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.

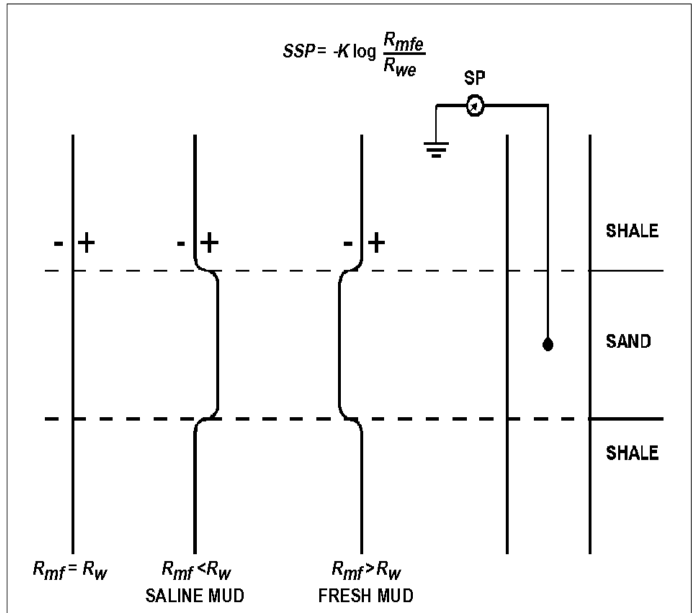
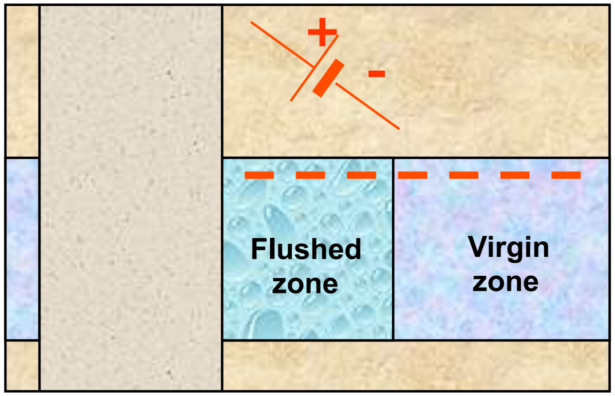
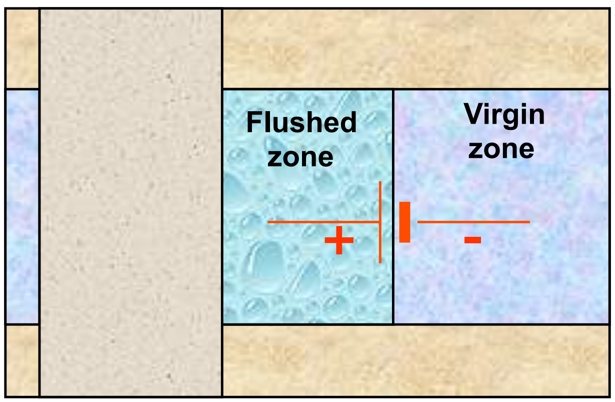


Figure B10: The SP Deflection and its R_{mf}-R_w Dependency

Spontaneous Potential



Membrane potential



Liquid-junction potential

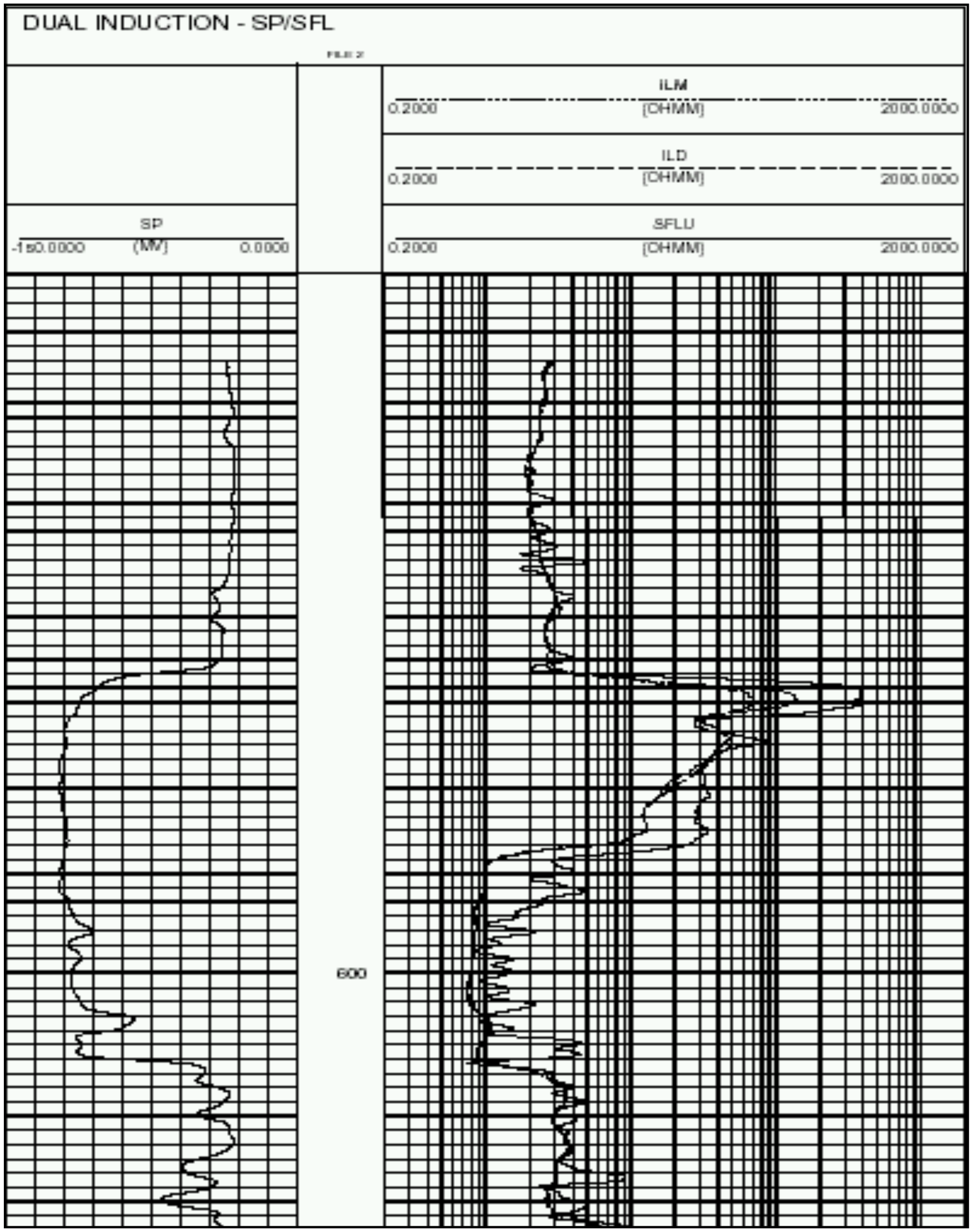
The magnitude of the SP generated is a function of the salinity contrast between mud and formation water.
Two are the main SP generation mechanisms:

- membrane potential,
- liquid-junction potential.

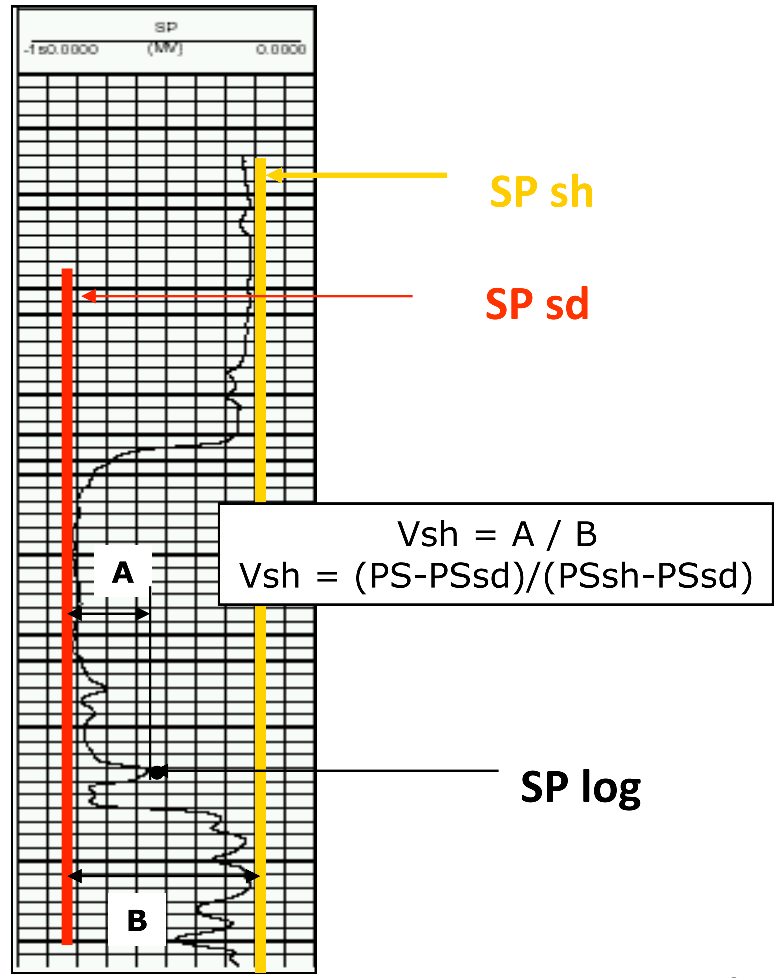
$$E_m = -\frac{R\theta}{Fn}\frac{I_a - I_c}{I_a + I_c}\ln\frac{C_1}{C_2}$$

$$E_l = -\frac{R\theta}{Fn}\ln\frac{C_1}{C_2}$$

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



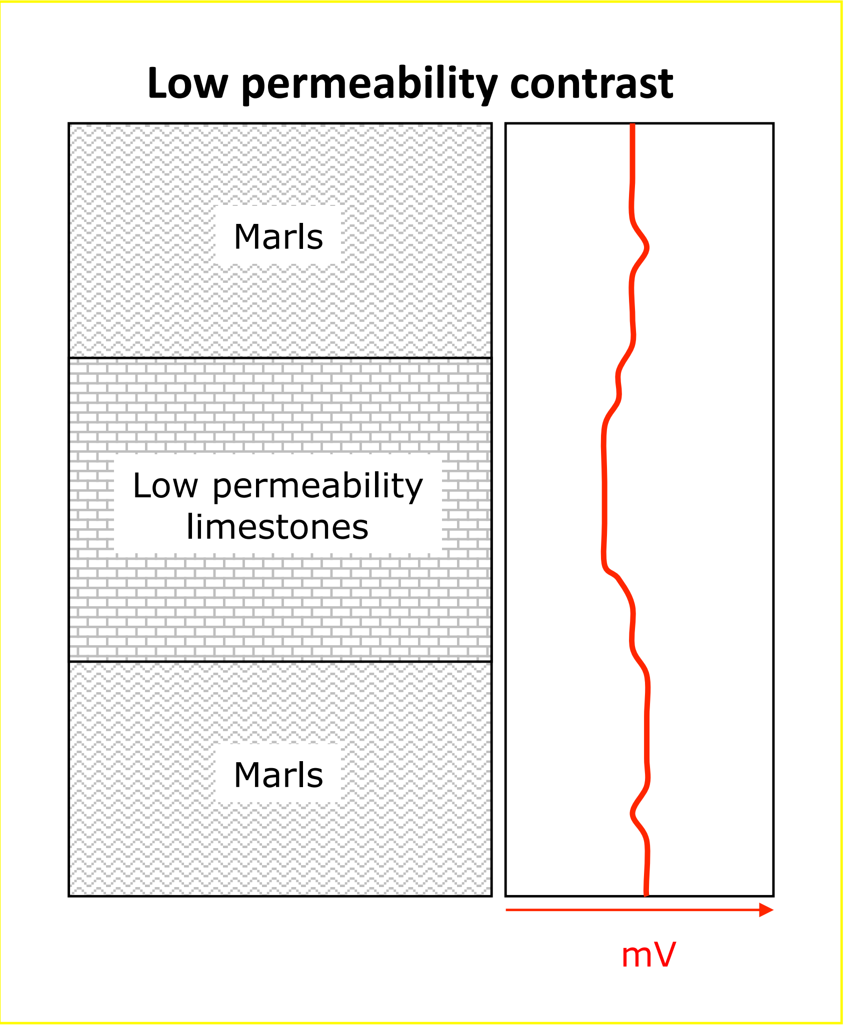
Spontaneous Potential (fresh mud and salty formation water)



SP log interpretation problems

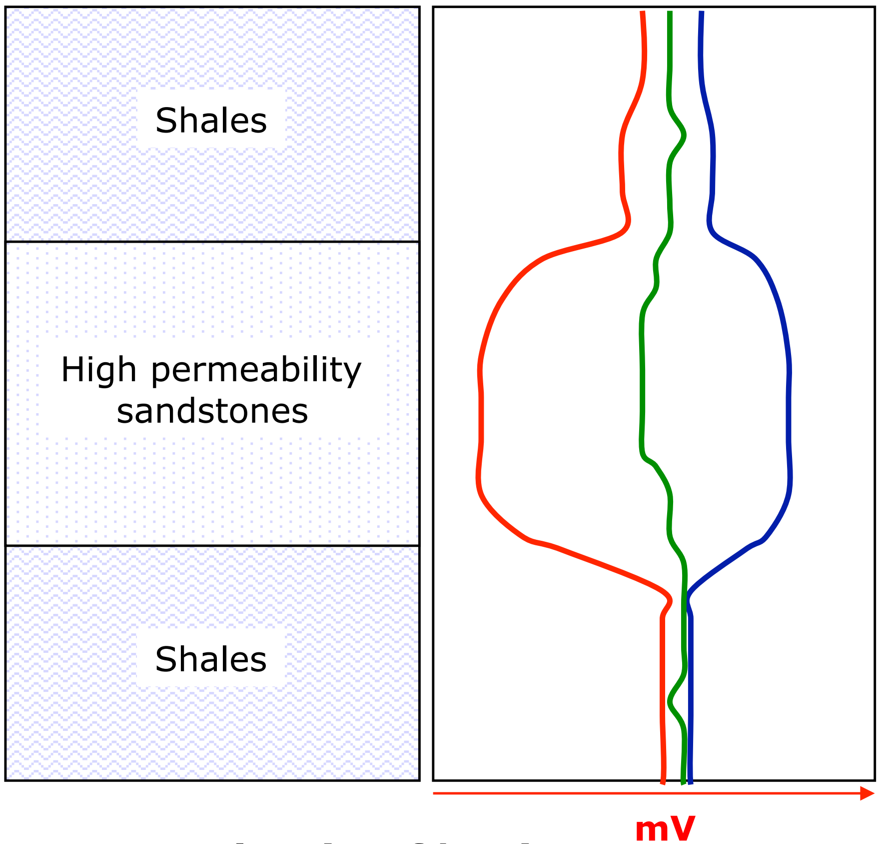
Main problems of SP log interpretation are mostly linked to:

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



SP log interpretation problems

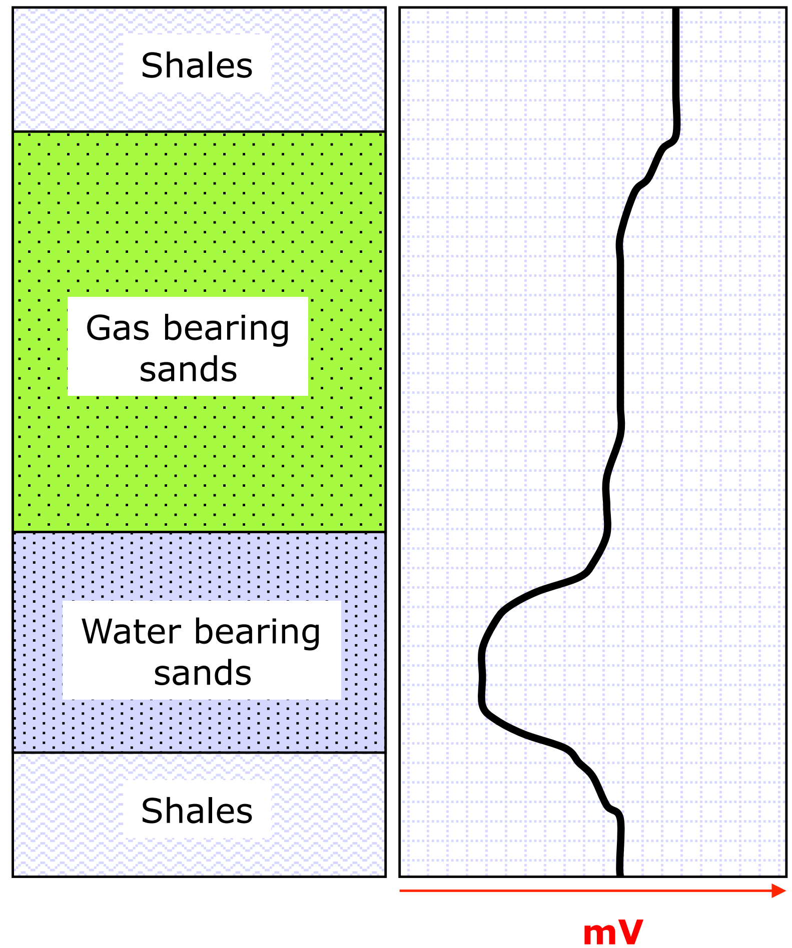
SP log behavior as a function of mud/formation water salinity contrast

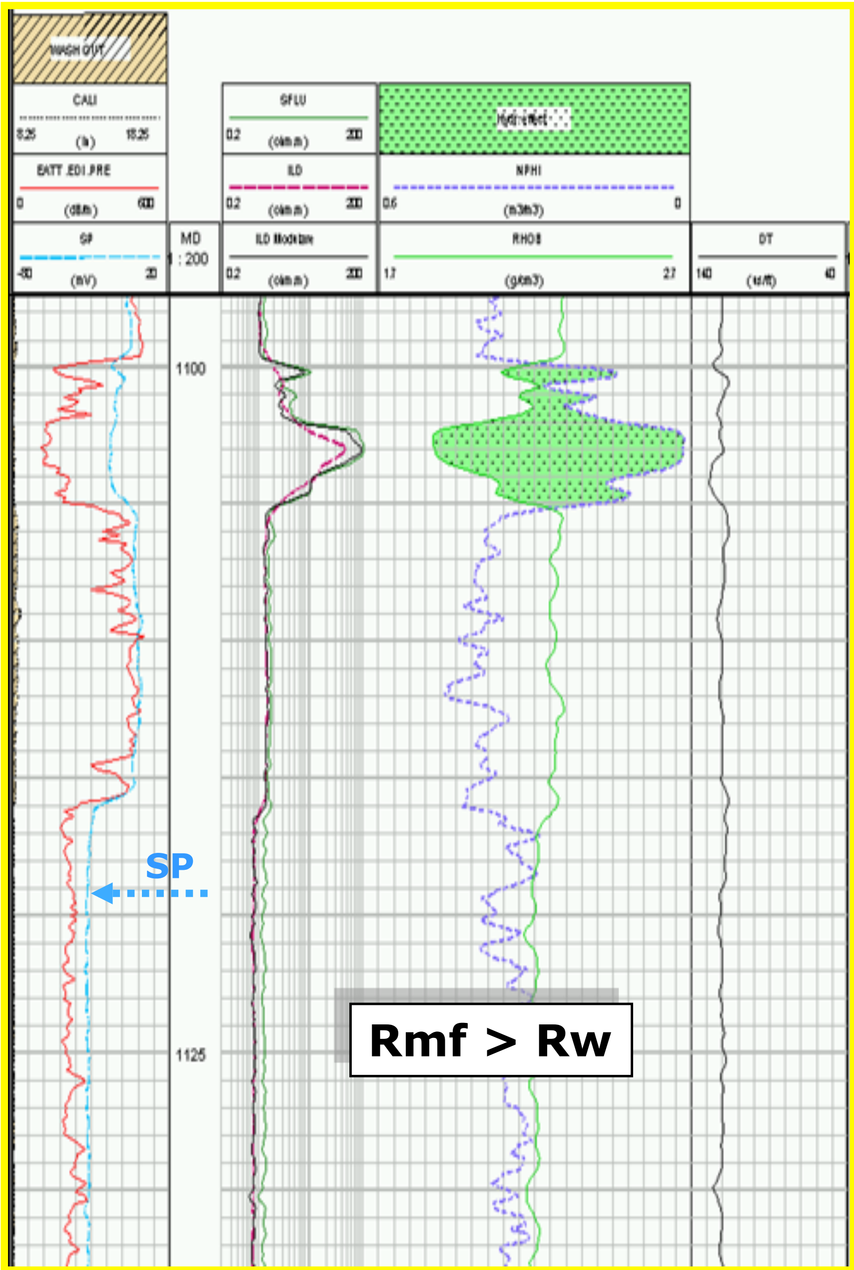


SSP = -K log (Rmf/Rw)

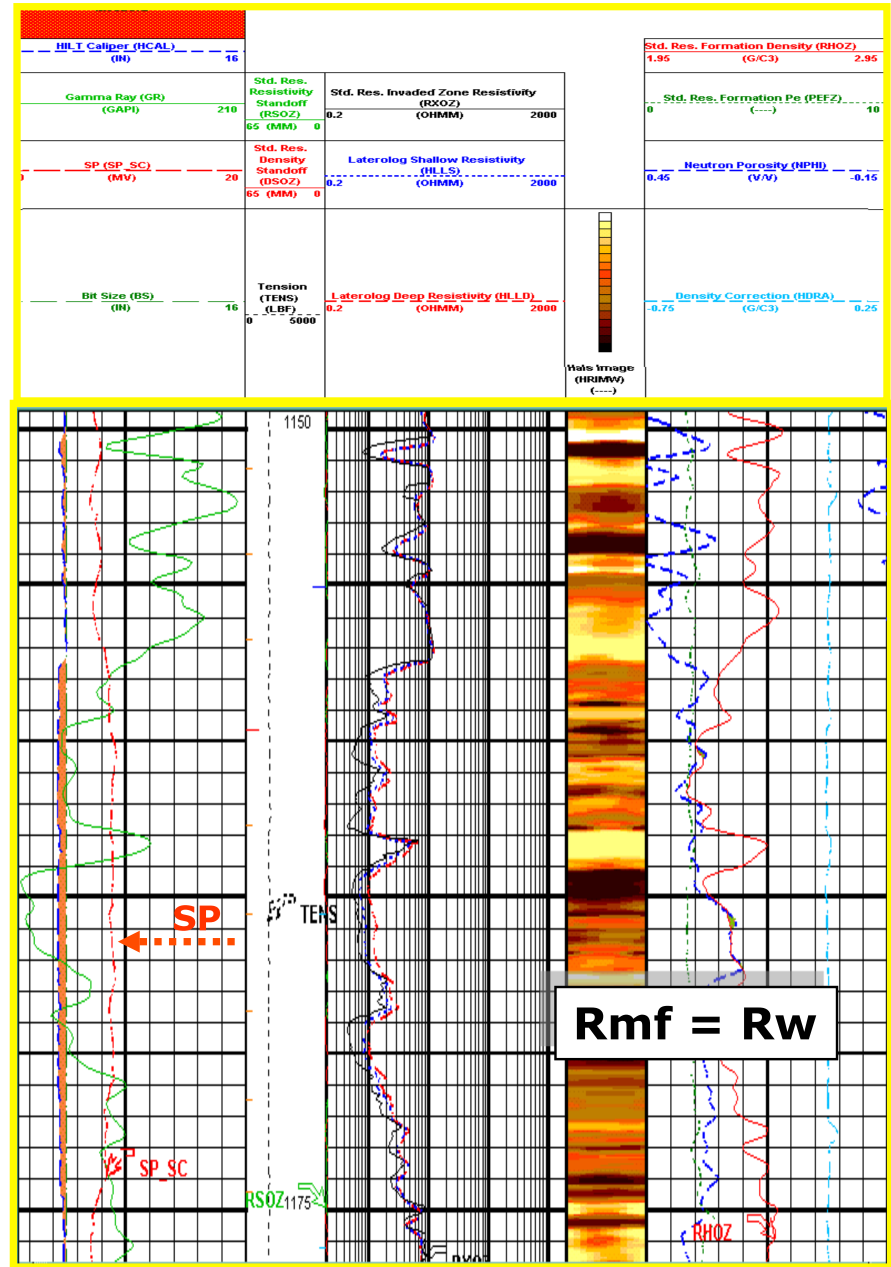
Rm > Rw   Rm = Rw   Rm < Rw

Hydrocarbon effect on the SP log





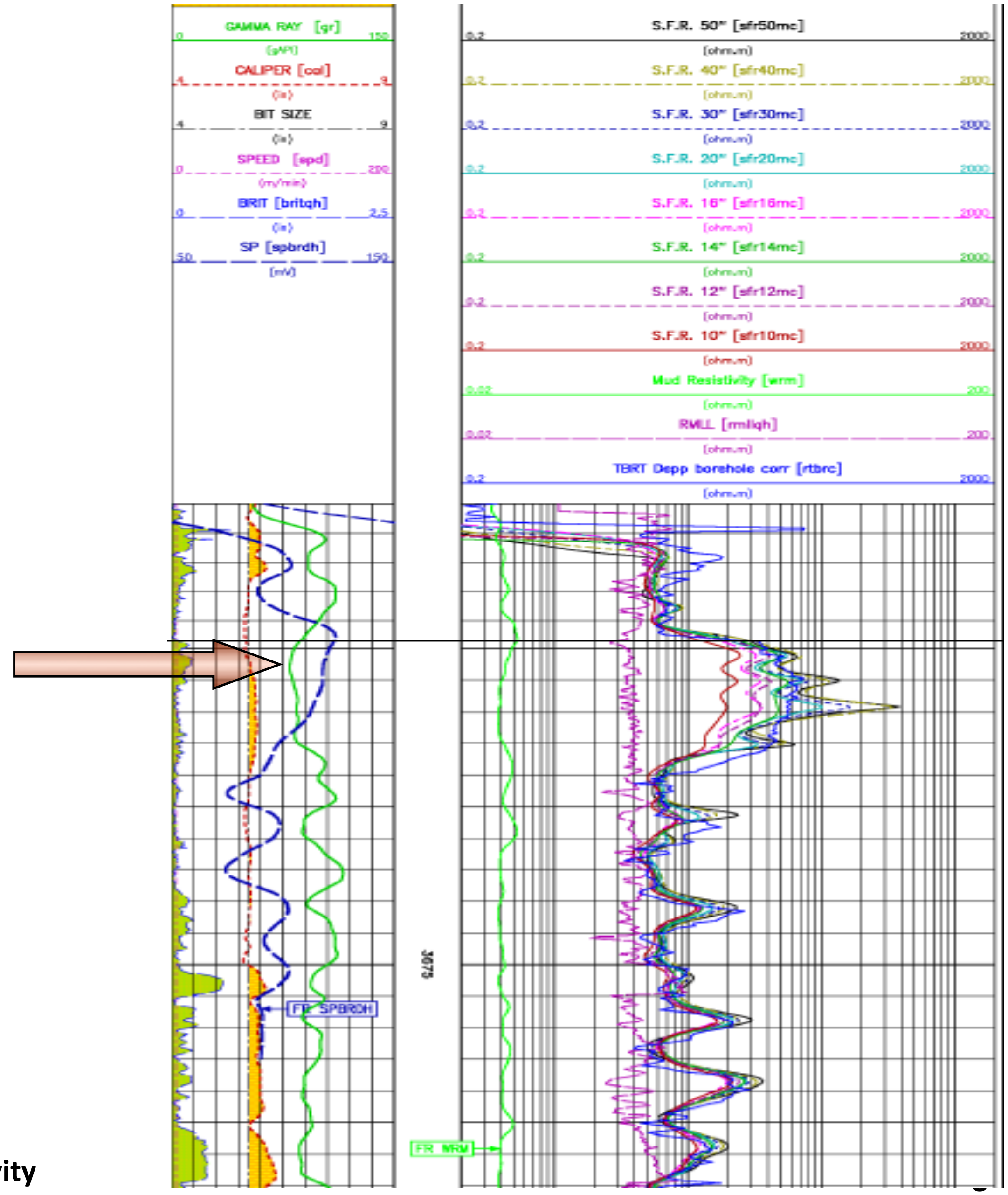
WASH OUT
CALI
8.25 (in) 18.25
SFLU
0.2 (ohm.m) 200
ILD
0.2 (ohm.m) 200
NPHI
0.6 (m3/m3) 0
SP
-80 (mV) 20
MD
1 : 200
RHOB
1.7 (g/cm3) 2.7
DT
140 (us/ft) 40
1100
1125
SP
Rmf > Rw



HILT Caliper (HCAL)
(IN) 16
Gamma Ray (GR)
(GAPI) 210
SP (SP_SC)
(MV) 20
Bit Size (BS)
(IN) 16
Std. Res. Resistivity Standoff (RSOZ)
65 (MM) 0
Std. Res. Density Standoff (DSOZ)
65 (MM) 0
Tension (TENS) (LBF)
0 5000
Std. Res. Invaded Zone Resistivity (RXOZ)
0.2 (OHMM) 2000
Laterolog Shallow Resistivity (HLLS)
0.2 (OHMM) 2000
Laterolog Deep Resistivity (HLLD)
0.2 (OHMM) 2000
Hals Image (HRIMW) (----)
Std. Res. Formation Density (RHOZ)
1.95 (G/C3) 2.95
Std. Res. Formation Pe (PEFZ)
0 (----) 10
Neutron Porosity (NPHI)
0.45 (V/V) -0.15
Density Correction (HDRA)
-0.75 (G/C3) 0.25
1150
1175
TENS
SP_SC
RSOZ
RHOZ
SP
Rmf = Rw

Inverted SP:

Rmf << Rw



SP log interpretation problems

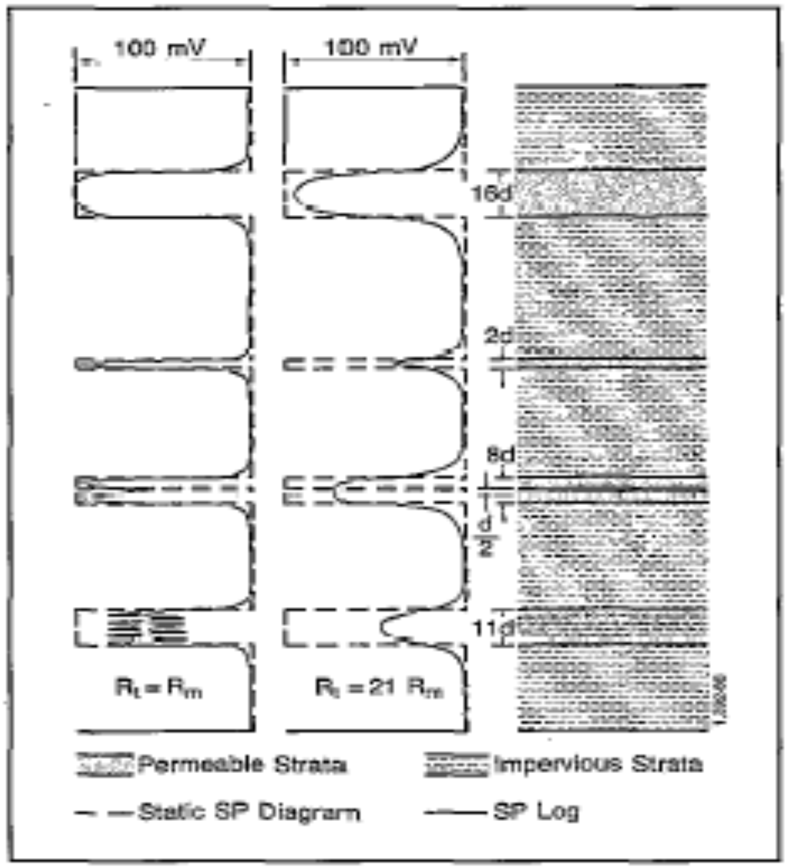
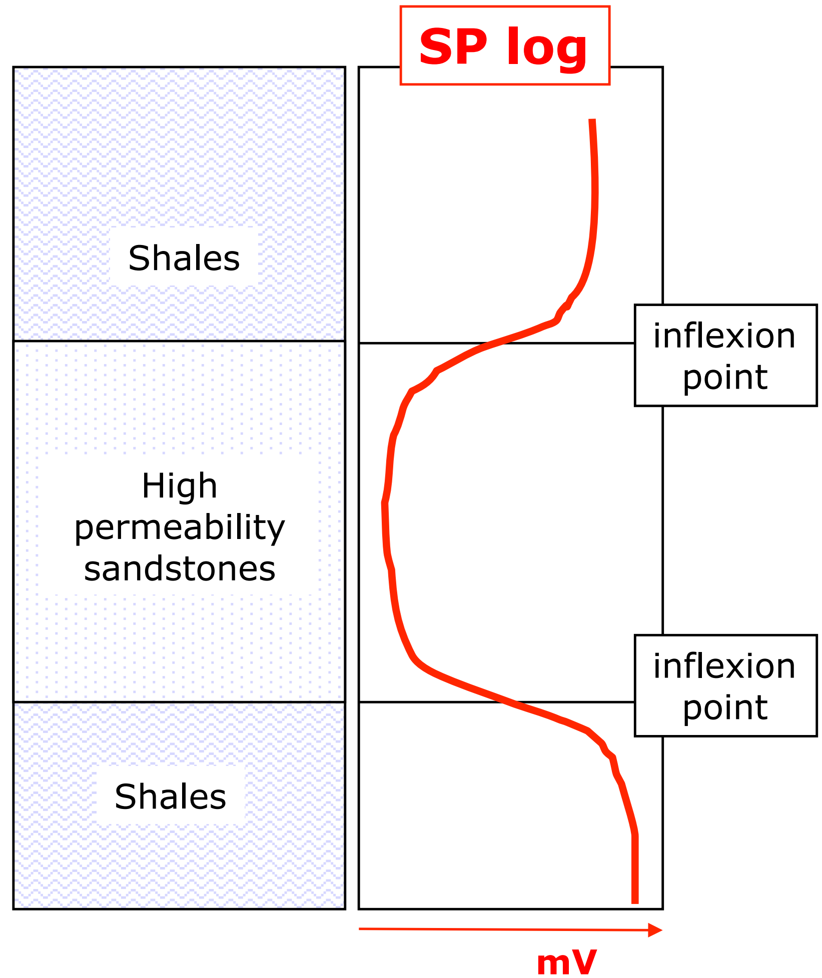


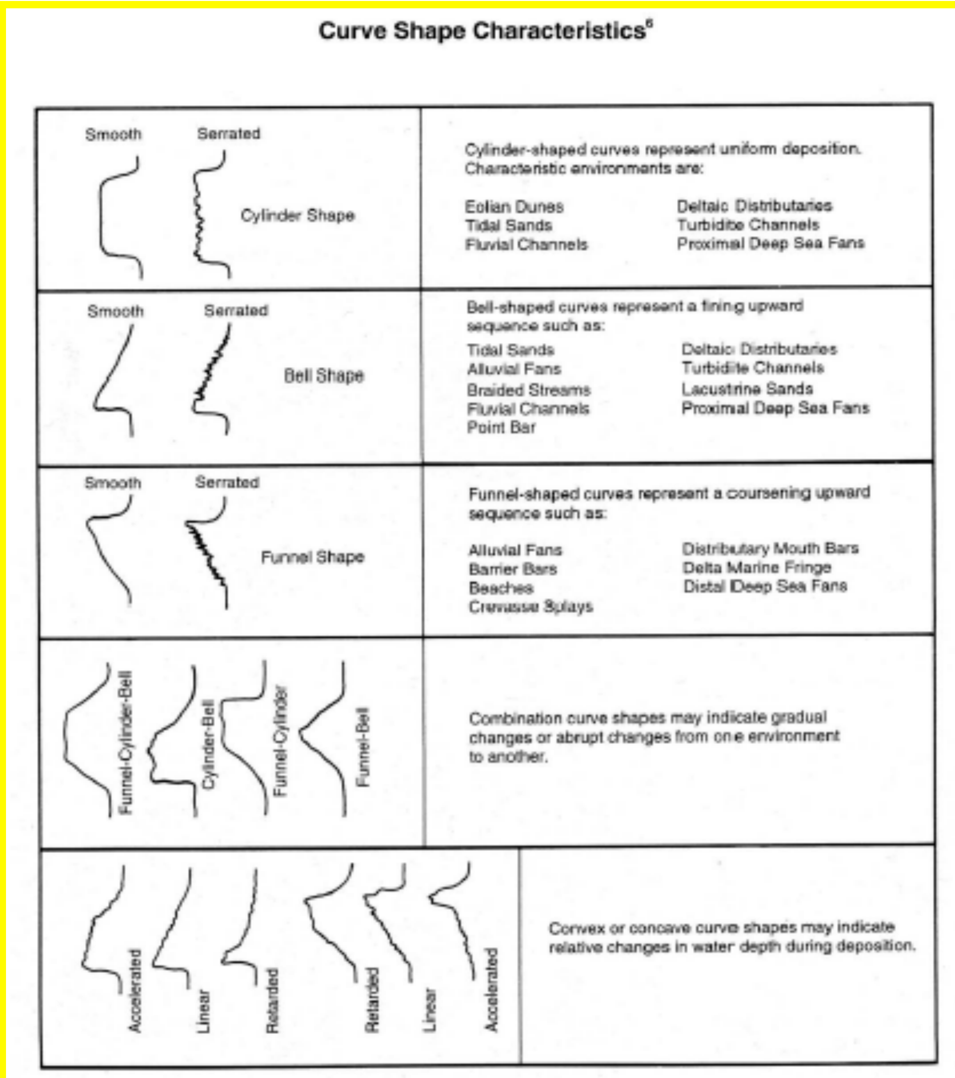
Fig. 3-3—SP curve in beds of different thickness for $R_t = R_m$ (left) and $R_t = 21 R_m$ (center).

Vertical resolution of the SP log



Boundary location by means of the SP log

Geological application of the SP log



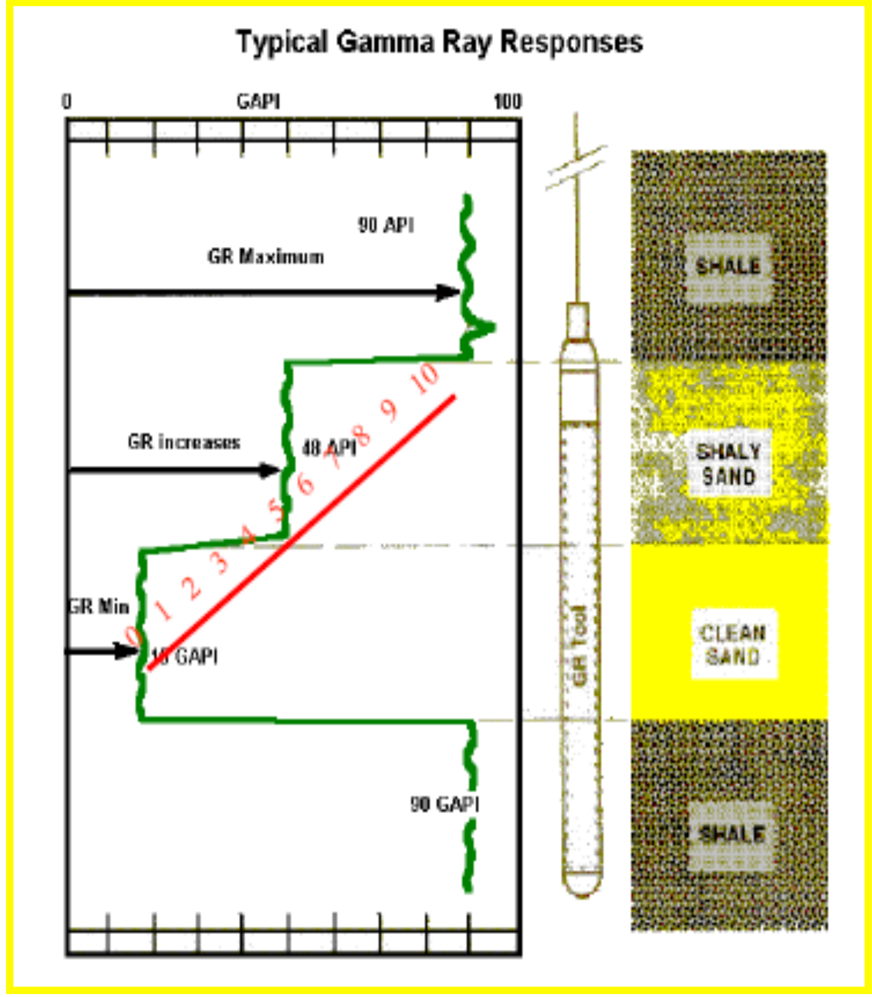
In absence of SP anomalies, when dealing with water saturated formations and with muds of constant salinity in all the wells under evaluation, the SP log may be used for geological correlation among wells and to define the different sedimentary facies (in order to define lateral and vertical evolution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

Gamma Ray log

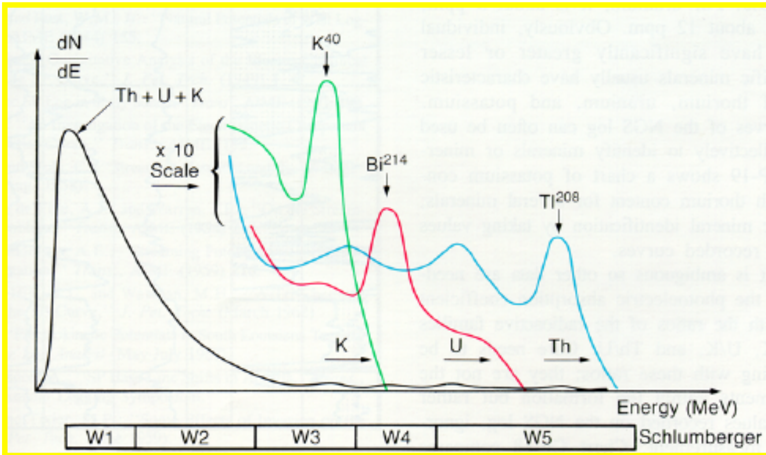
The natural radioactivity of geological formations is due to the presence in rock forming minerals of the radioactive isotopes of elements such as Uranium (U), Thorium (Th) and Potassium (K).

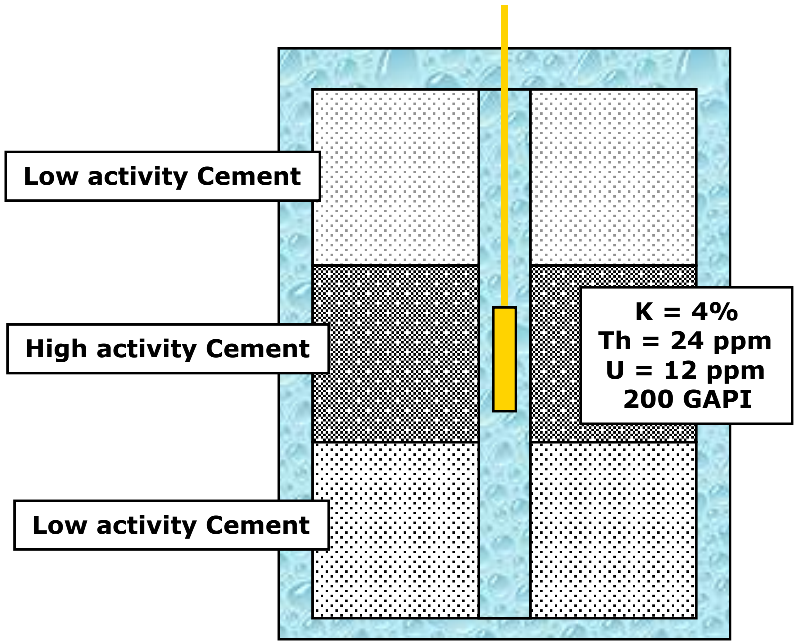
These isotopes are mostly related to clay minerals whose content in Th and K is generally higher than associated sand and sandstones.

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.

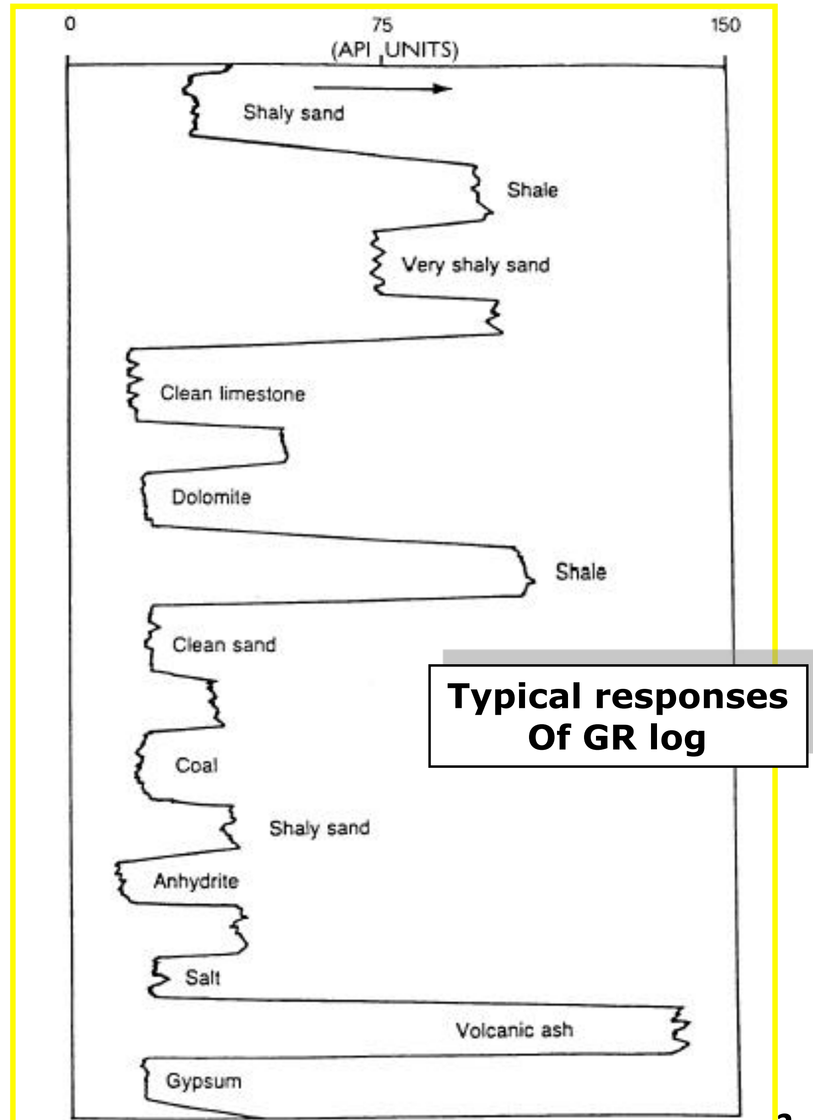


Gamma Ray log

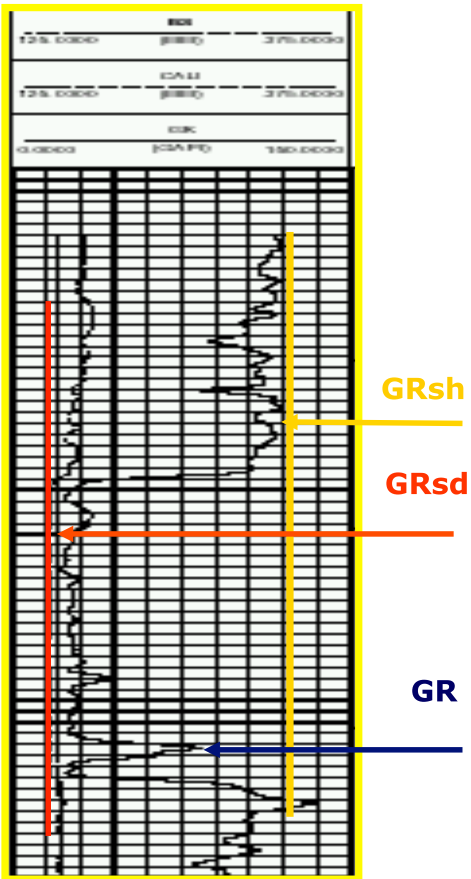


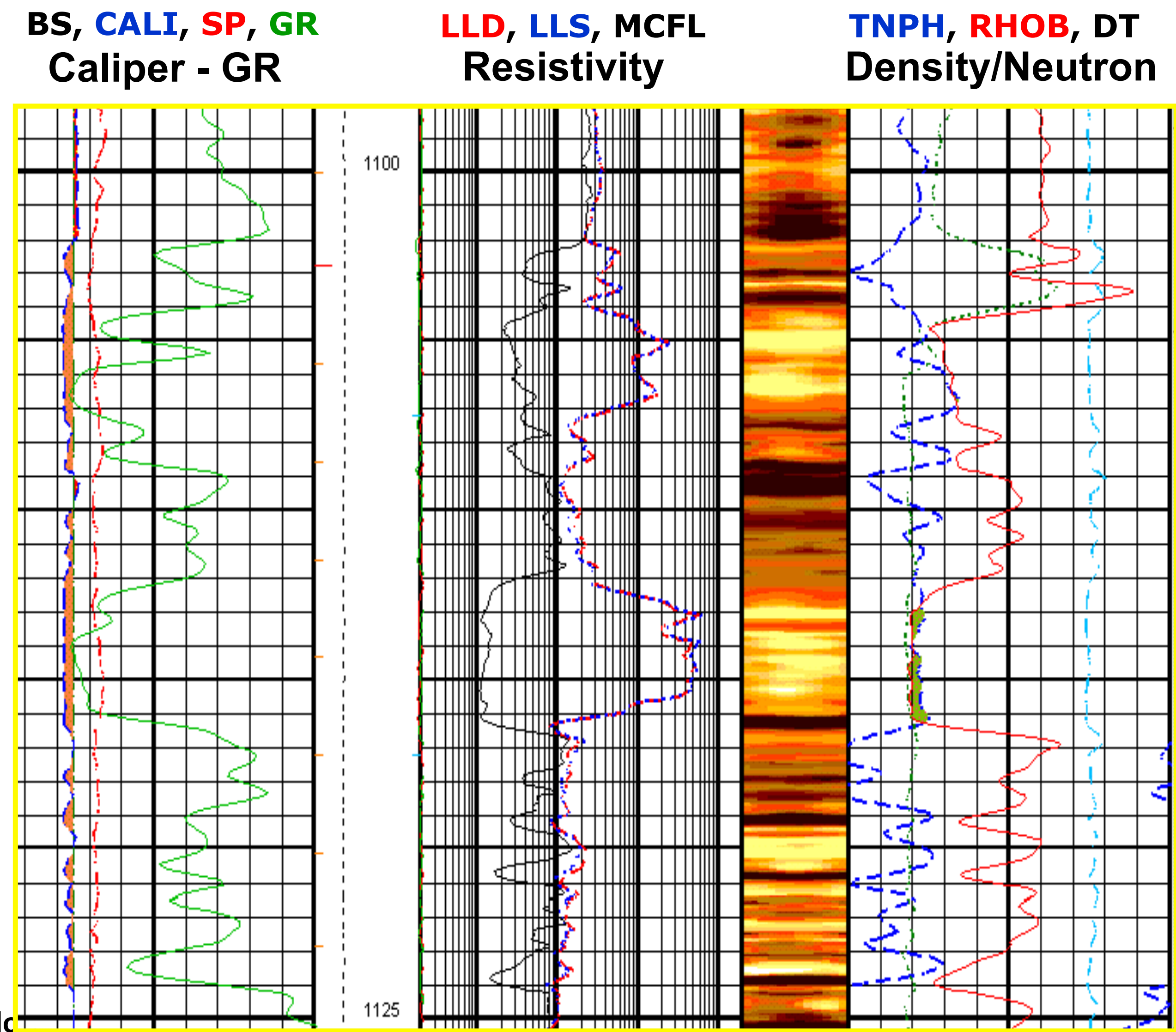


Gamma Ray American Institute Test Pit



Shale volume from GR log



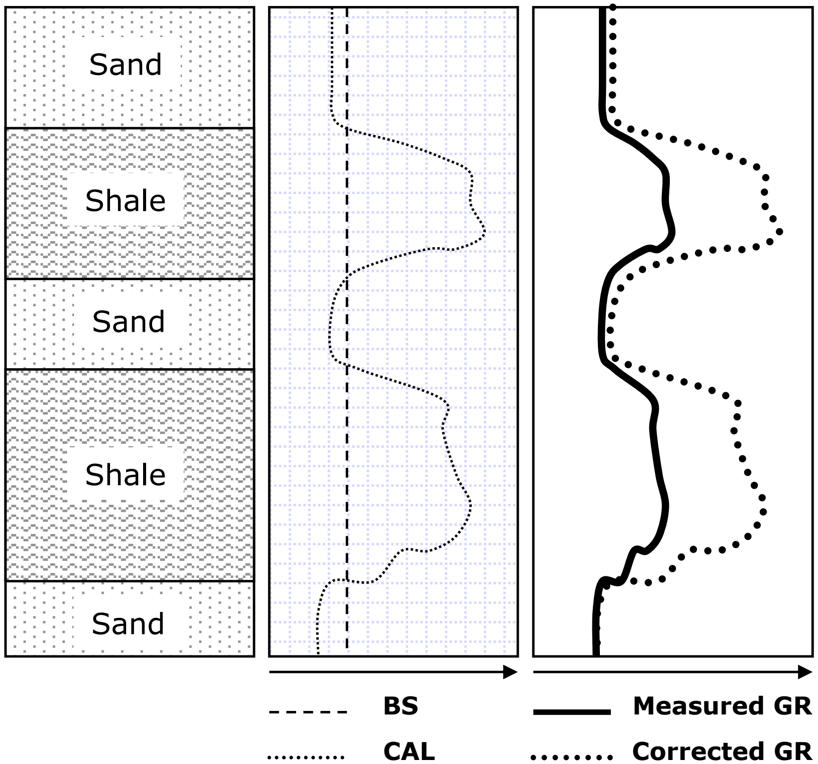


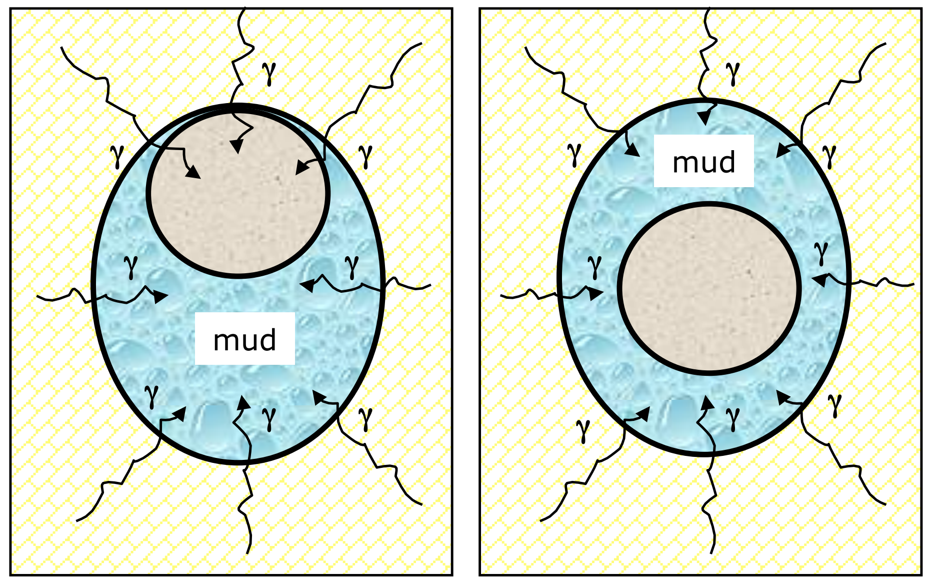
$$Vsh = \frac{(GR - GRsd)}{(GRsh - GRsd)}$$

Gamma Ray: environmental corrections

Main factors affecting GR measurements are:

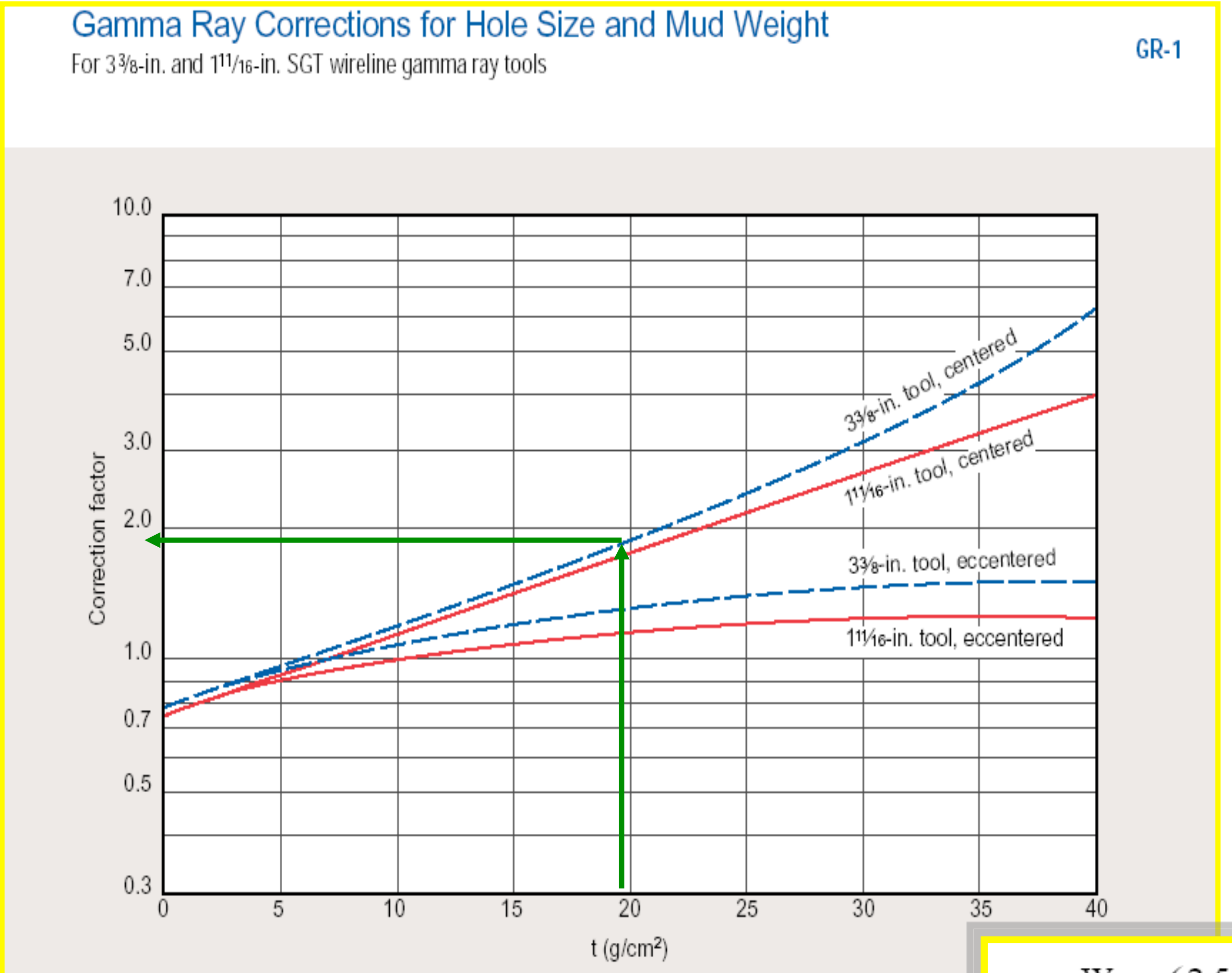
- hole diameter
- sonde position in the well
- mud loaded with radioactive material





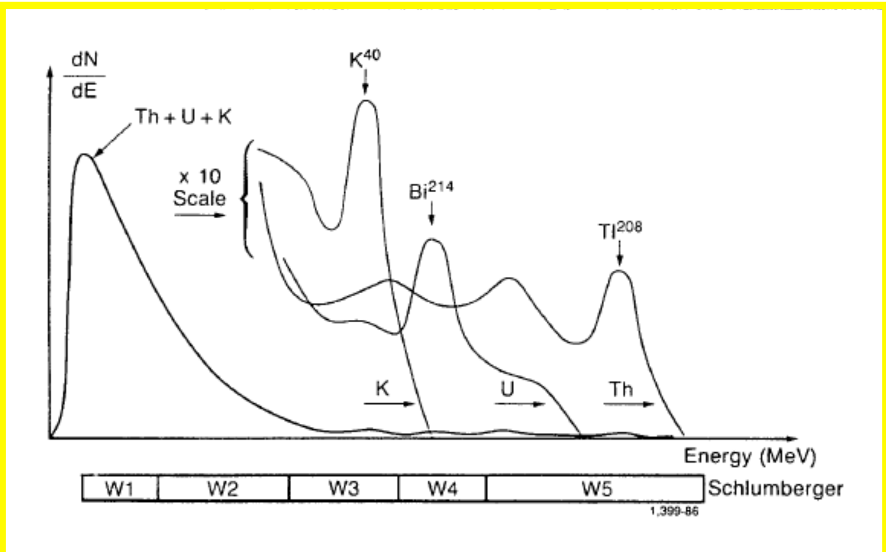
Tool eccentered **Tool centered**

Gamma Ray: environmental corrections

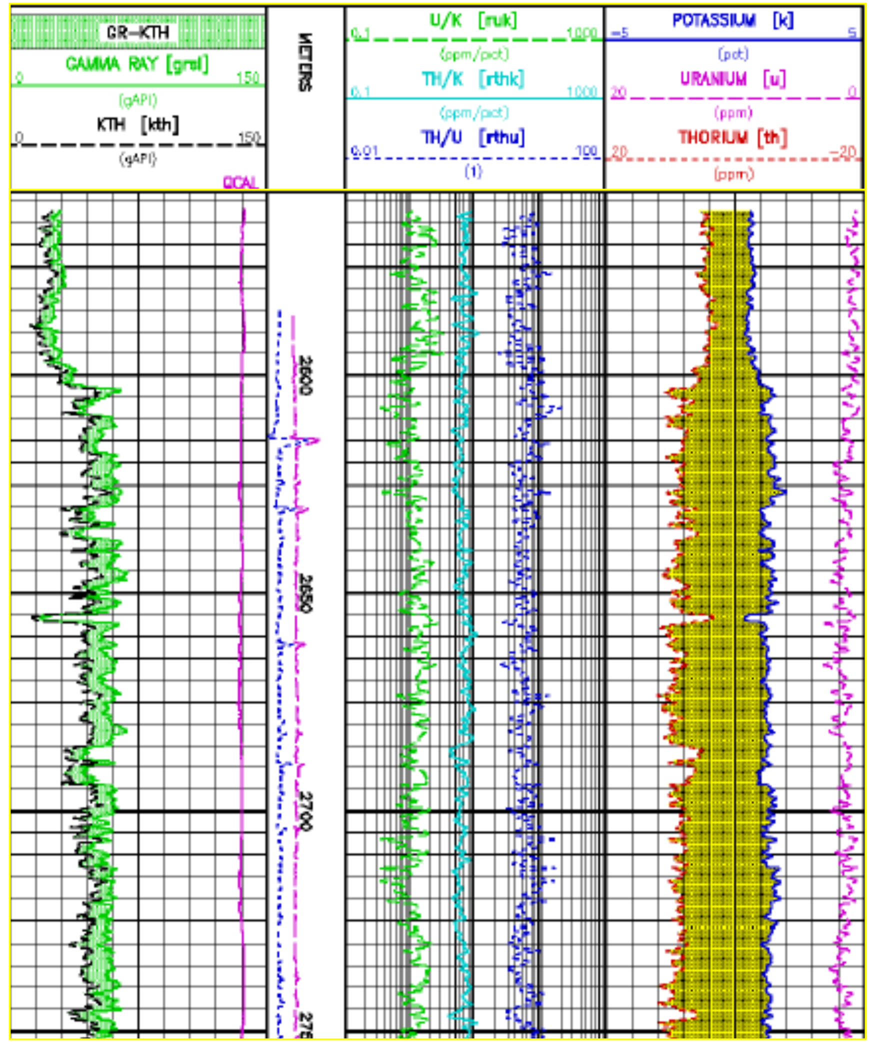


$$t = \frac{W_{mud}}{8.345}\left(\frac{2.54\,(d_{hole})}{2} - \frac{2.54\,(d_{sonde})}{2}\right).$$

Gamma Ray Spectrometry



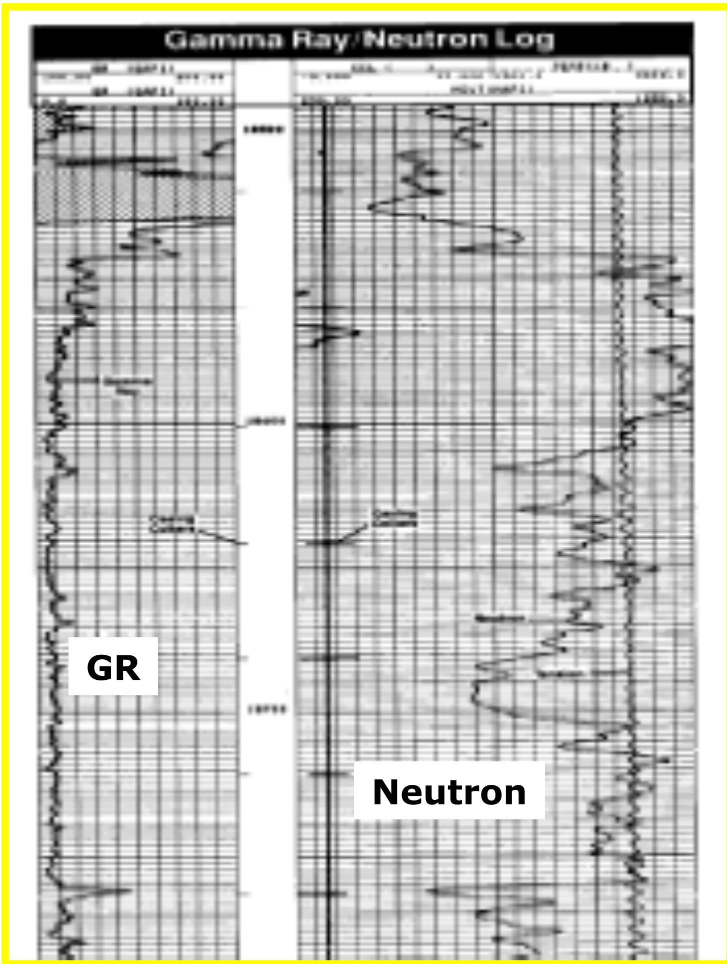
Gamma Ray emission spectra



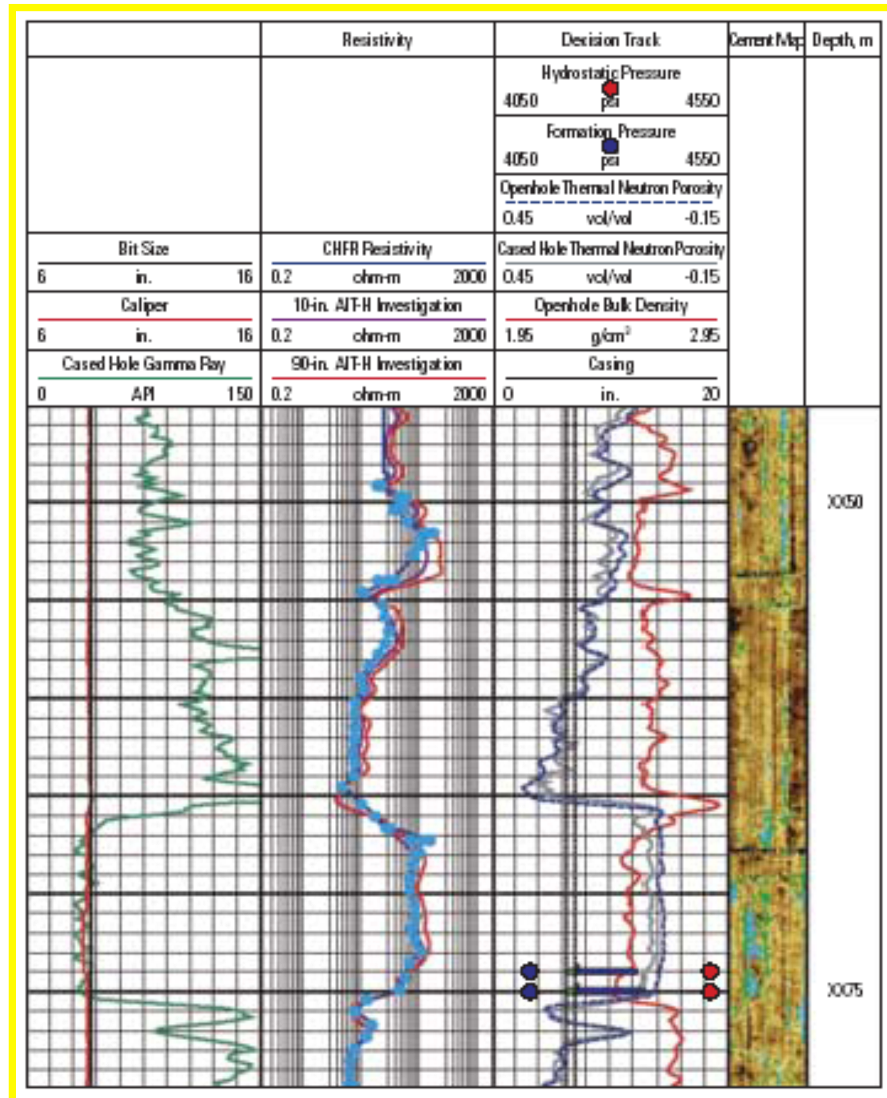
WLL Services

SLB	**NGS**
SLB	**HNGS (PEX)**
BA	**SL**

GR in cased hole

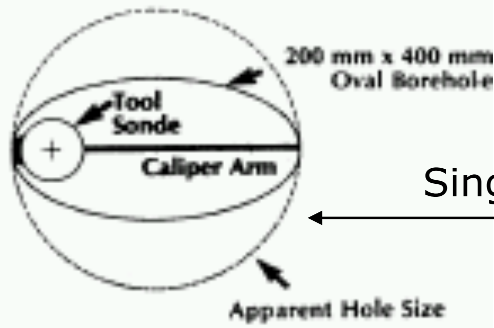


GR correlation Log in cased hole

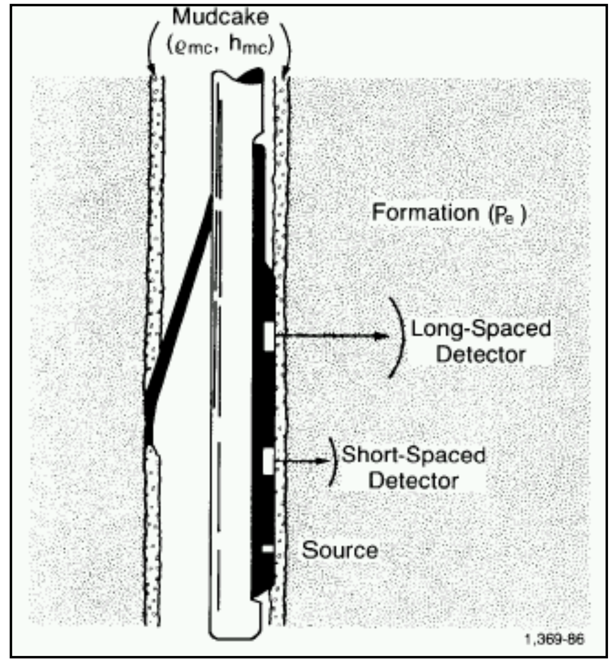


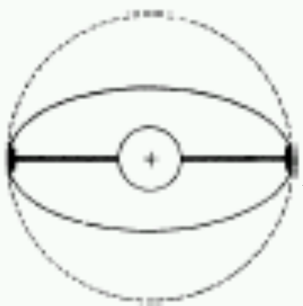
Formation Evaluation logging in CH

Caliper log

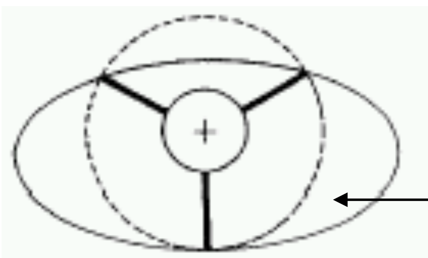


Single arm caliper

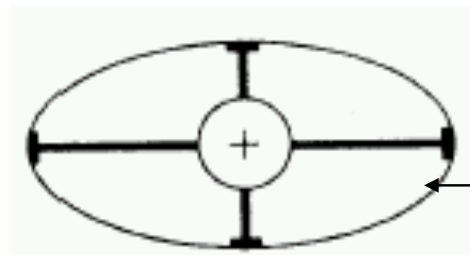




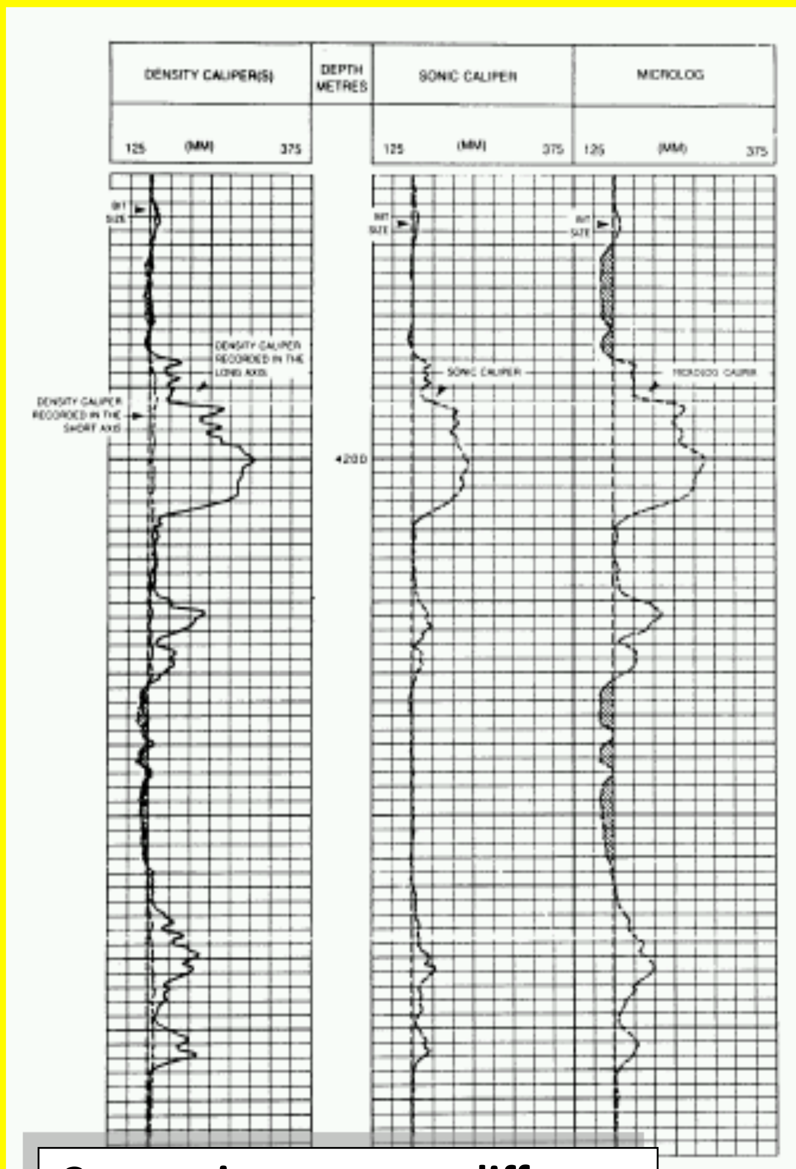
Two arm caliper

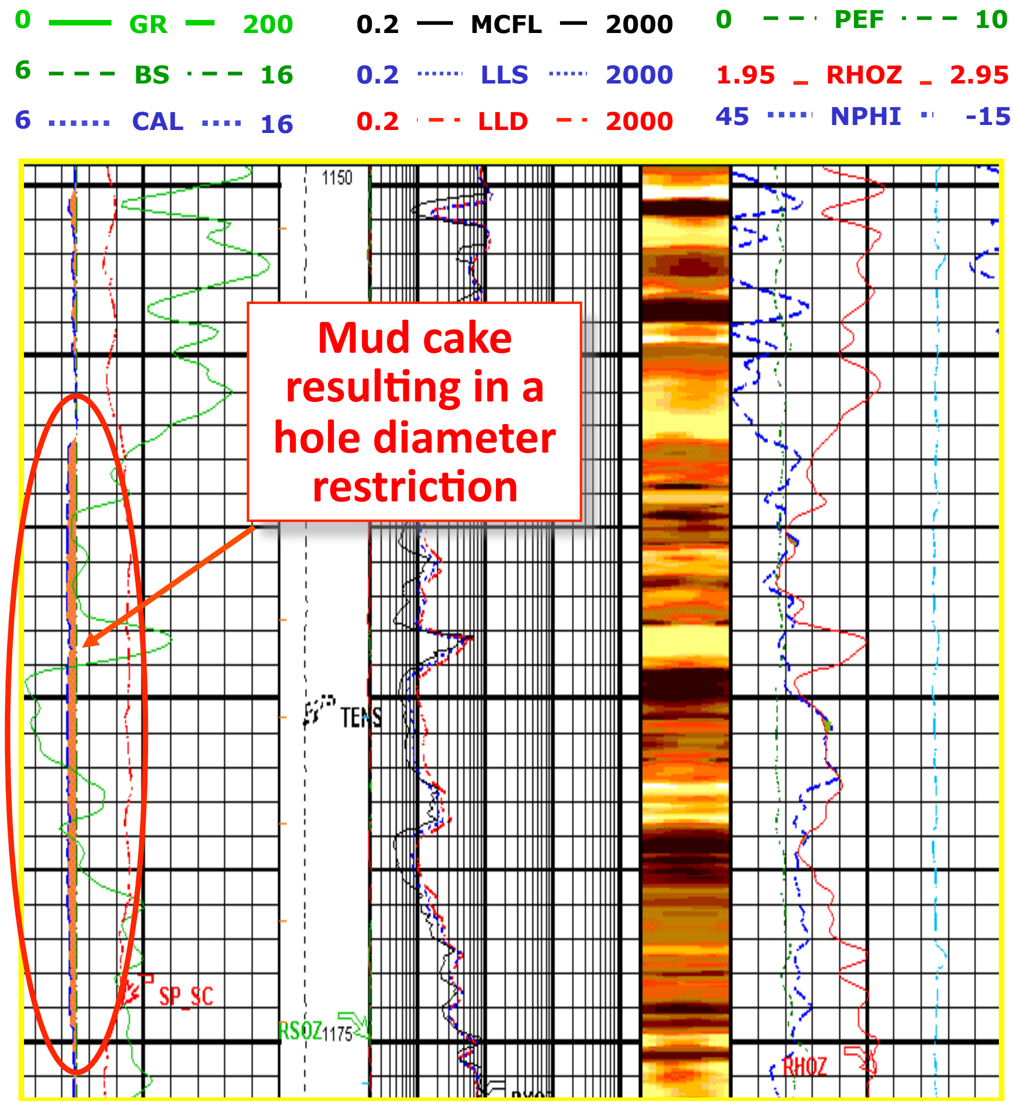


Three arm caliper



Four arm caliper

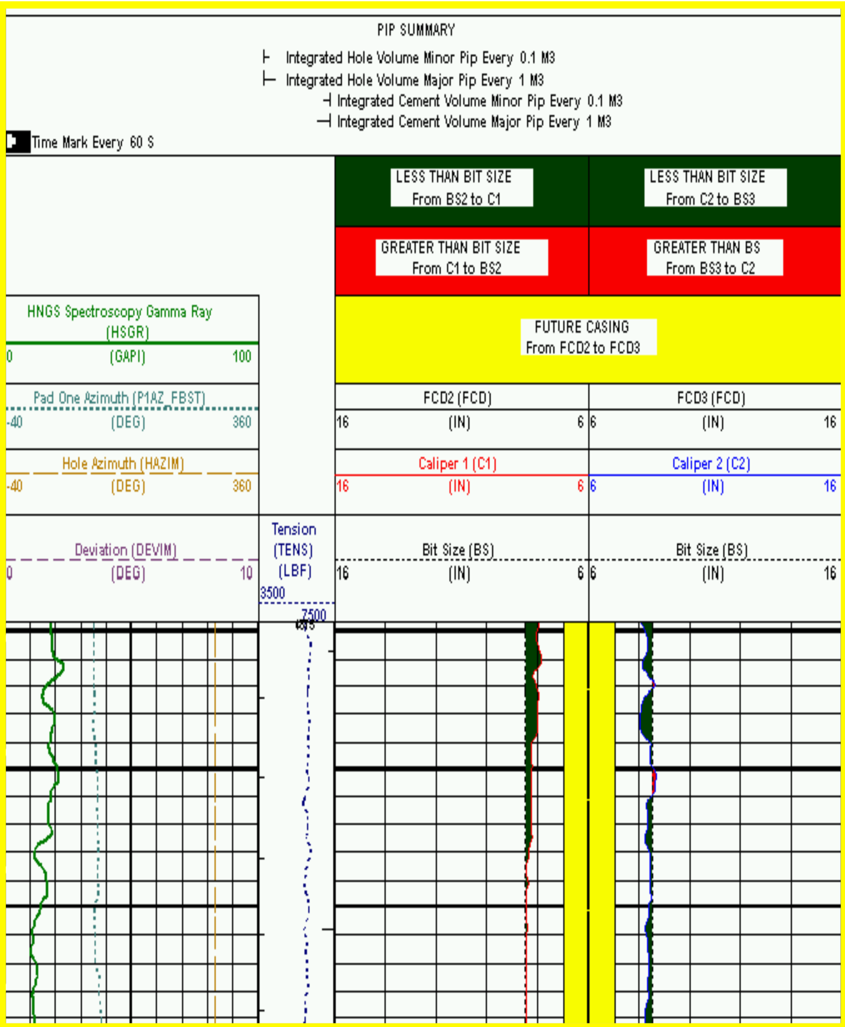


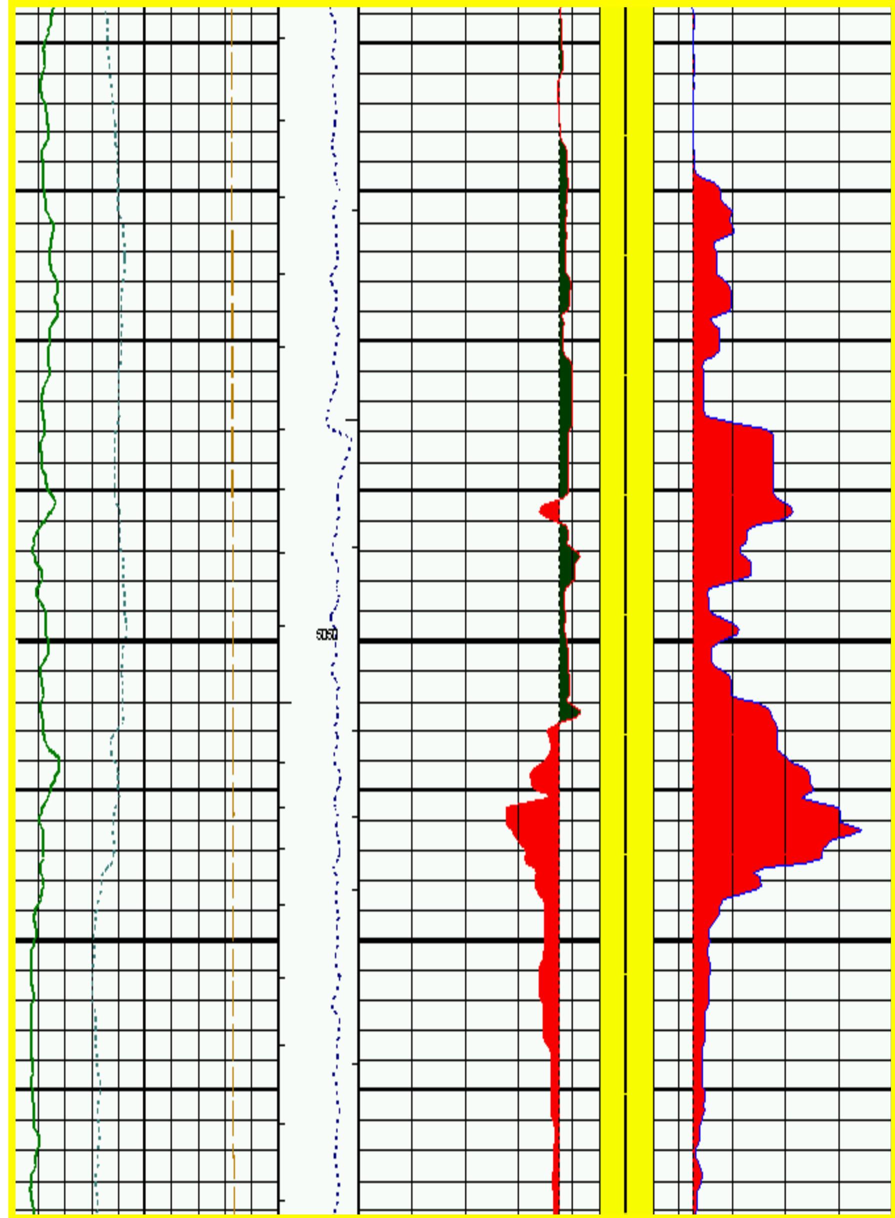


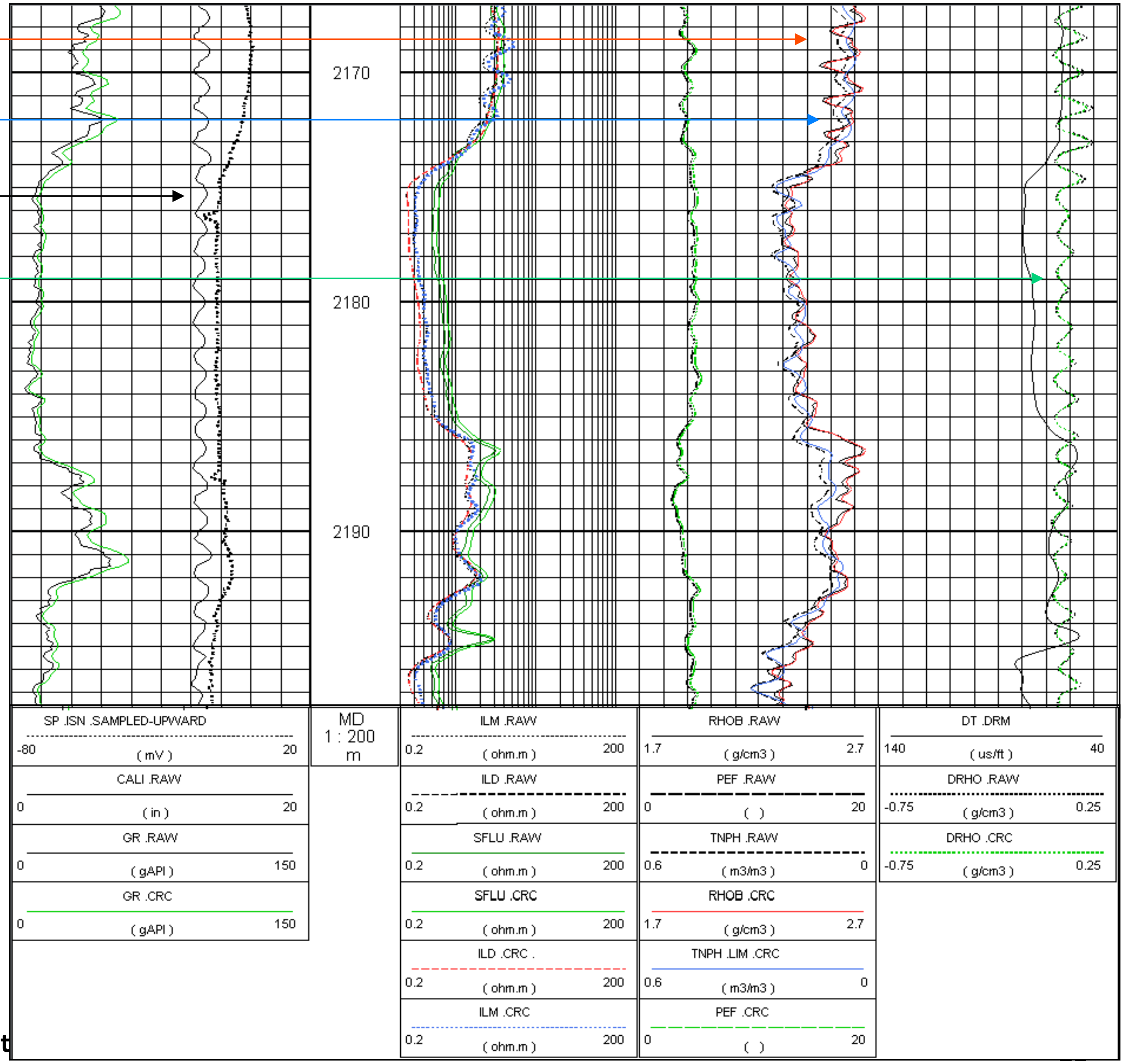
Comparison among different caliper measurements

esistivity

Borehole Geometry Tool (BGT)







“Noisy” logs due to poor borehole wall quality.

Classification of Resistivity logs

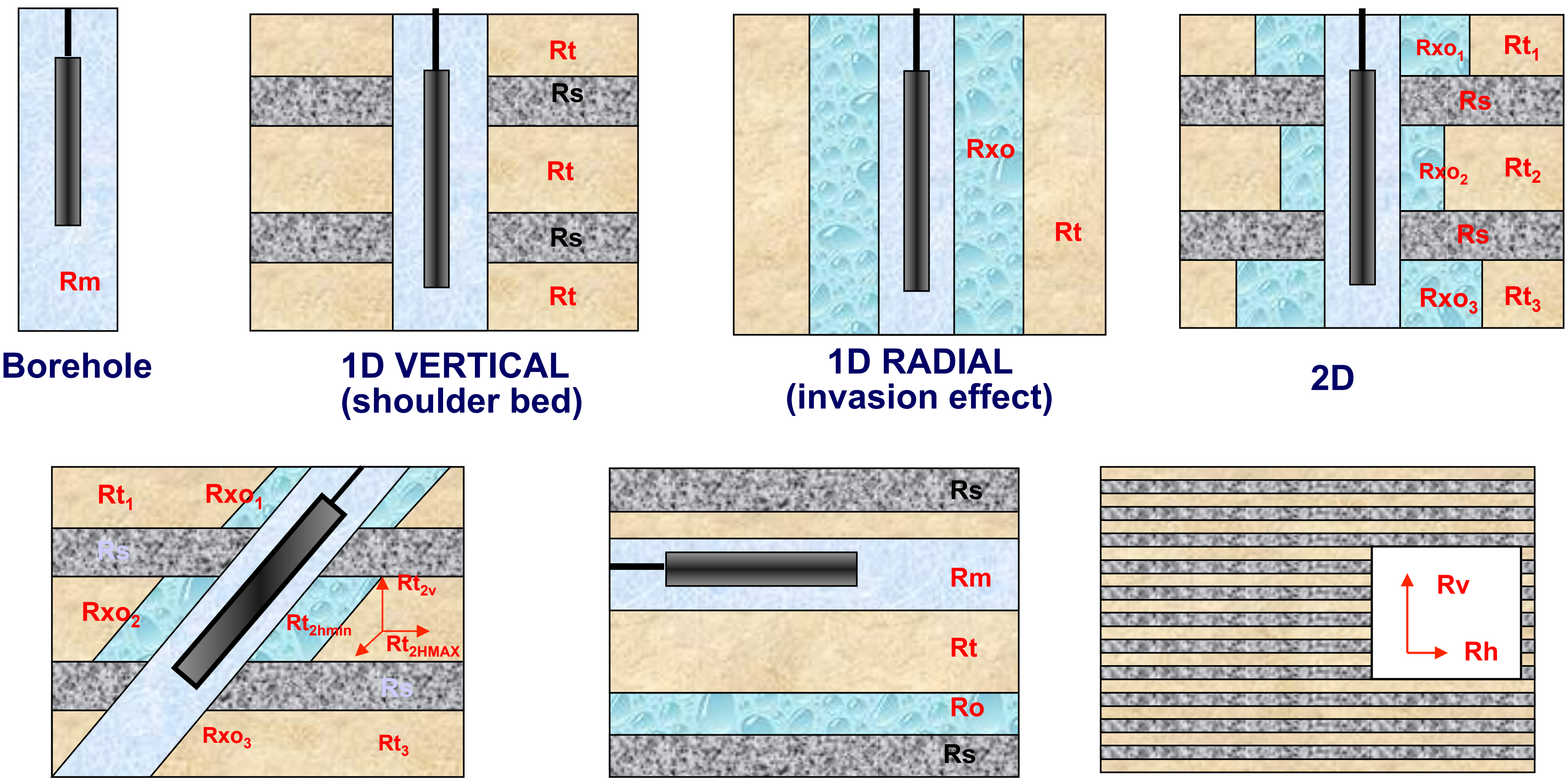
In relation to depth of investigation

- Macro-devices to measure Rt
- Micro-devices to measure Rxo

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)

Environmental effects affecting resistivity measurements



Borehole

1D VERTICAL (shoulder bed)

1D RADIAL (invasion effect)

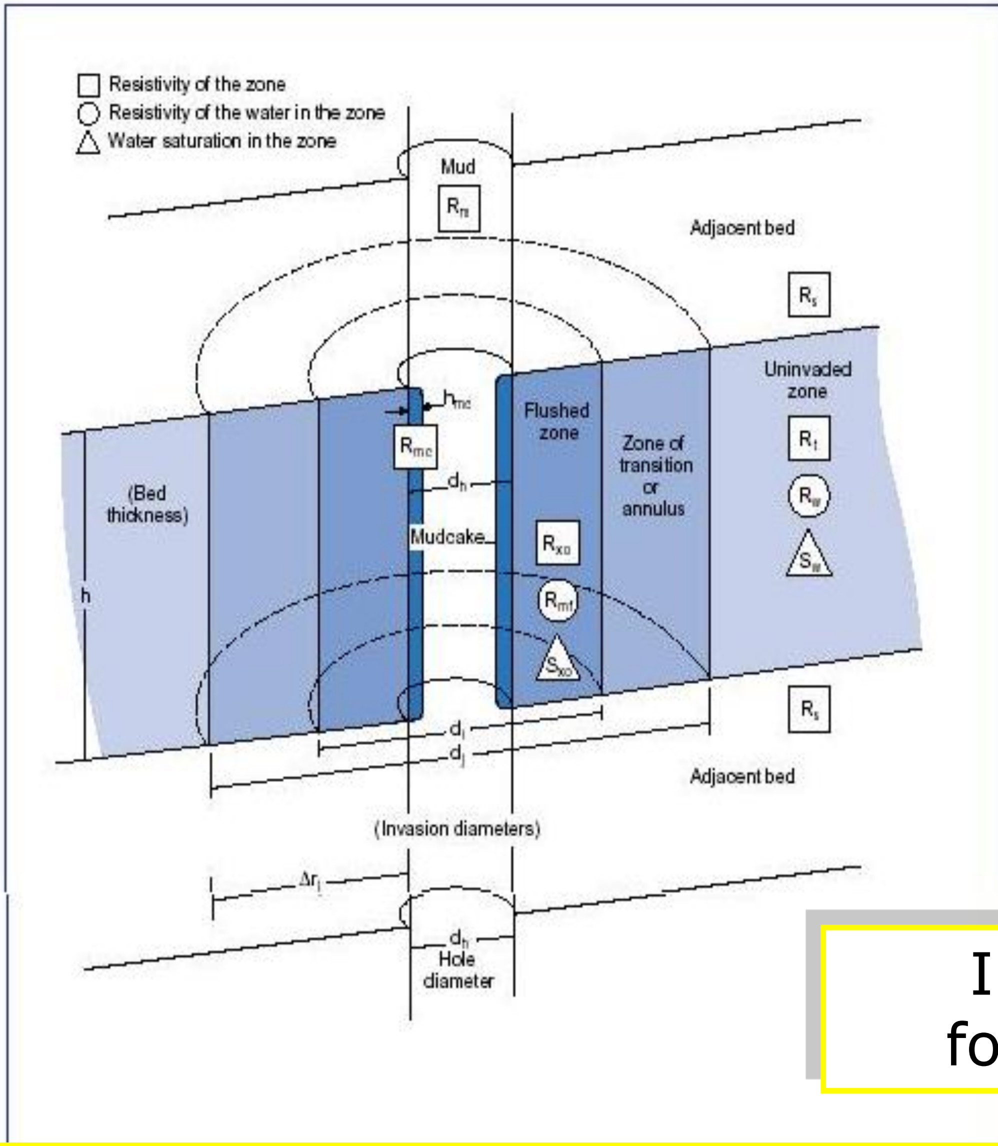
2D

2D +dip (dipping beds)

3D

Anisotropy

Symbols Used in Log Interpretation



Invasion effects and formation parameters

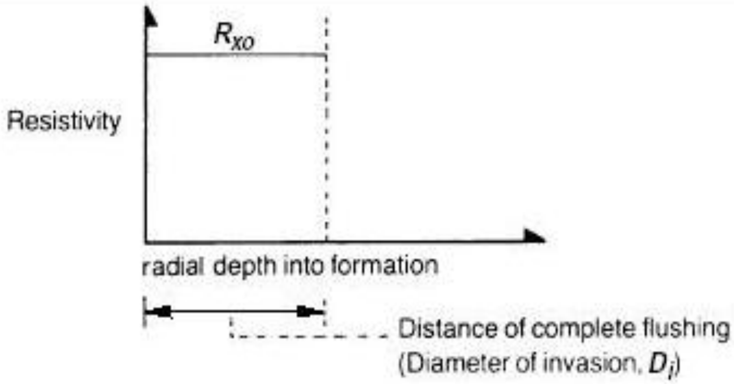


Figure B4: Invasion Process

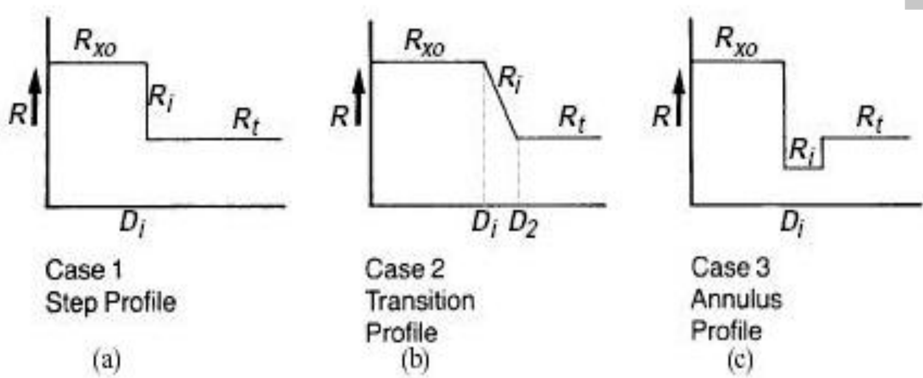


Figure B5

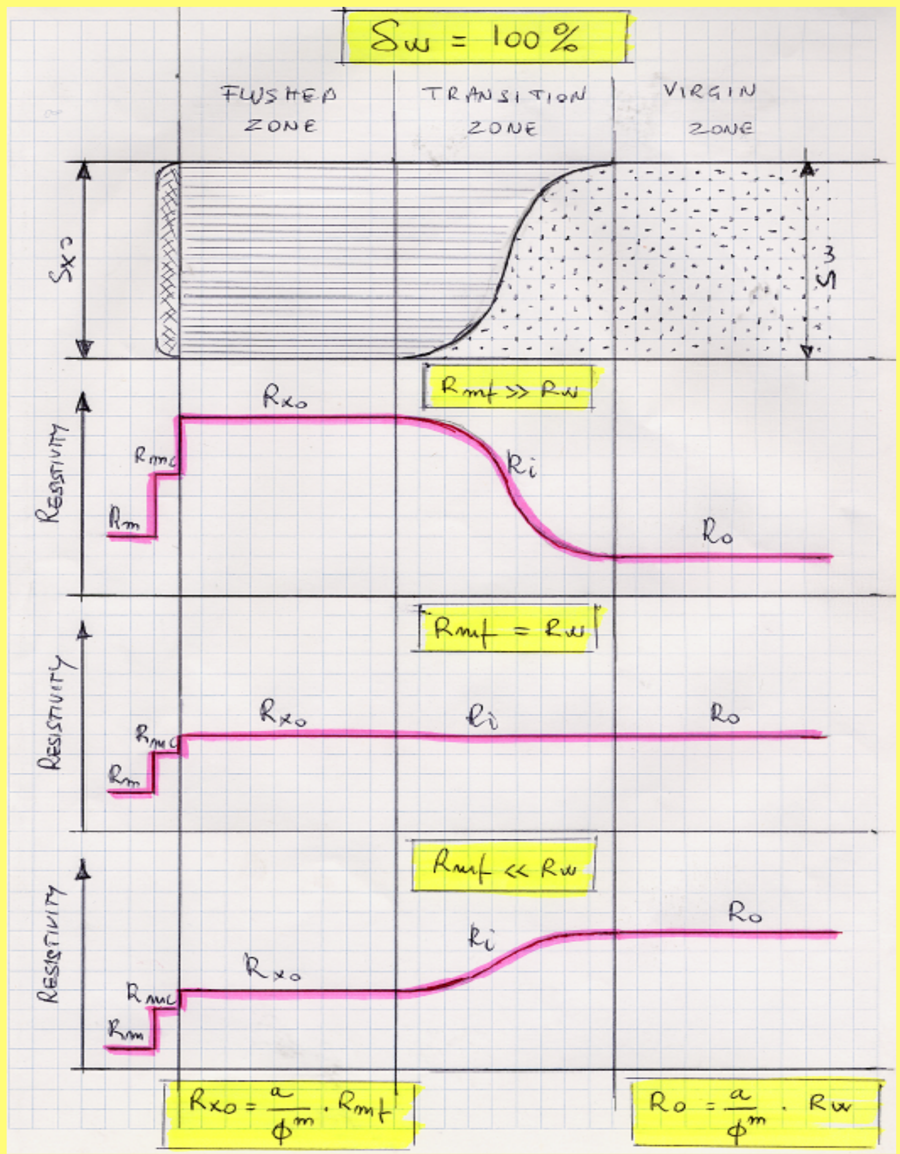
<u>$S_w = S_{xo} = 100\%$</u>

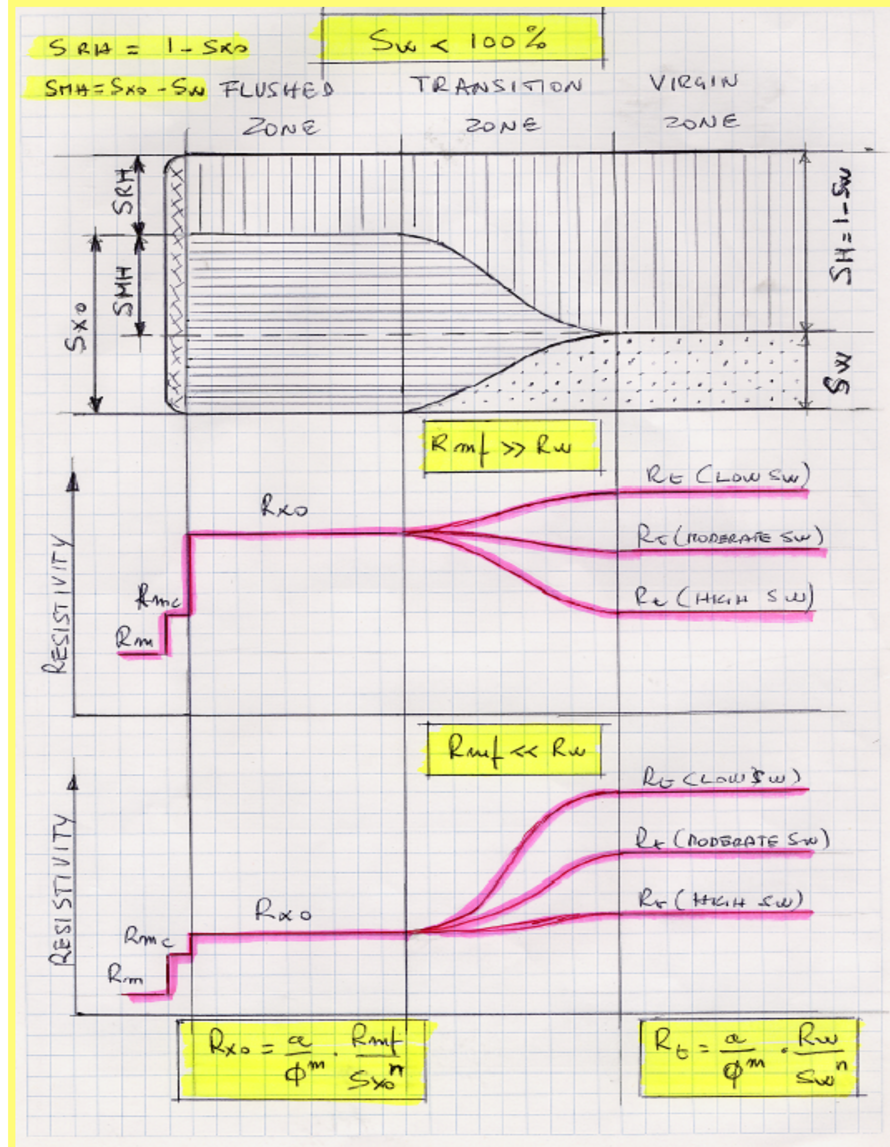
$Ro = F\ Rw = (1/\Phi^m)\ Rw$
$Rxo = F\ Rmf = (1/\Phi^m)\ Rmf$

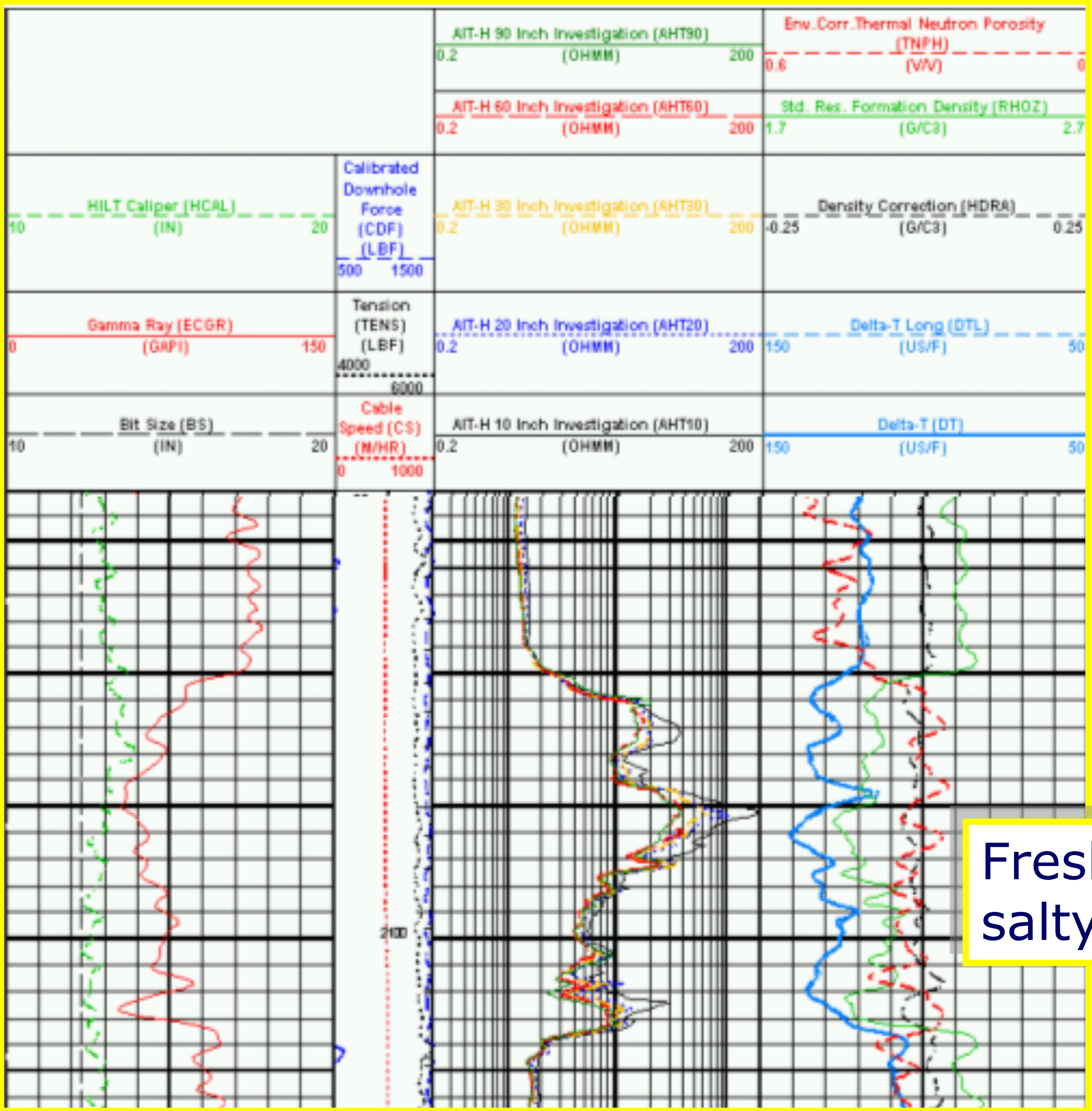
<u>$S_w < 100\%,\ S_{xo} < 100\%$</u>

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

Invasion and related resistivity profiles

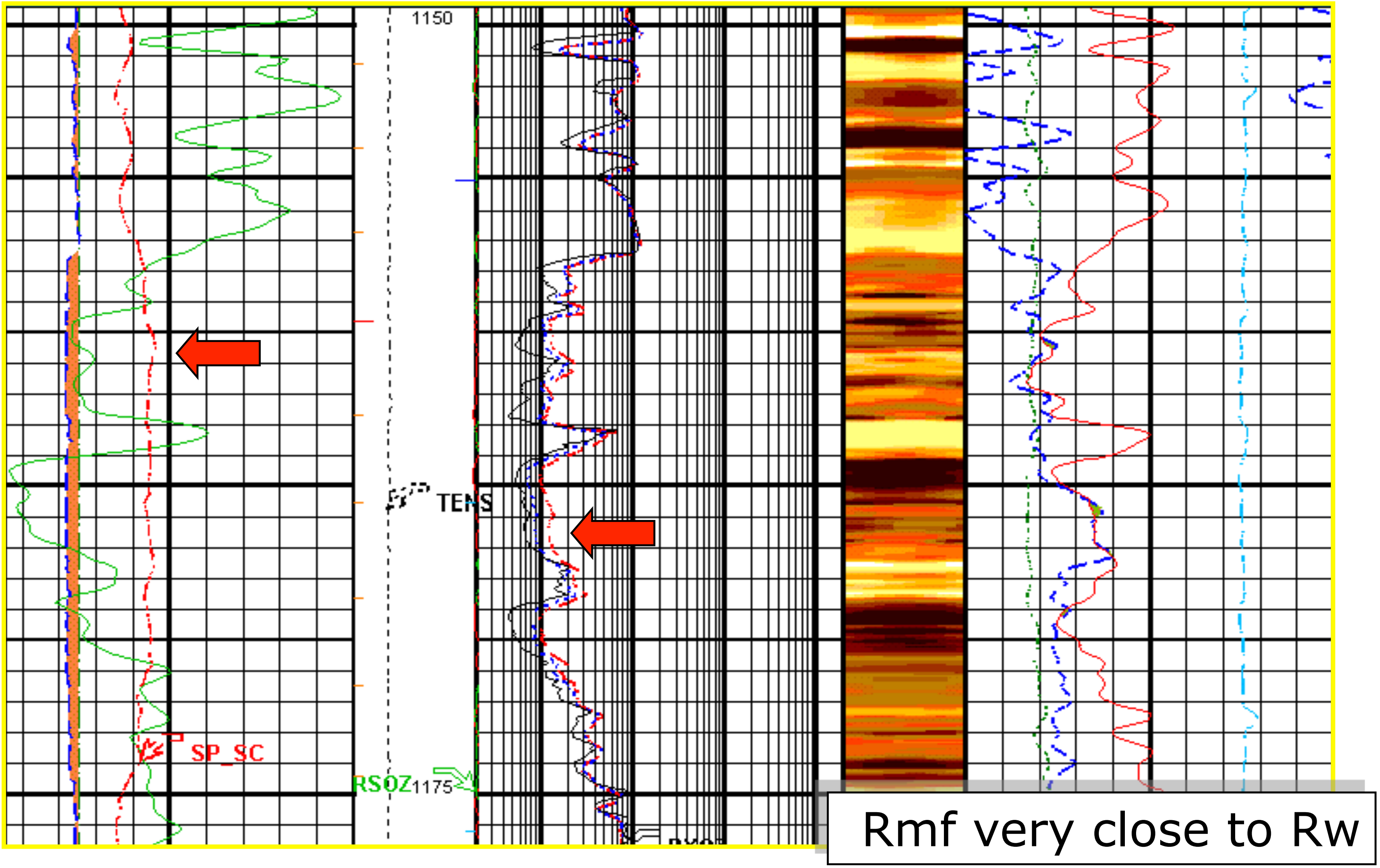




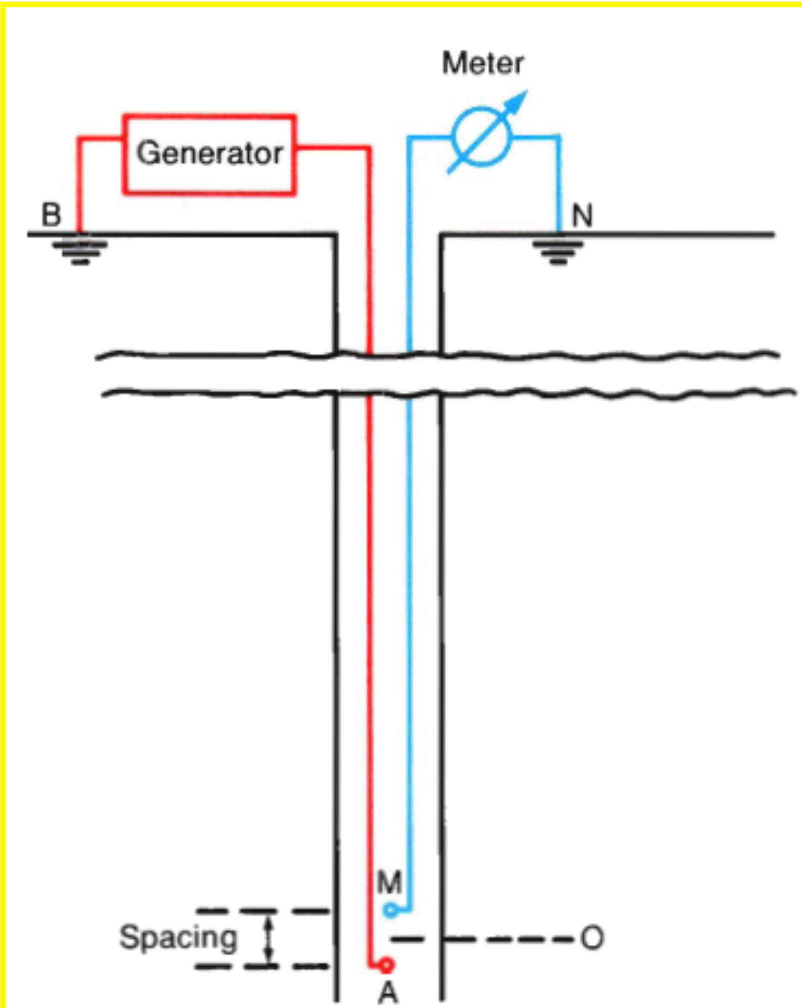


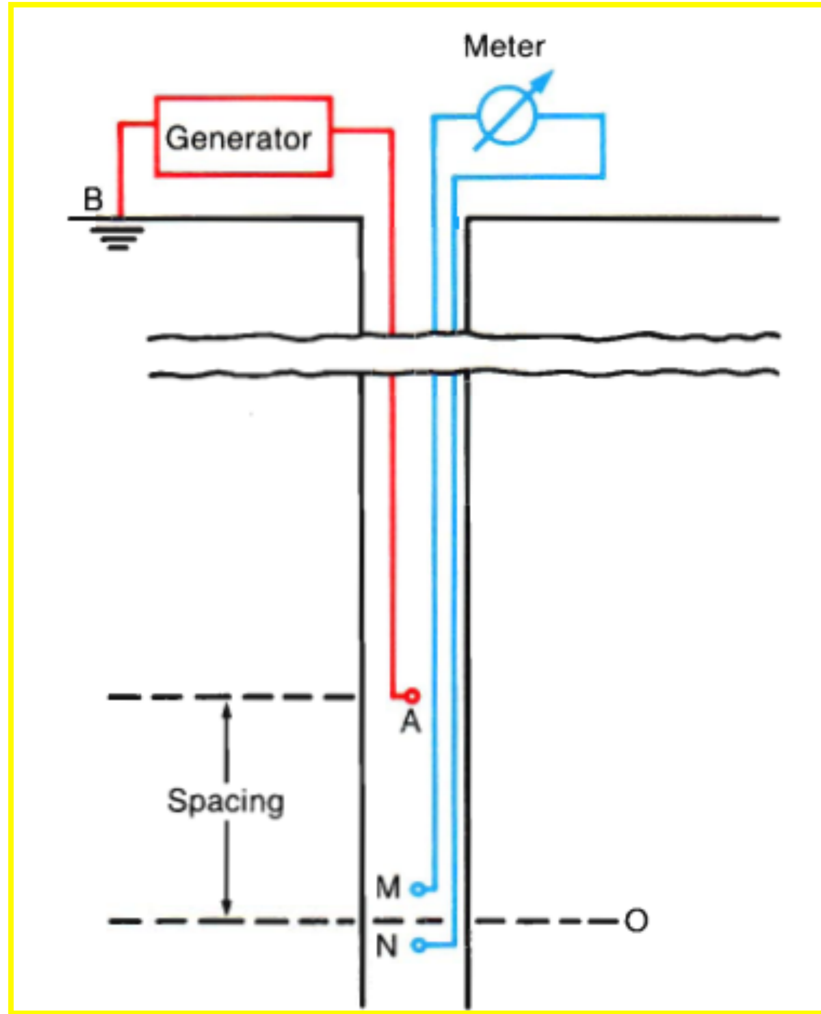
Fresh mud and salty formation water

Caliper - GR Resistivity Density/Neutron



Non focused electrical resistivity tools



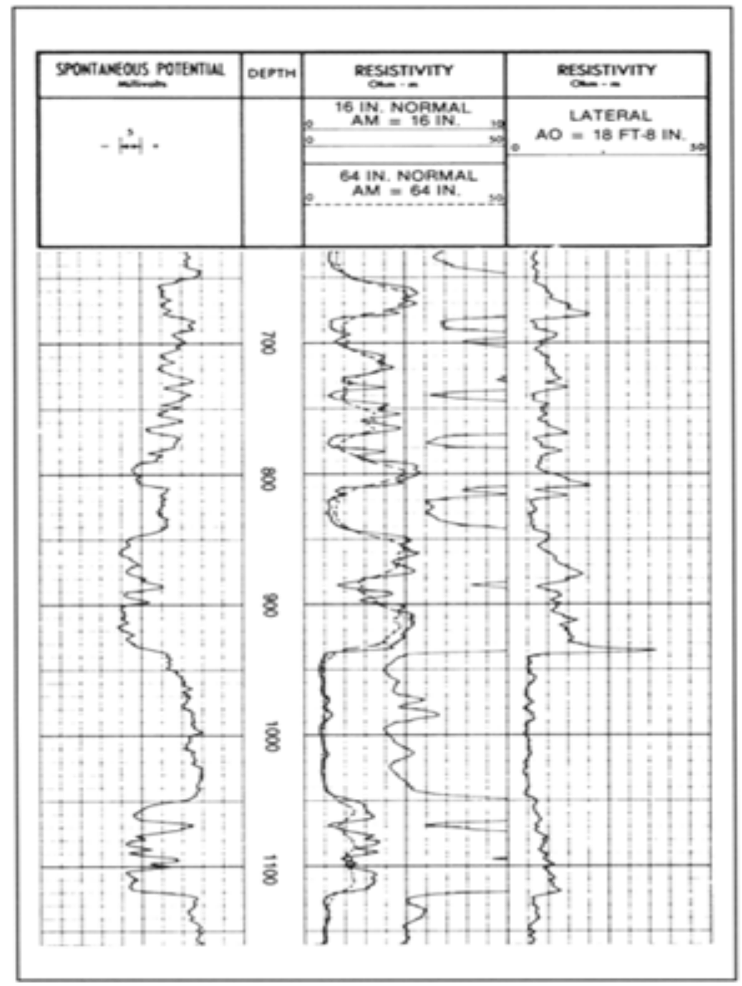


Old E (electrical) logs

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")



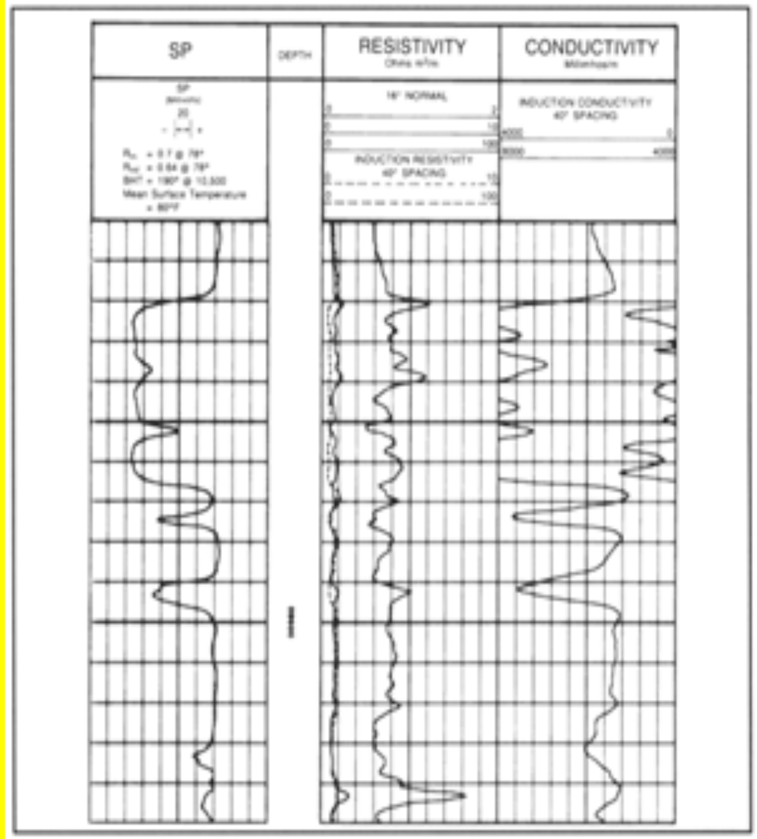
Electrolog example

Old E (electrical) logs

Induction Electrical Log (IES)

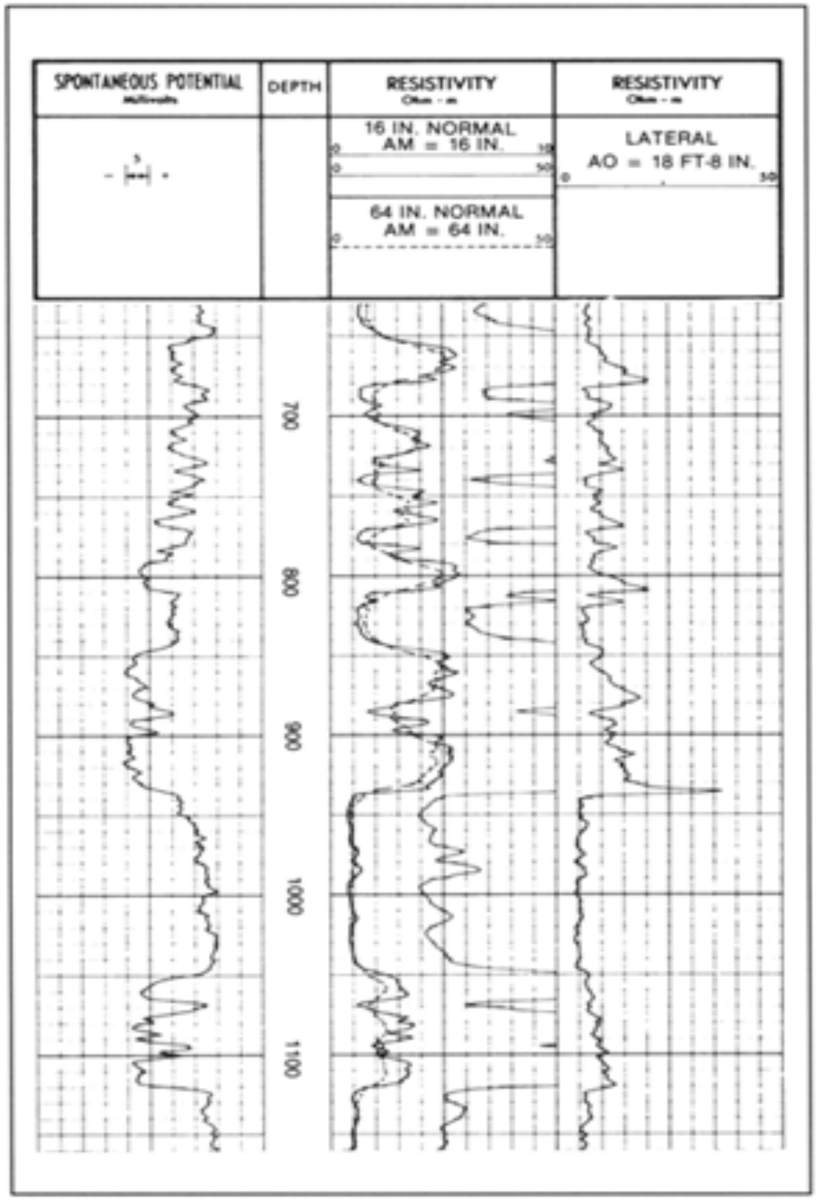
Track 1	Depth	Track 2	Track 3
SP (mv) *Linear scale*		**SN** (ohmm) **Ampl. SN** (ohmm) **6FF40 R** (ohmm) *Linear scale*	**6FF40 C** (ohmm) *Linear scale*

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

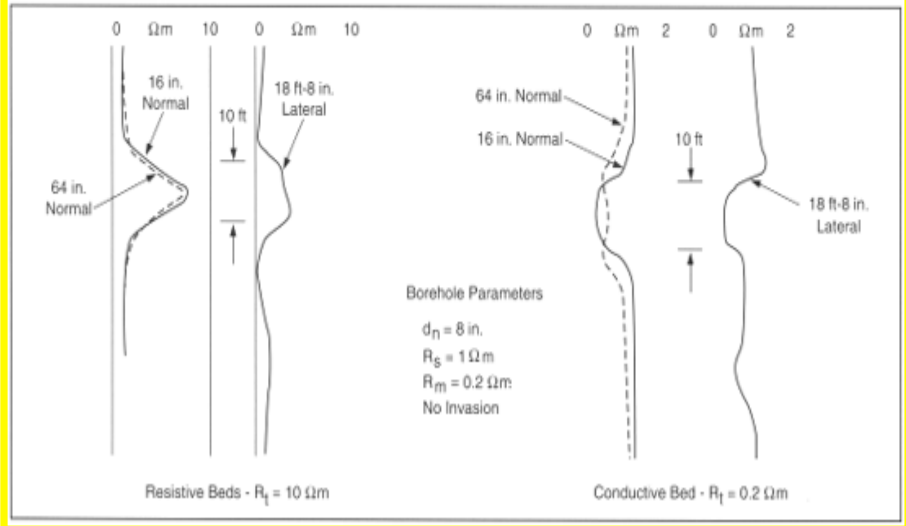


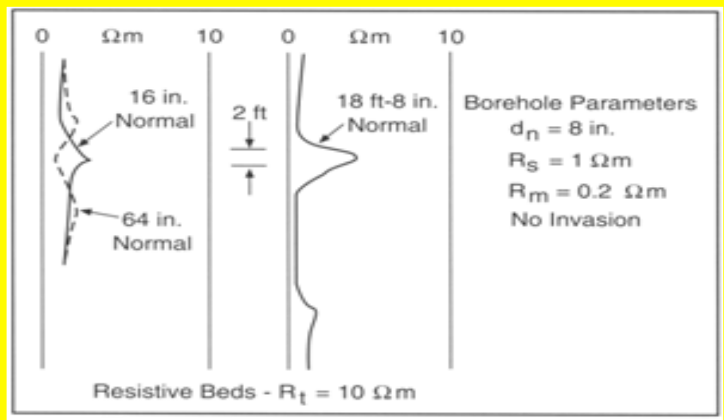
Induction Electrolog linear presentation example

Normal and lateral resistivity logs



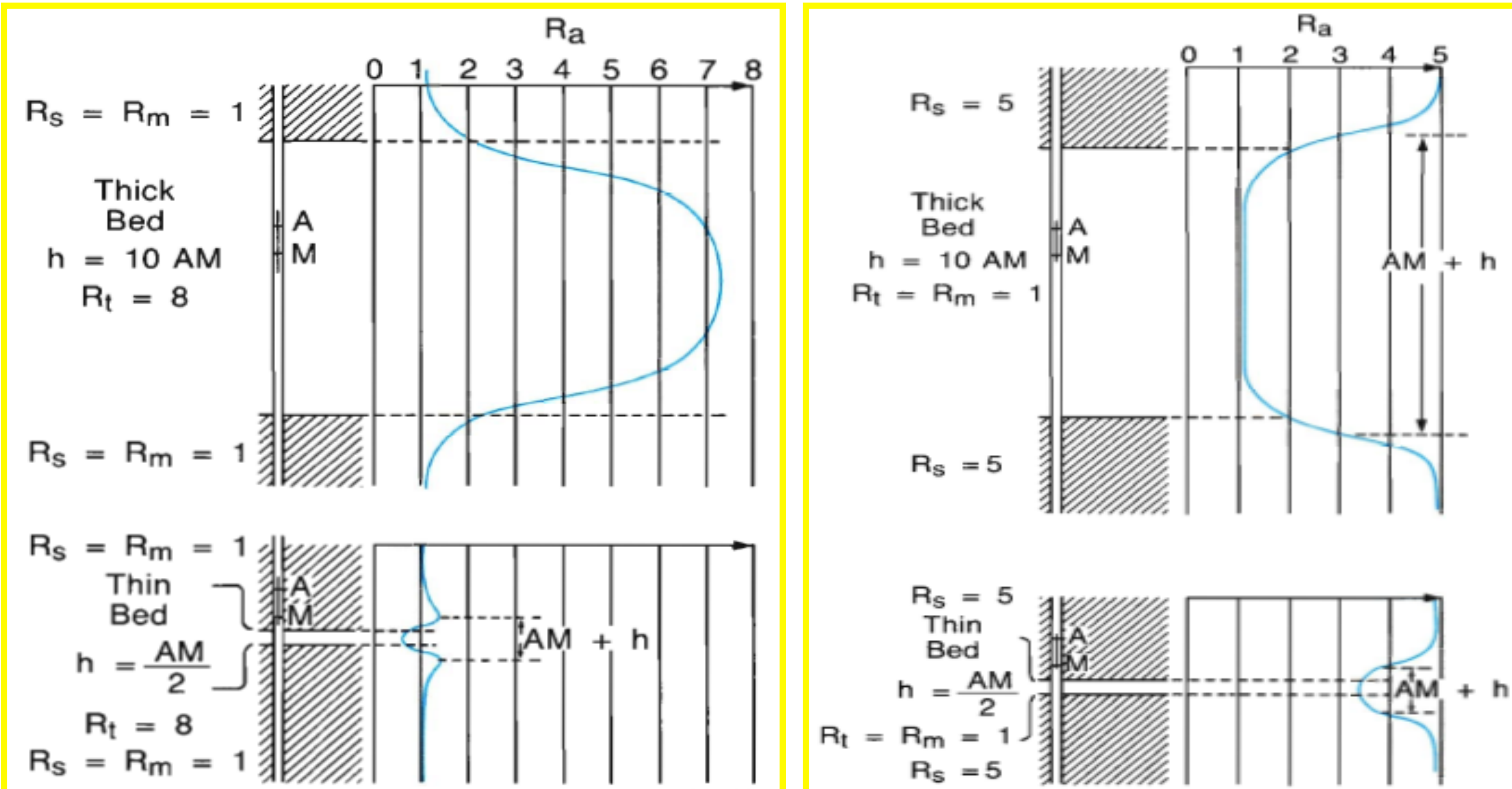
Electrolog example



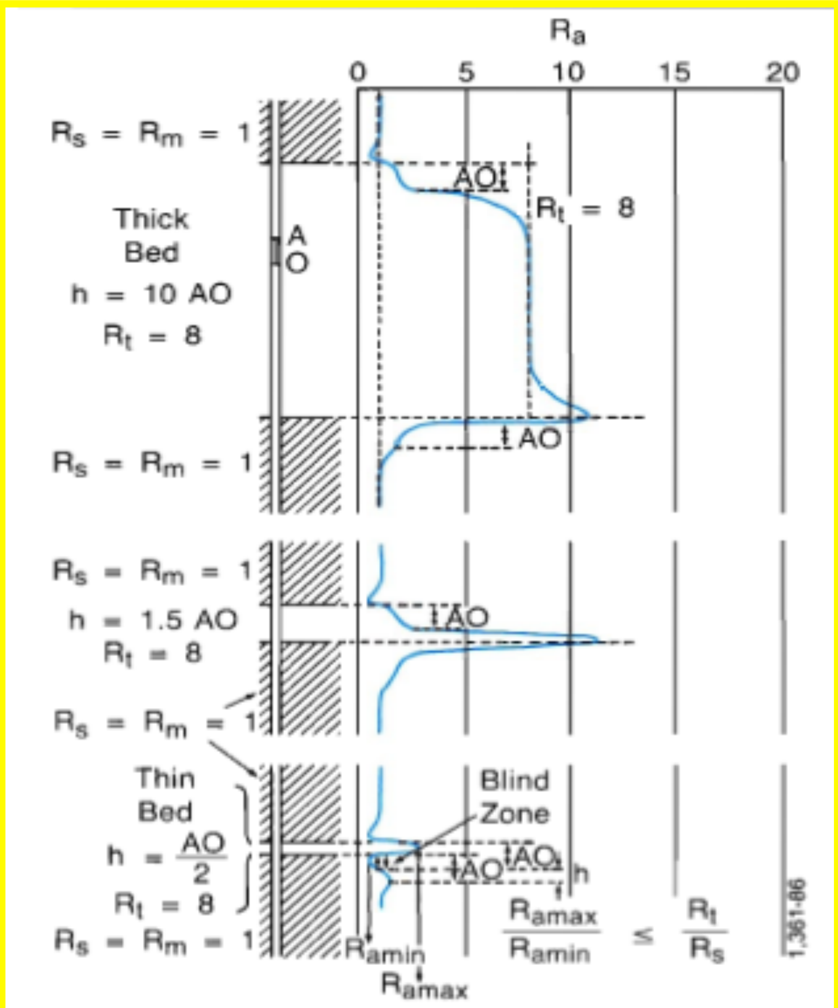


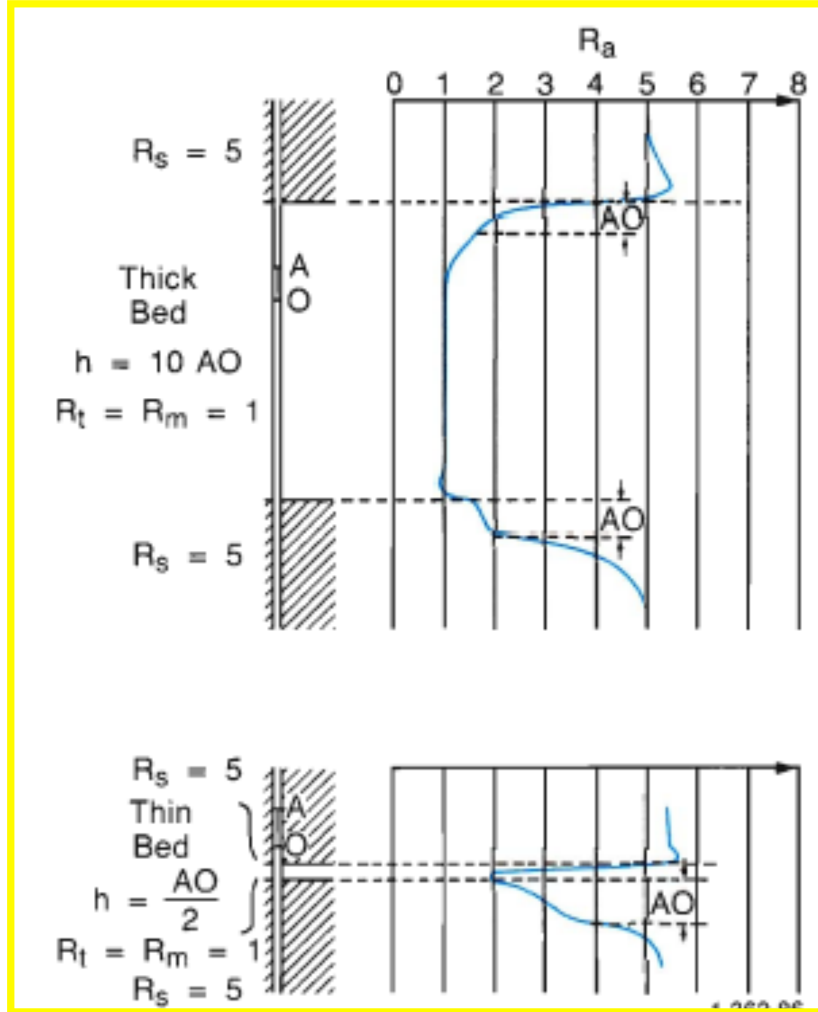
Resistivity reversal occurs when beds are thinner than a normal curve's electrode spacing

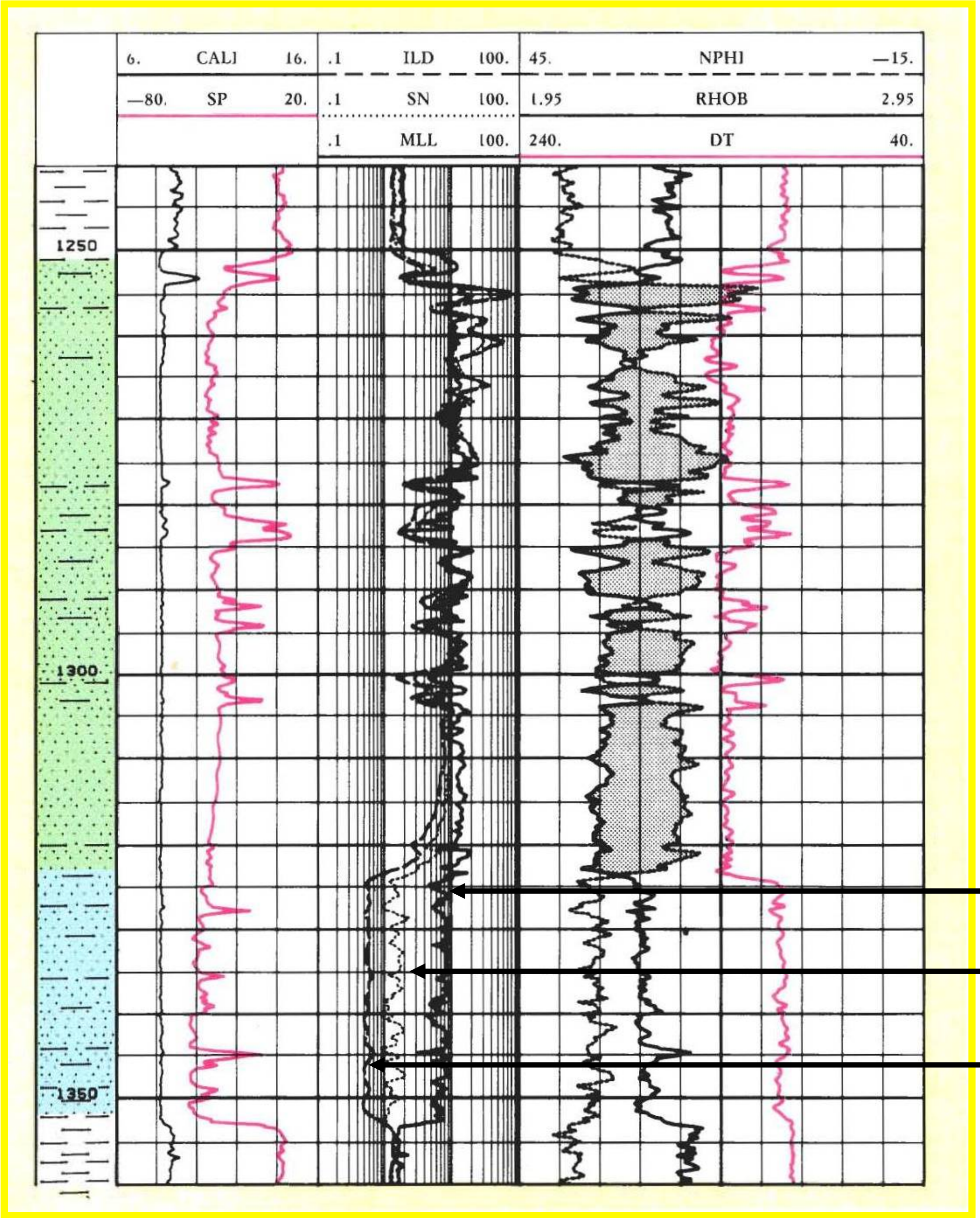
Normal electrical log responses: normal



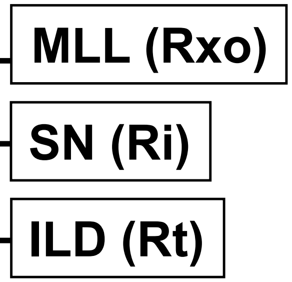
Lateral electrical log responses: lateral







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



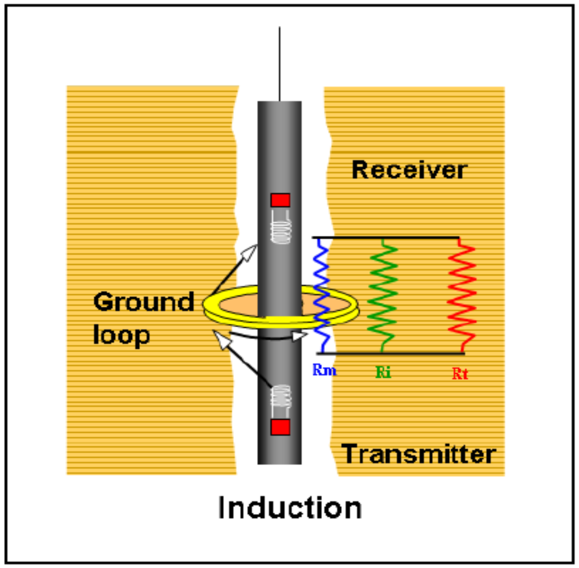


Figure 1A. Induction logging system.

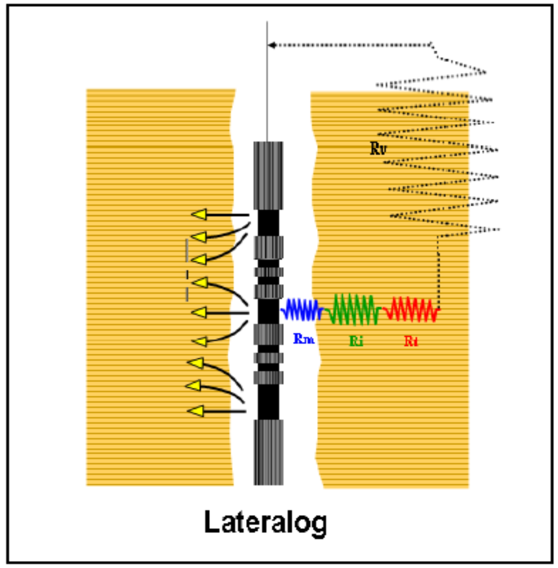


Figure 1B. Lateral logging system.

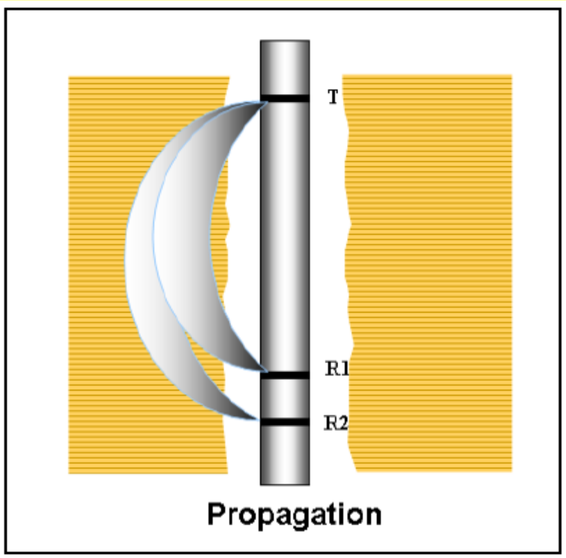


Figure 1C. Propagation logging system.

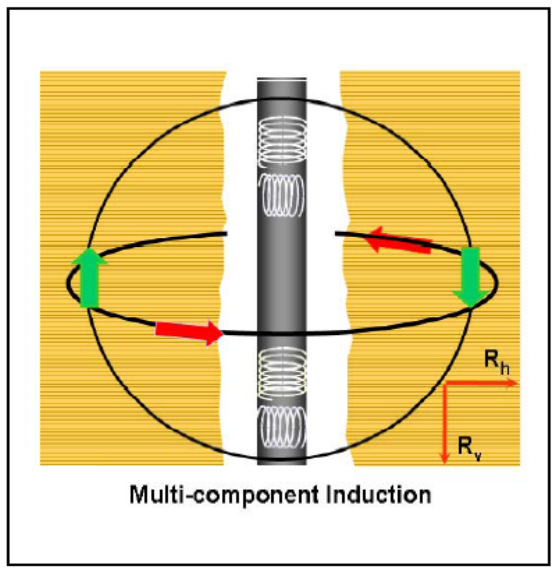
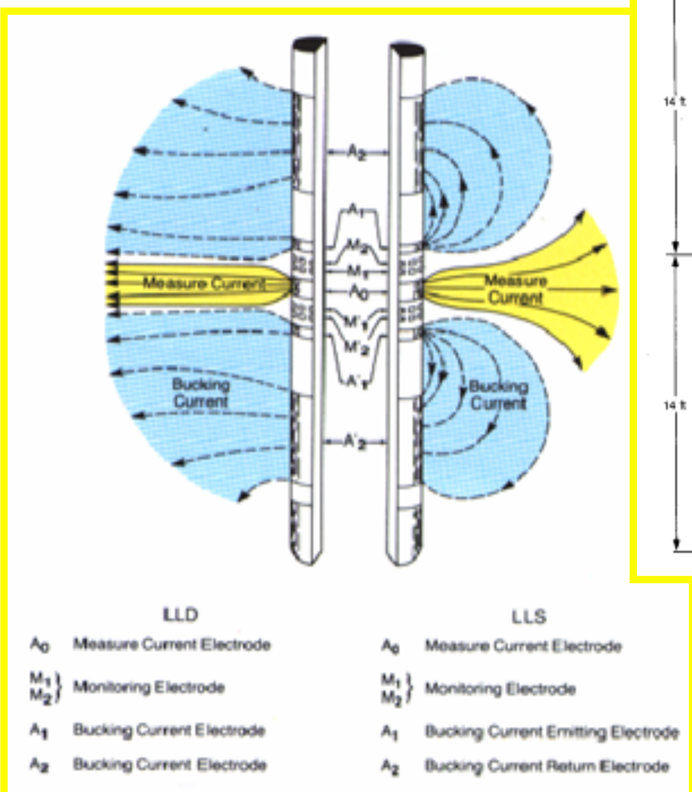
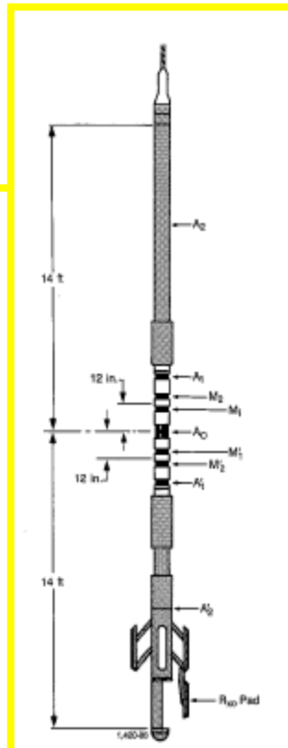


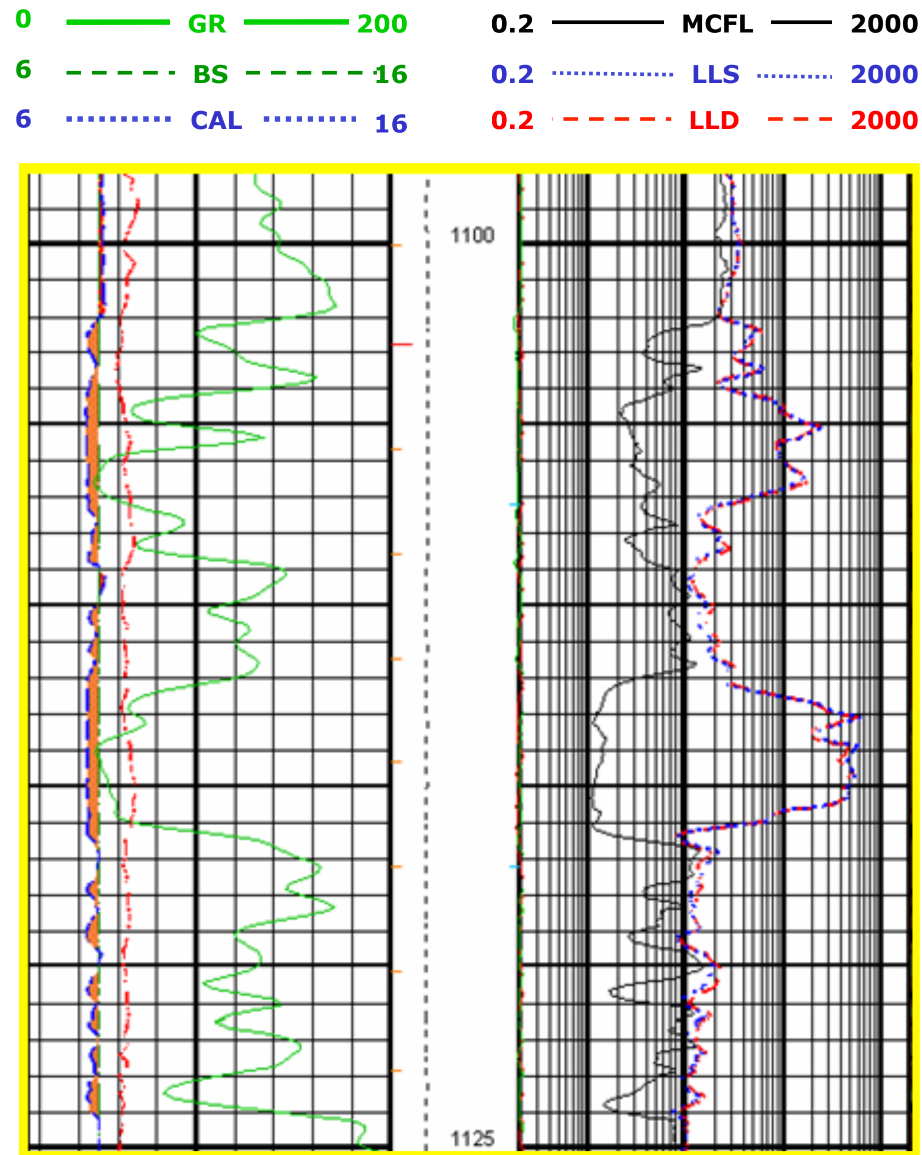
Figure 1D. Multicomponent induction logging system.

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

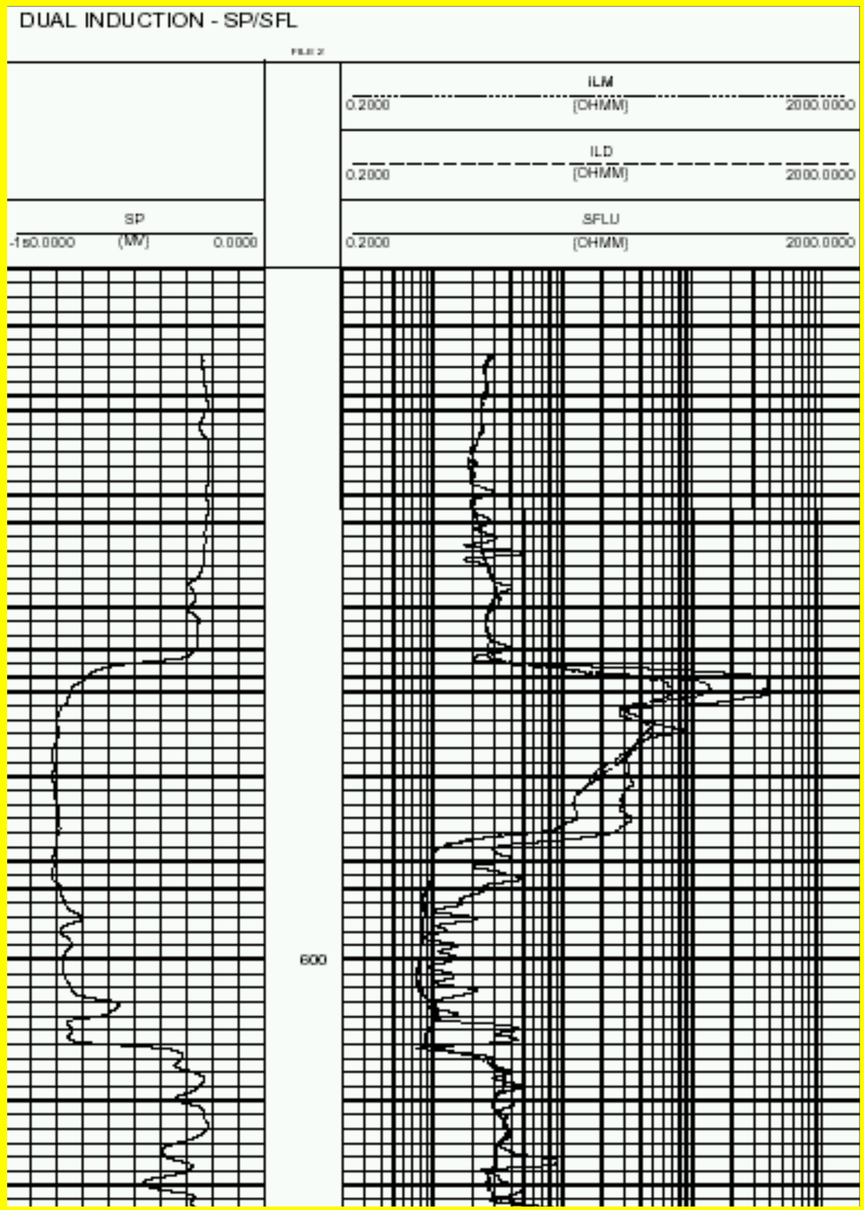
Dual Laterolog

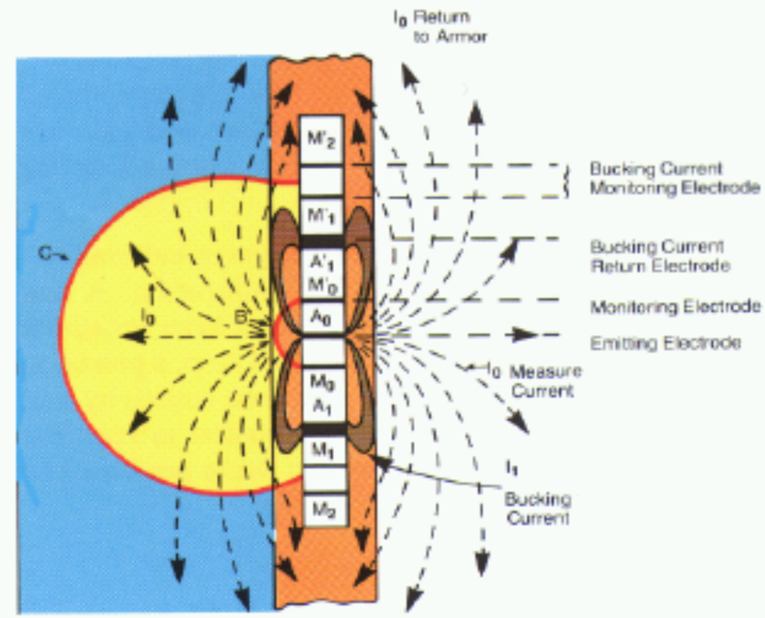






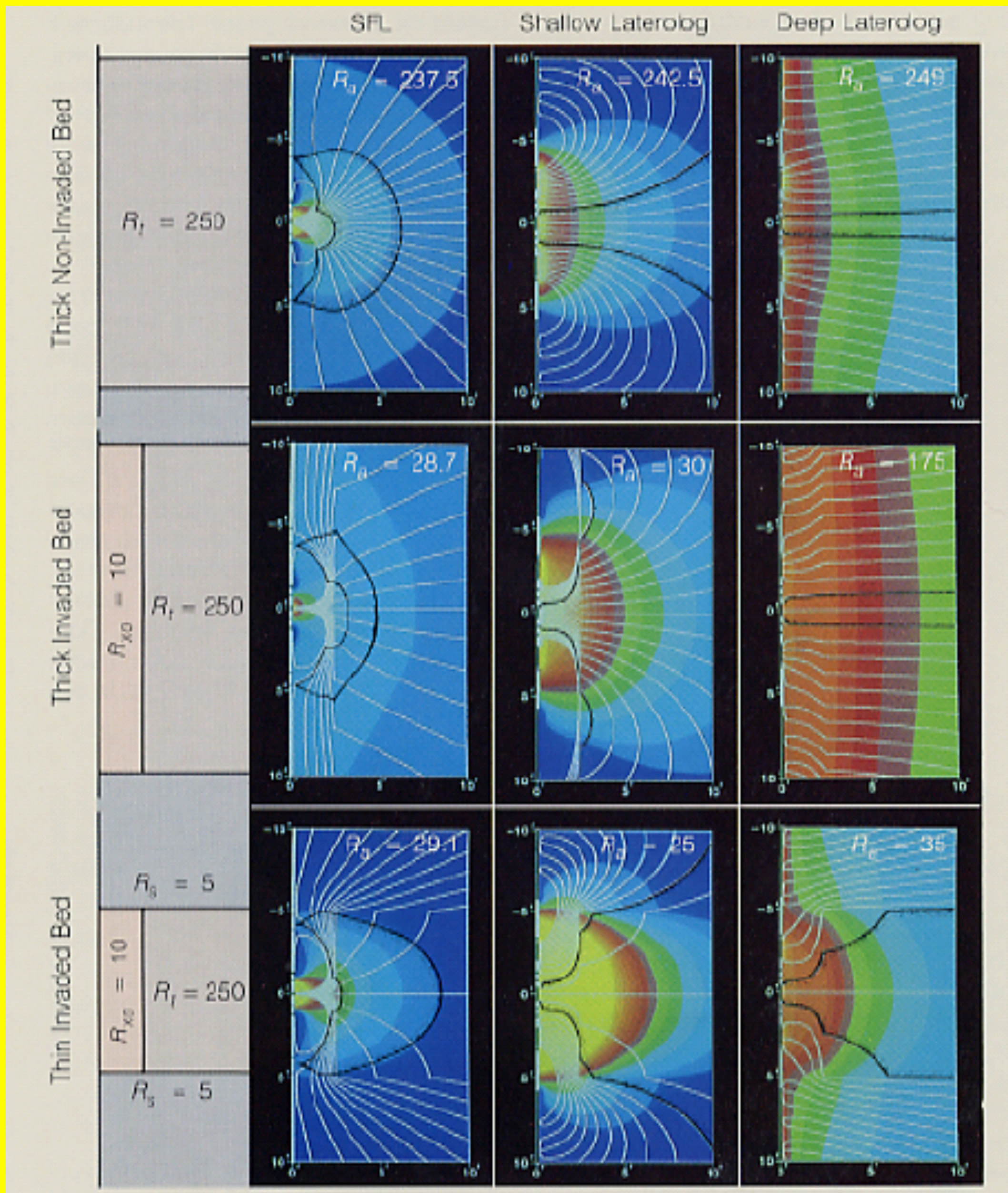
Sferically Focused Log





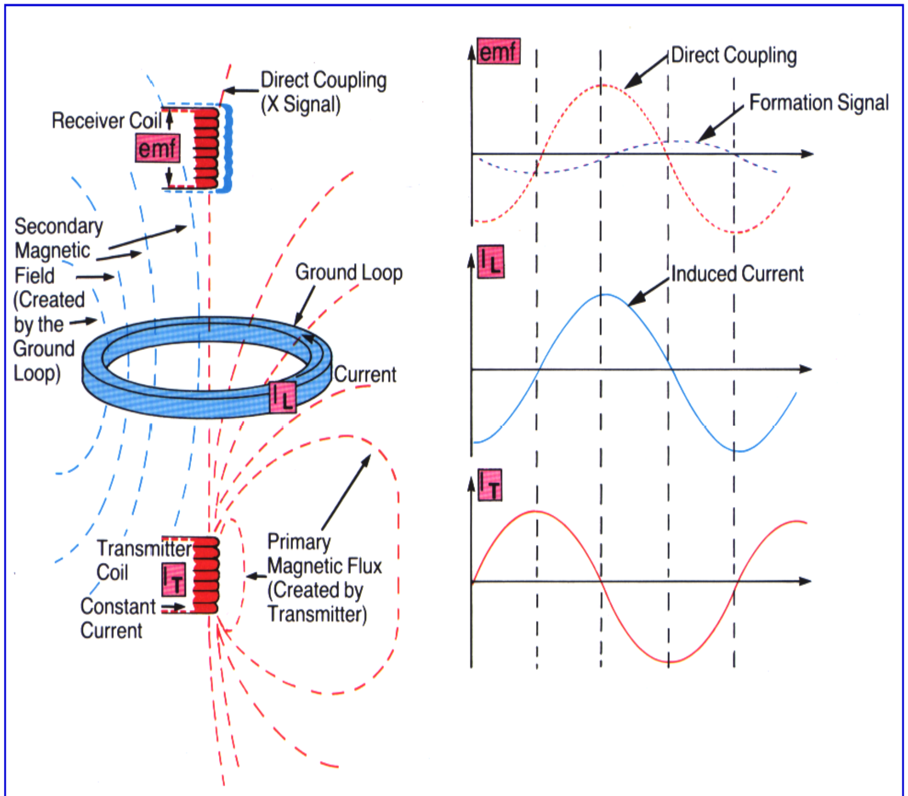
$$R_{SFL} = k\,\frac{(V_B - V_c)}{I_0}$$

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

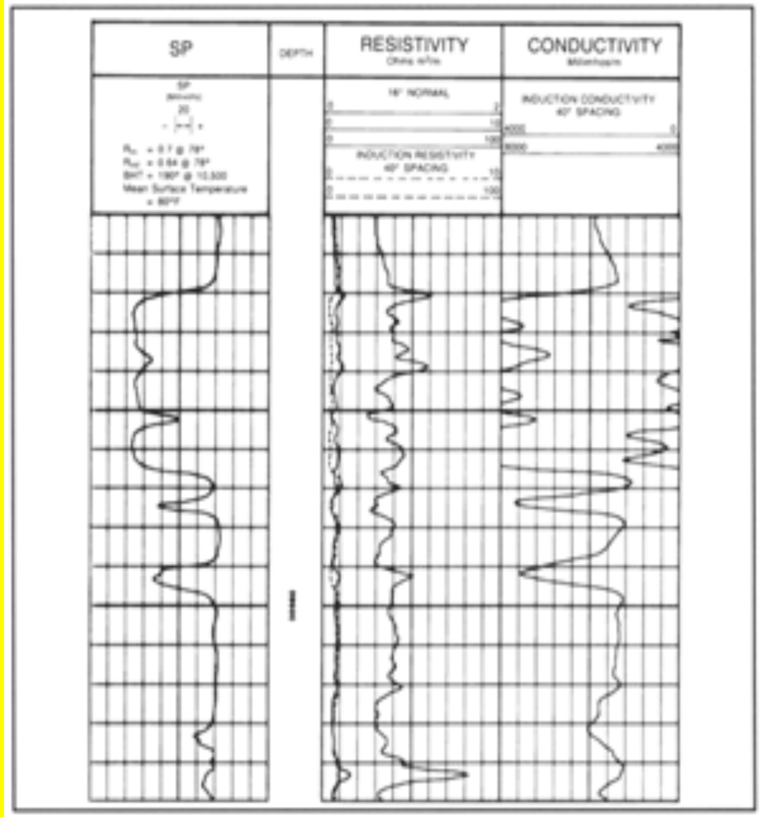


Environmental effects on focused galvanic tools

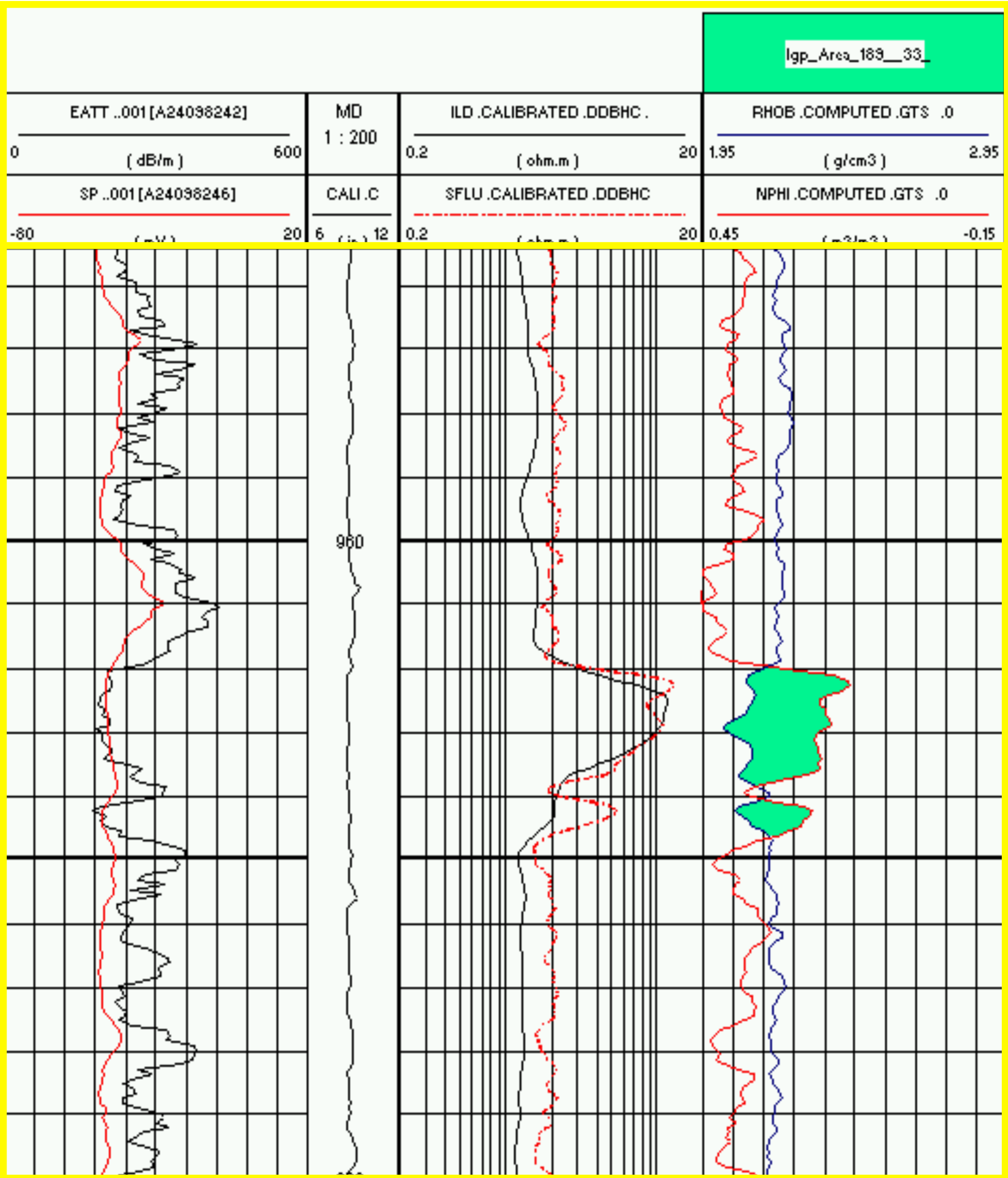
Induction logging



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

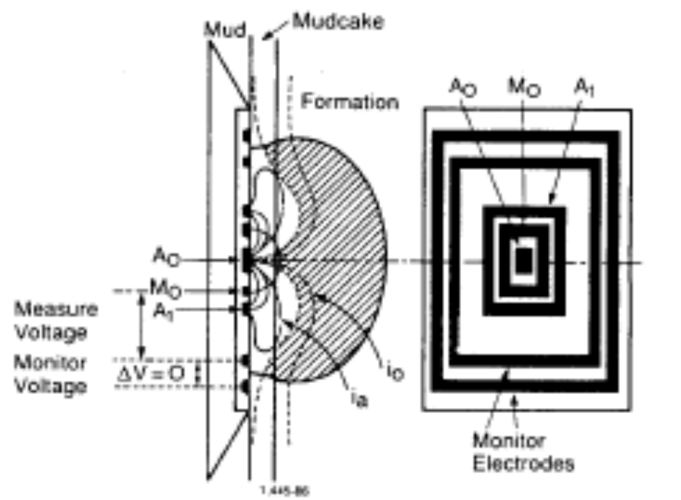
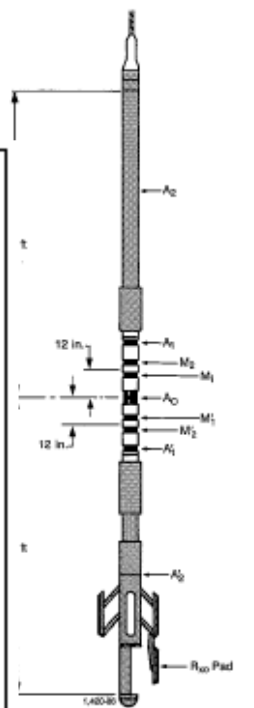
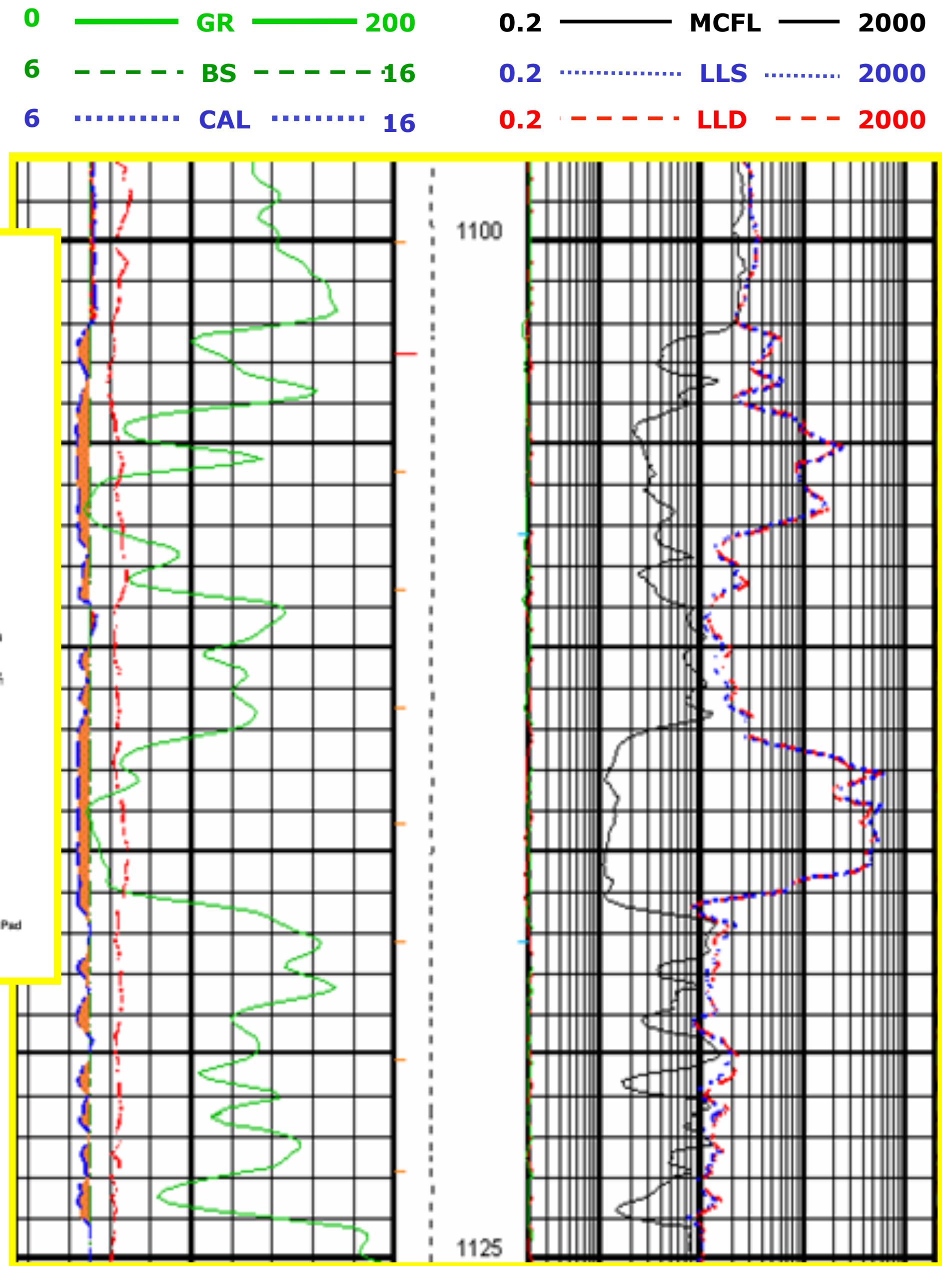


Figure B28: Current Distribution of MicroSFL device (left) and Electrode Arrangement (right)

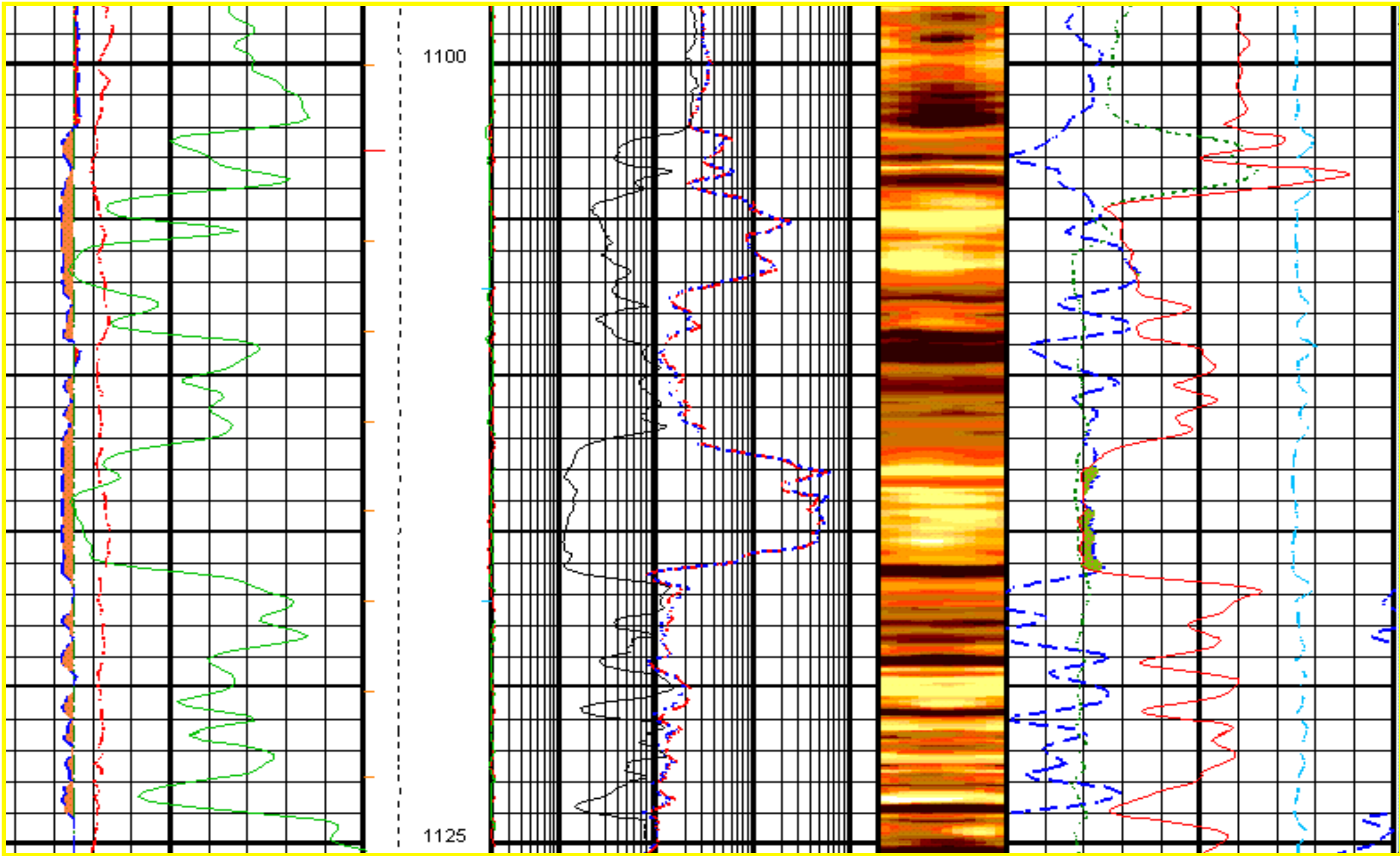




Caliper - GR

Resistivity

Density/Neutron



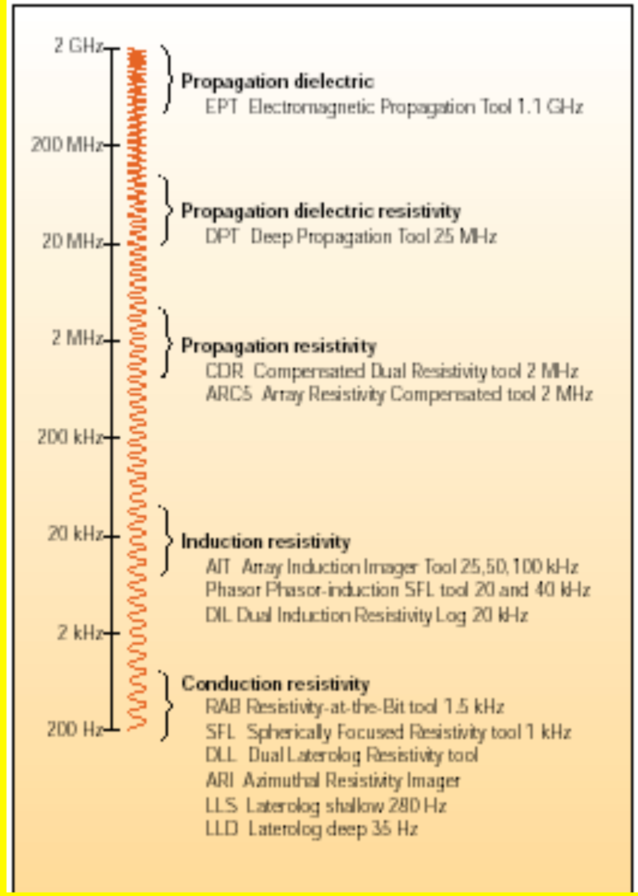
While Drilling resistivity logging

While Drilling resistivity logging are of two types:

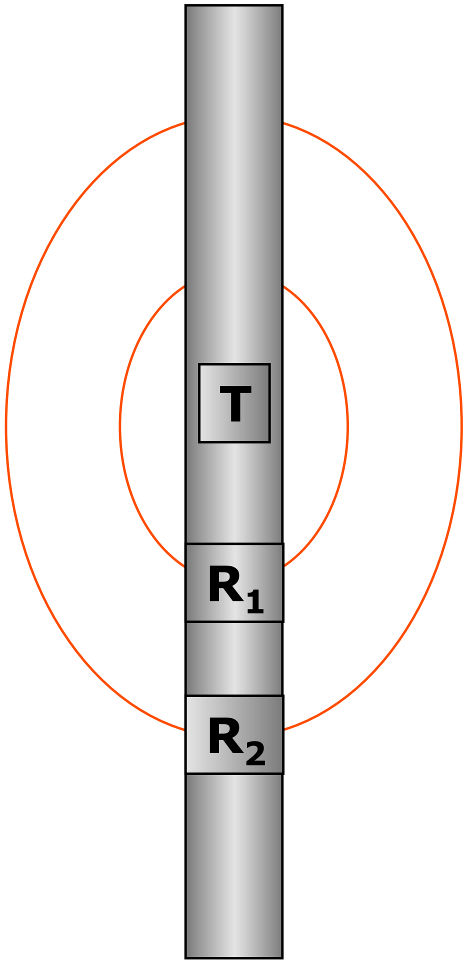
- galvanic;
- EM wave propagation.

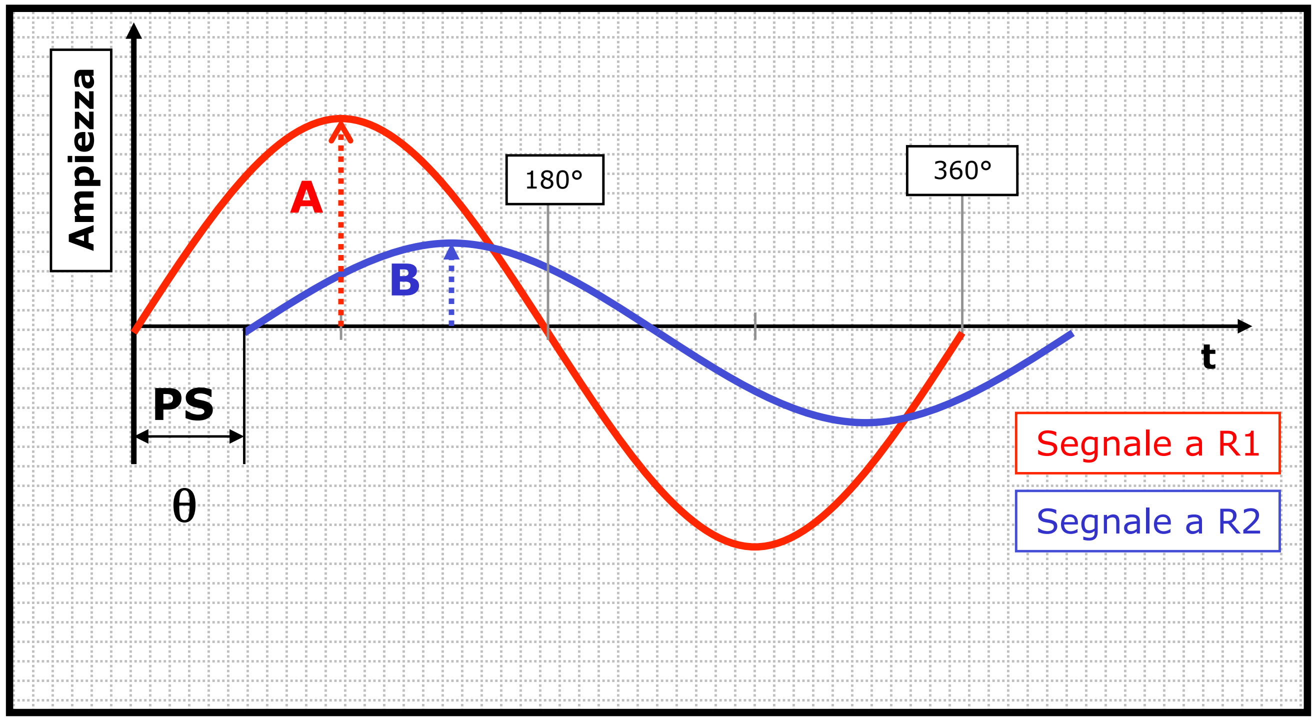
While Drilling Galvanic logs (Anadrill RAB only) can be used only in presence of Water Based conductive Muds.

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