GEO4250
Reservoir Geology

Basic Well Log Analysis

* Determination of Saturation *
Reminder

\[ N_p = \phi_e S_{hc} hAr \]

\[ S_w = \sqrt[n]{\frac{FR_w}{R_t}} = \sqrt[n]{\frac{R_0}{R_t}} \]

\[ S_w = 1 - S_{hc} \]

\[ \phi_s = \left( \frac{\Delta t_{log} - \Delta t_{matrix}}{\Delta t_f - \Delta t_{matrix}} \right) \quad \text{Sonic Porosity} \]

\[ \phi_{den} = \frac{\rho_{matrix} - \rho_b}{\rho_{matrix} - \rho_r} \quad \text{Density Porosity} \]

\[ \phi_n \quad \text{from log} \]

\[ \phi_e = \phi_t \times (1 - V_{sh}) \quad \text{Effective Porosity} \]

\[ F = \frac{R_0}{R_w} = \frac{a}{\phi^m} \]
Reminder

• Determined $R_w$ from the Spontaneous Potential

• Determined $\phi_t$ and $\phi_e$ from porosity and gamma ray logs

• The only parameter we lack now is the true resistivity of the formation
Resistivity

- The resistivity (specific resistance) of a substance is the resistance between opposite faces of a unit cube of that substance at a specific temperature.
- Symbol R, measured in Ω·m (ohm·m²/m).
- Resistivity is a basic measurement of a reservoir’s fluid saturation and is a function of porosity, type of fluid, amount of fluid and type of rock.
- Usually between 0.2 and 1000 ohm·m.

\[ R = \frac{r \times A}{L} \]

- With \( r \) = resistance in ohms; \( A \) = area in square meters; \( L \) = length in meters.
Resistivity

• Dependent on:
  – Presence of Formation water / Hydrocarbons
  – Salinity of Formation water
  – Temperature of Formation water
  – Volume of water-saturated pore space
  – Geometry of the pore space
  – Morphology and species of clay minerals
Tools

• Conventional Electrical logs
  First developed before 1950
  – Normal devices
    • Short Normal (SN)
    • Long Normal (LN)
  – Lateral devices
    • Laterologs (LL, e.g. LL3, LL7, LL8, LLD, LLS, SFL)

• Induction logging
  First developed after 1950
  – Induction devices
    • 6FF40 (combined tool: Induction, Normal and SP, 1960’s)
    • DIL-LL8 (improved induction-normal combination)
    • Induction SFL
    • DIL-SFL
    • Phasor Induction SFL
    • Other abbreviations: ILD, ILM, ILS, RD, RM, RS, RT
Conventional Electrical Logging

- Current of constant intensity between A and B
- Resultant potential difference measured between M and N
- The larger the ’spacing’, the deeper the measurement
Conventional Electrical Logging

Normal and Lateral Curves

Normal Device
- A: Beds more resistive than surrounding beds
- B: Beds less resistive than surrounding beds

Lateral Device
- C: Beds more resistive than surrounding beds
- D: Beds less resistive than surrounding beds
Induction Logging

- High frequency, alternating current of constant intensity is sent through a transmitter coil (A).
- The alternating magnetic field (B) created, induces currents in the formation surrounding the borehole (C).
- These currents flow in circular ground loops coaxial with the transmitter coil and create, in turn, a magnetic field (D) that induces a current in the receiver coil (E).
Resistivity Logging  
*Focusing*

- Minimization of borehole and adjacent formation affects
- Focusing currents to control the path taken by the measure current
Resistivity Logging

*Influence of well bore variables and log correction*

- Resistivity measurements are influenced by:
  - Borehole mud
  - Adjacent beds
  - Invaded zone
- Readings must be corrected, always in the following way:
  - Borehole effect
  - Adjacent bed effect
  - Invasion correction
Resistivity Logging
Corrections - Borehole Effect
Resistivity Logging

Corrections - Adjacent Bed Effect

Chart Rcorr-10 corrects the Dual Laterolog (LLD and LLS) for bed thickness.

To use, laterolog readings should first be corrected for borehole effects (see Charts Rcorr-2b and -2c). Then, enter Chart Rcorr-10 with the bed thickness and proceed upward to the proper RLL/Rs ratio (apparent laterolog reading corrected for borehole/adjacent-bed resistivity) curve. Read the ratio of the corrected laterolog value (RLLcorr) to the apparent laterolog value (RLL) in ordinate.

Example:

\[
\begin{align*}
R_{\text{LLD}} &= 4.2 \text{ ohm-m} \\
R_{\text{LLS}} &= 3.0 \text{ ohm-m} \\
R_s &= 30 \text{ ohm-m} \\
\text{Bed thickness} &= 6 \text{ ft} \\
\end{align*}
\]

Given

\[
\begin{align*}
\frac{R_{\text{LLD}}}{R_s} &= \frac{4.2}{30} = 0.14 \\
\frac{R_{\text{LLS}}}{R_s} &= \frac{3.0}{30} = 0.10 \\
\end{align*}
\]

Therefore

\[
\begin{align*}
\frac{R_{\text{LLD}}}{R_{\text{LLS}}} &= 0.88 \\
\end{align*}
\]

and

\[
\begin{align*}
R_{\text{LLDcorr}} &= 3.7 \text{ ohm-m} \\
R_{\text{LLScorr}} &= 2.4 \text{ ohm-m} \\
\end{align*}
\]
Resistivity Logging

Invasion Correction

'Tornado' or 'Butterfly' Chart

The invasion correction charts, sometimes referred to as “tornado” or “butterfly” charts, of the next several pages (labeled Rmt.) are used to define the depth of invasion $d_i$, the $R_{mt}/R_t$ ratio and the true resistivity $R_t$. All assume a step-contact profile of invasion and that all resistivity measurements have been corrected, where necessary, for borehole effect and bed thickness using the appropriate Rmt.-chart, prior to entry.

To use any of these charts, enter the abscissa and ordinate with the required resistivity ratios. The point of intersection defines $d_i$, $R_{mt}/R_t$, and $R_t$ as a function of one resistivity measurement.

Saturation determination in clean formations:

Either of the chart-derived values of $R_t$ and $R_{mt}/R_t$ can be used to find values for $S_w$. One value, which is designated as $S_{w,A}$ ($S_w$-Archie), is found using the Archie saturation formula (or Chart Sw-1) with the $R_t$ value and known values of $R_t$ and $R_t$.

An alternate $S_w$ value, designated as $S_{w,R}$ ($S_w$-Ratio), is found using $R_{mt}/R_t$ with $R_{mt}/R_t$ as in Chart Sw-2.

If $S_{w,A}$ and $S_{w,R}$ are equal, the assumption of a step-contact invasion profile is indicated to be correct, and all values found ($S_w$, $R_t$, $R_{mt}$, $d_i$) are considered good.

If $S_{w,A} > S_{w,R}$, either invasion is very shallow or a transition type of invasion profile is indicated, and $S_{w,R}$ is considered a good value for $S_w$.

If $S_{w,A} < S_{w,R}$, an annulus-type invasion profile may be indicated. In this case a more accurate value of water saturation may be estimated using the relation:

$$S_{w,AC} = S_{w,A} \left( \frac{S_{w,R}}{S_{w,A}} \right)^{1/2}$$

The correction factor $(S_{w,R}/S_{w,A})^{1/2}$ can be found from the scale below.

For more information see Reference 9.
Laterolog vs Induction

Both have unique characteristics that favor their use in specific, and often different, situations and application.

**Induction Log**
- Recommended in holes drilled with moderately conductive drilling muds, non-conductive muds and in empty or air-drilled holes
- Most accurate in low- to medium-resistivity formations
- \( R_{xo} > R_t \)

**Laterolog**
- Recommended in holes drilled with conductive muds (salt muds)
- Most accurate in medium- to high-resistivity formations
- \( R_{xo} < R_t \)
Resistivity Scaling
Determination of Saturation

\[ S_w = n \sqrt{\frac{FR}{R_t}} \]

\[ F = \frac{R_0}{R_w} = \frac{a}{\phi^m} \]

\[ S_w^n = \frac{aR_w}{\phi^mR_t}^{n=m=2,a=1} \rightarrow \phi S_w = \sqrt{\frac{R_w}{R_t}} \]

\[ \rightarrow \phi = \frac{\sqrt{R_w}}{S_w} \frac{1}{\sqrt{R_t}} \]
Determination of Saturation

**EXAMPLE**

- 100% water saturated formation
- $S_w = 1; R_t = R_0$
- $R_0$ vs $\phi$ is a straight line; $\phi = \sqrt{\frac{R_w}{R_t}}$
- If $S_w \neq 1$, but constant, all points also on a straight line
- From plotted points, assume some from 100% water saturated rock $\rightarrow$ line through $f=0$, $R=\infty$ and through the most westerly plotted points
- Slope of this line defines the value of $R_w$
- For $\phi=10\%$, $R_0 = 6.5$ ohm·m
- For compacted formations:
  - $F = 1 / \phi^2$
- So, in this case $F = 100$
- We also now that:
  - $R_w = R_0 / F$
- So, $R_w = 6.5/100 = 0.065$ ohm·m
Determination of Saturation

- Only possible for formations with constant matrix and for constant Formation Water Resistivities