Formation Evaluations: Well logs

What do we need to find out?

- Rock type?
  - Sandstone? Shale?
  - Limestone? Mineralogy?
- Rock Properties
  - Porosity
  - Permeability
  - Bedding Orientation
  - Fractures?
  - Temperature
  - Organic content
- Fluids
  - Type (water, oil, gas)
  - Saturation
  - Salinity
  - Pressure
- Engineering
  - Well trajectory (coord)
  - Shape of hole
  - Casing Joints
  - Quality of cement
  - etc

Reading in Selley Ch. 3

What for? (Log applications)

- Stratigraphic correlation
- Formation Tops
- Quantitative Oil, Gas, Water saturations
- Porosity
- Correlation with seismic data
- Sedimentological studies
- Reservoir modeling
- Structural studies
- Economics
- etc

What can we measure?

- Electrical Properties
- Natural radioactivity
- Induced radioactivity
- Acoustic Properties (sonic velocity)
- Shape of hole
- Noise
- Temperature
- Depth
- Tilt of hole
- etc

The Logging Operation

- Lower the tool to the bottom
- 100 to 200 feet repeat section measured at the bottom
- Then tool is raised through the entire well
- Casing may prevent some logs from working
- Logging speed: 1800 to 3600 ft/hour
- Information pertinent to both the logging run and the well is recorded on the header.
- Logs recorded digitally.
Log Types

- **Lithologic Logs**
  - Spontaneous Potential (SP)
  - Gamma Ray (GR)

- **Porosity Logs**
  - Neutron
  - Density
  - Sonic

- **Resistivity Logs (Fluid Type)**
  - Resistivity
  - Induction

- **Other**
  - Dipmeter
  - Caliper
  - Temperature
  - Acoustic
  - FMI
  - Many more ...

Spontaneous Potential (SP)

- One of the Oldest Logging Measurements
  - Used Commercially in 1931
- Discovered as Noise in Resistivity
- Found to be Related to Presence of Sandstone
- Lithology tool

The well works like a battery

\[ E = -K \log \left( \frac{a_w}{a_{mf}} \right) \]

- \( E \) in millivolts
- \( a_w = \) water salinity
- \( a_{mf} = \) mud salinity

Ion flow is easier in permeable sandstones
Typical SP log

SP has Poor Limestone Response

Spontaneous Potential (SP) Drift

SP readings are depth-dependent

Gamma Ray Log

- Lithology log
- Measures natural radioactivity
- Uses a scintilometer (Geiger counter)
- Potassium (K), Uranium (U), Thorium (Th), Phosphorous (P)
- K → abundant in clay → shales
- Unaffected by fluids
- High U → reducing environ. → abundant organic matter
- “API units”, relative to a standard

SP and Gamma Ray

- Gamma Ray in API Units
- Plotted on the left of the well
- Shales swing right

Marcellus Gamma Ray

Mahantango Fm.

Green = low GR
Purple = high GR

Pimpinella 1

Lower Marcellus
Onondaga Limestone
Spectral Gamma Ray
Distinguishes the different sources of gamma rays

Clay content
Organic content

Resistivity Log Applications

• Determination of Hydrocarbon-Bearing vs. Water-Bearing Zones
• Water Saturation $S_w$
• Geopressure Detection
• Depth of Invasion
• Stratigraphic Correlation

The Borehole Environment

$R =$ resistivity (ohms)

Resistivity

Resistivity of Saline Water - $R_w$
Resistivity of Water and Formation
Resistivity of Water, Hydrocarbons, and Formation
Resistivity of Tight Formation (no porosity)

Resistivity Tool Background

• Three Classes
  – Electrode Logs
  – Laterologs
    • Focused Electrodes
  – Induction
• Measure Resistivity in Ohms

Normal Resistivity Tool
Spacing of electrodes determines penetration
**Guard or Laterolog Tool**

The guard electrodes focus the current in a narrow disk.

**Induction (Conductivity) Tool**

Receiver coil measures the induced electrical field created in the rocks by the transmitter coil.

Works with oil based mud, or air

**Log Presentation and Scales**

- **Log Scale**
  - Ohms
  - ID, IM, LL8 measure resistivity at different distances from the borehole.
  - ID= deep induction
  - IM= medium induction
  - LL8= shallow induction

**Resistivity logs**:
- Spherically-focussed (SFL),
- medium induction (ILM),
- and deep induction (ILD)

*Is there oil in these reservoirs?*

**Model Resistivity Logs**

- Gas zone (IW)
- Water zone (2-20 Ω)
- Flushed zone
- Uninvaded zone

**Calculating Water Saturation**

\[ S_w = \frac{(R_{xo}/R_t)^{5/8}}{(R_{mf}/R_w)} \]

- \( R_{xo} \): Resistivity of flushed zone
- \( R_{mf} \): Resistivity of mud filtrate
- \( R_w \): Resistivity of formation water
- \( R_t \): Resistivity of uninvaded zone
Mud Resistivity Data
Wellbore Environment
Depth, Diameter, Temperature, Mud Parameters

Resistivity Imaging Logs
FMI = Formation Micro Imaging

Resolution vs. Investigation
Logging Tools

Sonic Logs
Measures of interval travel time in formation

\[
\Delta t = \frac{1}{V} \Delta \mu \sec/ft
\]

\( \Delta t \) is related to Density which depends on: Lithology, Porosity, and Fluid Content

Used to generate Synthetic Seismic traces to link wells logs to seismic data

Source-receiver arrangement for a sonic logging tool

\[
\phi_z = \frac{\Delta \mu - \Delta \mu_{RES}}{\Delta \mu_{RES}}
\]

Porosity Pore fluid

Glover
Sonic Log Example

Which unit is the best reservoir (low shale and high porosity)?

Well KGS Brungardt #1
Ellis Co., Kansas

Creating synthetic seismic data:

Acoustic impedance from Sonic log
Seismic Reflectivity
Wavelet
Synthetic Seismic

Correlate seismic data (in time) to well data (in depth)

Density Log

- Tool emits gamma rays
- Detects returning scattered gamma rays
- Gamma ray absorption is proportional to rock density
- Measures Density - $\rho$
- Tied to Lithology, Porosity, and Fluid Content

Density Log

$\text{DPHI} = \% \text{Porosity}$

$\text{RHOB} = \text{Bulk Density}$ $g/cm^3$

Porosity Calculation

$D\text{PHI} = \phi = \frac{\rho_\text{Ma} - \rho_\text{Flo}}{\rho_\text{Ma} - \rho_\text{Fl}}$

$\text{DPHI} = \phi_i = \text{density porosity}$
$\text{RHOB} = \rho_i = \text{bulk density (from the log)}$
$\text{RhoMa} = \rho_{\text{Ma}} = \text{matrix density}$
$\rho_{\text{Fl}} = \rho_f = \text{fluid density (often assumed to be mud filtrate density)}$

<table>
<thead>
<tr>
<th>Material</th>
<th>RhoMa (g/cm³)</th>
<th>Fluid Value (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>2.65</td>
<td>2.65</td>
</tr>
<tr>
<td>Limestone</td>
<td>2.71</td>
<td>2.71</td>
</tr>
<tr>
<td>Dolomite</td>
<td>2.87</td>
<td>2.87</td>
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<tr>
<td>Anhydrite</td>
<td>2.68</td>
<td>2.68</td>
</tr>
<tr>
<td>Marble</td>
<td>2.94</td>
<td>2.94</td>
</tr>
<tr>
<td>Coal</td>
<td>-1.2</td>
<td>-1.2</td>
</tr>
<tr>
<td>Brine</td>
<td>2.05</td>
<td>2.05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>1.0 to 1.2</td>
</tr>
<tr>
<td>Oil</td>
<td>0.85 to 0.95</td>
</tr>
<tr>
<td>Brine</td>
<td>1.000 to 1.200</td>
</tr>
</tbody>
</table>
Neutron Log (CNL)

- Tool has a neutron source
- H absorbs neutrons and emits gamma rays
- Tool detects the emitted gamma rays
- H is mostly in formation fluids (water and hydrocarbons)
- Can be run through casing
- Reads low in gas zones
- Cannot distinguish oil from water

Porosity calibration

If lithology is known, neutron and density logs can be calibrated for porosity

Applications of logs

- Stratigraphic studies
  - Sedimentary facies
- Well correlation
- Reservoir models
- Structural interpretation
  - Fault recognition

Gamma Ray Response to Grain Size
Relating log character to sedimentary facies

Building a reservoir model
1. Define facies in core
2. Relate facies to log
3. Predict facies in wells without core, but with good logs
4. Fill the gaps between wells

Log Datum Terminology
- KB - Kelly Bushing elevation.
- MD - Measured Depth along the wellbore from the Kelly bushing (usually)
- SS – Subsea Depth (Relative to Sealevel)
- TVD – True Vertical Depth, (important for non-vertical wells)
- SSTVD - Sub-Sea True Vertical Depth

Correlation Example
Major Sands on SP

DIRECTIONAL DRILLING

Correlation of directional wells
Directional Well  Vertical Well
**MWD (or LoggingWD) Measurement While Drilling**
- Tools are part of bottom hole assembly (BHA).
- Gamma ray, directional survey, tool face, borehole pressure, temperature, vibration, shock, torque etc.
- Telemetry for steering well
- Results transmitted digitally
  - mud pulser telemetry

**Logging While Drilling Data Transmission**

**Mud Pulse Telemetry** (Pressure pulses)

**Electromagnetic Telemetry** (Using conductivity of drill pipe)

**Wired Drill Pipe** (The future. Faster and better, but delicate)

**Geosteering**

- How do you move the logging tools through the horizontal well?

**FMI and Dipmeter Logs**

FMI= Formation Micro Imager
- Resistivity tools

Dipmeter

**Dipmeter Interpretation**

Older, simpler version of FMI

Vertical dip variation is characteristic of the structure
Take Home Ideas

• Well logs provide key data for understanding the subsurface
• Lithology, porosity and fluids are 3 important log families
• Usually you can’t measure these properties directly, so you must use proxies or indirect measurements
• Multiple logs used in combination are most powerful