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.

![Diagram of SP log](image_url)
Spontaneous 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.

\[
E_m = - \frac{R \theta I_a - I_c}{F n I_a + I_c} \ln \frac{C_1}{C_2}
\]

\[
E_l = - \frac{R \theta}{F n} \ln \frac{C_1}{C_2}
\]

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)

\[ V_{sh} = A / B \]

\[ V_{sh} = (P_{S} - P_{Ssd}) / (P_{Ssh} - P_{Ssd}) \]
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

\[ SSP = -K \log \left( \frac{R_{mf}}{R_w} \right) \]

- \( R_m > R_w \) - red
- \( R_m = R_w \) - green
- \( R_m < R_w \) - blue

Hydrocarbon effect on the SP log
$Rmf > Rw$

$Rmf = Rw$
Inverted SP:
Rmf << Rw
**SP log interpretation problems**

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.
Low activity Cement

High activity Cement

Low activity Cement

Gamma Ray American Institute Test Pit

K = 4%
Th = 24 ppm
U = 12 ppm
200 GAPI

Typical responses Of GR log

Gamma Ray log
Shale volume from GR log

Vsh = \frac{(GR - GR_{sd})}{(GR_{sh} - GR_{sd})}

BS, CALI, SP, GR
Caliper - GR

LLD, LLS, MCFL
Resistivity

TNPH, RHOB, DT
Density/Neutron

Basics of Geophysical Well Logs_Lithology & Resistivity
Gamma Ray: environmental corrections

Main factors affecting GR measurements are:
• hole diameter
• sonde position in the well
• mud loaded with radioactive material
Gamma Ray: environmental corrections

Gamma Ray Corrections for Hole Size and Mud Weight
For 3¼-in. and 1½-in. SGT wireline gamma ray tools

\[ t = \frac{W_{\text{mud}}}{8.345} \left( \frac{2.54 (d_{\text{hole}})}{2} - \frac{2.54 (d_{\text{soil}})}{2} \right) \]
Gamma Ray Spectrometry

Gamma Ray emission spectra

WLL Services
SLB NGS
SLB HNGS (PEX)
BA SL

Basics of Geophysical Well Logs_Lithology&Resistivity
GR in cased hole

GR correlation Log in cased hole

Formation Evaluation logging in CH

Basics of Geophysical Well Logs_Lithology&Resistivity
Caliper log

Single arm caliper

Two arm caliper

Three arm caliper

Four arm caliper

Basics of Geophysical Well Logs_Lithology&Resistivity
Comparison among different caliper measurements

Mud cake resulting in a hole diameter restriction
Borehole Geometry Tool (BGT)
“Noisy” logs due to poor borehole wall quality.

Basics of Geophysical Well Logs_Lithology & Resistivity
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

Basics of Geophysical Well Logs_Lithology&Resistivity
Symbols Used in Log Interpretation

Invasion effects and formation parameters
\[ Sw = S_{xo} = 100\% \]

\[ Ro = \frac{F \cdot R_w}{(1/\Phi^m)} \]

\[ Rxo = \frac{F \cdot R_{mf}}{(1/\Phi^m)} \]

\[ Sw < 100\%, \ S_{xo} < 100\% \]

\[ Rt = \frac{(1/\Phi^m)(R_w)}{Sw^n} \]

\[ Rxo = \frac{(1/\Phi^m)(R_{mf})}{S_{xo}^n} \]
Invasion and related resistivity profiles

\[ R_{xo} = \frac{a}{\phi_m} \cdot R_{mL} \]

\[ R_o = \frac{a}{\phi_m} \cdot R_w \]

\[ R_{xo} = \frac{\alpha \cdot R_{mf}}{\phi_m \cdot S_{w0}^n} \]

\[ R_b = \frac{a}{\phi_m} \cdot \frac{R_{mf}}{S_{w0}^n} \]
Fresh mud and salty formation water
Rmf very close to Rw
Non focused electrical resistivity tools
Old E (electrical) logs

Conventional Electrical Log (ES)

<table>
<thead>
<tr>
<th>Track 1</th>
<th>Track 2</th>
<th>Track 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>Depth</td>
<td>Depth</td>
</tr>
<tr>
<td><strong>SP</strong> (mv)</td>
<td><strong>SN</strong> (ohmm)</td>
<td><strong>IN</strong> (ohmm)</td>
</tr>
<tr>
<td>Linear scale</td>
<td>Linear scale</td>
<td>Linear scale</td>
</tr>
</tbody>
</table>

**SN** = Short Normal (spacing 16")
**Ampl. SN** = Amplified Short Normal
**LN** = Normal (spacing 64")
**IN** = Inverse or Lateral (spacing 18’ 8")
Old E (electrical) logs

Induction Electrical Log (IES)

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<tr>
<td><strong>SP</strong> (mv)</td>
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<td><strong>Ampl. SN</strong> (ohmm)</td>
<td><strong>6FF40 R</strong> (ohmm)</td>
</tr>
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<td><strong>Linear scale</strong></td>
<td><strong>Linear scale</strong></td>
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**SN** = Short Normal (spacing 16”)
**Ampl. SN** = Amplified Short Normal
**6FF40 R** = Induction log deep (40”) resistivity
**6FF40 C** = Induction log deep (40”) conductivity
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

\[
R_s = R_m = 1
\]

**Thick Bed**
\[h = 10 \text{ AM} \]
\[R_t = 8\]

\[
R_s = R_m = 1
\]

**Thin Bed**
\[h = \frac{AM}{2}\]
\[R_t = 8\]
\[R_s = R_m = 1\]
Lateral electrical log responses: lateral
Well Settala 1
SP/ILD/SN/MLL
FDC/CNL/BHC

MLL (Rxo)
SN (Ri)
ILD (Rt)
Resistivity tools: Wire Line (WLL) & While Drilling (LWD)
Dual Laterolog

Basics of Geophysical Well Logs: Lithology & Resistivity
Sferically Focused Log

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

\[ R_{SFL} = k \left( \frac{V_B - V_e}{I_0} \right) \]
Environmental effects on focused galvanic tools
Induction logging

Induction log principle

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ILI/SLI 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)*

Basics of Geophysical Well Logs_Lithology&Resistivity
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

\[ \text{AT (dB)} = K \log \left( \frac{B}{A} \right) = f (\sigma) \]

\[ \text{PS (deg.)} = f (\varepsilon) \]
LWD resistivities: Real time vs memory