Formation Evaluation: Recent Advances in Logging

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Outline

• Conventional formation evaluation
  • Porosity
  • Saturations
  • Permeability
• Petrophysical challenges: when does conventional interpretation fall short?
• New measurements
  • Advanced gamma ray induced spectroscopy
  • Dielectric dispersion
  • A few NMR applications
• Examples of new formation evaluation
Porosity

\[
\phi = \frac{V_{\text{pores}}}{V_{\text{sample}}}
\]

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

where
- \(\rho_b\) = Density log reading
- \(\rho_f\) = Density of the saturating fluid
- \(\phi\) = Porosity
- \(\rho_{\text{ma}}\) = Density of the matrix material

(1950’s... Neutron log: 1940’s...)

The density tools measure primary as well as secondary porosity. In a clean formation of known \(\rho_{\text{ma}}\) and \(\rho_f\), the \(\phi\) is defined by the given equation.
Saturations

\[ \Phi + S_h = 1 \]

Water saturation: \( \Phi = S_w \)

Hydrocarbon saturation: \( S_h \)

\( S_w + S_h = 1 \)

Water is conductive

Hydrocarbons are resistive

\( \rightarrow \) Resistivity has good sensitivity to saturation
Saturations - quantification

Gus Archie (1952):

\[ S_w^n = \frac{1}{\phi^m R_w R_T} \]

\( R_w (Sal_w, T) \)

- **m**: pore tortuosity. Original Archie paper: \( m = 2 \) for sandstone
- **n**: saturation exponent. Original Archie paper: \( n = 2 \) for sandstone

Many extensions to Archie formula \( \rightarrow \) many saturation equations, mainly for shale
But the principle remains the same...
Impact on oil in place

\[ S_w = \frac{1}{\phi^m R_T} R_w \]

\[ S_h = 1 - S_w \]

\( R_t = 20 \text{ ohm. m, } \phi = 20\% \)

Choose nominal values of \( Sal_w = 10 \text{ ppk, } m = 2, n = 2 \) \( \rightarrow \) \( S_w = 61\%, \ S_h = 39\% \)

If instead, choose \( Sal_w = 15 \text{ ppk, } m = 1.8, n = 2 \) \( \rightarrow \) \( S_w = 42\%, \ S_h = 58\% \)

Oil in place increase by 49% ...

If instead, choose \( Sal_w = 8 \text{ ppk, } m = 2.2, n = 2.5 \) \( \rightarrow \) \( S_w = 86\%, \ S_h = 14\% \)

Oil in place decrease by 64% ...
Permeability

How easily can fluids flow in the system?

Link expected to $m$ and $n$

Not much to quantify it...

Permeability is a measure of the ease with which a fluid flows through the connecting pore spaces of the formation. The unit of measurement is the millidarcy (mD). There is no universal relationship between porosity and permeability.
Petrophysical challenges

Complex mineralogy

Pore tortuosity

Fresh water

Wettability

Unknown / Varying water

Bitumen / Kerogen

Permeability

\[ S^n_w = \frac{1}{\phi m} \frac{R_w}{R_T} \]
Advanced gamma ray induced spectroscopy

Advanced spectroscopy answers (from inelastic):

**Carbonate**: split of calcite (CaCO$_3$) and dolomite (CaMg(CO$_3$)$_2$) (Mg yield)

**Shale oil and shale gas** → clay splitting (Al yield)

**Unconventionals (kerogen)** → Total Organic Carbon (C yield)
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Dielectric dispersion

Dielectric polarization is sensitive to:

Water-filled porosity: $\phi_w = \phi \cdot S_w$

Water salinity: $Sal_w$

Water phase tortuosity: $MN$

Shallow measurement → sensitive to the invaded zone.
But $MN$ can be used with deep resistivity to estimate oil in place:

$$\phi_w = \left( \frac{R_w}{R_t} \right)^{\frac{1}{MN}}$$
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NMR applications

Direct correlation between free fluid / bound fluid and permeability:

\[ k = a\phi^4 \frac{\text{free fluid}}{\text{bound fluid}} \]

Constituent viscosity

\[ \int T_2 \cdot dT_2 = \phi \]
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Summary

• Conventional formation evaluation worked fine for easy reservoirs

• Reservoirs currently put on production do not tend to be easy ones...

• Fair progress in interpretation development during the last 10 years to adjust to new challenges

• It should be just a start...

• Keeps petrophysics fun!