Carbonate Petrophysics in Wells Drilled with Oil Base Mud

Vinicius Machado, Paulo Frederico, Paulo Netto, Petrobras
Rodrigo Bagueira, Fluminense Federal University
Andre Souza, Elmar Junk, Lukasz Zielinski, Austin Boyd, Schlumberger
Brazilian Pre-Salt Carbonates

2 Km Water Depth, 2 Km Salt: (Oil Base Mud)
200 Km Offshore
Pre-Salt Carbonates: 18,000 ft TVD
Oil 28-30 Api, GOR 1350 scf/brl

Formigli, 2007
Pre-Salt Carbonates

• Microbial, Stromatalites
• Complex Lithology
  – Calcite, Dolomite, Quartz
  – NMR Porosity - PHIT
• Variable Permeability
  – 4 decade range
• Oil Wet
  – Very High Resistivity
  – Sw?
  – Swirr from NMR Bound Fluid

Formigli, 2007
# Dunham Classification for Carbonates

<table>
<thead>
<tr>
<th>Original components not bound together at deposition</th>
<th>Original components bound together at deposition. Intergrown skeletal material, lamination contrary to gravity, or cavities floored by sediment, roofed over by organic material but too large to be interstices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contains mud (particles of clay and fine silt size)</td>
<td></td>
</tr>
<tr>
<td>Lacks Mud</td>
<td></td>
</tr>
<tr>
<td>Mud-supported</td>
<td></td>
</tr>
<tr>
<td>Grain-supported</td>
<td></td>
</tr>
<tr>
<td>Less than 10% Grains</td>
<td>More than 10% Grains</td>
</tr>
<tr>
<td>Mudstone</td>
<td>Wackestone</td>
</tr>
</tbody>
</table>

C. G. St. C. Kendall, 2005 (after Dunham, 1962, AAPG Memoir 1)
Carbonate Classifications by Pore Size and/or Grain Size

• Archie-1952 (grain size / cuttings)
• Choquette and Pray 1970 (micro-meso-mega)
• Pittman 1971 (micro-macro)
• Marzouk 1995 (micro-meso-macro)
• Lucia 1967, 1983, 1995 (grain size & vugs)
• Ramakrishnan 1997-2001 (micro-macro-vugs)
• Cantrell & Hagerty 1999 (micro-macro)
• Clerke 2007 (micro I, II, III & macro)
Archie 1952

- Matrix Type
  - I (Crystalline)
  - II (Chalky)
  - III (Granular / Sucrosic)
- Grain Size (mm)
  - V.Fine (0.05), Fine (0.1),
  - Med. (0.2), Coarse (0.4)
- Visible Pore Size (x10 microscope)
  - Primary: Class A (less than 0.01mm, not visible)
  - Secondary: Class B (0.01-0.1mm)
  - Class C (greater than 0.1mm but less than grain size)
  - Class D (greater than grain size – vug)

Designed for field geologist looking at cuttings. Made initial correlation between rock-type and Swirr.
Choquette and Pray, 1970

- Micropores <1/16mm
- Mesopores 1/16-4mm
  - Small
  - Large
- Megapores 4-256mm
  - Small
  - Large

15 Porosity Types

Core & Outcrop Description
Pittman 1971

- **Micropores**
  - occur between calcite crystals
  - Less than 1 micron diameter
  - Visible with SEM
  - Impact on high SWIRR
- **Macropores**
  - Visible in thin sections
  - Greater than 30 microns
  - Can be inter-granular or intra-granular
Marzouk 1995: micro-meso-macro pores

Micrite (Calcite Crystal) 1-2 μm in length

Micrite Particle, clump of calcite crystals, 10-20 μm in diameter

Carbonate Grain, > 200 μm, composed of micrite crystals

Marzouk et al SPE 49475
Micritic Carbonate Porosity

Micrite Particles 10-20um

Micrite Grains > 200um

Meso Pores
0.3-4 micron

Micro Pores
< 0.3micron

Macro Pores
> 4 micron

Based on Pore Throat Radius from Mercury Porosimetry

Marzouk et al SPE 49475
Sample 1 30 p.u. 97 md.

Sample 2 18 p.u. 2 md.
Carbonate Classifications by Pore Size and/or Grain Size

- Archie-1952 (grain size / cuttings)
- Choquette and Pray 1970 (micro-meso-mega)
- Pittman 1971 (micro-macro)
- Marzouk 1995 (micro-meso-macro)
- Ramakrishnan 1997-2001 (micro-macro-vugs)
- Cantrell & Hagerty 1999 (micro-macro)
- Clerke 2007 (micro-macro)

- **Interparticle**
  - Fine/Class 3
    - (< 20um, Pd > 70psi)
  - Medium/Class 2
    - (20-100um, Pd 15-70psi)
  - Large/Class 1
    - (> 100um, Pd < 15psi)

- **Vuggy**
  - Separate Vugs
  - Touching Vugs

**Grain Size & Permeability Prediction**
(No distinction between intercrystall & interparticle)  
Lucia 1995
Intragranular Microporosity

Lucia 1995

**Graph:**
- **Y-axis:** Permeability (md)
- **X-axis:** Porosity (%)
- **Legend:**
  - Grainstone field
  - Dolograinstone with intragrain microporosity

Lucia 1995
Touching Vug Trend
(similar to fractures)

\[ k_f = 84.4 \times 10^5 \frac{W^3}{Z} \]
\[ \phi_f = \frac{W}{Z} \times 100 \]
\[ z = \text{Fracture spacing} \]
\[ w = \text{Fracture width} \]
\[ K_f = \text{Fracture permeability} \]
\[ \phi_f = \text{Fracture porosity} \]

Lucia 1995
Ramakrishnan

- Micro
  - Intragranular
- Macro
  - Intergranular
- Vugs
  - Absent grain

Bruggeman ...... $k_{\text{eff}} = \frac{k_{\text{matrix}}}{1 - 3f_v}$
(assumes $k_{vug} = \infty$)
Cantrell & Haggerty

- **Micro Porosity Types**
  - Microporous Grains
  - Microporous Matrix
  - Microporous Cements

- **Mechanisms**
  - Leaching
  - Crystal growth
  - Boring of grains

- **Macro Porosity**
  - Visible (>10 microns)
Clerke Pore Type from Mercury

- Macro Porosity
  - 260 microns
- Micro I (Intra-Granular)
  - 1 micron
- Micro II (Micritic)
  - 0.1 micron
- Micro III (Micritic)
  - Sub 0.1 micron

Clerke 2007
Carbonate Petrophysical Classifications

- Grain Size
  - Archie, Lucia
- Pore Size
  - Choquette & Pray, Pittman, Ramakrishnan
- Pore Throat Size
  - Marzouk, Hassall, Ramamoorthy, Clerke

Pore Size from $T_2$

\[ \frac{1}{T_2} = \frac{1}{T_{2B}} + \rho \frac{c}{r} \]

Where $c = 3$ for spherical pores
= 2 for cylindrical pores
= 1 for planar pores

* Looyestijn, 2004
Carbonate Petrophysical Workflow

- Ramamoorthy et al, SPWLA 2008
  - Lithology & Porosity
  - Pore System & Permeability (2 transforms)
  - Saturation & Relative Permeability
- Designed for Water Base Mud
- Oil Base Muds?

\[
K_{SDR} = A\phi^C\left(\rho T_{2lm}\right)^B
\]

\[
K_{MACRO} = A\phi^C\left(\frac{V_{MACRO}}{\phi - V_{MACRO}}\right)^B
\]

Where
- \(K_{SDR}\) = permeability (mD)
- \(A\) = pre-multiplier
- \(\phi\) = porosity fraction (pu)
- \(C\) = porosity exponent
- \(\rho\) = surface relaxivity (microns/second)
- \(T_{2lm}\) = log mean of \(T_2\) distribution (secs)
- \(B\) = exponent
Pore System & Permeability

Carbonate Porosity Partitioning from Logs

- **Total Porosity**
  - Micro porosity
  - Mesoporosity
  - Macroporosity

- **NMR Response**
  - $\Phi < \text{short } T_2 \text{ cutoff}$
  - $\Phi > \text{long } T_2 \text{ cutoff}$

- **Image Response**
  - Non vug porosity
  - Vug Porosity

- All pores $> 50$ – $100$ microns have the same $T_2$
- Blind to pores much smaller than a button

- NMR Response:
  - $\Phi < \text{short } T_2 \text{ cutoff}$
  - $\Phi > \text{long } T_2 \text{ cutoff}$

- Image Response:
  - Non vug porosity
  - Vug Porosity

- Total Porosity:
  - Micro porosity
  - Mesoporosity
  - Macroporosity

- NMR Response:
  - $\Phi < \text{short } T_2 \text{ cutoff}$
  - $\Phi > \text{long } T_2 \text{ cutoff}$

- Image Response:
  - Non vug porosity
  - Vug Porosity

- All pores $> 50$ – $100$ microns have the same $T_2$
- Blind to pores much smaller than a button
Pore Size from NMR $T_2$

- No diffusion on long $T_2$
  - Short Echo Spacing
  - or low gradient
- $T_{2B} > 1$ second
  - Water, OBMF, Light Reservoir Oils
- No diffusive coupling
  - Oil wet helps
- Pore fluids wetting the grains
  - Water in micro pores
  - Oil/OBMF in meso & micro pores

\[
\frac{1}{T_2} = \frac{1}{T_{2B}} + \rho \frac{c}{r} \quad \text{..... Eq 1*}
\]

Where $c = 3$ for spherical pores
= 2 for cylindrical pores
= 1 for planar pores

* Looyestijn, 2004
$T_2$ versus Pore Size: Effect of $T_2$ bulk

\[
\frac{1}{T_2} = \frac{1}{T_{2B}} + \rho \frac{c}{r}
\]

$K_{SDR} = A \phi^C \left( \rho T_{2lm} \right)^B$

- micro
- meso
- macro
Permeability and Macro Porosity

\[ K_{MACRO} = A \phi^C \left( \frac{V_{MACRO}}{\phi - V_{MACRO}} \right)^B \]

Kmacro vs Vmacro/PHIT

- Kmacro 30pu
- Kmacro 20pu
- Kmacro 10pu
$T_{2\text{bulk}}$ of Oil Base Mud Filtrate

Petrobras Research (CENPES)
Brazilian Universities Lab NMR:
UFF, USP, UFES, UFRJ, ON
Pre-Salt Carbonate Core: Lab NMR
Effect of Surface Relaxivity \((\rho)\)

\[
\frac{1}{T_2} = \frac{1}{T_{2B}} + \rho \frac{c}{r}
\]

T2 vs Pore Size for T2B=2, Rho=1 & 3

- Oil/OBM (rho=1)
- Water (rho=3)

Pore Radius Microns

T2 Sec
Wettability & Pore Size

\[ P_c = \frac{2 \gamma \cos \phi}{\Gamma} \]

- **Water-wet** $\phi < 90$
- **Neutral** $\phi = 90$
- **Oil-wet** $\phi > 90$

Micro Pores | Meso Pores | Macro Pores
Effect of Surface Relaxivity and Bulk $T_2$

\[ \frac{1}{T_2} = \frac{1}{T_{2B}} + \rho \frac{c}{r} \]

$T_{2B} \text{(obmf)} = 2.0 \text{ sec}$

$T_{2B} \text{(brine)} = 1.2 \text{ sec}$

Wettability Effect
On micro-meso-macro
Cut-off values
Lab – Log Comparison of Pre-Salt Core
Carbonate Porosity Partitioning

Carbonate Porosity Partitioning from Logs

---

**NMR Response**
- Micro porosity
  - $\Phi < \text{short } T_2 \text{ cutoff}$

**Image Response**
- Non vug porosity
  - Vug Porosity

**Mesoporosity**
- $\sim 0.5 \text{ microns}$
  - $\Phi < \text{short } T_2 \text{ cutoff}$

**Macroporosity**
- $\sim 5 \text{ microns}$
  - $\Phi > \text{long } T_2 \text{ cutoff}$

**Total Porosity**
- All pores
  - $> 50$ – $100 \text{ microns}$ have the same $T_2$

**Porosity**
- Blind to pores much smaller than a button
Electrical and Acoustic Images in Vuggy Carbonate

Under Evaluation: Vugs from Electrical Images & Acoustic Images in OBM
Summary: Carbonate OBM Petrophysics

• Porosity & Lithology
  – NMR Porosity helpful with complex mineralogy

• Porosity Partitioning & Permeability
  – Oil Wet and Light Oil
  – $K_{SDR}$ for Micro-Meso Porosity
  – $K_{MACRO}$ when Macro Porosity > cut-off

• Saturation
  – Swirr from NMR
References

1) Classification of Carbonate Reservoir Rocks and Petrophysical Considerations, G.E. Archie, AAPG 1952

2) Geologic Nomenclature and Classification of Porosity in Sedimentary Carbonates, Choquette and Pray, AAPG 1970

3) Microporosity in Carbonate Rocks, Edward Pittman, AAPG 1971

4) New Classification of Carbonate Rocks for Reservoir Characterization, I. Marzouk, SPE 49475, 1995


6) A Model-Based Interpretation Methodology for Evaluating Carbonate Reservoirs, T. S. Ramakrishnan, SPE 71704, 2001

7) Microporosity in Arab Formation Carbonates, Saudi Arabia, Cantrell & Hagerty, GeoArabia, Vol. 4, No. 2, 1999

8) Permeability, Relative Permeability, Microscopic Displacement Efficiency, and Pore Geometry of M-1 Bimodal Pore Systems in Arab D Limestone, Edward Clerke, SPE 10529, 2009