An Integrated Petrophysical Evaluation for Reservoir Characterization and Modeling of Field Development

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Outline

• Introduction & Challenges
• Integrated Reservoir Characterization Workflow
• Porosity, Permeability and Saturation In Cored Wells
• Reservoir Rock Type and Saturation Height Model
• Fluid Contacts and Calculation Technique
• Evaluation Results
• Conclusion
Introduction and Challenges

• The uncertainty of original oil in place (OOIP) is one of challenges in the reliable reservoir characterization and reservoir development.

• Multi fluid contacts, major-minor faults, variation of water saturation resistivity with SWI of core saturation height model and production data.

• It requires an integrated petrophysical evaluation approach of logs, special core analysis (SCAL), geology, geophysics, reservoir rock typing (RRT), saturation height model (SHM) and detailed reservoir/fluid analysis to provide reliable reservoir characterization and fluid contacts estimation.

• An integrated Permeability, RRT and SHM to be developed from porosity, clay bound, pore size, core and mobility data for reliable reservoir modeling of field development.
Hydrocarbon Volume Uncertainties

\[
IGIP = \frac{\text{Area} \times \text{Height} \times \text{Porosity} \times Sg}{B_g}
\]

&

\[
IOIP = \frac{\text{Area} \times \text{Height} \times \text{Porosity} \times So}{B_o}
\]

Remarks:
- Gas Volume in SCF with 43560
- Oil Volume in STB with 7758
- Area in Acres
- Height in Feet
- Porosity in v/v
- Saturation in v/v
- Gas Volume Factor in FT³/SCF
- Oil Volume Factor in BBL/STB
Integrated Reservoir Characterization Workflow Approach

- Calibrate Log Porosity with corrected core porosity.
- Use SCAL data of cementation exponent (m) and saturation exponent (n) for water saturation.
- Generate Permeability Log as function of porosity, bound water-clay, pore throat & diagenesis.
- Use Core Porosity and Permeability Distribution Data for reservoir rock type (RRT).
- Use Pore throat size and Distribution (MICP) for RRT.
- Use Capillary Pressure (Pc) and Water Saturation (SW) of SCAL Porous plate for RRT.
- Use Formation Pressures, Fluid Contacts, Gradients and Well test data.
- Build Saturation Height Function (SHF) for every RRT.
- Integrate core, logs and reservoir data for reservoir rock typing (RRT) and Saturation Height Function (SHF).
- Implement RRT and SHF in Reservoir Modeling (Static and Dynamic).

SPE-198634 & SPE-198636
Digital Rock Physics and Pore Network Model (AI) for EOR

- Core sample
- Computer Tomography
- Laboratory Calibration
- HM with Wells Production
- Optimum Recovery/EOR

3D Digital rock

Network extraction & Build PNM

Network model

Near Miscible WAG Flooding sequence with Fluid & Rock properties

Prediction of $P_c$ and $k_T$
Petrophysical Evaluation Approach

- In petrophysical evaluation the core (SCAL) has been used for input parameters.  
  \[ a = 1, \ m = 1.84, \ n = 1.75 \] (NOB @ 1500 psi) shallow reservoir condition. 
  \[ a = 1, \ m = 1.85, \ n = 1.70 \] (NOB @ 3700 psi) deep reservoir condition.

- Formation water salinity:
  Shallow reservoirs: 195-210 PPK from formation water analysis & formation pressure gradient 0.495-0.5 psi/ft.  
  Deeper reservoirs have lower formation water salinity: 80-120 PPK.

- Water Saturation Computation (Clean, Non-Clean & Pressure-Temperature Effect)

- Permeability Computation (Poro-VCL-PTR, Core).

- Reservoir Rock Typing (Poro-Perm, PTR, Pc_SW, Kr_SW & Core-logs).

- Fluid Contacts Evaluation (Logs, Formation Pressure, Reservoir system and SHF).

- Saturation Height Function (SHF: Core-Logs-FP).
Core, Logs and Fluid Data Evaluation

**Core Data**
- RCA: Porosity, Permeability
- SCAL: m,n, CEC, Pc-Sw, Kr
  - at reservoir condition (P/T)
- SEM/XRD & RM

**Petrophysical Evaluation**
- Core & Logs Calibration
- Mineral Volume, Porosity, Permeability
- Saturation and Fluid Contacts
- Reservoir Rock Typing
- Saturation Height Model (Pc-Sw)

**Well Logs Data**
- Porosity, SW, Permeability, Formation Pressure & Fluids Sampling

**Fluids & Gas**
- PVT/Production Data

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Core Porosity and Log Porosity

Irreducible water saturation increases with decreasing of pore throat size (radius) and/or capillary bound effects.

SPE-198634 & SPE-198636
Permeability Approach in Sandstone Reservoir

Permeability Equation (Core-Logs).

\[ \text{Permeability} = \frac{a \times 100000 \times \text{Porosity}^b}{10^{(c \times \text{Vclay})}} \]

With:
- \( a = 1.2 \) or \((0.9 - 1.5)\)
- \( b = 3.5 \) or \((3 - 4)\)
- \( c = 4.5 \) or \((4 - 5)\)

Permeability is calibrated with NOB corrected of core data L-X (shallow reservoir) & L-Y (deep reservoirs). Formation pressure mobility is used to compare it qualitatively.

The advantages of this permeability relationship:
- It will give permeability ranges considering porosity and volume of clay.
- It is following the real ranges of core’s porosity-permeability & mobility of formation pressure.
- It represents reservoir heterogeneities

SPE-198634
Permeability Approach in Carbonate Reservoir

**Permeability** = \((a*100000*Porosity^{b})(10^{c*v}) + d\)

Where:
- \(a = 1.0 \text{ or } (0.8 - 1.2)\)
- \(b = 5.0 \text{ (Y-A), 4.5 (Y-CD), for high perm } b = 4.2 \text{ & for low perm } b = 6\)
- \(c = 5.0 \text{ or } (4.5 - 5.5), \text{ cementation}\)
- \(v = \text{ clay & bound water constant}\)
- \(d = \text{ diagenetic & dolomite constant}\)

Permeability is calibrated with NOB corrected of core data. Formation pressure mobility is used to compare it qualitatively.

The advantages of this permeability relationship:
- It will give permeability ranges considering porosity, clay/bound water, cementation and diagenetic.
- It is following the real ranges of core’s porosity-permeability & mobility of formation pressure
- It represents reservoir heterogeneities

SPE-198636
Capillary Pressure, Water Saturation and Relative Permeability
Relative Permeability

- **Permeability** – The measure of the ability of a porous material to transmit a fluid
  \[ K = q \cdot \mu \cdot L / A \cdot \Delta P \]  
  units: (cm³/s) (cp) (cm) / (cm²) (atm)

- **Specific Permeability** – Permeability determined with only one fluid present in the pore space - \( K_w, K_o, K_g \)
  \[ K_w(\text{mD}) = q_w \cdot \mu_w \cdot L \cdot 1000 / A \cdot \Delta P \]

- **Effective Permeability** – Permeability to one fluid with more than one fluid present in the pore space - \( K_{eo}, K_{ew}, K_{eg} \)

- **Relative Permeability** – Effective Permeability divided by 'Base' Permeability, \( K_{base} \)
  (base permeability usually measured at the beginning of the experiment e.g. \( k_w, K_o(S_w) \))
  \[ K_{ro} = K_{eo} / K_{base} \]
  \[ K_{rw} = K_{ew} / K_{base} \]
  \[ K_{rg} = K_{eg} / K_{base} \]

Steady State  Unsteady State
Reservoir Rock Type and Saturation Height Model

- Drainage for SWI

- Imbibition for Sor

Facies:
- Channel
- Gravasite
- Overbank
- Mud

RRT & Sor

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Saturation Height Function for Every Reservoir Rock Types

\[
SW_{\text{RRT}} = \left[ \frac{a \left( Water\_gradient - Hydrocarbon\_gradient \right)}{HAFWL\_m \times 3.28} \right]^{\frac{1}{b}} \times \left( \frac{Permeability\_mD}{Porosity\_fraction} \right)^{0.5}
\]

Where:
- \( SW_{\text{RRT}} \) is water saturation of reservoir rock type (v/v)
- \( HAFWL \) is height above free water level (m)
- \( Perm \) is Permeability (mD)
- \( Porosity \) unit is v/v

Water Gradient : 0.495 psi/ft
Oil Gradient : 0.320 psi/ft
HAFWL : Height above free water level, ft
\[
Pc (\text{psi}) = \text{Diff Water and Oil Gradient} \times \text{HAFWL (ft)}
\]

<table>
<thead>
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<th>RRT-1</th>
<th>NRI Range</th>
<th>RRT-2</th>
<th>NRI Range</th>
<th>RRT-3</th>
<th>NRI Range</th>
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<td>a</td>
<td>2</td>
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<td>SV-1</td>
<td>Non reservoir</td>
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<tr>
<td>b</td>
<td>3</td>
<td>RRT1 &gt;= 1.5</td>
<td>b</td>
<td>4.1</td>
<td>1.5 RRT2 &gt;= 0.85</td>
<td>b</td>
<td>4.5</td>
<td>0.85 RRT3 &gt;= 0.21</td>
<td>b</td>
<td>7</td>
<td>0.2 b RRT4 &gt;= 0.07</td>
</tr>
</tbody>
</table>

a is constant IFT and contact angle for every RRT
b is constant saturation and entry pressure for every RRT

It is recommended to use SHF for every RRT and to avoid normalized SHF, details can be found in SPE-198634
Reservoir Fluid Contacts and Calculation Technique

- Reservoir fluid contact, free water level (FWL) is determined by formation pressure gradients (Gas-Water or Oil-Water) and the logs are used to confirm the fluid contacts.
- When only oil down to (ODT) or gas down to (GDT) can be identified from the well logs then:
  - ODT or GDT of well logs at original condition can be used to calculate possible free water level (PFWL) or current oil water (OWC) contacts for depletion case.
  - It is important to solve fluid contacts (oil-water or gas-water) for reservoir model with many reservoir units and compartmentalized reservoirs.
  - Calculation technique with SHF, RRT and SW are used for this purpose.

In keys original wells
RRT, SW Logs & Saturation Height Model (Cored Well L-X)
Well logs, Core, Formation Pressure & Fluid Sampling
Well logs and Well Test Data

<table>
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<tr>
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<td>OH_05 (GR)</td>
<td>GB</td>
<td>OH_06 (GR)</td>
<td>GB</td>
</tr>
</tbody>
</table>

Good Ave Perm_Log (141mD) and Perm_DST(176mD) comparison
Important to Apply Correct Fluid Contacts for Saturation Height Model

Contacts (PFWL) for every subunits provide better matching $\text{SHF}$ with $\text{SW}_{-}\text{resistivity}$ compared to one oil water contact (PFWL). It is important to apply different oil water contact for subunits considering variation of formation pressure and water production during well production.
Saturation Height Model & SW Logs (Different Fluid Contacts)

Water Saturation logs (Resistivity, NMR & Sigma) and SHF (one and three FWLs)
Porosity, Permeability, Saturation Height Model & SW Logs In Carbonate Reservoir
Saturation Height Model & SW Logs in Carbonate Reservoir

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Good SW and SHF Logs comparison

CGR for VCL

PFWL: ~4470 m TVDSS
POWC_YA1_SHF: ~4250 m TVDSS
POWC_YA2_SHF: ~4350 m TVDSS

PFWL: ~4500 m TVDSS
POWC_YB_SHF: ~4350 m TVDSS
POWC_YCD_SHF: ~4600 m TVDSS
Conclusions

• The integrated petrophysical evaluation from logs, special core analysis (SCAL), geology, geophysics, reservoir rock typing (RRT), saturation height model (SHM) and detailed reservoir/fluid analysis are important to be used.

• The important to use core(SCAL)-logs calibration in the integrated petrophysical evaluation for reliable porosity, saturation, permeability, RRT and SHF, for reliable reservoir model.

• The different of water saturation resistivity with core saturation height model have been evaluated for an improving reservoir characterization.

• An initial water saturation, relative permeability and residual oil saturation from SCAL data have been used in evaluation. The sigma-pulse neutron capture and PLT are used to verify fluid contacts and water saturation changes during well production.

• The integrated reservoir evaluation approach has provided reliable assurance and important benefits for reservoir characterization and reservoir management of complex reservoirs.
Technical References

- Muhammad A Gibrata, Lamia R, Yanfidra Y and S Ghedan, An Innovative Integrated Reservoir Characterization Driven by Modified Saturation Height-RRT Model (SCAL based) for a Reliable Reservoir Modeling in Complex Sandstone Reservoirs, SPE-198634.
Acknowledgements, Thanks & Questions

I would like to thank and acknowledge Dragon Oil (ENOC) management.
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