Resistivity Logging Tools and Interpretation Core

RESISTIVITY LOGGING TOOLS AND INTERPRETATION CORE

The Resistivity Logging Tools

LEARNING OBJECTIVES

By the end of this lesson, you will be able to:

✓ Explain the tool physics and applications of resistivity logging tools
✓ Discuss the relationship between a logging tool’s depth of investigation and bed resolution
✓ Describe the ideal mud properties and formation environment for good Induction log and Laterolog log data
✓ Explain the purpose of the “tornado charts”
✓ Compare and contrast the wireline Induction log and the LWD EWR log
✓ Discuss the types of microresistivity logs
SOURCES OF RESISTIVITY MEASUREMENTS

- Old electric logs (lateral log, normal log)
- Induction logs
- Laterologs
- Microresistivity logs
- Dielectric logs (microwaves)
- LWD EWR and resistivity at the bit
THE RESISTIVITY LOGGING TOOLS – OLD ELECTRIC LOGS

OLD ELECTRIC LOGS—LATERAL LOGS AND NORMAL LOGS

© PetroSkills, LLC., 2016. All rights reserved.
OLD ELECTRIC LOGS—LATERAL LOGS AND NORMAL LOGS

Lateral Log

- First commercial resistivity logging tool
- AM spacing is long
- MN spacing is short
- Long AO spacing reduces influence of invaded zone on deep resistivity measurements

Normal Log

- Replaced Lateral Log
- Two AM spacings
  - 64" (1.6 m)
  - 16" (0.4 m)
- Not usable in thin beds
OLD ELECTRIC LOGS—LATERAL LOGS AND NORMAL LOGS

Limitations
- Require special expertise to interpret
- Must have conductive (WBM) mud
- Highly affected by bed boundaries
- Can have asymmetrical response, making Rt determination more of an art than science
- Complicated by current leakage along borehole
- No focusing of current paths

Generally no longer used; may encounter in old data or Russian logs.
THE RESISTIVITY LOGGING TOOLS – INDUCTION LOGS

DEPTH OF INVESTIGATION AND RESOLUTION

*_frequency = \downarrow \text{depth of investigation}*

Induction Log and Laterolog
DEPTH OF INVESTIGATION AND RESOLUTION

- Deeper depth of investigation
- Worse resolution
- Shallower depth of investigation
- Better resolution

INDUCTION LOGS

- Step up from "electric logs"
- Measure conductivity—the inverse of resistivity
  - Units: mhos/m, millimhos/m, or millisiemens
- Apparent conductivity ($C_a$)
  - $C_a = C_{mud} + C_{xo} + C_t$

\[
\frac{1}{R_a} = \frac{1}{R_{mr}} + \frac{1}{R_{xo}} + \frac{1}{R_t}
\]

- High-resistivity muds provide best resistivity data
- Conductive, saltwater muds provide poor resistivity data
### Induction Logs

#### Pros
- More focused than old electric logs
- Measure multiple depths (ILM, ILD)
- Work well in freshwater muds, air-filled wells, and oil-based muds

#### Cons
- Poor bed resolution (~ 6 ft or 1.8 m)
- Poor performance in salt mud systems

**Newer AIT devices provide better data than DIL**
- Calculate numerous measurement diameters
- Higher tolerance for saline boreholes
- Calculate several thin bed resolutions

---

#### 6FF40
- Introduced in 1950s
- 6 induction coils, 40” (1 m) spacing
- 1 deep-reading conductivity curve
- Short normal log for shallow resistivity curve
- Primary resistivity log for freshwater mud wells

![Diagram of 6FF40 induction logging tool](image)
INDUCTION LOGS

Dual Induction Log (DIL)
- Introduced in 1960s, still run today
- 2 measurement diameters
  - Medium depth (ILM)
  - Deep reading (ILD)
- Included LL8 (later SFL, MSFL) for shallow resistivity curve
- Multiple readings to correct $R_s$ to $R_t$

INDUCTION LOGS

- Induction logs work best in:
  - Low resistivity formations
  - Low $R_t$ and high $R_{xo}$
  - A low resistivity zone between high resistivity shoulder beds
  - Oil-based mud (OBM & SOBM)
**INDUCTION LOGS**

Example:
SOBM has a resistivity of 2000 Ω.m (conductivity = 0.5 mS/m)

\[
\text{Conductivity} = \frac{1}{\text{resistivity}}, \text{ so divide } 2000 \text{ Ω.m into } 1 \text{ S/m, or } 1000 \text{ mS/m. Therefore, } 1000/2000 \text{ Ω.m} = 0.5 \text{ mS/m}\]

Rt is 20 Ω.m (conductivity = 50 mS/m)

\[
\text{Divide } 20 \text{ Ω.m into } 1 \text{ S/m, or } 1000 \text{ mS/m. Therefore, } 1000/20 \text{ Ω.m} = 50 \text{ mS/m}\]

The mud in this borehole with 0.5 mS/m has a very small influence on the deep formation conductivity of 50 mS/m.

---

**DUAL INDUCTION LOGS**

[Graph showing dual induction logs with SP mV and Resistivity ohms m²/m scales, marked with ILD, ILM, and SFL.]
Conclusions

- WBM (have SP and MSFL curves)
- Relatively fresh water mud (large separation between SFL and ILD curves)
- Interval is water-bearing (low resistivity of ILD curve)
- Bottom interval is impermeable (all curves similar)
THE RESISTIVITY LOGGING TOOLS – NEWER INDUCTION TOOLS

PHASOR PROCESSING OF 6FF40

- Improve processing of 6FF40
- 3 frequencies and complex sharpening filter improve thin bed resolution and resistivities
ARRAY INDUCTION TOOL (AIT)

- Multiple transmitter-receiver sets
- 28 signals
- 5 depths of investigation

3-D EXPLORER

- Introduced commercially in early 2000s
- Acquires horizontal and vertical resistivities
- 3 orthogonal measurements—X, Y, and Z
- 2 oriented conductivities—horizontal and vertical
**RT SCANNER**

Combination of AIT and 3DX

---

**INDUCTION LOGS—SUMMARY**

- Emit electromagnetic waves
- Measure conductivity
- Ideal for $R_t$ in low resistivity zones
- Work in freshwater and oil-based mud and air-filled holes
NEWER INDUCTION LOGS—SUMMARY

Tool Comparison
- AIT provide better thin bed resolution and more accurate $R_t$ than DIL.
- 3DX and $R_t$ Scanner cost more than AIT or DIL; only justified for highly laminated thin beds.
THE RESISTIVITY LOGGING TOOLS – MICRORESISTIVITY LOGS

MICRORESISTIVITY LOGS

Shoulder bed $R_s$

Undisturbed Zone $R_t$

Flushed (Invaded) Zone $R_{xo}$

Goal of Resistivity Logging

Shoulder bed $R_s$

Flushed (Invaded) Zone $R_{xo}$

Undisturbed Zone $R_t$

Goal of Resistivity Logging

Shoulder bed $R_s$

Mud $R_m$
MICRORESISTIVITY LOGS

Designed to measure flushed zone resistivity ($R_{xo}$)

Pros
- Very good vertical resolution
- Depth of investigation very shallow (to read flushed zone)

Cons
- Depth of investigation very shallow (subject to borehole effects)
- Can be adversely affected by condition of mud and rugosity of borehole
TWO TYPES OF MICRORESISTIVITY DEVICES

Mandrel Devices (no contact with formation)
- 16" Short normal (SN) – old electric
- Laterolog 8 (LL8)
- Spherically Focused Log (SFL)
- AIT calculated shallow curves

Inexpensive shallow data, but not always a good $R_{xo}$ reading.

Pad Devices (direct contact with formation)
- Microlog (ML)
- Microlaterolog (MLL)
- Micro Spherically Focused Log (MSFL)
- Micro Cylindrically Focused Log (MCFL)

MSFL and MCFL are the most modern and provide good $R_{xo}$ data.

PAD DEVICES—THE MICROLOG

Oil-filled rubber pad pressed against hole wall

Measuring electrodes provide excellent thin bed detection
PAD DEVICES—THE MICROLOG

- Similar to Microlog, but with 4 concentric electrodes
- Mud cake as little influence up to ⅜” (1 cm) mud cake thickness
- Uninvaded formation does not affect response if invasion depth is > 3–4” (7–10 cm)
- Largely replaced by MSFL

PAD DEVICES—MICROLATEROLOG

- Similar to Microlog, but with 4 concentric electrodes
- Mud cake as little influence up to ⅜” (1 cm) mud cake thickness
- Uninvaded formation does not affect response if invasion depth is > 3–4” (7–10 cm)
- Largely replaced by MSFL
PAD DEVICES—MSFL AND MCFL

Micro Spherically Focused Log (MSFL)
- Similar to Microlaterolog
- Different electrode spacing and distribution to reduce effect of mud cake
- Main signal contribution from 1–2" (2.5–5 cm) behind mud cake

Micro Cylindrically Focused Log (MCFL)
- Newer version of MSFL

Both are good for measuring $R_{xo}$.

MICRORESISTIVITY LOGS

- No longer run extensively
- Largely replaced by AIT and Array Laterolog
- Still run where $R_{xo}$ data are needed
THE RESISTIVITY LOGGING TOOLS – COMPARING TOOLS

MEASURING RESISTIVITY

Dual Laterolog Tool (DLT)
- Designed for conductive drilling muds
- Shallow and deep depths of investigation
- Provides shallow (LLS) and deep (LLD) resistivity measurement
- Does not function in non-conductive mud environments
### Dual Induction Tool (DIT)
- Works best in non-conductive drilling mud.
- Strength of induced current related to conductivity of the formation.
- Two depths of investigation.
- Provides induction medium (LM) and induction deep (LD) resistivity curves.

### The AIT and Array Laterolog
- Provide 5+ depths of investigation.
- Largely replaced dual resistivity tools.

### Saline Muds
- Dual Laterolog (DLL)
- Laterolog deep (LLD)
- Laterolog shallow (LLS)
- Micro Spherically Focused Log (MSFL)

### Freshwater and Oil-Based Muds
- Dual induction Log (DIL)
- Induction log deep (ILD)
- Induction log medium (ILM)
“TYPICAL” RESISTIVITY LOG PRESENTATION

Laterolog Readings over an Oil- and Water-Bearing Sand

- Logarithmic scale (0.2–20 Ω.m)
- LL deep
- LL shallow
- MSFL

Multiple curves
- Multiple investigation diameters
- Qualitative interpretations
  - Porosity
  - Fluid contacts
  - Permeability

© PetroSkills, LLC., 2016. All rights reserved.
“TYPICAL” RESISTIVITY LOG PRESENTATION

Laterolog Readings over an Oil- and Water-Bearing Sand

- Porous wet zone
- Saltwater mud with same salinity as formation water

Laterolog Readings over an Oil- and Water-Bearing Sand

- Hydrocarbon-water contact (OWC) or oil/gas column above
"TYPICAL" RESISTIVITY LOG PRESENTATION

Laterolog Readings over an Oil- and Water-Bearing Sand

- Unable to distinguish oil from gas
THE RESISTIVITY LOGGING TOOLS – LWD EWR

LOGGING WHILE DRILLING (LWD) RESISTIVITY

How to choose: Wireline or LWD?
LOGGING WHILE DRILLING (LWD) RESISTIVITY

Example 1: Offshore deepwater well with short drilling times
- Wireline
  - High rig rates ($300k/day)
- LWD
  - Triple combo tool set ($30k/day)
  - Dipole sonic ($10k/day)

Example 2: Land well with long drilling times
- Wireline
  - Low rig rates
  - Pay logging company $100k to $1m to run logs
- LWD
  - Per day rate adds up over time
LWD TOOLS

- Resistivity at the bit (RAB)
- Laterolog
- EWR

LWD TOOLS

- Wireline measurement principles adapted for LWD
- EWR have multiple depths of investigation similar to wireline
- RAB can read at or close to bit
- EWR and Laterolog can measure formation resistivity prior to invasion
- Horizontal wells drilled with OBM: run the EWR tool
- Can be run after drilling to study invasion and resistivity over time
LWD TOOLS—THE EWR TOOL

- Same EM principle as Induction log
- Higher frequency (2 mHz)

LWD RESISTIVITY: THE EWR TOOL

- 2 transmitters
- 2 receivers
- 2 resistivity curves
  - Phase shift resistivity
  - Attenuation resistivity
- Latest tools more sophisticated but similar in function
LWD RESISTIVITY: THE EWR TOOL

- Similar to DIT and AIT
- Responds to conductivity
- Water- and oil-based muds
- Multiple depths of investigation
- Bed resolution to 1 foot (0.3 m)