Module for:

Resistivity Tools

(adapted/modified from lectures in PETE 321 (Jensen/Ayers))

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Drilling Disturbs Formation
Washouts and Filtrate Invasion

● Drilling and rock crushing
  ■ Damage Zone

● Mud systems and invasion
  ■ Oil-based Mud
    — Small conductivity mud.
    — Shallow invasion.
    — Thin cake.

  ■ Water-based Mud
    — Moderate to very conductive mud.
    — Shallow to deep invasion.
    — Thin to thick cake.
Effects of Drilling Mud and Mud Filtrate Invasion
Mud Filtrate Invasion

Uninvaded Zone ($R_t$)

Invaded Zone ($R_xo$)

过渡带

泥饼 (Rmc)

泥浆 (Rm)

井筒

Modified from J. Jensen, PETE 312 Lecture Notes
Symbols used in Log Interpretation

- Resistivity of zone
- Resistivity of the water in the zone
- Water saturation in the zone

Symbols:
- $R_m$: Mudcake
- $R_m$: Mudcake
- $R_w$: Water
- $R_s$: Resistivity
- $h$: Hole diameter
- $h_{mc}$: Thickness of mudcake
- $d_h$: Invasion diameter
- $d_i$: Depth of invasion
- $d_j$: Depth of adjacent bed
- $\Delta r_j$: Difference in depth

From NExT, 1999, after Schlumberger
Common Terminology

Borehole

\[ R_m = \text{Borehole mud resistivity} \]
\[ R_{mc} = \text{Mud cake resistivity} \]

Invaded zone

\[ R_{mf} = \text{Mud filtrate resistivity} \]
\[ R_{xo} = \text{Invaded zone resistivity} \]
\[ S_{xo} = \text{Invaded zone water saturation} \]

Uninvaded zone

\[ R_w = \text{Interstitial water resistivity} \]
\[ R_t = \text{Uninvaded zone resistivity} \]
\[ S_w = \text{Uninvaded zone water saturation} \]
Factors which Affect Resistivity Measurements
(Filtrate Invasion — Drilling Mud — Shoulder Beds — Mud Cake)

Resistivity tools are affected by:

- Invasion of mud filtrate.
- Mud in the borehole.
- Resistivity of the shoulder beds.
- Mud cake.

All resistivity readings must be compensated for these effects.

(From Halliburton, p. 11-9)
Applications of Resistivity Well Log Data

**Uses:**
- Establish permeable zones.
- Discriminate hydrocarbon versus water saturated zones.
- Estimate water/moveable hydrocarbon saturations.
- Estimate porosity (based on resistivity).
- Correlate strata areally.
Families of Resistivity Tools

- **Electrode** tools: electrical current sent by electrodes into formation
  - Requires water-base muds

- **Induction** tools: generate a magnetic field that induces a current in the formation
  - Oil-base, air, or fresh-water muds
Electrode Tools
(require water-based muds)

- **Wireline** (conveyed on line)
  - Dual Laterolog (LLD and LLS)
  - Azimuthal tool (deep and shallow)
  - Spherically-focused
  - Micro-resistivity

- **LWD** (Logging-While-Drilling)
  - Resistivity at bit (or at least close)
  - Side-scanning electrodes
Principles of Electrode Tools
(Common Elements/Features)

Elements/Features:

- **Electrode emits current, \( I \):**
  - Electrode \( A \).
  - Green lines give current flow.
- **Electrodes sense voltage, \( V \):**
  - Electrodes \( M \) and \( N \).
  - Red lines show equipotentials.
- **Formation resistivity, \( R \):**
  - \( R = kV/I \).
  - \( k \) is tool constant.
- **Simple electrode model ignores:**
  - Current does flow up borehole.
  - Radial changes in \( R \) (invasion).

\[ V = I \cdot R \]
Dual Laterolog Tool
Deep and Shallow Current Patterns

Characteristics:
- **Multiple currents:**
  - Measure.
  - Bucking (or guard).
- **Objectives:**
  - $R_t$: Laterolog Deep (LLD).
  - $R_{xo}$ and $R_t$: Laterolog Shallow (LLS).
  - Eliminate borehole effect.
  - Eliminate shoulder effect.

(Electrode Resistivity Tools)
Selection Chart for Laterolog Tool
(Compares Laterolog and Induction Tools)

Selection Chart:
- Correlation based on porosity, $R_{mf}/R_w$, and $R_w$.
- Gives indication of optimal application ranges.

(From Halliburton, p. 12-2)
Recent Tool: Azimuthal Resistivity

Features

- Thin bed analysis:
  - Vertical Resolution < 1 ft.
- Variable depths of investigation.
- Azimuthal resistivity.
- Applications:
  - Fracture detection.
  - $R_t$ in dipping beds.

(Electrode Resistivity Tools)
Example Well Log: Azimuthal Resistivity

Comments

- Azimuthal resistivity profile in light blue — note the greater level of detail in the signal.
- Computed image is potentially useful for identifying fractures.
Spherically Focused Resistivity Tool

Tool Characteristics:

- SFL tool gives *shallow resistivity*.
- Usually run in combination with induction logs.
- Good tool for thin-bed detection/analysis.
- Has a different order of electrodes than the latero log tool.

(Electrode Resistivity Tools)
Flushed Zone Measurements

Tool Characteristics:

- Pad-type tools:
  - Pads reduce borehole effects.
  - Mud cake may still be an issue.
- Very shallow resistivity:
  - 2 to 5 cm profile is typical.
- Several types of tools.
"Microlog" Tool:
- Measures $R_{1x1}$ and $R_2$.
- No current focusing.
- Does not yield $R_{xo}$.
- High resolution.
- Mudcake detector:
  - $R_{1x1} < R_2$.
  - Gives an indication of permeable zones.

(Electrode Resistivity Tools)
MicroSFL (Spherical Focus) Tool:

- Measures only $R_{MSFL}$.
- Current focusing tool.
- Provides $R_{xo}$ estimate.
- Good resolution.
- Small mud cake effect.
Other Flushed Zone Tools:

- Other types of focused $R_{xo}$
  - Microlaterolog.
  - Microguard.
  - Proximity.
- Electromagnetic propagation
  - Uses electromagnetic (EM) waves.
  - Measures conductivity and propagation.
  - Ultra-high frequencies.
- Borehole scanners
  - Multi-pad.
  - Image of borehole wall.
Microresistivity Tools
(Properties)

Characteristics of Microresistivity Tools:
• Very high vertical resolution (≈ 2 in/5 cm).
• Very small depth of investigation (a few inches).
• Most tools are pad mounted.
• Measurements are only in the invaded zone.
• Affected by mudcake on the borehole wall.
Microresistivity Tools  
(Well Log Example 1)

Example 1: Microresistivity Log

- The microresistivity tool response is given by the "Short Guard" profile on this log.
- Most microresistivity logs are "spiky" due to a very high vertical resolution (≈ 2 in/5 cm).
- Good tool for thin-bed identification.

(From Halliburton, p. 12-3)
Microresistivity Tools
(Well Log Example 2)

Example 2: Microresistivity Log

- Microresistivity log response is given by the "Micro SFL" (MSFL) profile on this log.
- With a depth of investigation of only a few inches, microresistivity tools reflect the character of the flushed/invaded zones.
- Note how the MSFL log reading is nearly constant in zones where the LLD and LLS logs show a profile inversion.
- This due to the fact that the MSFL reads only mud filtrate saturated formation.

(From Halliburton, p. 13-18)
Introduction to Induction Resistivity Tools

**Introduction:**
- Induction log was originally developed to measure formation resistivity in boreholes containing oil-based and fresh water-based drilling muds.
- Electrode devices (conventional electric logs) do not function in non-conductive mud systems.
- Induction logging devices are focused to minimize influence of borehole and surrounding formations.
- Designed for deep investigation to determine $R_f$.
- New induction log devices are being developed using improved electronics, telemetry, and computer processing.
Introduction to Induction Resistivity Tools
(Tool Characteristics)

Induction Resistivity Tools:
● Several types:
  ■ Dual Induction:
    — Deep (ILD)
    — Medium (ILM)
  ■ High Resolution Induction
    — HRD, HRM (Halliburton)
    — IDPH, IMPH (Schlumberger)
  ■ Dielectric induction
  ■ Array Induction
  ■ EWR/CDR
● All induction tools have similar physical principles...
Induction Resistivity Principles (1/2)

Fundamentals:

- **Transmitter coils:**
  - Current \( I_T \).
  - Creates magnetic field \( H_T \).
- **Formation currents, \( I_t \):**
  - Caused by magnetic field \( H_T \).
  - Create magnetic field \( H_L \).
- **Receiver coils:**
  - Senses magnetic field \( H_L \).
  - Records output voltage \( e_R \).

(Induction Resistivity Tools)
Induction Resistivity Principles (2/2)

Estimation of Resistivity Response:
- Voltage \( (e_R) \) proportional to conductivity \( (C) \).
- Resistivity computed as:

\[
R(\text{ohm} \cdot \text{m}) = \frac{1000}{C \ (\text{mmho/m})}
\]

- Similar to laterolog tools, induction tools are focused.
- Depth of measurement depends on:
  - Frequency:
    - Older tools, single frequency (approximately 20 kHz).
    - Newer tools, multiple frequencies.
  - Number and position of coils.

(Induction Resistivity Tools)
Induction-Electrical Log Presentation (Old Format)

Old Format:

- Linear scales.
- Conductivity on track 3.
- Resistivity on track 2.
- Short normal:
  - Unfocused shallow.
  - Bed definition.
- Induction $R_t$.

(Induction Resistivity Tools)
Dual Induction Presentation (Newer Format)

Newer Format:
- Logarithmic scale for resistivity well log profiles.
- Resistivity tracks occupy 2/3 of the well log plot.
- Deep Induction ($R_t$).
- Medium induction ($R_{xo}$) and ($R_t$).
Dual Induction Presentation (Newest Format)

Newest Format:
- Logarithmic scale for resistivity well log profiles.
- Five (5) different induction log measurements.
- Resistivity traces allow for transition zone.
Wireline Versus LWD Tools

**LWD** (Logging While Drilling)
- **Borehole and formation**
  - Little invasion.
  - Small borehole effect.
- **Equipment**:
  - Steel collars, bit.
  - Few/no electrodes.
- **Shallow DOI (20-60 in.), high-frequencies.**

**Wireline** (Open Hole)
- **Borehole and formation**
  - Moderate to deep invasion.
  - Moderate to significant borehole effects.
- **Equipment**
  - Fiberglass/plastic tools.
  - Many electrodes.
  - Variable diameter of investigation (DOI) (10-90 in.).
  - Variable induction frequency.
  - Pad or mandrel.
  - Early LWD copied wireline tools/technologies.

Steel Resistivity vs Freq.

```
Freq, MHz
0.00E+00 2.00E-03
5.00E-04 1.00E+00
1.00E-03 4.00E+00
1.50E-03 8.00E+00
2.00E-03 10.00E+00
```
Introduction}

Rules:

- Separation of deep and shallow resistivity curves suggests presence of a permeable formation.
- If the formation pore fluid is more resistive than the mud filtrate, then $R_{\text{deep}} > R_{\text{shallow}}$ — irrespective of the type of tool (e.g., the profile in hydrocarbon bearing layers with a saline water-based mud in the borehole).
- If the mud filtrate is more resistive, then $R_{\text{shallow}}$ is greater than $R_{\text{deep}}$ (e.g., a fresh water bearing formation with an oil-based mud in the wellbore).
- Across shale zones there is no separation because there is no permeability and hence, no invasion. All resistivity readings should overlay in shales.
Dual Induction Profile — Common Features

Features:
- Deep resistivity trend reads less than the shallow trend (*i.e.*, the "short guard"), indicating a lower pore fluid resistivity: *i.e.*, $R_w < R_{mf}$
- Also, note a slight separation between the deep and shallow profiles — indicates invasion.

(From Halliburton, p. 12-3)
Deep Laterolog $R_t$ reading is higher than the Shallow Laterolog $R_t$ reading. 

*Suggests* the presence of hydrocarbons (*i.e.*, a more resistive pore fluid as compared to the mud filtrate).

Here, deep Laterolog $R_t$ reading is lower than shallow Laterolog or Micro SFL. This situation results when the mud filtrate is more resistive than the formation pore fluid.

(From Halliburton, EL 1007)
Mud Filtrate Invasion — Invaded/Transition Zones

Typical resistivity profile: resistivity of pore fluid > resistivity of mud filtrate

From Halliburton, EL 1007)
Effect of Mud Filtrate Invasion on Fluid Saturation

Difference between $S_{xo}$ and $S_w$ indicates movable hydrocarbons

From Halliburton, EL 1007)
**Effect of Mud Filtrate Invasion on Fluid Saturation**

### Filtrate Invasion Effects:
- Invasion of mud filtrate causes a change in pore fluid saturations.
- A difference in $S_{xo}$ and $S_w$ indicates movable hydrocarbon saturation.

<table>
<thead>
<tr>
<th></th>
<th>Original Conditions</th>
<th>After Invasion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Residual Oil</strong></td>
<td>$S_{xo} = 70%$</td>
<td>$S_{w} = 30%$</td>
</tr>
<tr>
<td><strong>Moveable Oil</strong></td>
<td>$(S_{xo} - S_{w}) = 40%$</td>
<td><strong>Mud Filtrate</strong></td>
</tr>
<tr>
<td><strong>Connate Water</strong></td>
<td>$S_{w} = 30%$</td>
<td><strong>Mud Filtrate</strong></td>
</tr>
</tbody>
</table>

From Halliburton, EL 1007}
Two families of resistivity devices:

- **Electrode tools**: Current sent into formation, requires water-based drilling muds.
- **Induction tools**: Generate a magnetic field that induces a current in the formation, use in oil, air, or fresh-water based drilling muds.

Resistivity devices:

- Latero/Guard tools.
- Spherically focused tools.
- Microresistivity tools.
- Resistivity at (or at least close to) bit (LWD).

Induction:

- Older dual induction.
- Newer multi-frequency, signal enhanced devices.
Resistivity well logging tools used to:

- Establish permeable zones.
- Discriminate hydrocarbon versus water saturated zones.
- Estimate water/moveable hydrocarbon saturations.
- Estimate porosity (based on resistivity).
- Correlate strata areally.

Induction logs:

- Run in non-salt saturated mud \((R_{mf} > 3 R_w)\).
- Run where resistivity < 200 ohm-m.
- Run with oil-based drilling mud.

Laterolog or dual laterologs:

- Run in salt-saturated drilling mud \((R_{mf} \approx 3 R_w)\).
- Run where resistivity > 200 ohm-m.
- Run where thin beds are present.
Points To Commit to Memory:

- Resistivity tool types:
  - **Electrode tools**: Current sent into formation, requires water-based drilling muds.
  - **Induction tools**: Generate a magnetic field that induces a current in the formation, use in oil, air, or fresh-water based drilling muds.

- Factors which affect resistivity well logs:
  - Invasion of mud filtrate.
  - Mud in the borehole.
  - Resistivity of the shoulder beds.
  - Mud cake.

- Applications of resistivity well log data:
  - Establish permeable zones.
  - Discriminate hydrocarbon versus water saturated zones.
  - Estimate water/moveable hydrocarbon saturations.
  - Estimate porosity (based on resistivity).
  - Correlate strata areally.
E.T. O’Daniel 28 (1U interval – Horizontal log section)
E.T. O’Daniel 28 (1U interval – Horizontal core section 1)
E.T. O’Daniel 28 (1U interval – Horizontal core section 2)
E.T. O’Daniel 28 (1U interval – Horizontal core section 3)

7417 ft