Chapter 8
Induction logs

Lecture notes for PET 370
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Resistivity Logs

Introduction

• Why resistivity logs?

  Estimate Rt

• Invasion

• Resolution (vertical, horizontal)

• Classification
  - based on depth of investigation
  - salt vs fresh mud
# Resistivity Logs

<table>
<thead>
<tr>
<th>Name</th>
<th>Years</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microlog (ML)</td>
<td>up to 1955</td>
<td>obsolete</td>
</tr>
<tr>
<td>Minilog</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximity (PL)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Induction (6FF40)</td>
<td>1955-80</td>
<td>obsolete</td>
</tr>
<tr>
<td>Induction</td>
<td>1970-85</td>
<td>ISF</td>
</tr>
<tr>
<td>Induction</td>
<td>1965</td>
<td>DIL-LL8, DIFL, DISG</td>
</tr>
<tr>
<td>Deep Phasor Induction</td>
<td>1975</td>
<td>DIL-SFL</td>
</tr>
<tr>
<td>Phasor</td>
<td>1985</td>
<td>Current</td>
</tr>
<tr>
<td>AIT</td>
<td>1990</td>
<td>Current</td>
</tr>
<tr>
<td>DLL-MLL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DLL-MSFL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salt Mud</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Micro-laterolog</td>
<td>1955-80</td>
<td>obsolete</td>
</tr>
<tr>
<td>(MLL)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow Laterolog-7 Latero-3 / Guard</td>
<td>1972</td>
<td>DLL-MLL DLL-MSFL current</td>
</tr>
</tbody>
</table>
Resistivity Logs

- IES or IEL; short normal or spherically focused curve with a deep induction. *(No correction for invasion!)*

- Replaced in the mid-1960s with a Dual induction tool (shallow, medium, and deep curves); DIL-LL8, DIFL, DISG

- Improved DIL with the addition of the spherically focused shallow log; DISF

- Next improvement is known as the *Phasor Induction Tool* - better thin bed resolution and automatic corrections

- Latest generation induction tool known as *Array Induction Tool* or Imager - eliminates need for assumption of a step function for the invasion profile.
Resistivity Logs

Example: Old ES

Bagley Penn Field
Chambers No. 2
Lea County, NM
Resistivity Logs

Example: IEL

<table>
<thead>
<tr>
<th>SPONTANEOUS POTENTIAL</th>
<th>DEPTH</th>
<th>RESISTIVITY</th>
<th>CONDUCTIVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Millivolts</td>
<td></td>
<td>Ohms m²/m</td>
<td>Millimhos/m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>+</td>
<td>10</td>
<td>4000</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

Rmf = 0.64 @ 78°
BHT = 190° @ 10,500
Resistivity Logs

Example: High resolution or Phasor induction

Source: Halliburton
Resistivity Logs

Example: Array induction

<table>
<thead>
<tr>
<th>Layer</th>
<th>Resistivity (ohmm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEL, unaveraged (SFL)</td>
<td>2000.0</td>
</tr>
<tr>
<td>Medium resistivity (ILM)</td>
<td>2000.0</td>
</tr>
<tr>
<td>Deep resistivity (ILD)</td>
<td>2000.0</td>
</tr>
<tr>
<td>10 Inch investigation</td>
<td>2000.0</td>
</tr>
<tr>
<td>90 Inch investigation</td>
<td>2000.0</td>
</tr>
<tr>
<td>20 Inch investigation</td>
<td>2000.0</td>
</tr>
<tr>
<td>30 Inch investigation</td>
<td>2000.0</td>
</tr>
<tr>
<td>60 Inch investigation</td>
<td>2000.0</td>
</tr>
</tbody>
</table>

Source: Halliburton
Resistivity Logs

Selection – Induction log

• where fresh mud or oil-base mud (or air-filled holes) is used,

• where the $R_{mf}/R_w$ ratio is greater than 3,

• where $R_t$ is less than 200 ohm-m
Resistivity Logs

- measures conductivity $C = 1000/R$ (mmho/m)
- current is fed to a transmitter which generates a magnetic field and hence a circular current in the media.
- This current induces a voltage at the receiver.
- Array of transmitter-receiver coils; jamming the signal into the desired formation. Thus, minimizes borehole, invasion, and adjacent bed effects.
- Typically, six or more coil pairs, 40” spacing from main coil to obtain deep reading.
- Only resistivity tool to run in air drilled holes.
**Resistivity Logs**

\[ \frac{1}{R_{ILD}} = \frac{G_m}{R_m} + \frac{G_{xo}}{R_{xo}} + \frac{G_t}{R_t} + \frac{G_s}{R_s} \]

or

\[ C_{ILD} = G_m C_m + G_{xo} C_{xo} + G_t C_t + G_s C_s \]

**Induction Equivalent Circuit**
Resistivity Logs

Example 1

**Given**

\[ R_t = 10 \text{ ohm-m} \]

Fresh mud, \( R_m = 1 \)

\( R_{xo} = 20 \)

\( d_i = 65'' \)

What is the apparent (measured) resistivity?
Read apparent resistivity from well log, $R_a$

Correct for borehole effect (if necessary)

Correct for bed thickness effect (if necessary)

Correct for invasion effect (if three curves are present)

True formation resistivity, $R_t$
Given
1.5” standoff in a 14.6” hole
R_m = 0.35 ohm-m
ILD = 50 ohm-m (20 mmho/m)

What is borehole-corrected conductivity?
Resistivity Logs

• The bed thickness effect is a $f(\text{bed thickness, vertical resolution of tool, resistivity contrast } R_t/R_s)$

• Corrections necessary for:
  – thick beds w/ $R_t/R_s >> 1$
  – thin beds with large $R_t/R_s$ contrast
Resistivity Logs

Bed thickness correction

Deep Induction Log Bed Thickness Correction (Schlumberger)
Assume a step profile for invasion

Tornado charts to correct for invasion, determine $R_t$, $R_{xo}$, and $d_i$

- $R_t$ correction factor between 0.75 and 1.0
- Depth of invasion is reflected by induction resistivity contrast:
  - $R_{im}/R_{id} > 1.5$ indicates deep invasion
  - $R_{im}/R_{id} < 1.2$ indicates shallow invasion
Resistivity Logs

Invasion Correction

Example

$R_{ILD} = 10 \ \Omega m$

$R_{ILM} = 14 \ \Omega m$

$R_{SFL} = 90 \ \Omega m$

Find: $R_t$, $Rxo$ and $di$. 
Resistivity Logs

Invasion Correction

Example

\[ R_{ILD} = 10 \ \Omega m \]
\[ R_{ILM} = 14 \ \Omega m \]
\[ R_{SFL} = 90 \ \Omega m \]
Resistivity Logs

Example:
SFL-ILM-ILD

Big Lake (San Andres)
Improvements

(1). Thinner bed resolution (2 ft.)

(2). Comprehensive set of automatic corrections for:
- shoulder effect and thin bed resolution
- skin effect
- borehole and cave effect
- large boreholes
- invasion effects
Resistivity Logs

Example: High resolution or Phasor induction

Conventional induction log

Phasor induction log
Array Induction Image Tool (AIT) or High Resolution Imager (HRI)

Main features:

1. full borehole corrections over a range of $R_t/R_m$ contrasts

2. the ability to use short array information to solve for effective borehole parameters

3. Five log curves are presented at median depths of investigation of 10, 20, 30, 60 and 90 inches. Three vertical resolutions of 1, 2 and 4 ft.

4. improvement in invasion profiles for both oil- and water-based muds. This includes accurate $R_t$ estimate and a quantitative description of the transition zone.

5. Capability of producing resistivity and saturation images of the formation.
Resistivity Logs

Example: Array induction

DIL log

Ambiguous reading

Correct reading

AIT log

Source: Halliburton
Resistivity Logs

Example: Array induction

Estimated invaded volumes from AIT log (Halliburton)
Resistivity Logs


Chapter 5, Sec 5 and 6

Schlumberger, Log Interpretation Charts, Houston, TX (1995)

Western Atlas, Log Interpretation Charts, Houston, TX (1992)