CLASTICS; How to choose the right petrophysical evaluation method using standard logs

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Petrophysics: key inputs to volumes evaluation

\[
\text{STOIIP} = \frac{\text{GRV}}{G} \cdot \phi \cdot (1 - Sw) \cdot \frac{1}{B_0}
\]

- **Geophysicist/Geologist**
  - Oil initially in place: STOIIP
  - Gross rock volume: GRV
  - Net to Gross: N/G
  - Porosity: \( \phi \)
  - Water saturation: \( Sw \)

- **Petrophysicist**
  - logs, welltests, core (permeability)
  - logs, core (stressed porosity)
  - logs, core (Archie \( m \) & \( n \), Dean-Stark \( Sw \))
  - saturation-height (core capillary pressure)

- **Reservoir Engineer (PVT)**
  - laboratory measurements on fluids

Formation volume factor \( B_0 \)
Clastic Reservoirs: data measured at different scales

- Micron Scale: pore throats
- Macroscopic Scale (cm): core plug data
- Mega Scale (m): log data
- PLT data
- Giga Scale: geocellular grid cells welltests (extended range)
Well logs: basic log suite

### Well: T1

<table>
<thead>
<tr>
<th>Reference (M)</th>
<th>CAL</th>
<th>0.2</th>
<th>IN</th>
<th>0.2</th>
<th>6</th>
<th>OHMM</th>
<th>16</th>
<th>0.2</th>
<th>0.45</th>
<th>R DEEP</th>
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<td>150</td>
<td>NEU</td>
<td>200</td>
<td>v/v</td>
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<td>0.15</td>
<td>R_MIC</td>
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<td></td>
<td>150</td>
<td>0.2</td>
<td>0.45</td>
<td>240</td>
<td>DEN</td>
<td>DT</td>
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<td>0.2</td>
<td>DTS</td>
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<td></td>
<td>630</td>
<td>0.2</td>
<td>1.95</td>
<td>0.2</td>
<td>OHMM</td>
<td>200</td>
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</tbody>
</table>
Volume of Shale

- In the Total Porosity System, Vsh is used only to eliminate shale intervals from the analysis (i.e., a lithology cut-off).

- In the Effective Porosity System, Vsh is used in the quantification of porosity and water saturation from logs and any uncertainties or errors in the calculation of Vsh are continued on throughout the petrophysical evaluation.

- Some petrophysicists try to differentiate between Volume of Shale and Volume of Clay, but for practical purposes, they are often regarded as the same property. Vsh calculation is never an absolute measurement beyond laboratory core analysis.
Volume of Shale

- **Vsh (Gamma Ray)**
  - Linear
  - Non linear
    (Larionov, Tertiary sands)

- **Vsh (Density/Neutron)**
  - Preferred where sands contain radioactive minerals (e.g. Potassium Feldspars)
  - Not recommended for gas sands – will cause an underestimate of Vsh.

\[
V_{sh} = I_{GR} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}}
\]

\[
V_{sh} = 0.083(2^{3.7I_{GR}} - 1)
\]
Vsh Evaluation
Which Porosity?

- **Total Porosity (Phit):**
  
  Takes account of electrochemically (clay) bound water, capillary bound water and free fluids.
  
  Simplest approach, calibration to core data is straightforward.

- **Effective Porosity (Phie):**
  
  Attempts to eliminate the non contributing porosity fraction attributed to clay within the reservoir.
  
  Takes account of capillary bound water and free fluids.

*For most reservoir simulator intialisation purposes, electrochemically or clay bound water is part of the binding solids and only capillary bound water, immoveable hydrocarbons and free fluids are assigned to the effective pore space*
Which Porosity/Permeability? – ensure consistency with the simulator

\[ \sum_{p=1}^{n_p} \nabla \cdot \left( \rho_p y_{c,p} \frac{k_{krp}}{\mu_p} (\nabla P_p + \rho_p g \nabla D) \right) = \sum_{p=1}^{n_p} \left( \frac{\partial}{\partial t} (\phi_e \rho_p y_{c,p} S_p) \right) + q_c \]

*absolute permeability tensor (usually to brine)*

*effective porosity*

…………… the partial differential equation that forms the basis for dynamic simulation

Courtesy of Worthington and Hattingh, SPE 160248, 2012
Porosity: total and effective

Effective Porosity = $c/a$

Total Porosity = $b/a$

$$\phi_e = \phi_t - V_{sh} \phi_{ssh} = \phi_t (1 - S_{wb})$$
Porosity Evaluation

- **Total porosity (Phit)**
  - Preferred approach where conventionally dried core plug data are available
  - Phit from logs can be compared to and calibrated with overburden-corrected core analysis data.
  - Phit from QC’ed Density Log is recommended log analysis approach.

  \[
  Phit = \frac{(Rhomatrix - Rhob)}{(Rhomatrix - Rhofluid)}
  \]

- **Effective porosity (Phie)**
  - Effective Porosity measurements on core can be unreliable – humidity drying is poorly calibrated
  - Effective Porosity from logs demands a robust Vsh interpretation and an estimate of shale porosity
  - More reliable to use Total Porosity for both core and log evaluation
  - Effective Porosity can be estimated from Total Porosity later.

  \[
  Phie = Phit - Vsh \times \frac{(Rhomatrix - Rhoclay)}{(Rhomatrix - Rhofluid)}
  \]

  _Total porosity of clay fraction_
Porosity: Phit evaluation integration with core data

- \[ \text{Phit} = \frac{\text{Rhomatrix} - \text{Rhob}}{\text{Rhomatrix} - \text{Rhofluid}} \]

**Rhomatrix:**
from statistical analysis of core grain density data (2.64 \~ 2.67 g/cc)

**Rhofluid (apparent):**
from plot of core porosity against density log per fluid type.

\[ \rho_f = Sxo \cdot \rho_{mf} + (1-Sxo) \cdot \rho_{hc} \]
Porosity Evaluation

Well: T1

UWI:
Short name:
Long name:

Elevation:
Elevation datum:
Total depth:
Coordinate system:

X:
Y:
Longitude:
Latitude:

SPUD date:
Completion date:
Status:
Operator:

Country:
Field:
State:
Company:

Reference (M) 1:250

CAL 6 IN 16
GR

Reference
0 API 150

R_DEEP 0.2 OHMM 200
R_SHAL 0.2 OHMM 200
R_MIC 0.2 OHMM 200

Sand - Shale (ND)

0.45 v/v -0.15
DEN

DTS 240 US/F 40

GCA_VSH 0 v/v 1
GCA_PHIE 0.5 v/v 0

GCA_VSH 0 v/v 1
GCA_VSH_TERT 0.5 v/v 0
GCA_PHIE_TERT

Core porosity

0.5 v/v 0

630
640
650
Water Saturation: distribution in the reservoir

[Diagram showing water saturation distribution with key points such as P_c, S_w, GOC, OWC, FWL, and resistivity log.]
Archie's (1942) equation

\[ F = \phi^{-m} = \frac{R_o}{R_w} \]

\[ \& \]

\[ Sw = \left( \frac{R_o}{R_t} \right)^{\frac{1}{n}} \]

\[ Sw = \sqrt[n]{\frac{R_w}{R_t \times \phi^m}} \]

Based on core data, but applicable to logs and has stood the test of time.
Archie: m & n considerations

- m (cementation/tortuosity exponent) derived from FRF SCAL data
- n (saturation exponent) derived from RI SCAL data
- m variable with porosity system and in general decreases with better quality rock,
- n is dependent on wettability – increases with oil wetness as the conductive brine phase becomes disrupted
- n can reduce as a function of grain surface rugosity and clay presence

\[ Sw = \left( \frac{a \cdot R_w \cdot \phi^{-m}}{R_t} \right)^{\frac{1}{n}} \]
Archie: n Saturation Exponent

- Archie rocks are where resistivity ratio vs. saturation plots as a straight line in log-log scale. The slope of the line is equal to $n$.

- The blue curve is typical of shaly sands. Increased conductivity is caused by clay-water interaction.

- The red curve is typical of strongly oil-wet carbonates which deviate from Archie behaviour.

\[ Sw = ((a \cdot R_w \cdot \phi^(-m))/R_t)^{(1/n)} \]
Archie: Sources of Water Resistivity (Rw)

- Pickett plot over water leg
  - Graphical solution of Archie for case $Sw = 100\%$

- Formation water samples
  - be careful of mud filtrate contamination
  - be sure to differentiate between results quoted as Total Dissolved Solid (TDS), ppm Chlorides and ppm NaCl eqv.
  - N.B.: ppm NaCl equivalent = 1.645 * ppm total chlorides.

- Spontaneous potential (SP log)

- Rw is dependent on temperature (variable) and salinity (constant)
- Rw expressed in Ohmm and salinity in ppm NaCl eqv.
Archie: Water Resistivity, $R_w$ from Pickett plot

A plot of porosity against deep resistivity on a log-log scale

$R_w \sim 0.034 \text{ Ohmm}$

$m$ can be also estimated from the slope of the gradient
Archie’s Equation: Limitations

- Assumes that the formation itself has no electronic conduction
- Does not account for vuggy porosity
- Starts to become unstable as formation water salinities decrease < 20,000 -30,000 ppm NaCl eqv.
- Affected by conductive minerals e.g pyrite, glauconite
- Affected by presence of conductive clays in the formation
- Archie is not a universal equation for all rock types
Saturation from Resistivity: Shaly Sands
Shaly Sand Evaluation: Total Porosity System

\[ Sw = \left( \frac{(a \cdot Rwe \cdot \phi^{(-m^*)})}{Rt} \right)^{(1/n^*)} \]

Combined term \( Rwe \) can be expanded from Archie Eqn. to cover the effects of water conductivity and dispersed clay conductivity.

\[ Rwe = \frac{1}{\left( \frac{1}{Rw} + B \cdot Qv/Sw \right)} \]

Where:  
- \( B \) is mobility of clay counter ions.....*function of Temp & Rw*  
- \( Qv \) is the clay conductivity.....*from SCAL*  
- \( m^* \) is clay corrected Archie m.....*from SCAL*  
- \( n^* \) is clay corrected Archie n.....*from SCAL*

Sw now appears on both sides of the equation, but computers handle this effortlessly through iteration.  
.. we now have the Waxman – Smits equation in its simplest form!
Example;

Having determined the B.Qv clay conductivity term by means of SCAL or log analysis, the Waxman-Smits Eqn. has the potential to produce a lower Sw value than Archie.

If no conductive clay present, then Sw (W-S) = Sw (Archie)
**Saturation in Shaly Sands: Summary**

**Clean sand:** Archie Eqn.

**Shaly Sand**

*Total porosity system (PHIT)*

- Waxman-Smits Eqn.
- Juhasz Eqn*
- Dual Water Eqn.

Require:
- \(B.Qv\)
- \(V_{sh}\)
- \(R_{sh}\)
- \(\text{core Qv measurements, but requires } V_{sh}\)

*Juhasz eqn formulated to enable evaluation independent of core Qv measurements, but requires \(V_{sh}\).

**Shaly Sand**

*Effective porosity system (PHIE)*

- Indonesia Eqn**.
- Mod.Simandoux Eqn.

Require:
- \(V_{sh}\)
- \(R_{sh}\)
- \(\text{from core Qv measurements, but requires } V_{sh}\)

**Laminated sand/shale (thin beds):** Advanced interpretation techniques e.g Thomas Stieber cross-plot analysis to evaluate lamination volume and true resistivity of sand laminae. Multicomponent induction resistivity logs allow differentiation of horizontal and vertical resistivity.
Saturation: integration with capillary pressure data; Sat-Ht function and FWL
Integrated Evaluation

"Difference between Sw from Sat-Ht function (SHF) and Sw from logs indicates possibility of a swept or flushed zone"
Alternative means of saturation estimation

- Dean Stark: direct extraction of water phase from uninvaded core
  - only reliable with OBM systems

- Saturation-Height Function estimation from capillary pressure data from core
  - Need to identify Free Water Level in order to apply the
  - Very useful to independently verify the Sw derived from log data

- Pulsed Neutron measurements from advanced logging tools
  - works through casing
  - useful for remaining oil saturation determination after sweep

- Dielectric logs – can measure remnant oil saturation in invaded zone

- Nuclear Magnetic Resonance
  - Requires significant levels of processing
Outline Evaluation Workflow

- **Organise**
  - Log data, logging parameters, core data, mudlogging data, make log QC plots.

- **Edit**
  - Depth match logs, edit washouts, depth shift core data.

- **Correct**
  - Environmental corrections to logs (only if necessary – don’t double correct), Establish Rt from Resistivity curve arrays (tornado charts), compaction correct core data.

- **Think**
  - What porosity system? Shaly Sand? Laminated Sands?
  - Select appropriate petrophysical models.
• **Evaluate and Integrate**
  – Appropriate Vsh, Porosity, Saturation methods.
  – Core analysis data – calibrate porosity, SCAL data – calibrate water saturation from resistivity with FRF/RI
• **Groundtruth**
  – Check Vsh against lithology from geological descriptions.
  – Compare log porosity to corrected core data.
  – Compare log Sw to Sw from Capillary Pressure Data (Sat-Ht).
• **Communicate**
  – To the users of your interpretation – methods, uncertainties, assumptions and ranges.
• **Document**
  – Write up as you go, saves re-work.
Useful Reference:
ISBN:0-7506-7883-6

Acknowledgements to Phil Gibbons, GCA for log evaluation examples.