Introduction to Petrophysics

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Outline

• Objectives of Petrophysics
• Data Acquisition
• Quicklook Evaluation
• Formation Pressure
• Permeability
Objectives of Petrophysics

• Identify and quantify hydrocarbon resources in the subsurface and evaluate rock properties

• Objectives for this course:
  – What data we acquire
  – Describe basic principles of common open hole logging tools
  – Quick look evaluation on a standard set of open hole logs:
    • Lithology
    • Volume of Shale
    • Porosity
    • Saturation
    • Net / Gross
What it is all about

• Porosity (PHI, \(\Phi\)): Fraction (or %) of rock not occupied by solids
• Porosity contains fluids: Water/oil/gas
• Water saturation (Sw): Fraction (or %) of porosity filled with water

*Schematically*
Petrophysics - Basic deliverables for a well

Petrophysical variables at each relevant depth:

– Porosity
– Water saturation
– Shale volume
– Net Reservoir (Net Sand)
– Permeability

NONE OF these are measured by LOGS in the well !!

The petrophysical variables are estimated based on mathematical relations including log measurements and parameter values

*Arne Fylling, Petrophysicist Course
Data Acquisition Methods

- **Wireline (EWL)**
  - Vertical or low angle wells
  - Logging tools conveyed by electrical wireline
  - Generally most advanced and highest quality logs

- **Pipe Conveyed Logging (PCL)**
  - Highly deviated wells
  - Logging tools are lowered down the well by drill pipe, with the tool connected at the end

- **Logging while drilling (LWD)**
  - Sensors as a part of the drilling assembly
  - Sending real time signals through the drilling mud
Scale

Petrophysical scene
Data Acquisition

• Depth of investigation
  – The distance away from the borehole that a logging tool can measure

• Resolution
  – Capability to distinguish and properly measure thin beds
VERTICAL RESOLUTION OF WELL LOGS

Outcrop or Core

24in

Sonic 24in

GR 12in

Density 6in

Resistivity Image <1in
# Petrophysical Measurements

<table>
<thead>
<tr>
<th>Covered in this course</th>
<th>Not covered in this course</th>
</tr>
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<tbody>
<tr>
<td>Radioactivity</td>
<td>Nuclear Magnetic Resonance</td>
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<tr>
<td>Resistivity</td>
<td>Geosteering</td>
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<tr>
<td>Sonic</td>
<td></td>
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<td>Pressure</td>
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Family of Nuclear Tools

Radioactivity is a result of decay of an unstable nucleus through emission of particles or energy
Quick Look Evaluation

- Lithology
  - GR, DEN/NEU, Resistivity, Sonic
- Volume of Shale
  - GR
- Porosity
  - DEN
- Saturation
  - Resistivity, Porosity, etc
- Net / Gross
  - Cutoffs porosity and VSH
Quick Look Evaluation - Lithology

Density / Neutron Combinations (Limestone compatible scale)

**Water-filled sands**
- Density left of neutron porosity

**Oil-filled sands**
- Density slightly lower than in water
- Neutron slightly lower than in water

**Gas-filled sands**
- Density read lower than oil/water
- Neutron porosity low (low HI)

**Shale**
- High neutron porosity (bound water)
- Slightly higher density than sands
- Neutron plots left of density

**Calcites:**
- High density, low neutron

<table>
<thead>
<tr>
<th>GR</th>
<th>Density</th>
<th>Neutron</th>
<th>Density Neutron</th>
<th>Resistivity</th>
<th>Dt</th>
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<tr>
<td>0</td>
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<td>1.95</td>
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<td>2000</td>
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Shale Fraction

• Shale fraction: The fraction of the rock containing fine grained material and consisting of clay- and silt-sized particles. Shale contains clay minerals as well as particles of quartz, feldspar, mica, iron oxide and organics and other minerals.

• VSH: The shale fraction including the water bound to the shale constituents.

• VSHDRY: The shale fraction without the water bound to the shale constituents;
  \[ VSHDRY = VSH \times (1 - PHISH) \]

• VCL: The volume of the clay mineral including the clay bound water.
GR - VSH Quick Look Evaluation

- Gamma Ray (GR) Evaluation Technique
  - Natural occurring radioactive elements in nature:
    - $^{40}K$, Potassium
    - $^{232}Th$, Thorium
    - $^{238}U$, Uranium
  - Spectral GR tool can discriminate between these elements, standard GR tool only provides the total GR counts

  - Reservoir rocks (Sandstone/Limestone/Dolomite)
    → low GR
  - Shale has large amount of Th and K atoms
    → high GR

\[
V_{sh} = \frac{GR - GR_{min}}{GR_{max} - GR_{min}} \\
V_{sh} : \text{Shale volume} \\
GR : \text{GR Log reading} \\
GR_{max} : \text{GR Log reading in Shale zone} \\
GR_{min} : \text{GR Log reading in clean Sand zone}
\]
Porosity

Porosity ($\Phi$): Fraction of rock not occupied by solids

1. Core porosity evaluated at reservoir conditions shall normally be the reference $\Phi$
2. Our default assumption is that standard core porosity is equivalent to a total porosity (PHIT)
3. In massive intervals with beds resolved by logs, log-estimated $\Phi$ shall be consistent with core measurements =>
   - PHIT estimated from a density log shall generally be consistent with core porosity.
4. Effective porosity: $\Phi_{IE} = \Phi_{IT} - V_{SH} \times \Phi_{ISH}$
Interpretation/Uses

• The density tool is extremely useful as it has high accuracy and exhibits small borehole effects.

• Major uses include:
  – Porosity
  – Lithology (in combination with the neutron tool)
  – Gas identification (in combination with the neutron tool)
  – Mechanical properties (in combination with the sonic tool)
  – Acoustic properties (in combination with the sonic tool)
Quick look Evaluation - Porosity

Density Evaluation technique

Porosity ($\Phi$): Fraction of rock not occupied by solids

\[ \rho_b = \rho_f \phi + \rho_{ma} (1 - \phi) \]

\[ \phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \]

where
- $\rho_b$ = Density log reading
- $\rho_f$ = Density of the saturating fluid
- $\Phi$ = Porosity
- $\rho_{ma}$ = Density of the matrix material

Typical density of common minerals/fluids

- Quartz sand: 2.65 g/cc
- Calcite: 2.71 g/cc
- Shale: 2.6-2.7 g/cc
- Gas: 0.3 g/cc
- Oil: 0.8 g/cc
- Water: 1.0 g/cc
Neutron Logging

- Source: Neutron source (chemical or electronic),
- Detectors: Neutron (thermal or epithermal)
- Measures neutron porosity (counts) which is a measure of the hydrogen index of the formation (H in the rock)
- HI in shales high
- HI of Gas $\ll$ HI of water and oil

**Applications:**
- Lithology (w/ DEN or Sonic)
- Gas identification (w/ DEN or Sonic)
- Correcting porosity for lith. and HC effects (w/ DEN or Sonic)
- Quantification of Gas fraction (w/ DEN or Sonic)
- Porosity (w/ DEN or Sonic)
- VSH
Sonic Logging

- The *sonic* or *acoustic* log measures the travel time (slowness) of an elastic wave through the formation
  - Increasing with decreasing porosity
  - Can also derive the velocity of elastic waves through the formation

- Compressional waves (P-waves):
  - parallel to the direction of propagation

- Shear waves (S-wave):
  - perpendicular to the direction of propagation

- Stoneley wave:
  - propagate along the walls of a fluid-filled borehole

**Typical values for transit times** (matrix value without porosity)
- Sandstone – 51 - 58 μs/ft
- Limestone – 47.5 μs/ft
- Shale – 62 to 167 μs/ft
- Filtrate – 189 - 200 μs/ft
- Casing – 57 μs/ft
Sonic Logging

- The *sonic* or *acoustic* log measures the travel time (slowness) of an elastic wave through the formation.

- **Applications:**
  - Geophysical interpretation:
    - Synthetic seismograms (calibration of seismic surveys)
    - Acoustic Impedance (\( V_p (m/sec) \times \rho_b (g/cc) \))
  - Porosity estimation (Wyllie or Raymer-Hunt Gardner)
  - Rock mechanical properties (elastic properties, rock strength)
  - Identification of gas (DT slower in gas)
  - Fracture indicator and Qualitative permeability from Stoneley
  - Cement Bond Logging
Saturation

• Saturation
  – the fraction of the formation pore volume occupied by a specified fluid
  
  Fraction of gas+oil+water=1=100%

• Water Saturation ($S_w$)
  – the fraction of the pore volume that contains formation water
Resistivity – Induction & Laterolog

**Electrical resistivity** - resistance to current, inverse of conductivity

**Induction principle (Faraday’s Law):**

- Current in a source coil (S) induces a magnetic field in the formation \((H_p)\)
- The magnetic field sets up a geo-electric current in the formation \((J)\), which generates a secondary magnetic field \((H_s)\)
- A current is induced in the receiver coil (R) with change in amplitude and phase
- Works best in resistive mud (OBM)

**Laterolog:**

- Focusing of current from the tool into the rock by focusing electrodes making the current flow only in the lateral direction
- Need electrical contact with the formations, i.e. conductive drilling mud (WBM)
Quick look Evaluation - Saturation

- Water saturation ($S_w$) from **resistivity logs**
  - Matrix (dry rock) is a good insulator $\rightarrow$ high resistivity
  - Oil and gas is a good insulator $\rightarrow$ high resistivity
  - Water is a good conductor $\rightarrow$ low resistivity
  - Shales contain bound water and is therefore a conductor $\rightarrow$ low resistivity

**Archie Equation:**

$$S_w = \left( \frac{aR_w}{\Phi^m R_t} \right)^{\frac{1}{n}}$$

- $a =$ tortuosity factor
- $m =$ cementation exponent
- $n =$ saturation exponent
- Standard values: $a=1, m=2, n=2$

**Archie with standard values:**

If $S_w = 1$ (in water zone):

$$R_w = \Phi^2 R_t$$

- $R_w =$ Formation water resistivity
- $R_t =$ True formation resistivity
- $\Phi =$ Total porosity
Net / Gross

• **Gross Rock:** Comprises all the rock within the thickness under consideration

• **Net Reservoir:** Net sand intervals which have useful reservoir properties
  – From cutoffs on Porosity and VSH

• **(Net Pay):** Net reservoir intervals which contain significant hydrocarbons

For reservoir modelling purposes we present the distribution of Net Reservoir (and Net/Gross), while the presence of hydrocarbons (pay) is modelled based on estimated Saturation-Height functions and fluid levels
Quicklook Evaluation - Summary

In clean water bearing formations (Sw = 1):

\[
R_w = \phi^2 R_t
\]

assuming \( a = 1, m = n = 2 \)
Formation Pressure

– Formation Pressures (EWL and LWD)
  • Fluid densities (fluid type)
  • Fluid contact levels (free fluid levels)
– Formation fluid samples (EWL)
  MDT (SLB), RDT (HAL), RCI (Baker)
Formation Pressure

1. The probe is pushed against the formation

2. Formation pressure obtained by withdrawing a small amount of fluid from the formation to generate a short transient test.

3. Formation pressure is the stable pressure reached after shut-in

4. How fast the formation equalize the pressure indicates its permeability (mobility)
Formation Pressure

- Evaluation Technique
  - An unlimited number of pressure tests (minimum 3 good) can be performed at different depths to produce a pressure profile
  - The slope of the line defines fluid density
  - The intersection defines free fluid levels
Free Water Level vs Oil Water Contact

![Diagram of capillary pressure curves and formation pressure vs. TVDss](image)

Note: Same FWL, but Oil/Water contacts vary with rock quality:
- Plug#1 (high perm.)
- Plug#3 (low perm.)
Permeability - fundamentals

- Permeability quantifies the capability of rocks to transmit fluid
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Permeability – Sources of Information

- **Quantitative:**
  - Primary (Direct measurement):
    - Core measurement
    - Production test analysis
    - WFT analysis
  - Secondary (Indirect):
    - Core calibrated log correlation/regression
    - Multivariable linear regression/neural network prediction
    - NMR, (Stoneley)

- **Qualitative** indication of permeable rock:
  - Invasion effects:
    - Presence of mud cake
    - Resistivity curve separation

Permeability estimates are typically based on establishing empirical-/statistical relationships between permeability and porosity measured on core plugs and available logs.
Permeability vs Porosity trends

- Example where grain size affects the permeability – porosity relationship
Summary Petrophysics

Objective: Identify and quantify hydrocarbon resources in the subsurface and evaluate rock properties

- Logging techniques (EWL, PCL, LWD)
- Tools measuring physical properties of the rock and fluids present:
  - Gamma, Neutron porosity, Density, Sonic, Resistivity, Formation pressure
- Reservoir properties interpreted from tool measurements – a model!
  - Vshale, Porosity, Water saturation, Net reservoir, Permeability
- Average properties per zone calculated for input to geologist/reservoir engineer
- Results give
  - Reservoir quality and fluid type
- Results contribute to
  - STOIIP
  - Recoverable reserves (producing capacity)
Summary Petrophysics - CPI Plot
Raw and Interpreted Curves