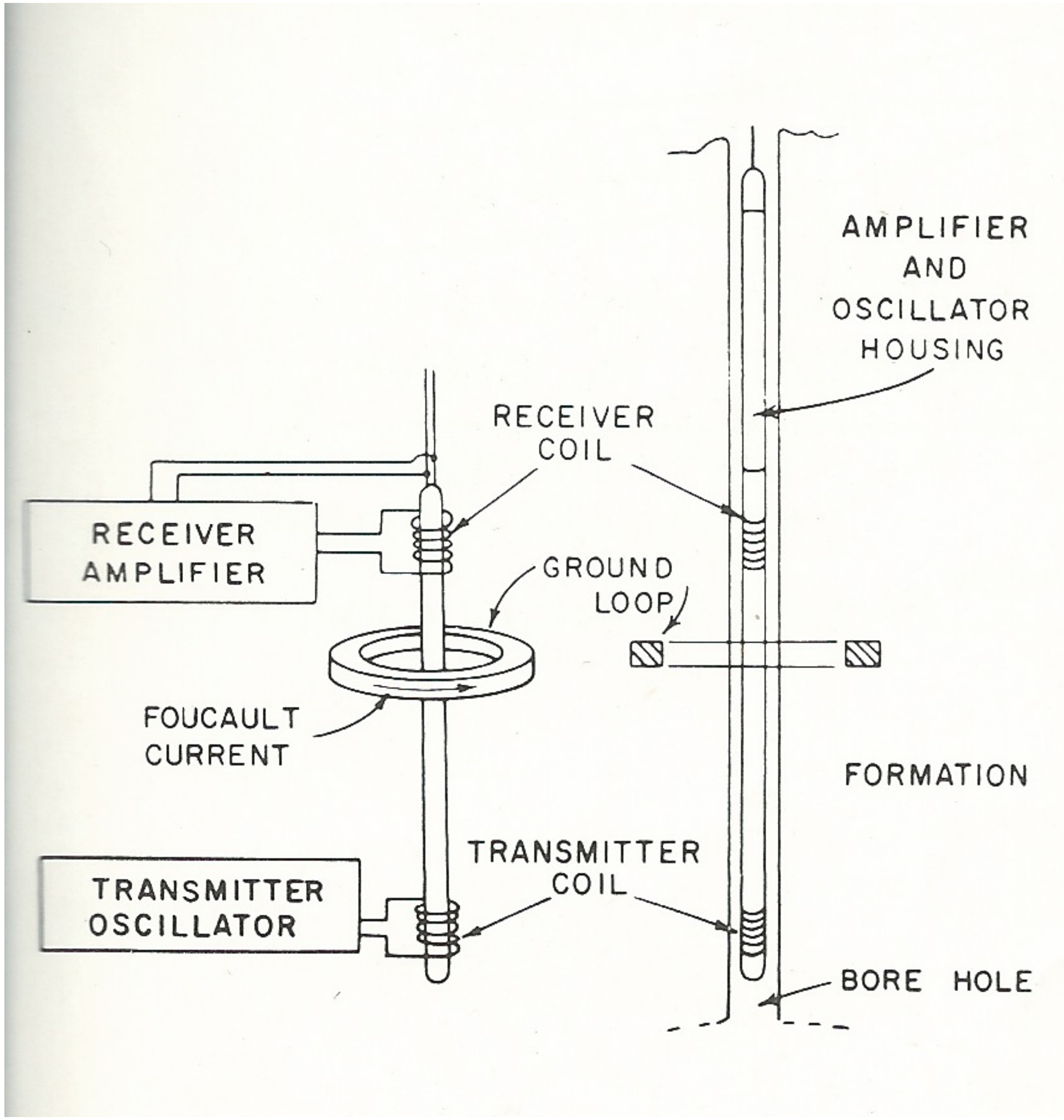
Quick choice of induction/electrode



Depth of resistivity log investigation

Flushed zone (Rxo)	Invaded zone (Ri)	Uninvaded zone (Rt)
Microlog	Short normal	Long Normal
Microlaterolog	Laterolog-8	Lateral Log
Proximity log	Spherically Focused log	Deep Induction Log
Microspherically Focused log	Medium Induction Log	Deep Laterolog
	Shallow Laterolog	Laterolog-3
		Laterolog-7
		Induction Log 6FF40

Induction log: schematic 2-coils induction system



Induction electric log

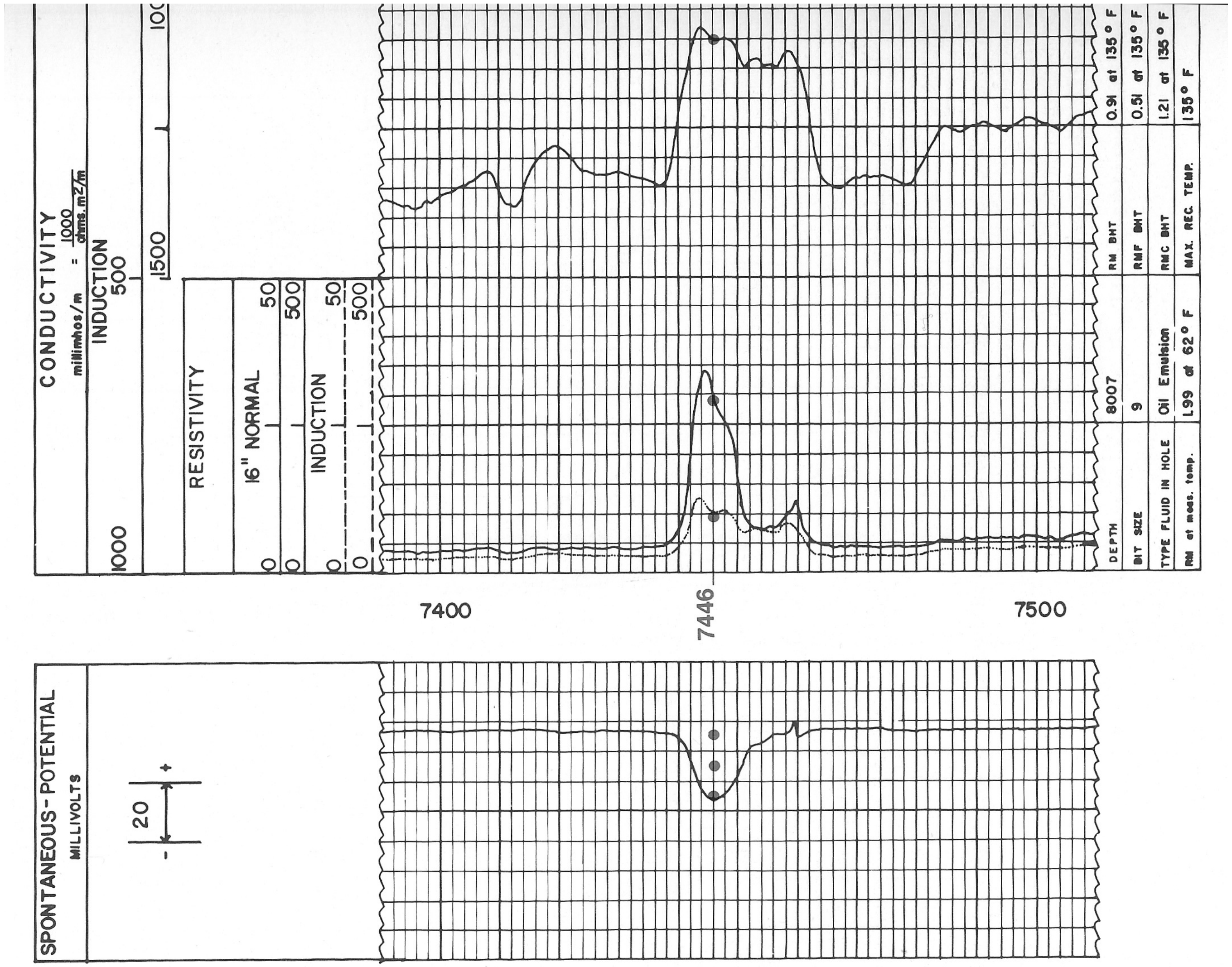
Normally composed of three curves:

1. Short normal
2. Induction
3. Spontaneous potential

Example (see next):

- SP = -40 mV
- R (short normal)=28 Ω m $\equiv$ Resistivity invaded zone (Ri)
- R (deep) = 10 Ω m $\equiv$ True Resistivity of formation (Rt)

Induction electric log



It can be run in oil- , foam- , air-filled boreholes

Dual Induction Focused log

The DIFL is the modern induction log and it is used in **formations deeply invaded by mud filtrate**.

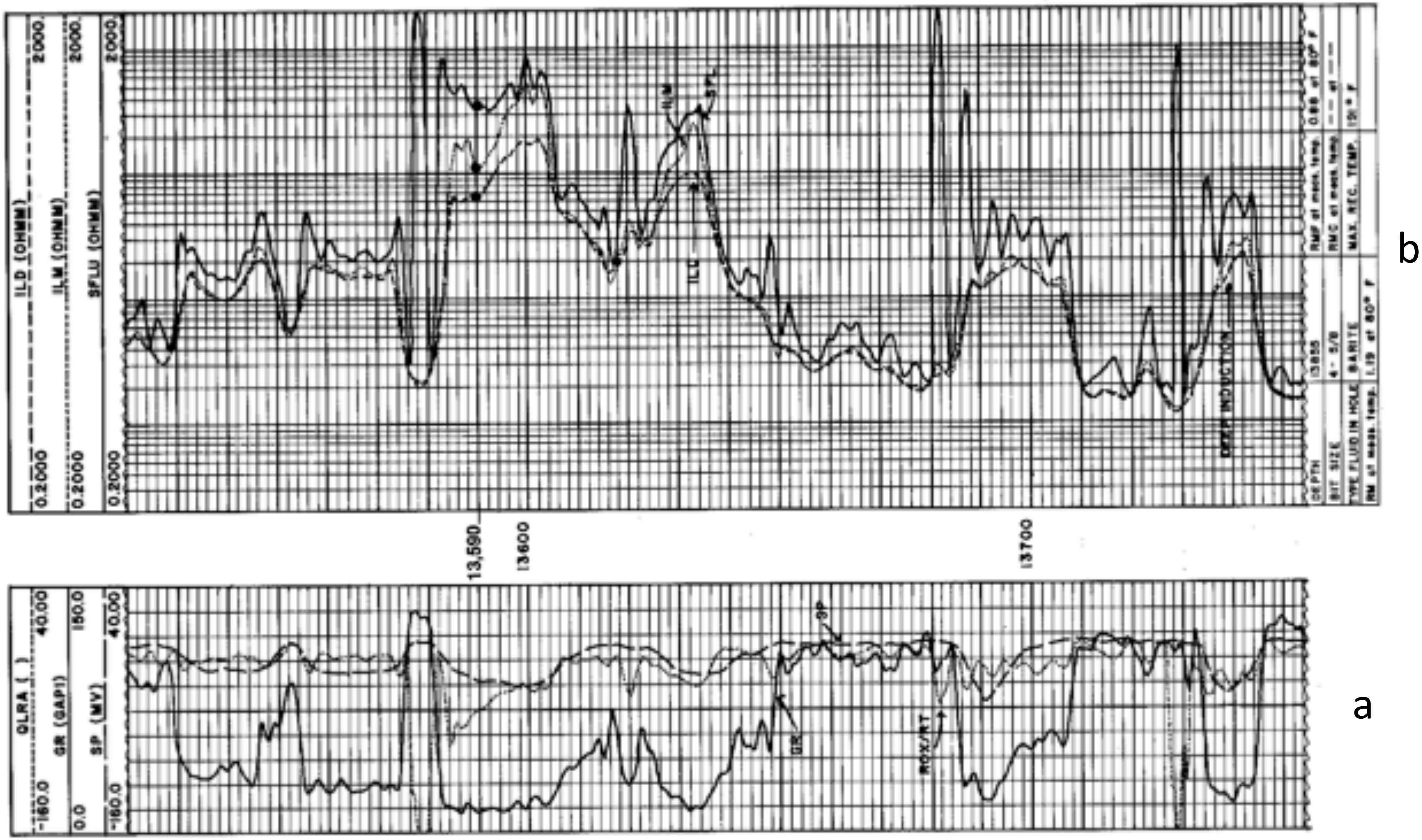
It consists of 3 measurements performed by 3 different devices:

1. Deep reading (Rild≡Rt) similar to previous IEL);
2. Medium-reading (Rilm≡Ri);
3. Shallow-reading > Focused Laterolog≡Short normal < reads Rxo

Resistivity values obtained from the 3 readings are used to:

a. Correct Rild to Rt (due to deep invasion they may not be the same);
b. Determine diameter of invasion
c. Determine Rxo/Rt value (used to discriminate water-hydrocarbon bearing zones)

Dual Induction Focused log



Dual Induction Focused log

In (a):

-Gamma ray

-SP

-Rxo/Rt

In (b):

R_{ILD} = 70 Ω m

R_{ILM} = 105 Ω m

R_{SFL} = 320Ω m

And from such values we further get

R_{SFL}/R_{ILD} = 320/70=4.6

R_{ILM}/R_{ILD} = 105/70=1.5

Correction of R_{ILD} to Rt

-Plot the R_{SFL}/R_{ILD} and R_{ILM}/R_{ILD} values
-Read the R_T/R_{ILD} value >> (0.82)
-Read the diameter of invasion d_i >> (65in)
-Read the Rxo/Rt value >> (7.0)

Now:
(R_T/R_{ILD} from the chart) x log reading = R_T corrected
In this case: 70 x 0.82 = 57.4 ohm m (true formation resistivity)

(R_{xo}/R_T from the chart) x R_T corrected = R_{xo} corrected

Resistivity derived porosity

Porosity in a porous and permeable water-bearing formation can be related to shallow resistivity (Rxo) by:

$$S_{xo} = \sqrt{F \cdot \frac{R_{mf}}{R_{xo}}}$$

Where Sxo=1.0 (100%) in water-bearing zones, therefore

$$1.0 = \sqrt{F \cdot \frac{R_{mf}}{R_{xo}}} = F \cdot \frac{R_{mf}}{R_{xo}}$$

$$F = \frac{R_{xo}}{R_{mf}}$$

Resistivity derived porosity

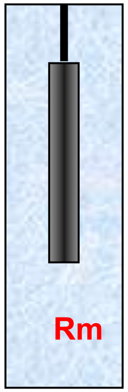
But

$$F = \frac{a}{\Phi^m} = \frac{R_{xo}}{R_{mf}}$$

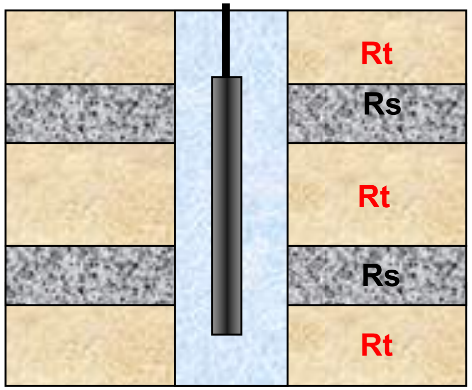
$$\Phi = \left(\frac{a \cdot R_{mf}}{R_{xo}} \right)^{\frac{1}{m}}$$

With
a = 1, 0.62, 0.81 for carbonates, unconsolidated-consolidated sands respectively
m = 2.0 for consolidated sands and carbonates, 2.15 for unconsolidated sands

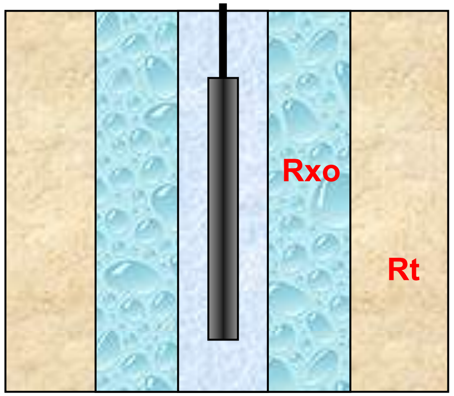
Environmental effects affecting resistivity measurements



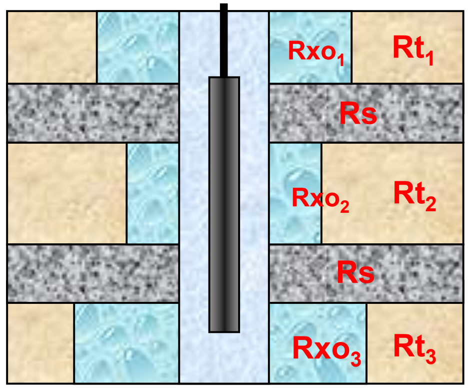
Borehole



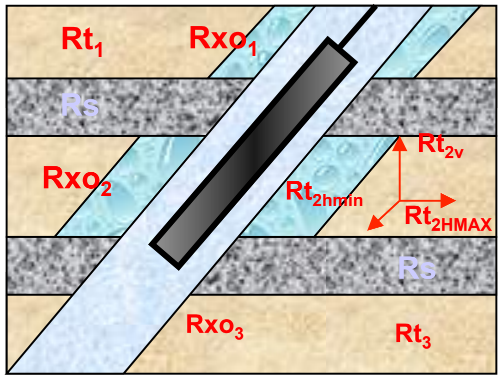
1D VERTICAL
(shoulder bed)



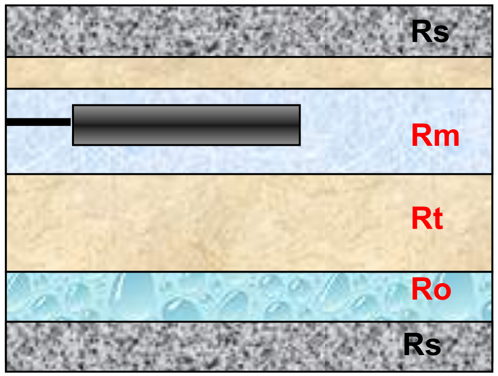
1D RADIAL
(invasion effect)



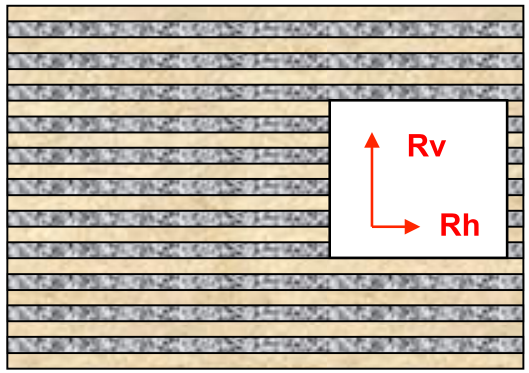
2D



2D +dip
(dipping beds)

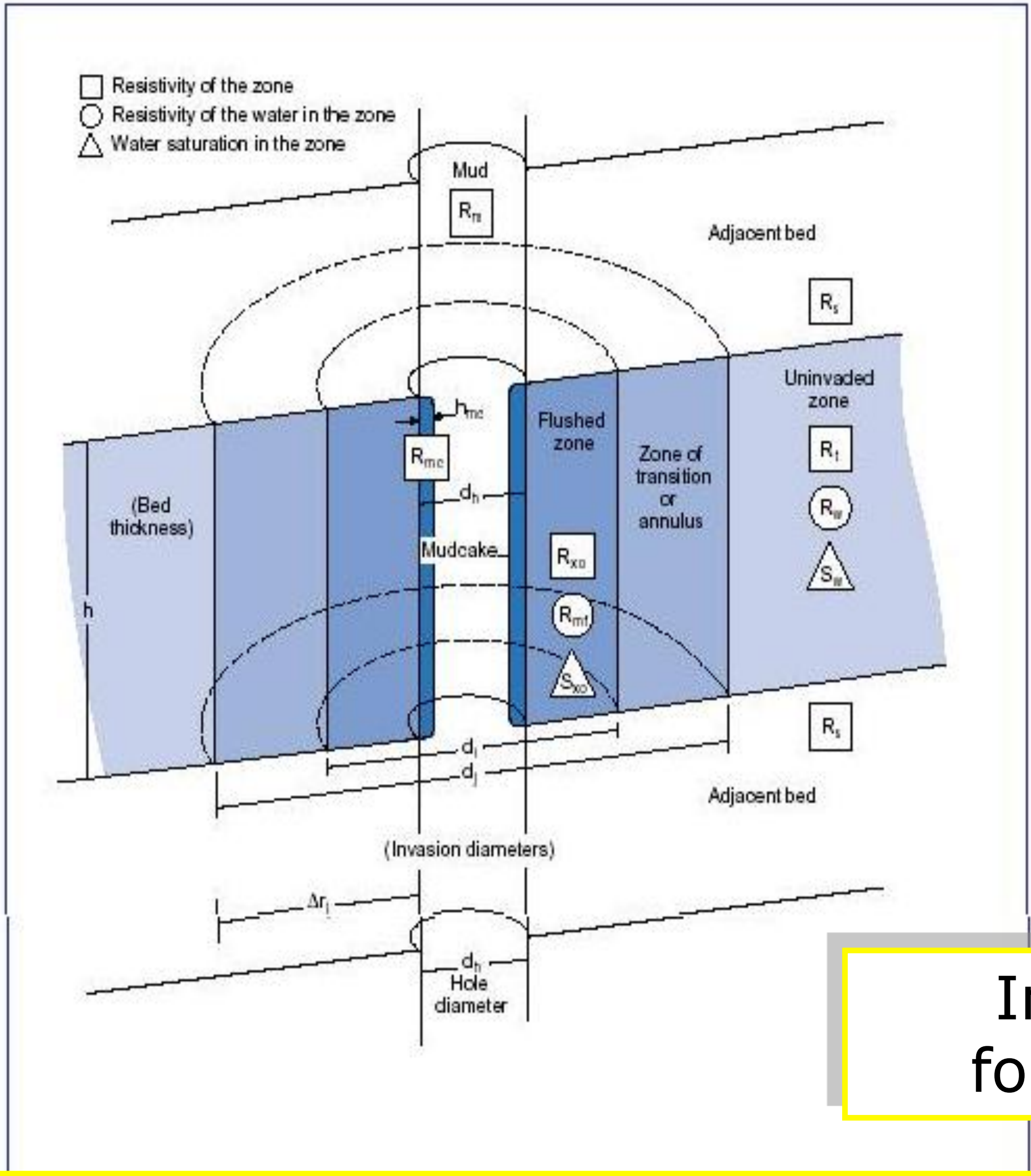


3D



Anisotropy

Symbols Used in Log Interpretation



Invasion effects and formation parameters

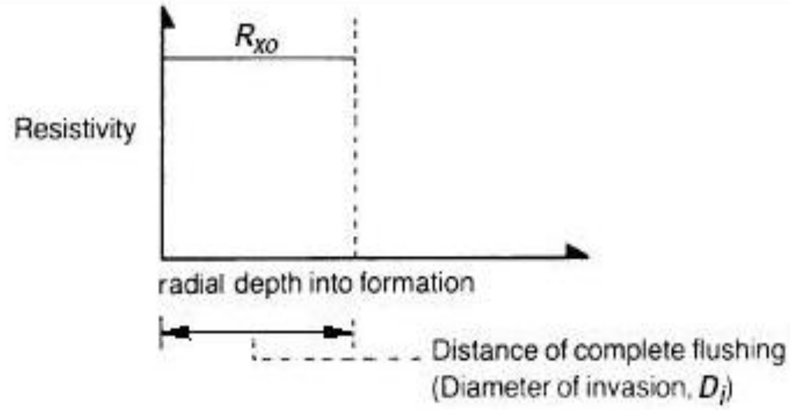


Figure B4: Invasion Process

$Sw = Sxo = 100\%$

$Ro = F\ Rw = (1/\Phi^m)\ Rw$
$Rxo = F\ Rmf = (1/\Phi^m)\ Rmf$

$Sw < 100\%,\ Sxo < 100\%$

$Rt = (1/\Phi^m)(Rw)/Sw^n)$
$Rxo = (1/\Phi^m)(Rmf)/Sxo^n)$

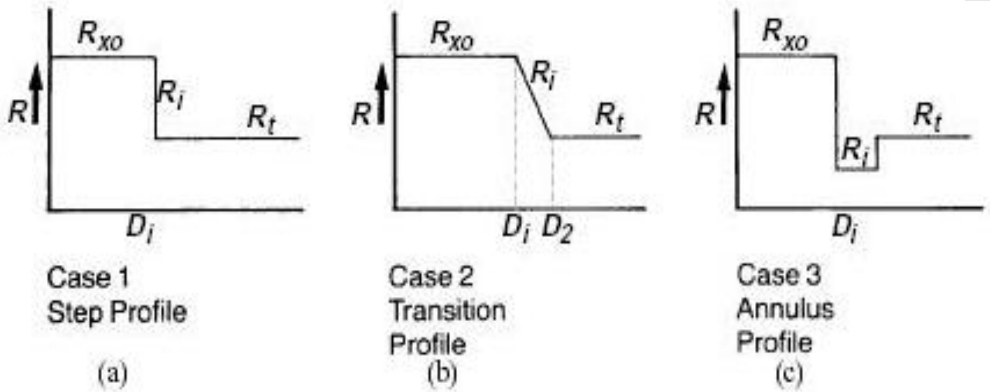
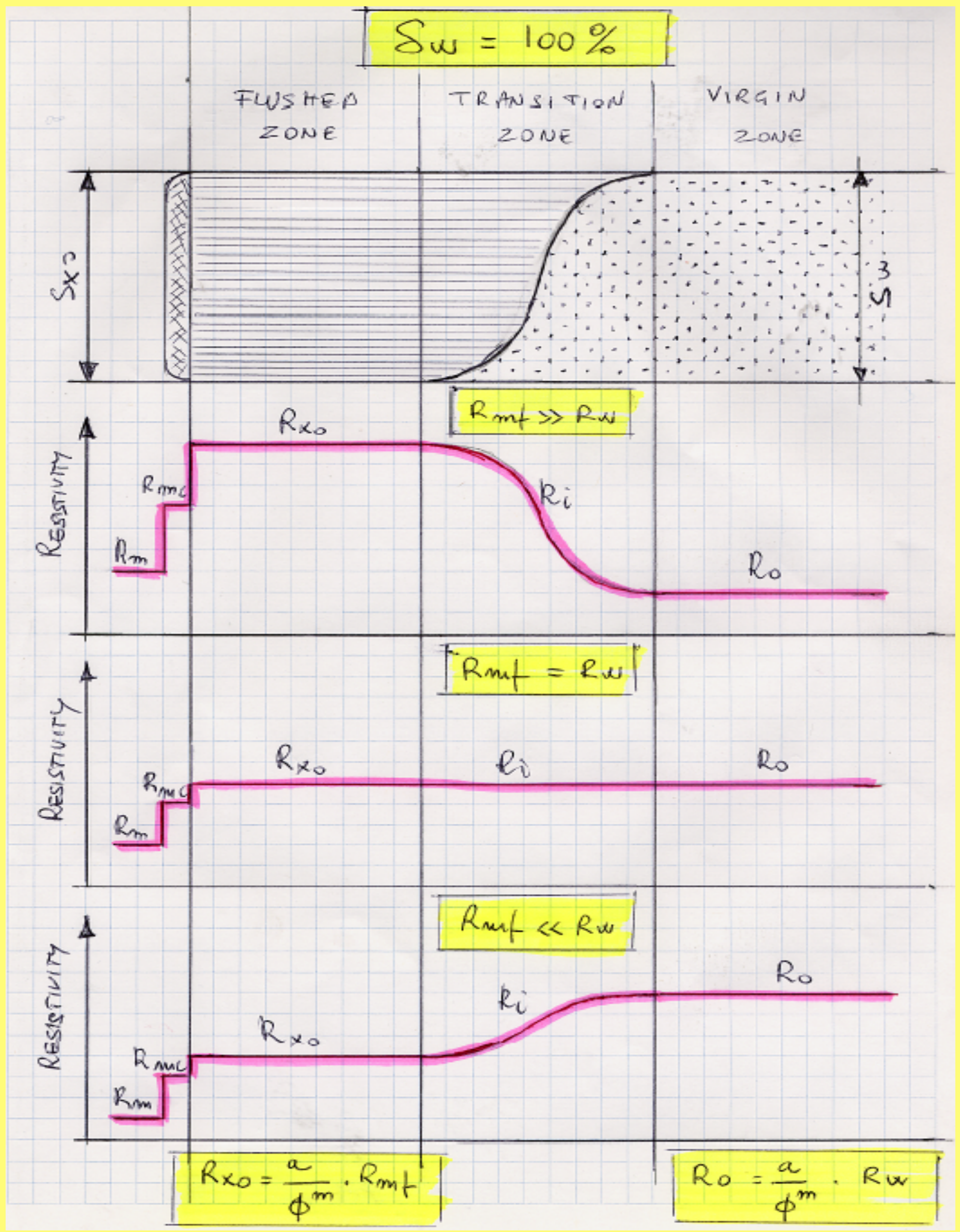
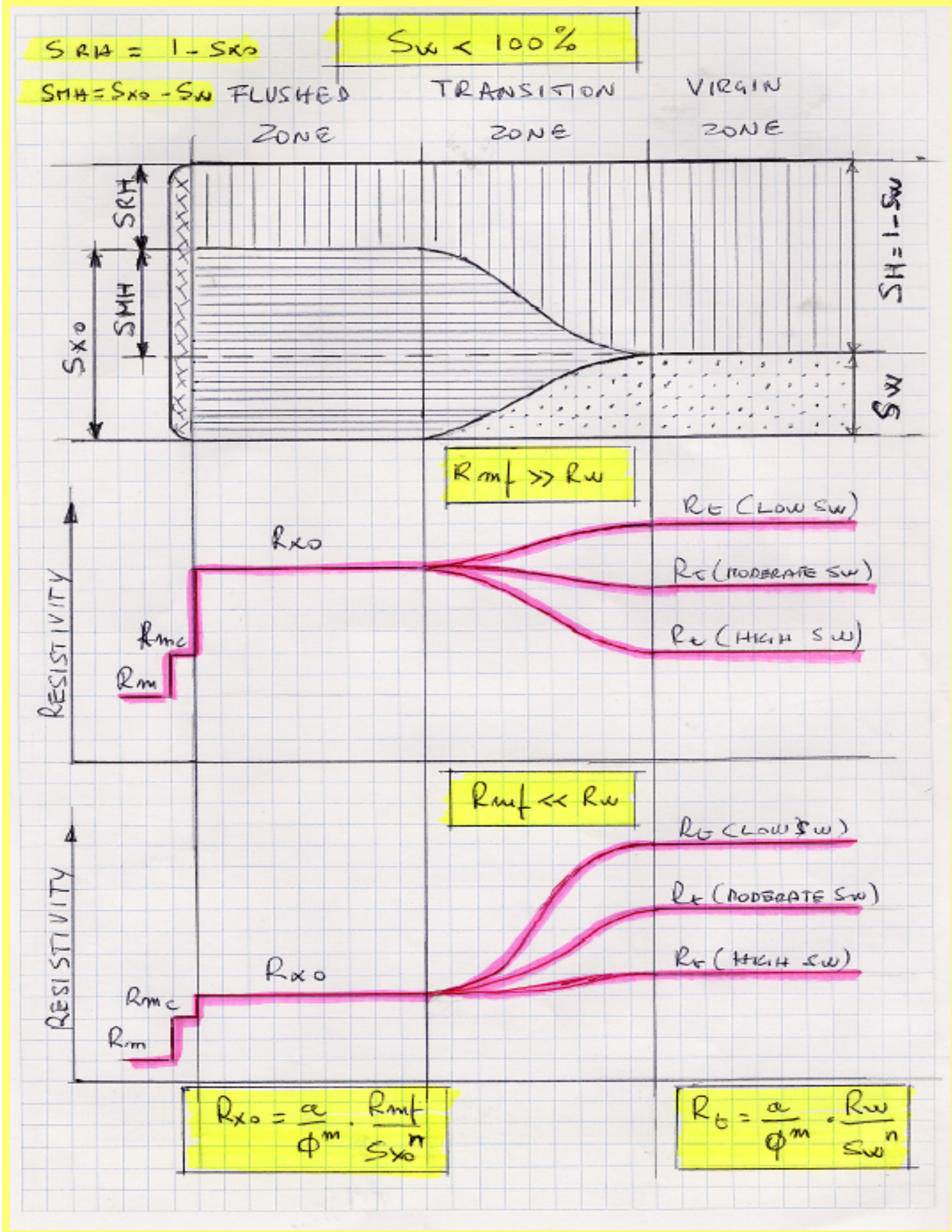
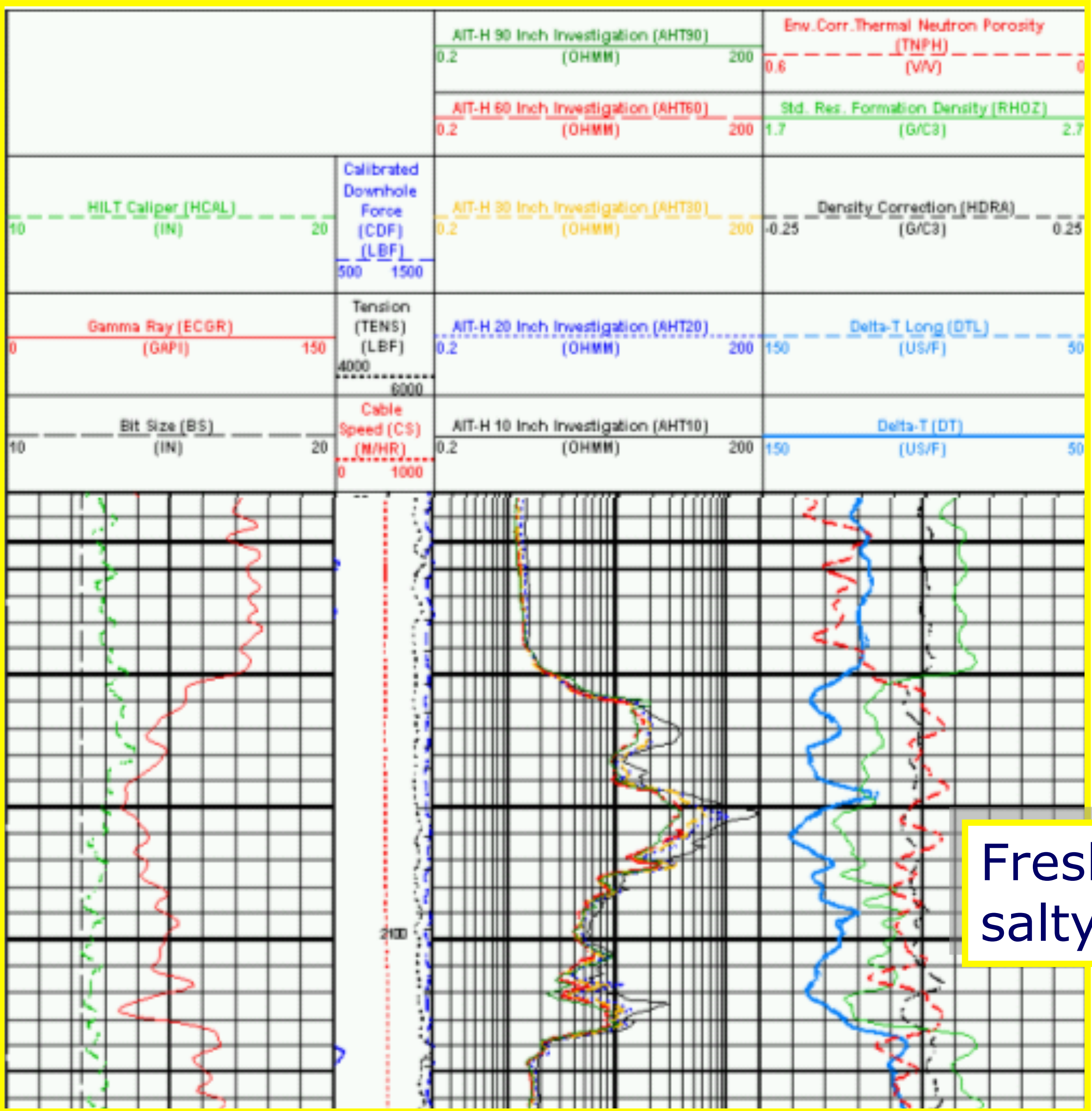


Figure B5

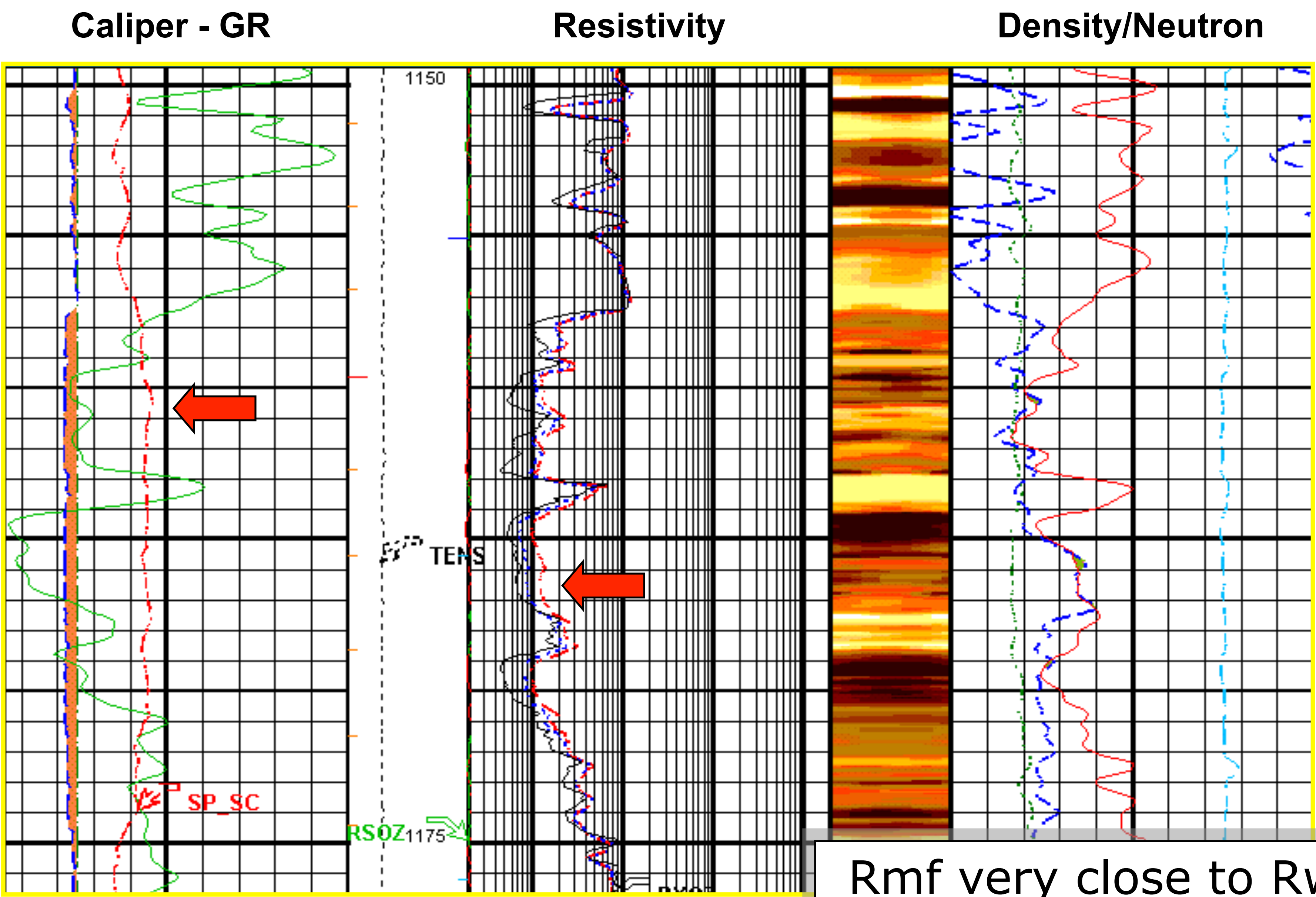
Invasion and related resistivity profiles





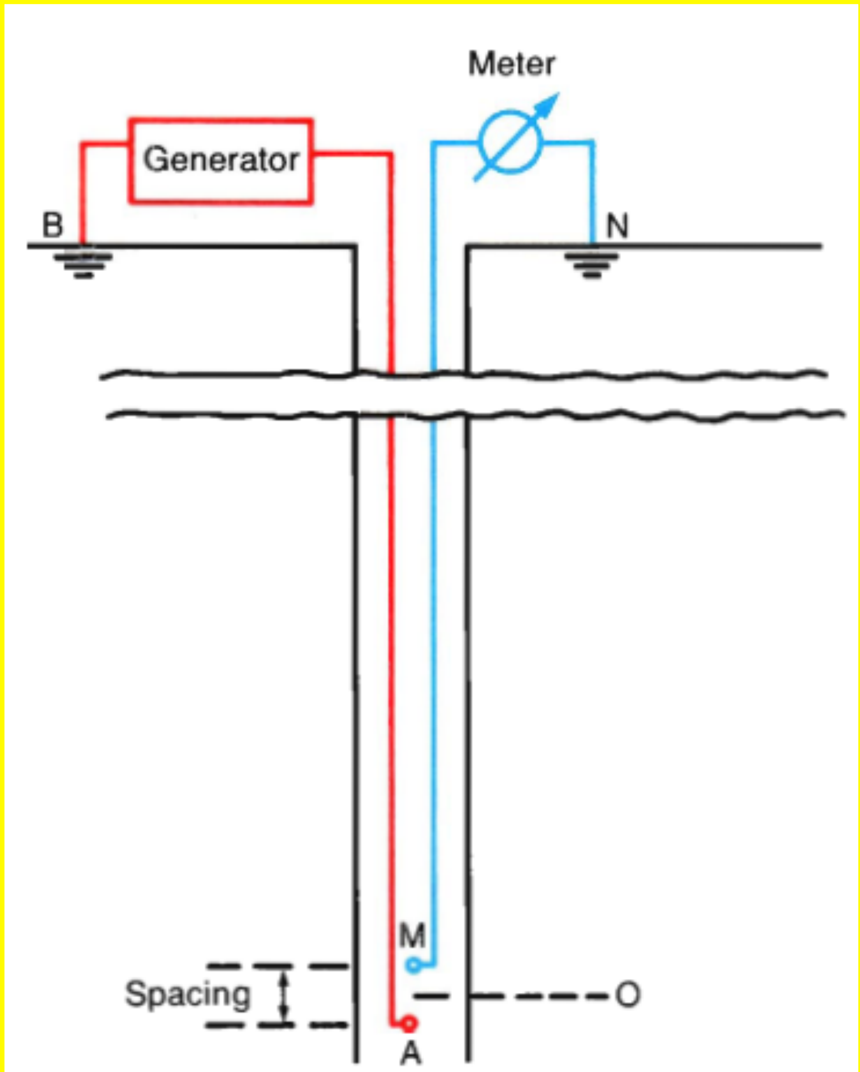


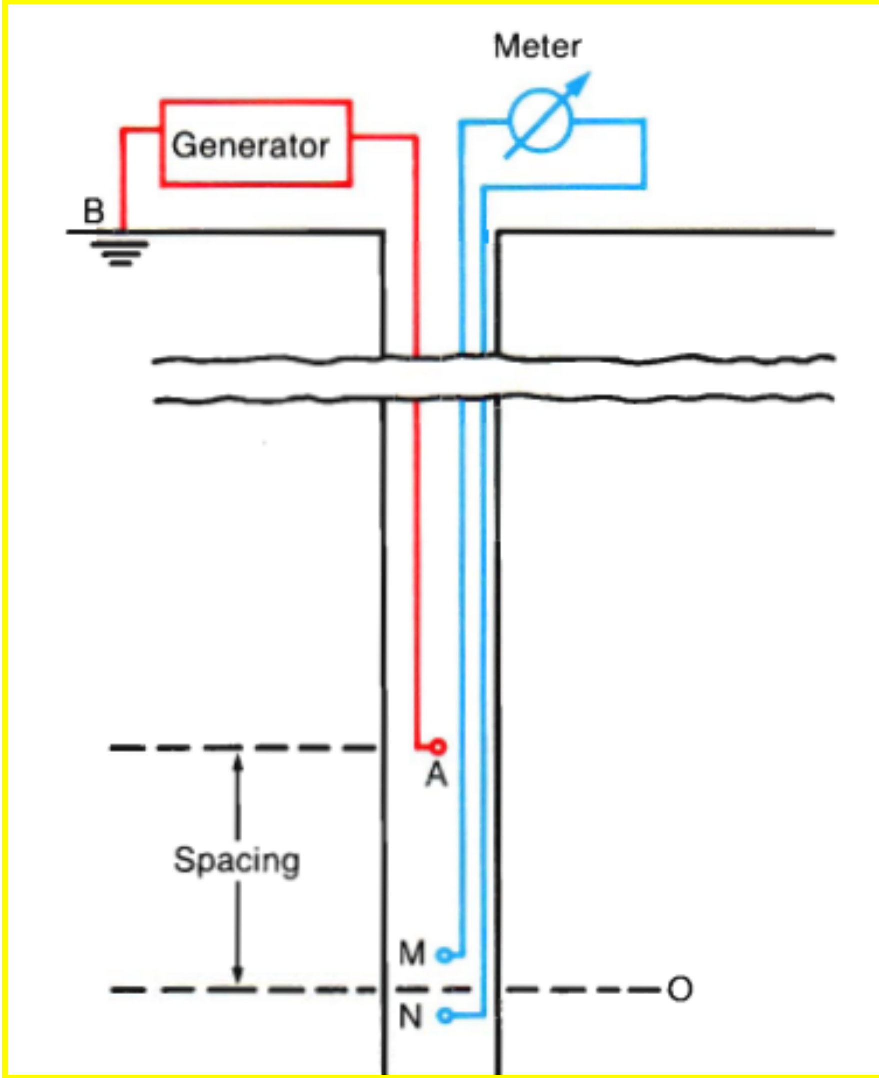
Fresh mud and salty formation water



Rmf very close to Rw

Non focused electrical resistivity tools



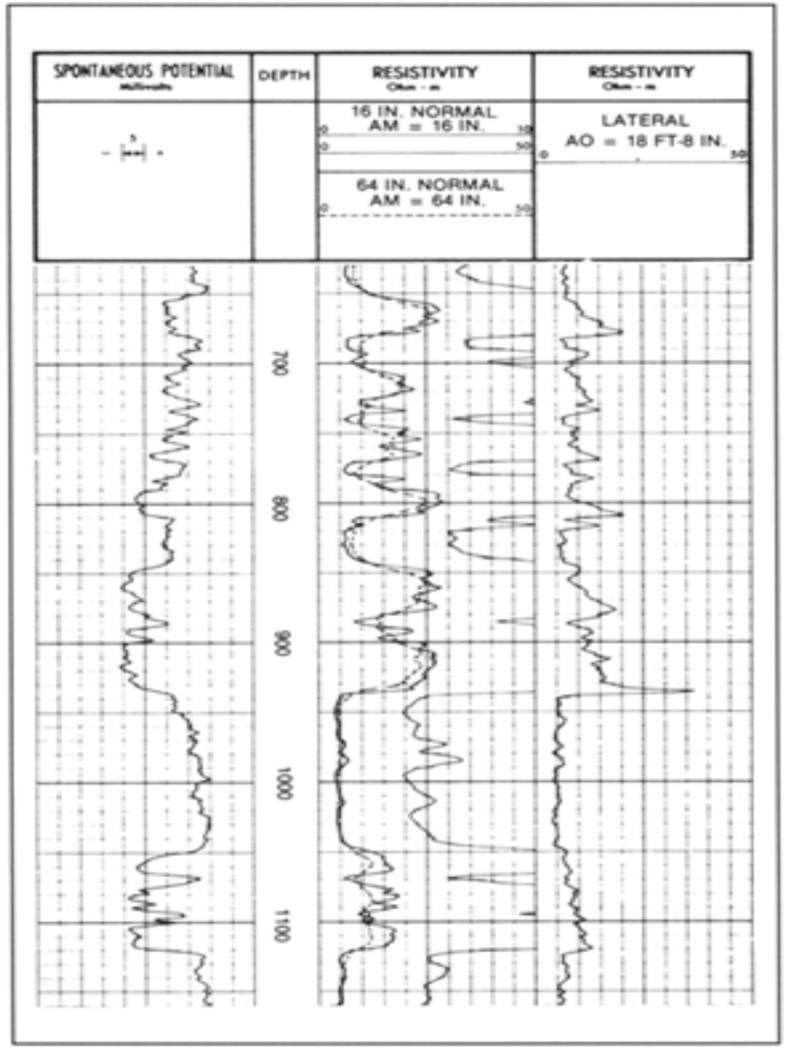


Old E (electrical) logs

Conventional Electrical Log (ES)

Track 1	Depth	Track 2	Track 3
SP (mv) *Linear scale*		**SN** (ohmm) **Ampl. SN** (ohmm) **LN** (ohmm) *Linear scale*	**IN** (ohmm) *Linear scale*

SN = Short Normal (spacing 16”)
Ampl. SN = Amplified Short Normal
LN = Normal (spacing 64”)
IN = Inverse or Lateral (spacing 18’ 8”)



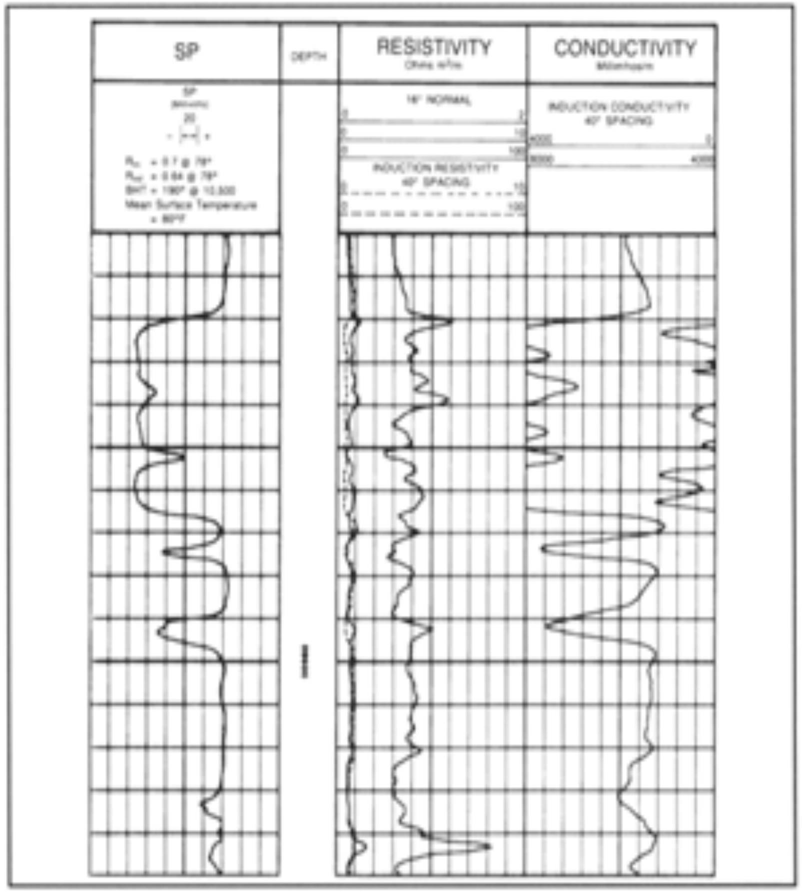
Electrolog example

Old E (electrical) logs

Induction Electrical Log (IES)

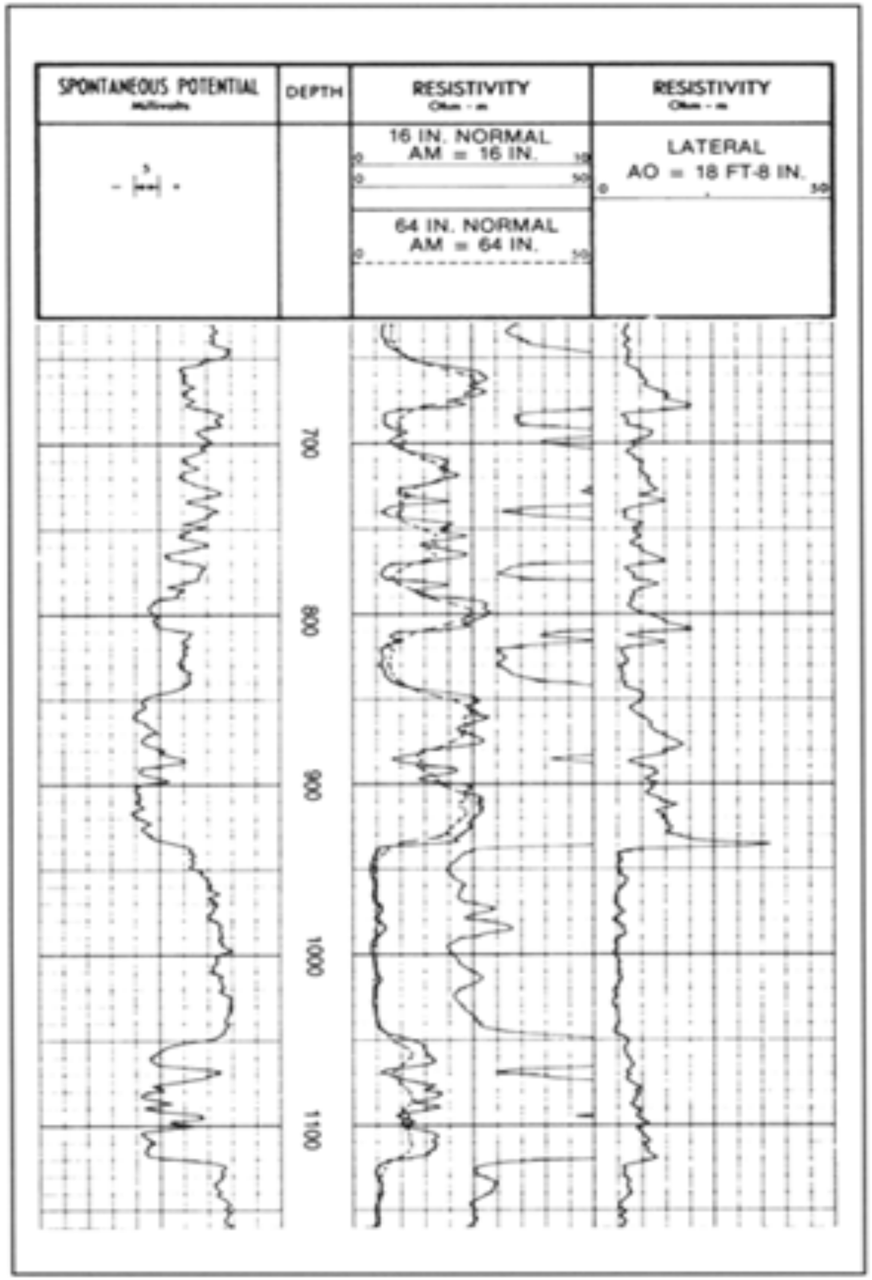
Track 1	Depth	Track 2	Track 3
SP (mv) *Linear scale*		**SN** (ohmm) **Ampl. SN** (ohmm) **6FF40 R** (ohmm) *Linear scale*	**6FF40 C** (ohmm) *Linear scale*

SN = Short Normal (spacing 16”)
Ampl. SN = Amplified Short Normal
6FF40 R = Induction log deep (40”) resistivity
6FF40 C = Induction log deep (40”) conductivity

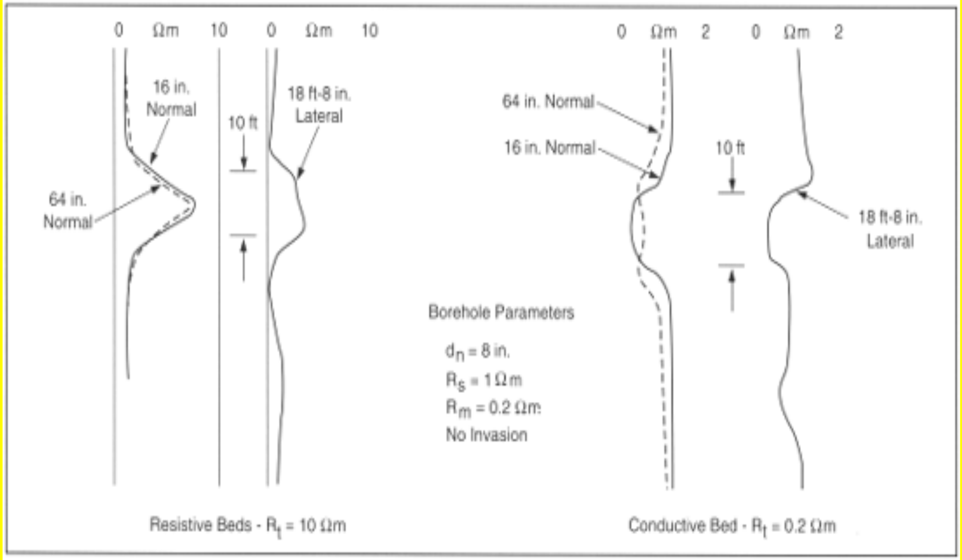


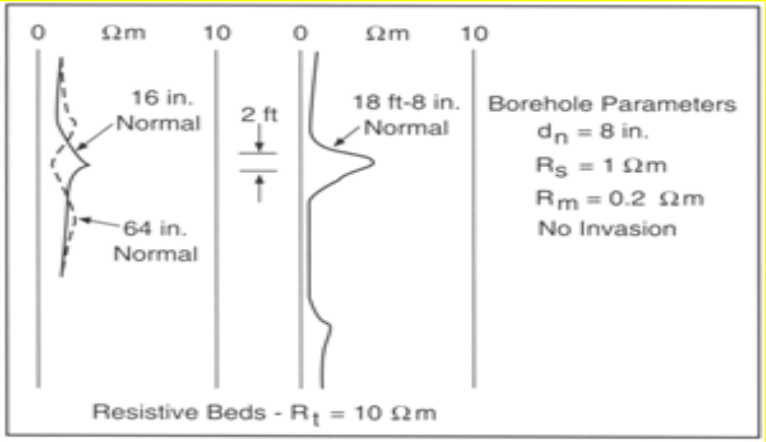
Induction Electrolog linear presentation example

Normal and lateral resistivity logs



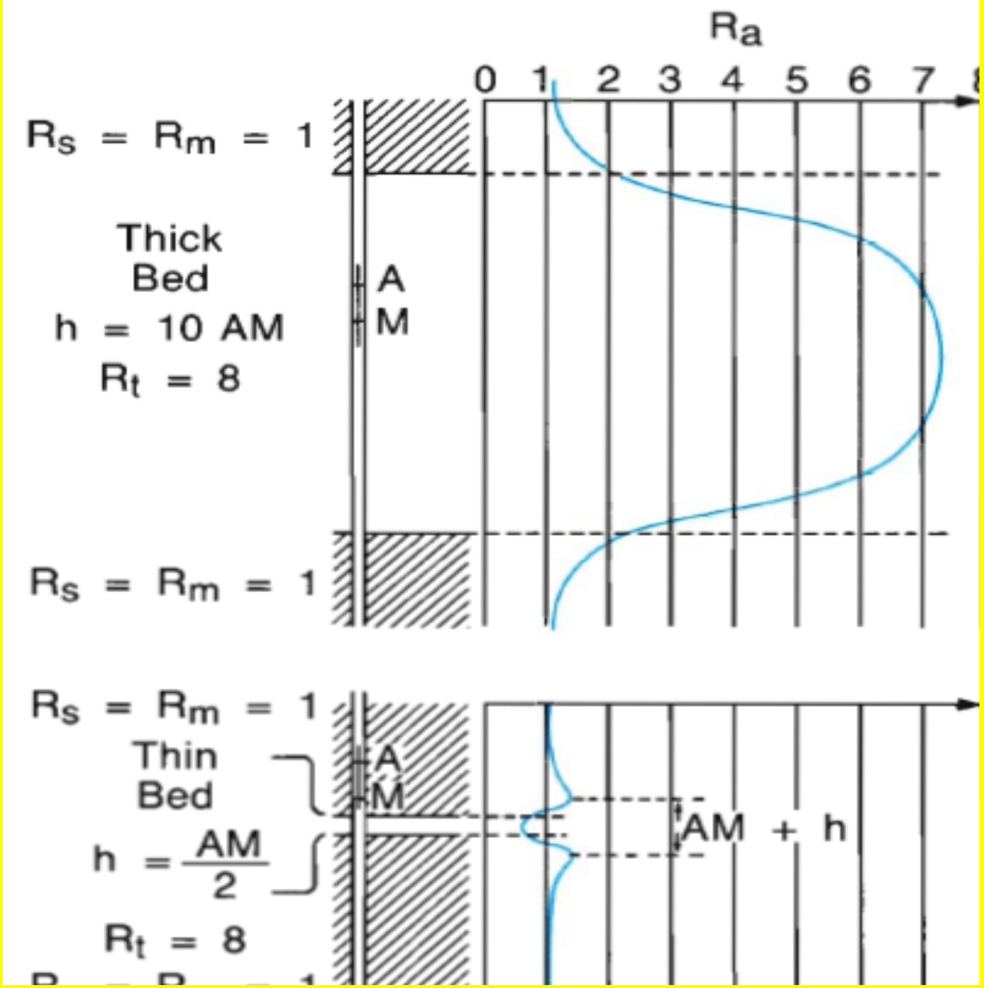
Electrolog example

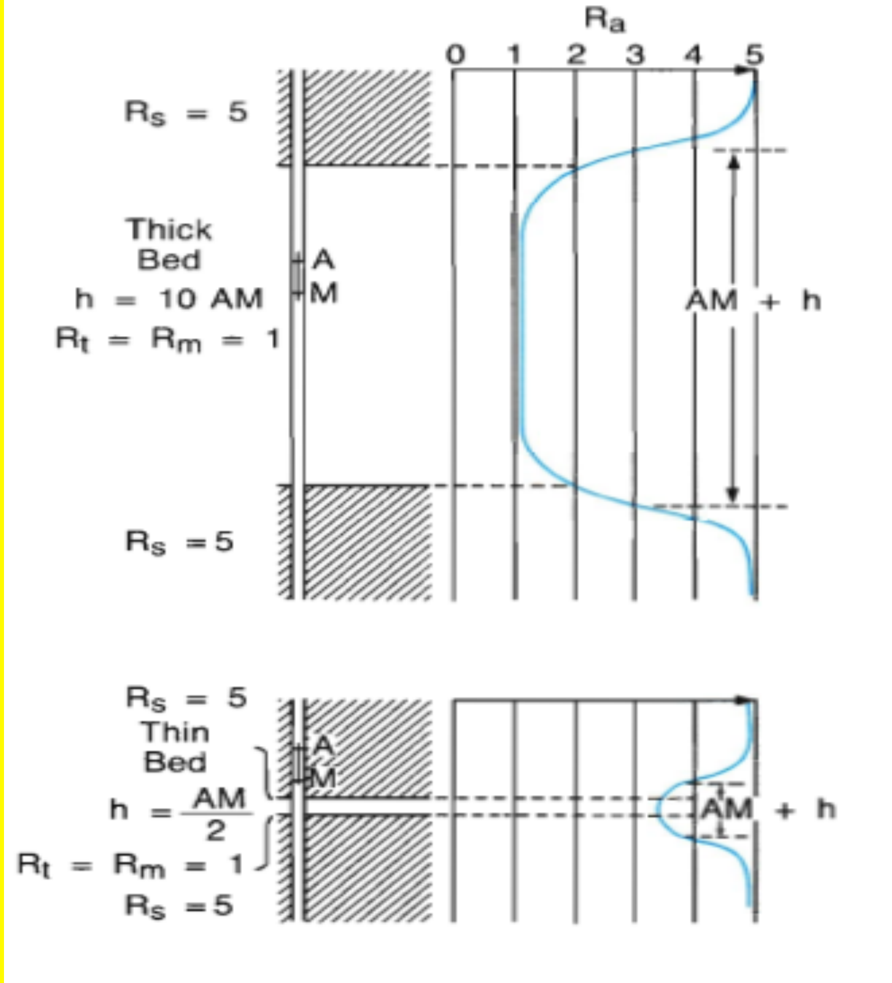




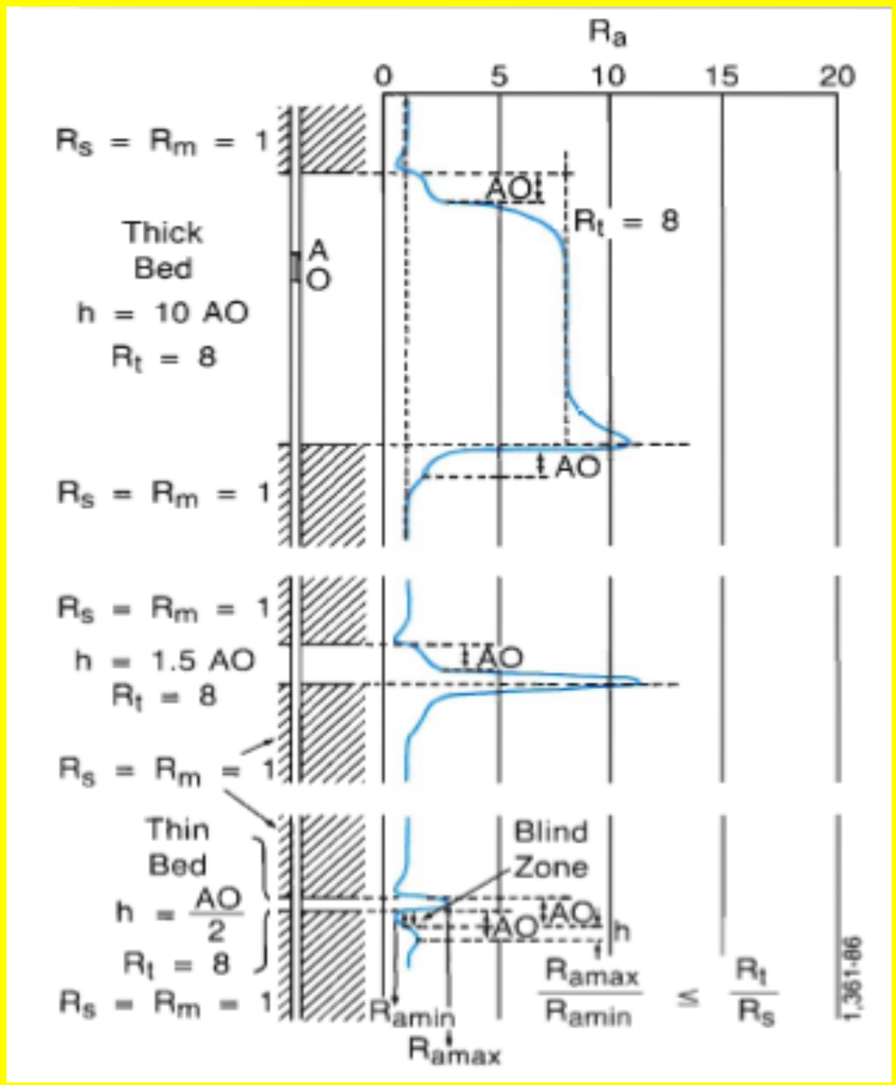
Resistivity reversal occurs when beds are thinner than a normal curve's electrode spacing

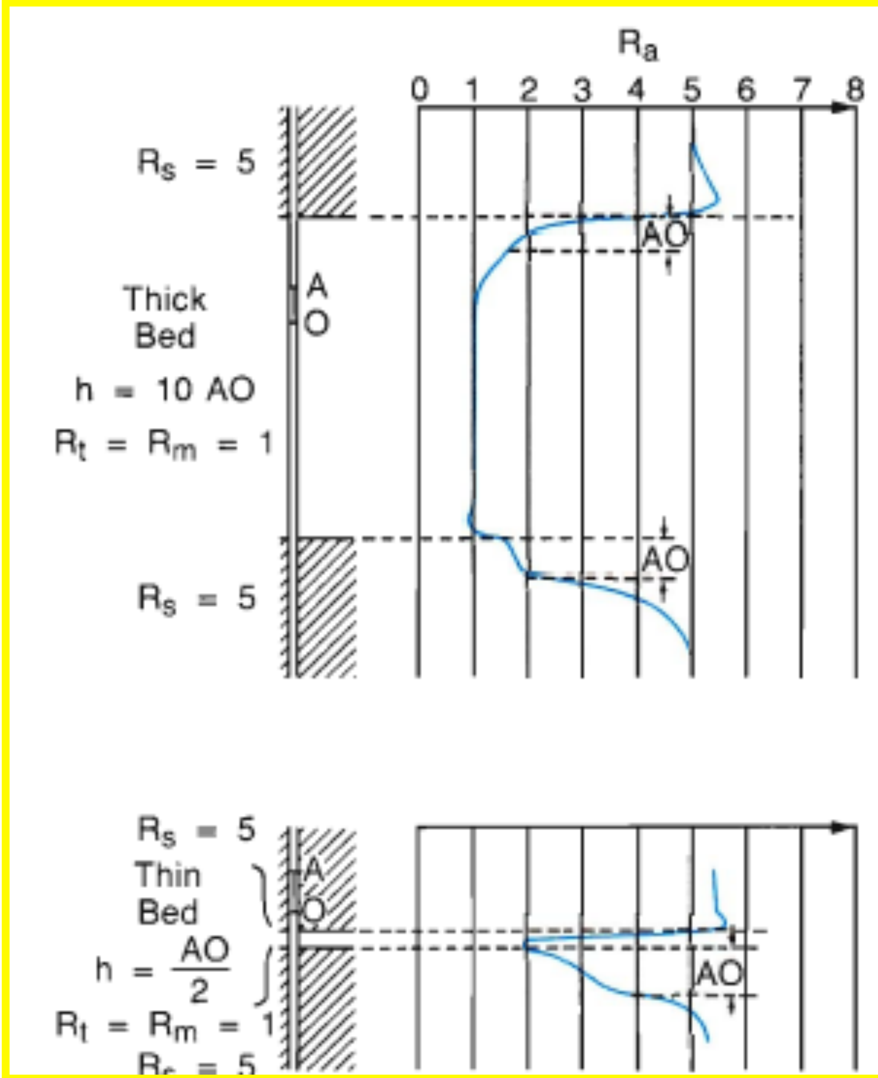
Normal electrical log responses: normal



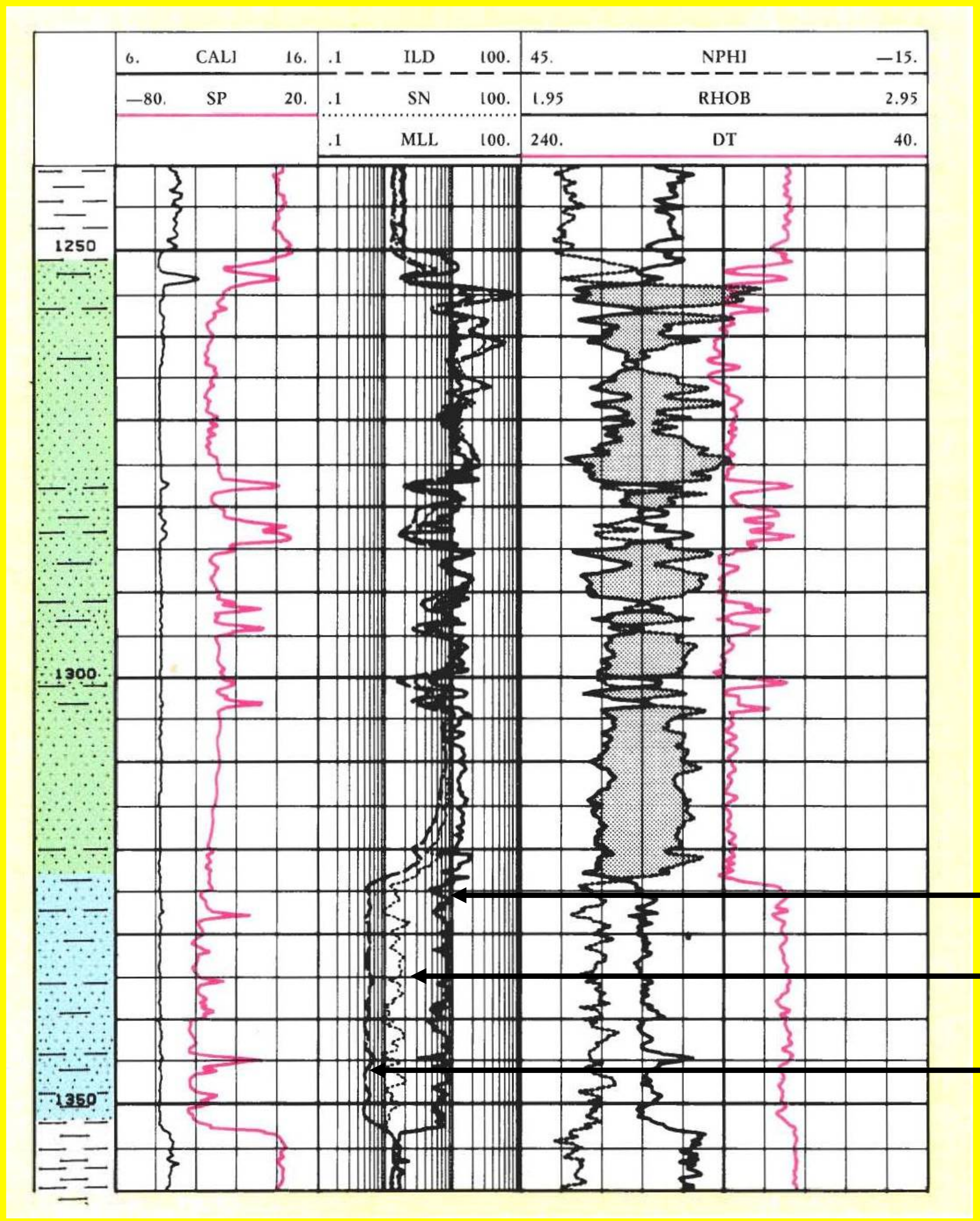


Lateral electrical log responses: lateral





Well Settala 1
SP/ILD/SN/MLL
FDC/CNL/BHC



MLL (Rxo)

SN (Ri)

ILD (Rt)

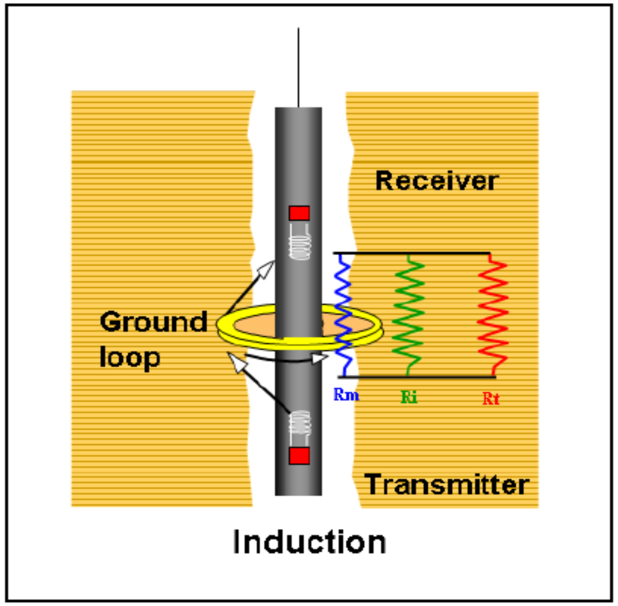


Figure 1A. Induction logging system.

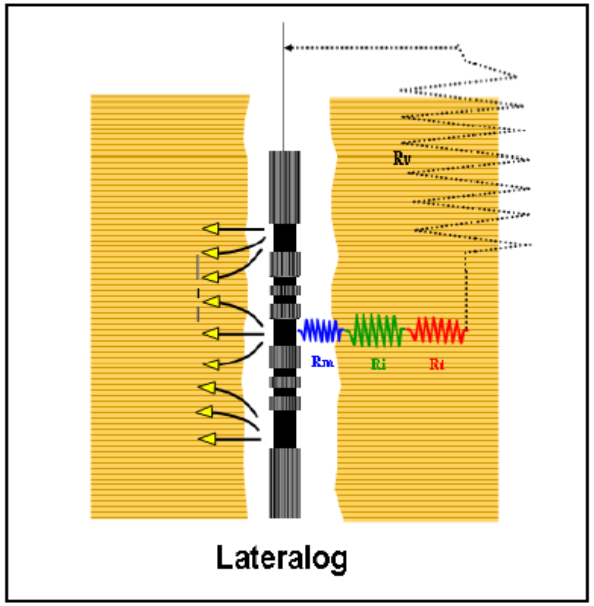


Figure 1B. Lateral logging system.

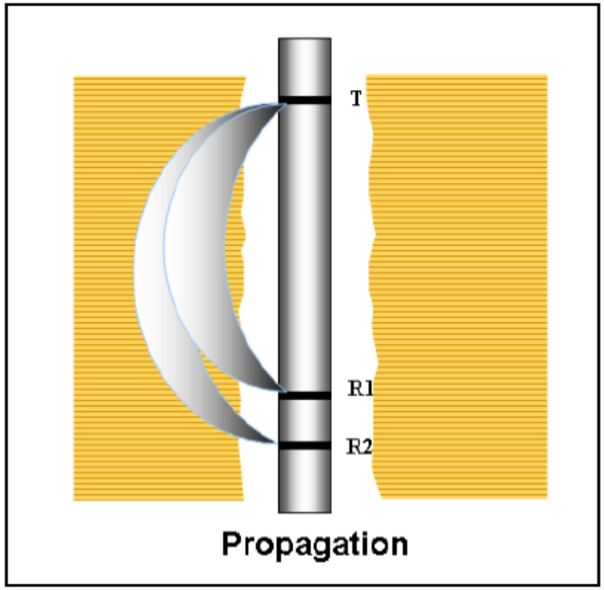


Figure 1C. Propagation logging system.

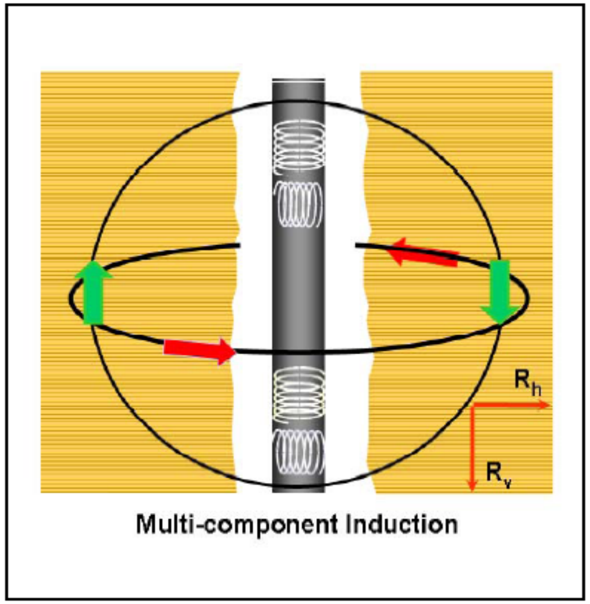
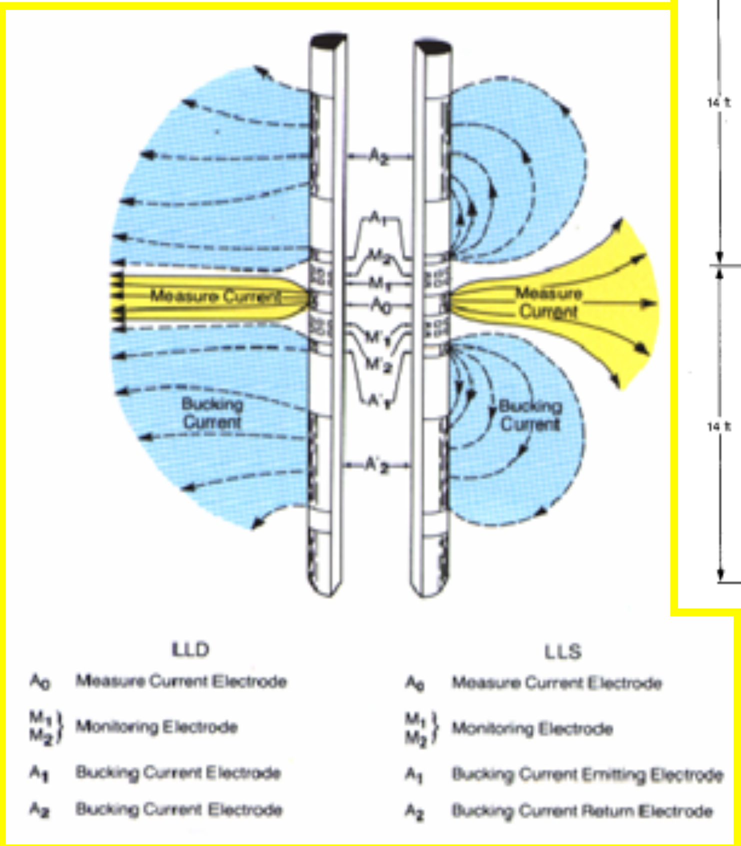
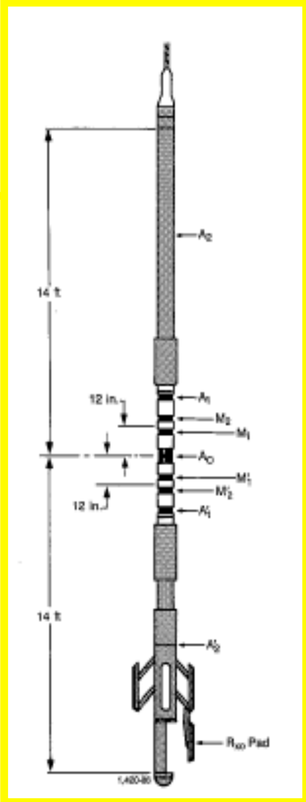


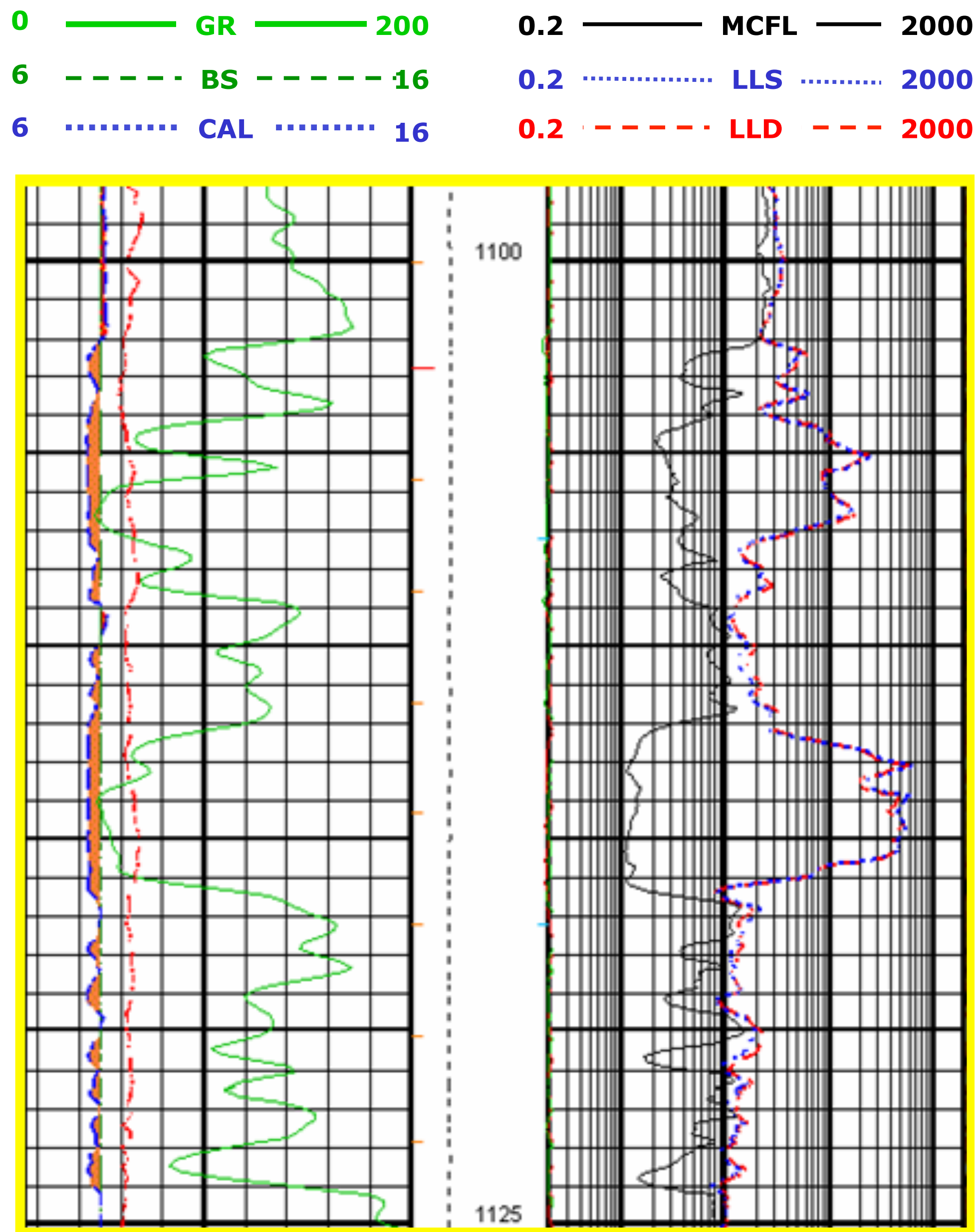
Figure 1D. Multicomponent induction logging system.

Resistivity tools: Wire Line (WLL) & While Drilling (LWD)

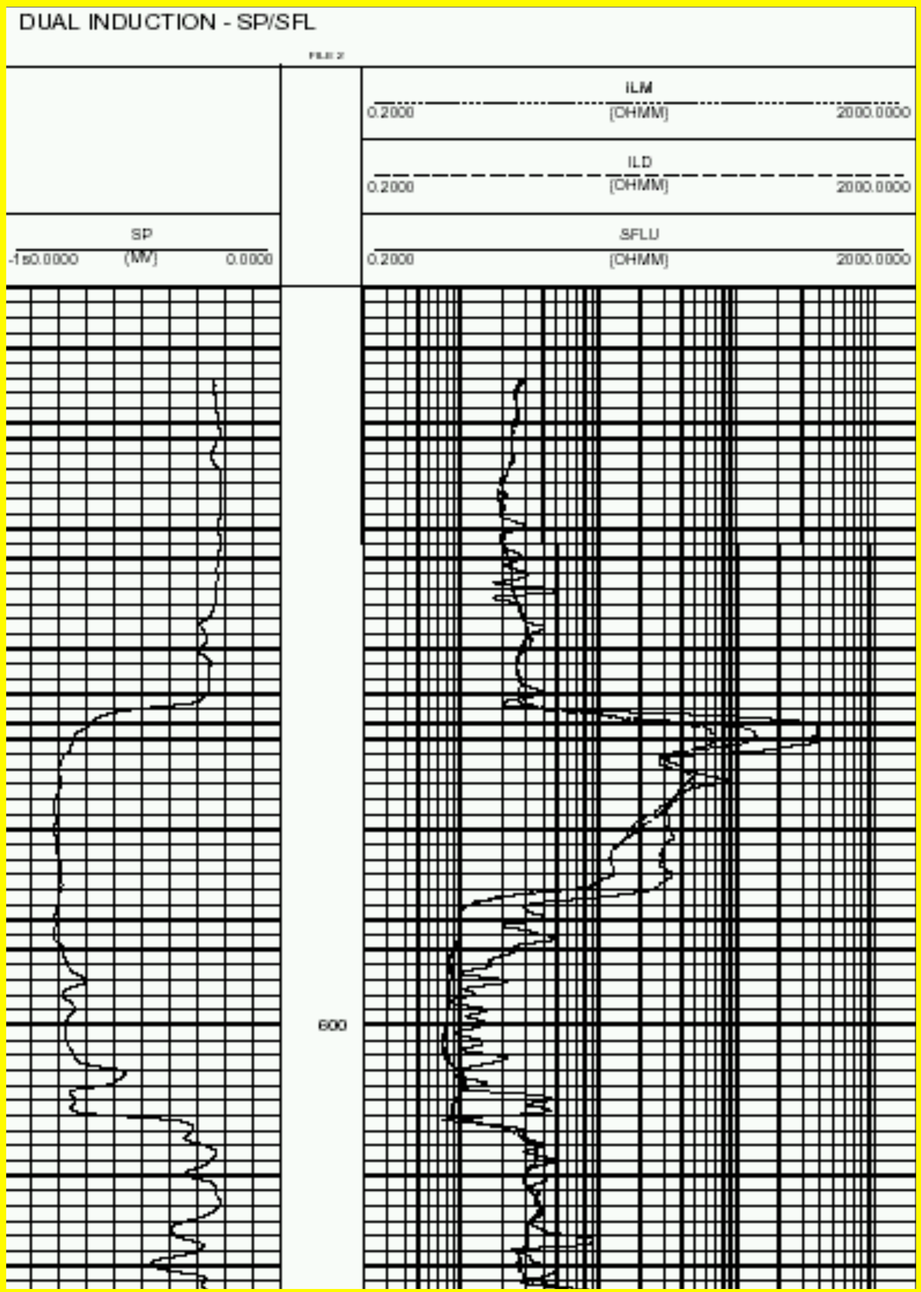
Dual Laterolog







Sferically Focused Log



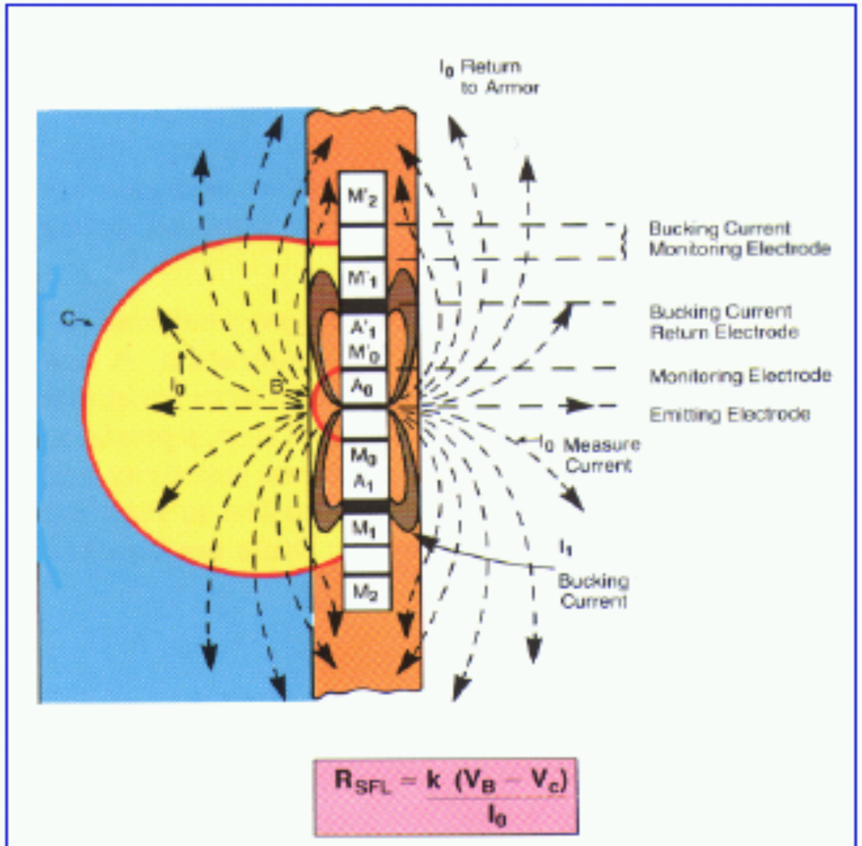
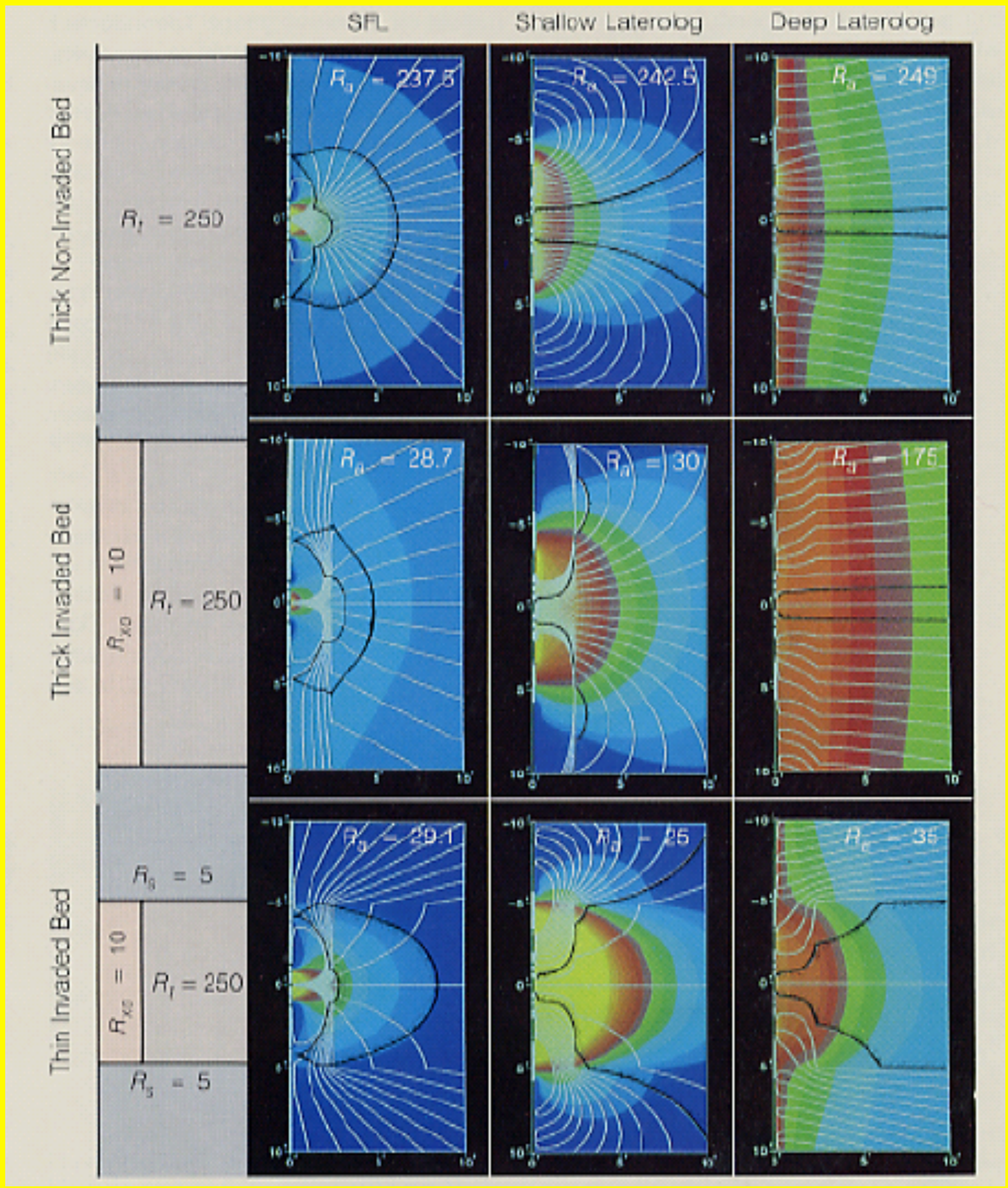
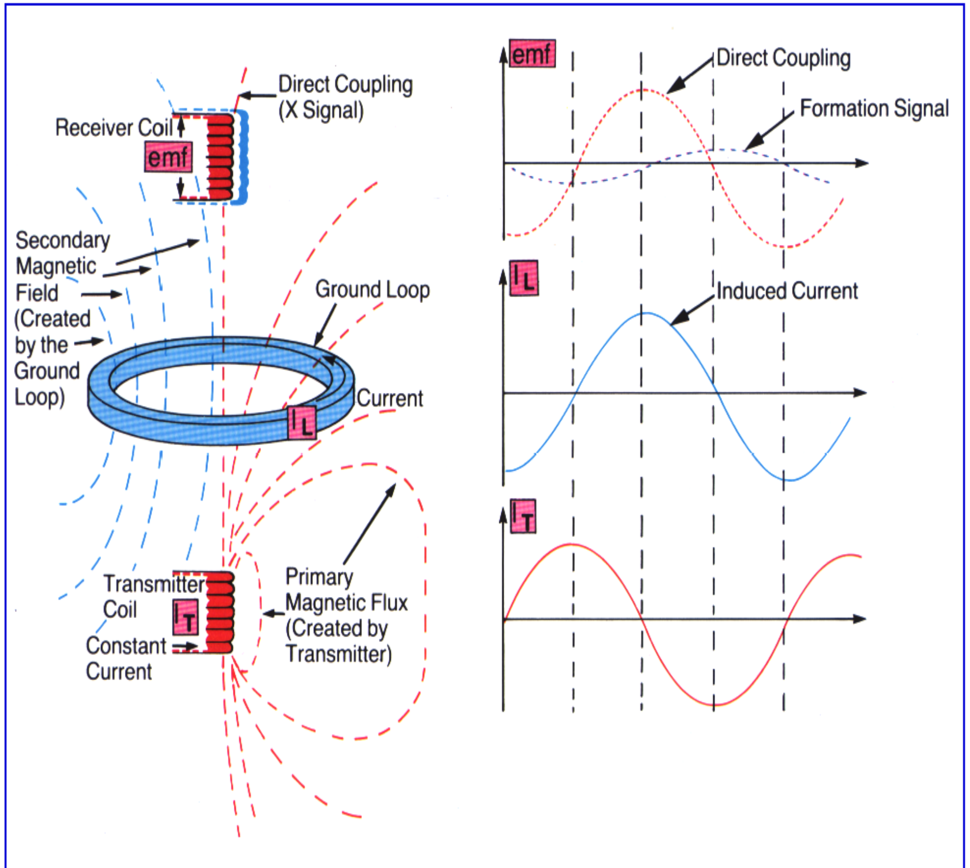


Figure B14: Electrode array of SFL tool and schematic representation of surveying current (i_o) lines (dashed) and focusing current (i_o) lines (solid).

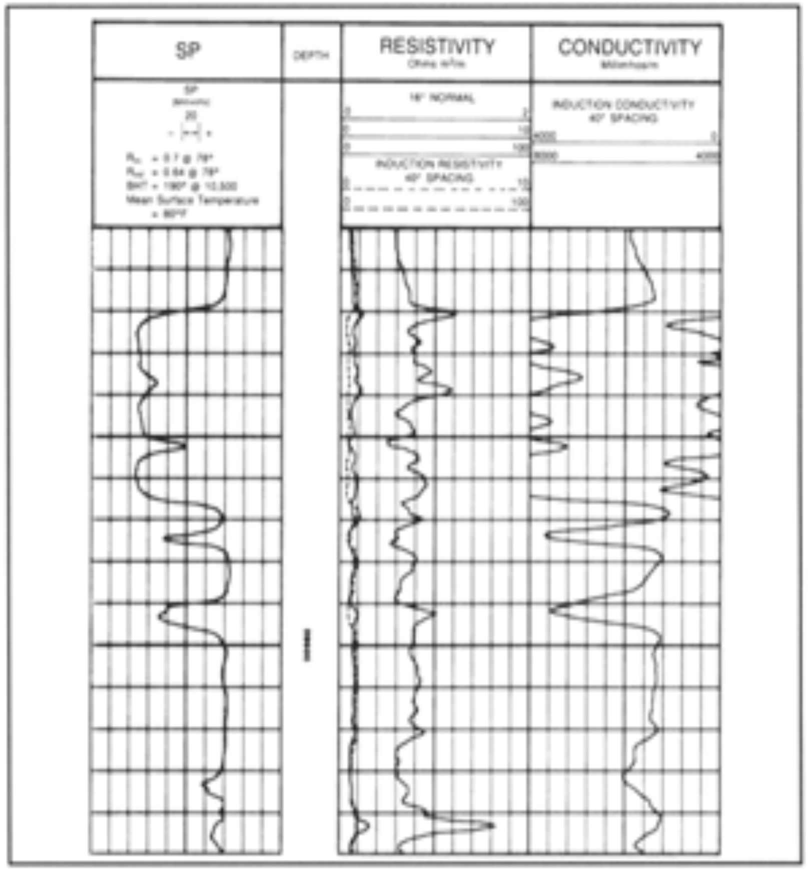


Environmental effects on focused galvanic tools

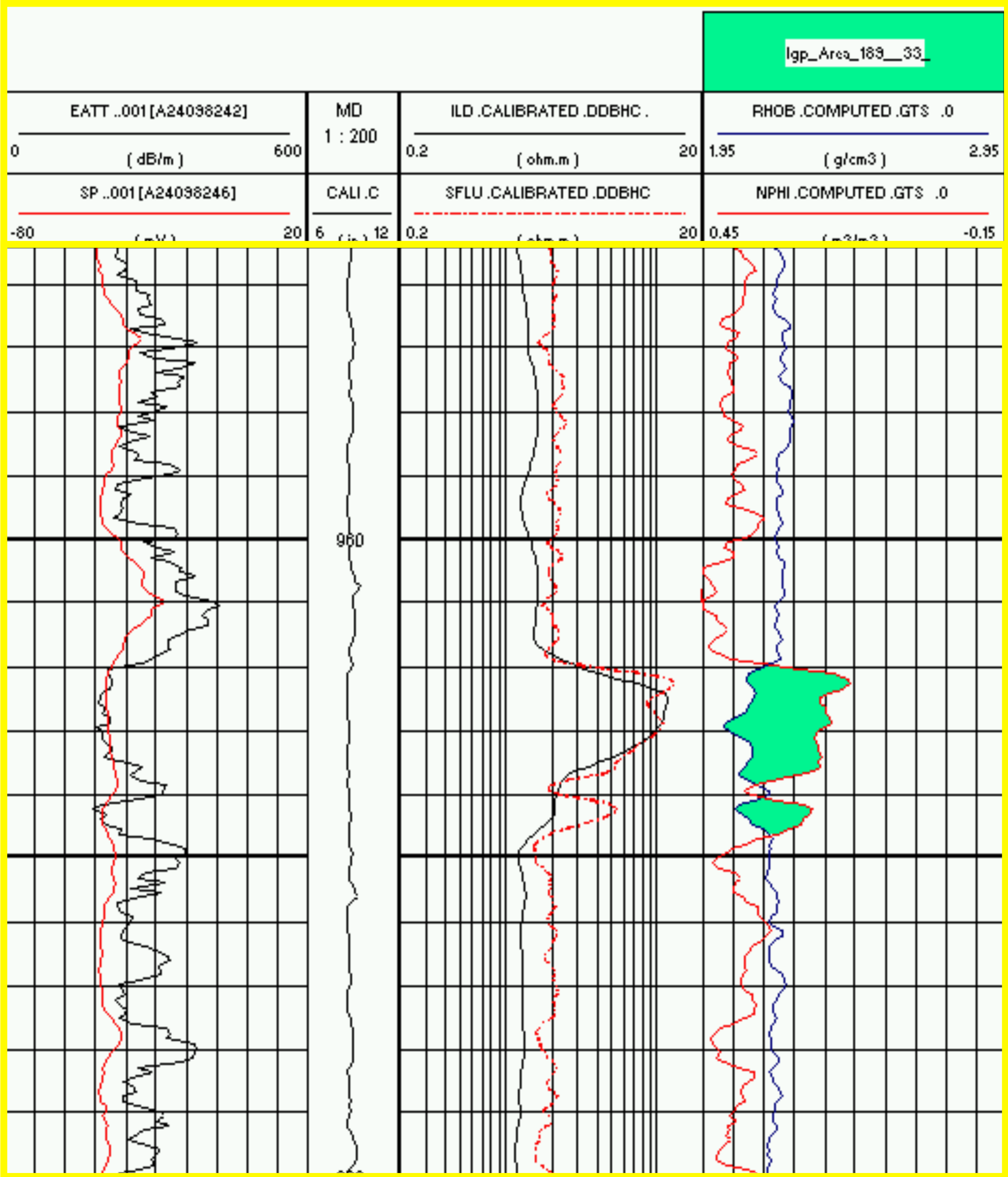
Induction logging



Induction log principle



Induction Electrolog linear presentation example



ILD/SFL example

- black curve ILD
- red curve SFLU

North Adriatic
fresh WBM

Rxo logging: the MSFL tool

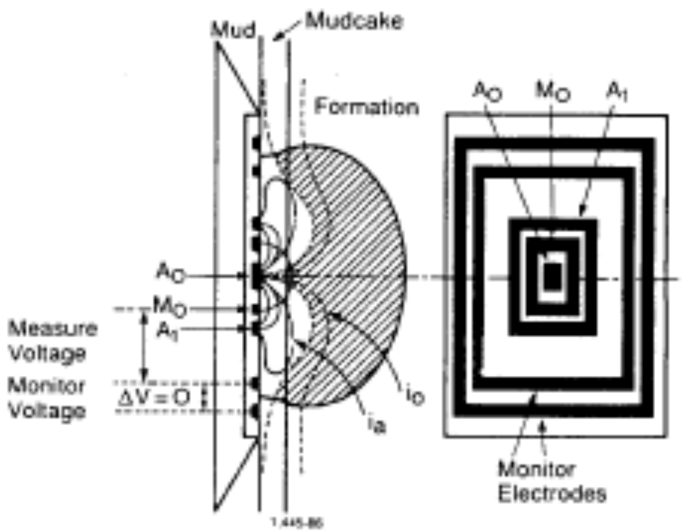
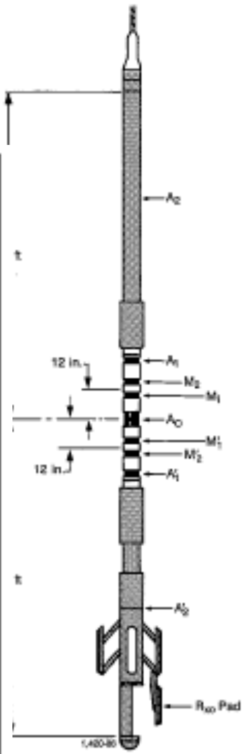
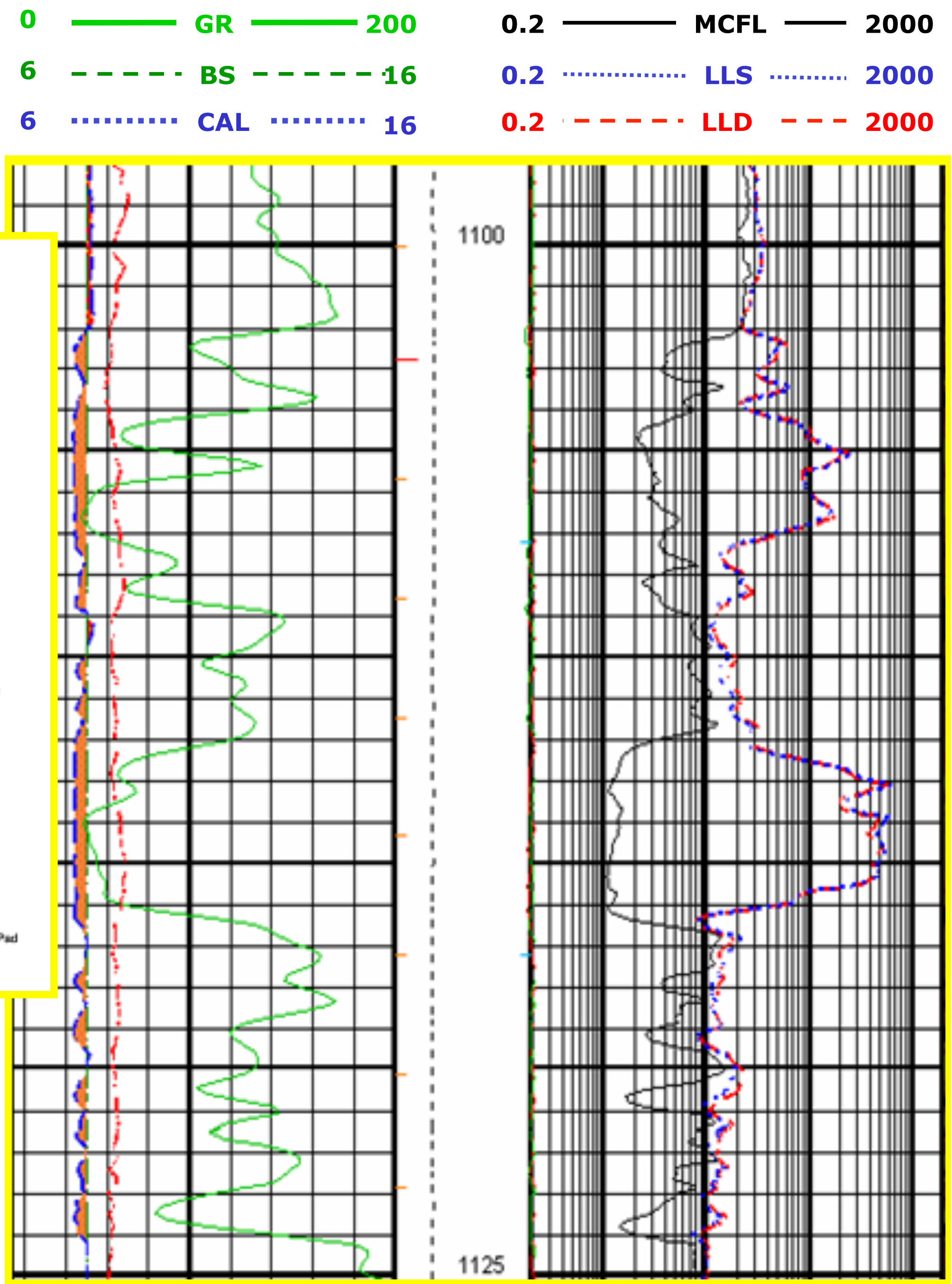
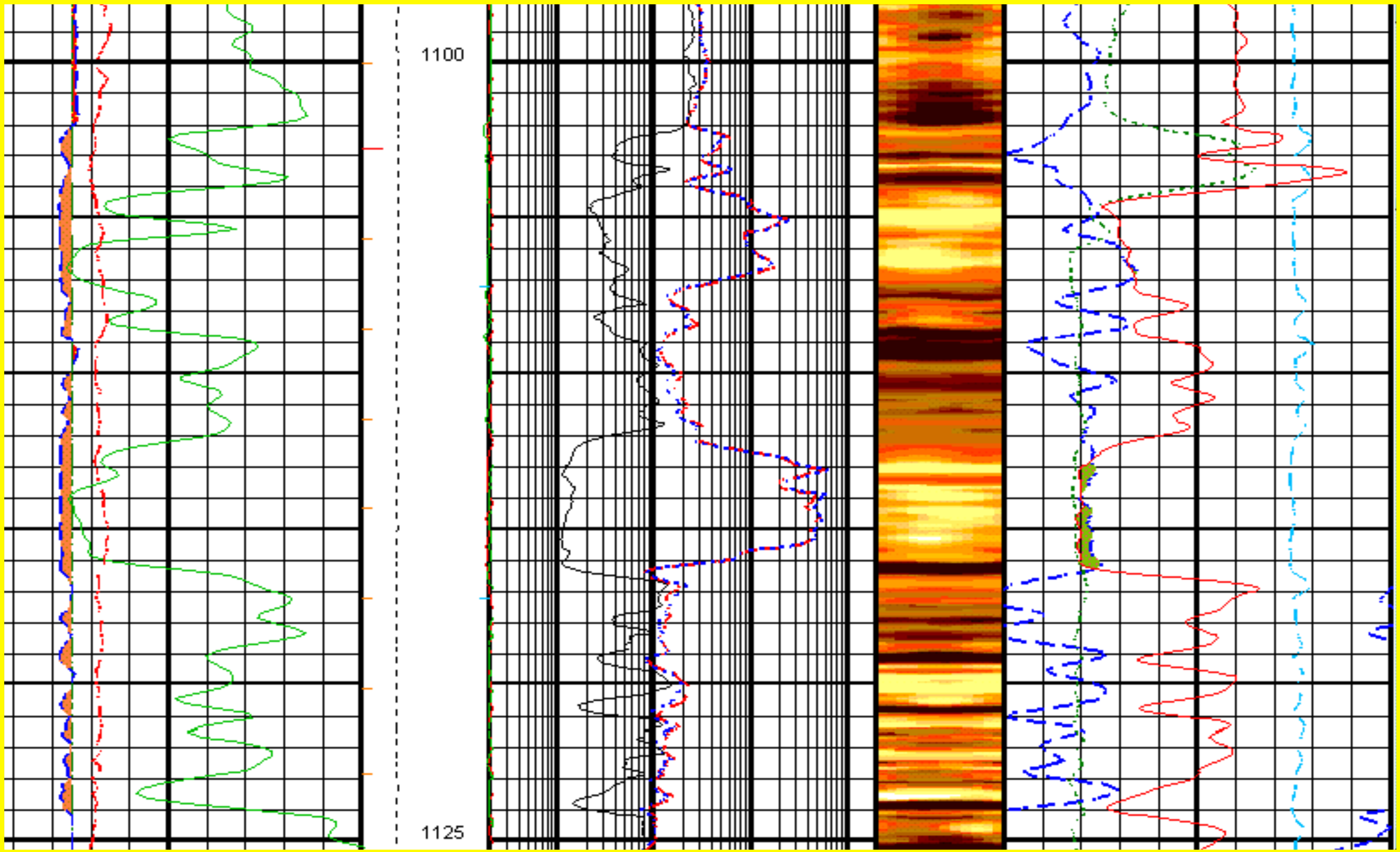


Figure B28: Current Distribution of MicroSFL device (left) and Electrode Arrangement (right)





Caliper - GR Resistivity Density/Neutron



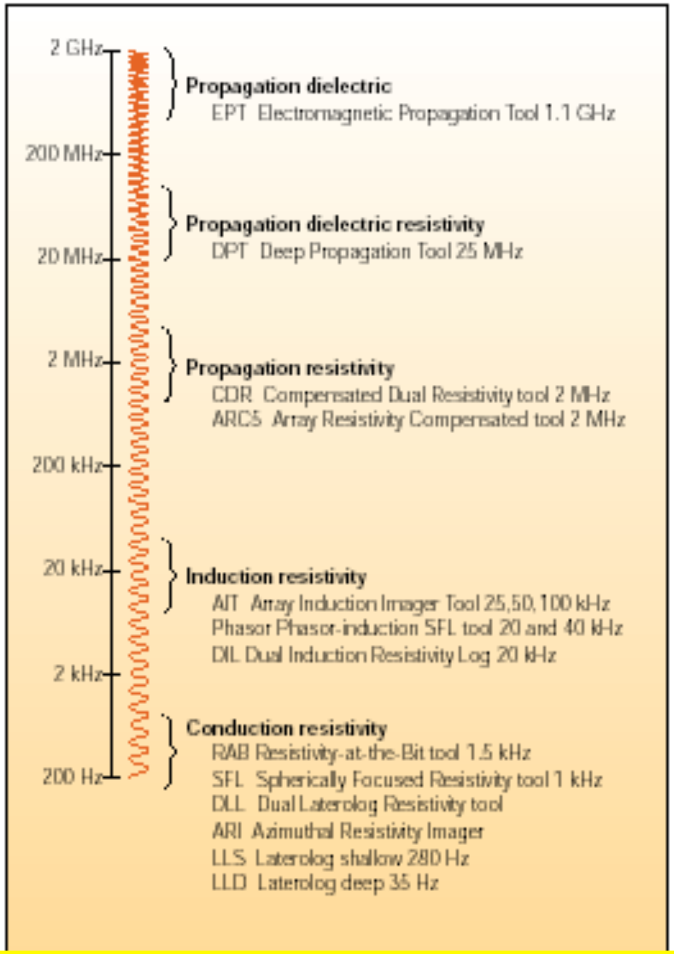
While Drilling resistivity logging

While Drilling resistivity logging are of two types:

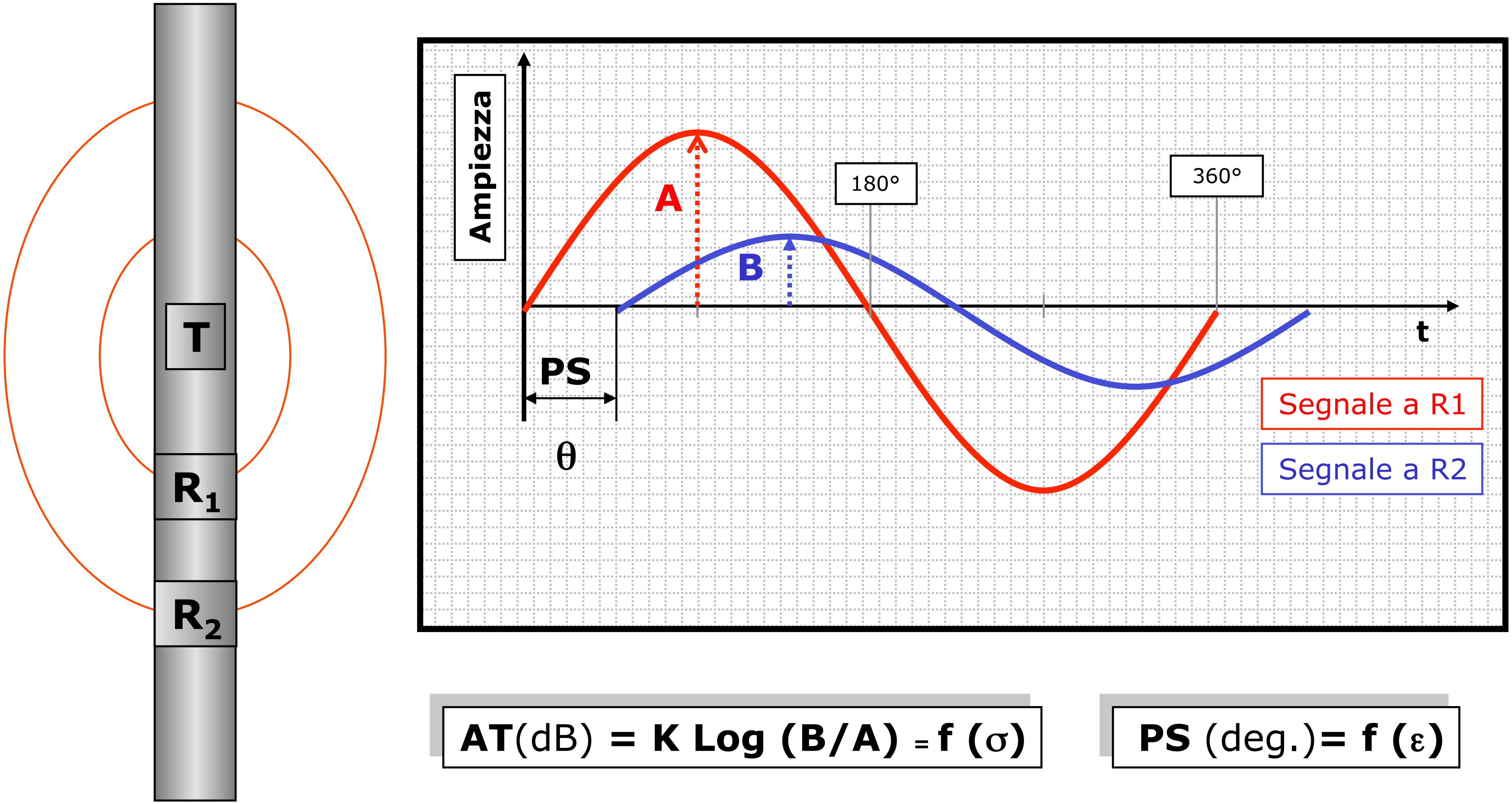
- galvanic;
- EM wave propagation.

While Drilling Galvanic logs (Anadrill RAB only) can be used only in presence of Water Based conductive Muds.

EM wave propagation logs, due to the presence of metallic body of the system, can be obtained only using higher frequencies with respect to the Wire Line induction ones with advantages and disadvantages.



LWD Propagation Resistivity



AT(dB) **= K Log (B/A) = f (σ)**

PS (deg.)**= f (ε)**

LWD resistivities: Real time vs memory