An Integrated Approach to Characterization and Modeling of Carbonate Reservoirs*

G. Michael Grammer

Search and Discovery Article #50784 (2013)**
Posted February 28, 2013

*Adapted from presentation at Tulsa Geological Society dinner meeting, February 5, 2013
**AAPG©2012 Serial rights given by author. For all other rights contact author directly.

Abstract

Carbonate reservoirs are characterized by significant heterogeneity at a number of scales, ranging from exploration to production and enhanced production scale. An understanding of how primary depositional facies, diagenesis, and the sequence stratigraphic framework control the development of pores in carbonate rocks, and how the variation in pore architecture influences reservoir permeability is a fundamental process in the accurate characterization of carbonate reservoirs. In addition, with the ubiquitous use of geostatistical models to define and predict 3-D reservoir architecture in the subsurface, it has become increasingly important to accurately define the probable geometric distribution of potential reservoirs and seals at multiple scales to provide geologically based, three-dimensional reservoir models that can be used to develop dynamic reservoir simulation and flow models. To effectively do this, the challenge is to integrate data on the primary depositional environment (facies, probable geometry, and susceptibility to diagenetic modification), the sequence stratigraphic framework, and the petrophysical characteristics of carbonates at multiple scales, utilizing a combination of core, wireline-log, 3D seismic data and the incorporation of both modern and ancient analogs. Examples from the Michigan Basin and other productive basins provide a means to review the controls on carbonate reservoir heterogeneity, ranging from the pore architecture scale to geometrical attributes of flow units at the reservoir-scale and to discuss how these parameters can be incorporated and integrated into the development of viable, petrophysically based reservoir models of carbonate reservoirs.

Selected References


Harris, P.M., and J. Ellis, 2010, Depositional facies patterns and resultant heterogeneity in carbonate sand reservoirs; insight from modern analogs: AAPG Annual meeting, unpaginated.


Qualman, H., G.M. Grammer, W. Harrison, III, and M. Pranter, 2009, 3-D interpretation of the sequence stratigraphy and reservoir property distribution in the Belle River Mills Silurian (Niagaran) reef, St. Claire County, MI, in D.G. Morse, (chair), Forging the future from the past; 2009 Eastern Section AAPG annual meeting: AAOG Eastern Section Meeting Abstracts, p. 48-49.


Wold, J.L., G.M. Grammer, and W.B. Harrison, 2008, Sequence stratigraphy and 3-D reservoir characterization of a Silurian (Niagaran) reef; Ray Reef Field, Macomb County, Michigan: AAPG Eastern Section Meeting abstracts, v. 49.
An Integrated Approach to the Characterization and Modeling of Carbonate Reservoirs

G. Michael Grammer

Chesapeake Energy Chair of Petroleum Geology
Boone Pickens School of Geology
Oklahoma State University
Geologically Constrained
Reservoir Characterization – Is it worth the effort?

“The use of oversimplified geological models based on data from a limited number of widely spaced wells is probably one of the most important reasons for the failures in predicting field performance.”

Damsleth et al.
JPT (April 1992)

Especially true in carbonates, which are typically very heterogeneous, both laterally and vertically at both exploration and production scales!!!
Integrated Reservoir Characterization

Wireline Logs

Core and Thin Sections

Analogs

Sequence Stratigraphy

Geologic Modeling

3-D Seismic

Sonic Velocity/K

Pore Architecture

- Carbonate rocks
- Compacted mud samples

Time-average equation
Woods equation (for suspension)
Theoretical maximum

1000
2000
3000
4000
5000
6000

12% 43%

2000 m/s
5000 m/s

Wireline Logs

Core and Thin Sections

Analogs

Sequence Stratigraphy

Geologic Modeling

3-D Seismic

Sonic Velocity/K

Pore Architecture

- Carbonate rocks
- Compacted mud samples

Time-average equation
Woods equation (for suspension)
Theoretical maximum
High-resolution Outcrop analysis and Sequence Stratigraphy

Grammer et al. (1996, 2002)
Sequence Stratigraphy for Reservoir Characterization

Modified from Weber (1997)

G = Grain-Dominated  P = Mixed Grain and Mud  M = Mud-Dominated
Importance of Combining Outcrop and Modern Analogs
Detailed Facies Mapping from Ground-truthed Satellite Images (ex. Exumas, GBB)
Stratigraphic and Flow Simulation Modeling

Water front moving away from injectors (green). Note flow constrained by vertical facies boundaries.

Courtesy of P.M. Harris
Reservoir Characterization – An Integrated Approach

- Interpretation of lithofacies and depositional environment
- Original porosity & permeability
  - modification potential
- Sequence stratigraphic framework
- Stacking patterns tied to wireline logs
- Reservoir geometry (lateral & vertical distribution)
- Pore network characterization & petrophysical effects
- Distribution of reservoir flow units
- Reservoir modeling

Data Input: Seismic (3-D), Wireline Logs, Cores, Cuttings, Modern and Ancient Analogs, Modeling
Example - Eagle Ford Shale Play

- Explain Lateral and Vertical Heterogeneity
- Predict Vertical Compartmentalization (Seq Strat in Deep Water CO3’s?)
Eagle Ford “Shale”
Vertical Stacking Patterns and Sequence Stratigraphic Framework

Idealized Facies Succession

1: Laminated Argillaceous Mudstone
2: Weakly Laminated Calcareous Foraminiferal Mudstone
3: Laminated Foraminiferal Wackestone
4: Bioturbated Skeletal Lime Wackestone
5: Laminated Inoceramid and Foraminiferal Wackestone to Packstone
6: Skeletal Packstone to Wackestone
7: Foraminiferal Packstone to Grainstone

Workman and Grammer (2013)
Eagle Ford: Reservoir Facies

- Laminated Foram Wkst (3-5% $\phi$ / 2-6 nD)
- Late transgressive- to early highstand- deposits near storm wave base.
- Light- to medium- grey
- Organic-rich
- Planktonic foram tests form mm-scaled traction laminae with erosive bases indicative of reworking by weak contour currents.

<table>
<thead>
<tr>
<th>Dominant Mineralogy</th>
<th>(Avg. %)</th>
<th>TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clays (n=27)</td>
<td>11.80</td>
<td></td>
</tr>
<tr>
<td>Quartz (n=27)</td>
<td>9.19</td>
<td></td>
</tr>
<tr>
<td>Calcite (n=27)</td>
<td>71.47</td>
<td></td>
</tr>
<tr>
<td>(n=12)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TOC
Workman and Grammer (2013)
Eagle Ford: Intra-formational Seal

- Foram Pkst/Grnst (~2% φ / 1-2 nD)
- Light grey & highly cyclic (m scale)
- Mid- to upper slope, latest highstand deposits
- Well lithified beds (3-10’s of cm thick) of planktonic foram tests.
- Brittle

<table>
<thead>
<tr>
<th>Dominant Mineralogy (Avg. %)</th>
<th>TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clays (n=15)</td>
<td>Quartz (n=15)</td>
</tr>
<tr>
<td>4.63</td>
<td>7.56</td>
</tr>
</tbody>
</table>

Workman and Grammer (2013)
4th Order HFS’s:

- Total of 39 HFS’s, shallowing-upward sequences

- Thickness related to structural setting.

- Influence of allocyclic and autocyclic processes.

- Use for the correlation and evaluation of the lateral and vertical variability and continuity of facies belts (potential reservoir units and seals).

Workman and Grammer (2013)
Example: Albion-Scipio Trend (HTD)

- Discovered in 1957
- Production: >147 MMBO, 260 BCF (A-S)
- 30 mi X 1 mi
- Developed on 20-acre spacing
- Trend development based primarily on structural sag mapping
- Lateral and Vertical Heterogeneity
Lateral Distribution of HTD in AlbionScipio
Burrowed Facies - Primary stratigraphic reservoir
HTD (Φ, K) distribution is controlled by primary fabric and depositional geometries (lateral) in addition to structural surfaces (vertical).
HTD (Φ, K) distribution is controlled by primary fabric and depositional geometries (lateral) in addition to structural surfaces (vertical).
Silurian (Niagaran) Reefs in the Michigan Basin

- Over 1000 pinnacle reefs discovered
- Good porosity and permeability in various facies but significant reservoir heterogeneity
- Regional Seal (A-2 Evaporite)
- The reef play is the most successful play in Michigan – production of 475 MMBO and 2.8 TCF of gas
- Ultimate recovery – 1 billion BOE from over 1,000 pinnacle reefs
- Gas storage
Regional Setting

- During the Niagaran the Michigan Basin was a shallow intracratonic sea measuring 155 mi (250 km) wide and up to 650 ft (200m) water depth at basin center.

- ~30 degrees south latitude

- Three 3rd order eustatic sea level changes in Niagaran time

- Three depositional zones:
  - Carbonate Platform
  - Carbonate “Ramp” with Pinnacle and Reef Complexes
  - Deep Basin
• Earlier focus was on models for reef growth and facies distribution

• Stacking patterns start to become recognizable in early models, but wasn’t focus of earlier studies

• Reservoirs characterized by significant lateral and vertical heterogeneity
Silurian Sea Level

Three eustatic sea level fluctuations occurred during the Niagaran (Wenlockian) and into the Ludlovian.

Modified from Ross & Ross, 1996
3-D Seismic over Niagara Reef (Northern Trend)

Toelle et al. (2009)
Reservoir Characterization of Niagaran Reefs

Gill (1973, 1977)
Modeling Workflow

Integrate Data from:

1. Wireline Logs from 94 wells
2. Facies data from 32 cores
3. Porosity/permeability from whole core analysis and minipermeameter
4. Sequence stratigraphic architecture (timelines)
<table>
<thead>
<tr>
<th>Facies Number</th>
<th>Depositional Features</th>
<th>Mudstone</th>
<th>Wackestone</th>
<th>Mud-Rich Packstone</th>
<th>Grain-Rich Packstone</th>
<th>Framestone</th>
<th>Grainstone</th>
<th>Boundstone</th>
<th>Relative Sea-Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>6B</td>
<td>TIDAL FLAT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Deep Platform</td>
</tr>
<tr>
<td>6A</td>
<td>TIDAL FLAT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Shallow Platform</td>
</tr>
<tr>
<td>5</td>
<td>LAGOON</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Restricted/Tidal Flat</td>
</tr>
<tr>
<td>4</td>
<td>CAPPING GRAINSTONE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>REEF</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2B</td>
<td>BIOHERM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2A</td>
<td>BIOHERM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1B</td>
<td>DEEP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1A</td>
<td>DEEP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Idealized Facies Succession from Core**

**Restricted Environments** -
- Cyanobacterial Mat Boundstones
- Brecciated, Cyanobacterial Mat Boundstone
- Burrowed, Peloidal Wackestones to Grainstones

**Higher-Energy, Shoals (Back Reef)** -
- Skeletal Grainstones

**Reef Core** –
- Coral/Stromatoporoid Framestone

**Muddy Bioherm** -
- Bryozoan/ Crinoidal Wackestone to Packstone
- Mudstone to Skeletal Grainstone with Stromatactis Texture

**Deeper-Water** -
- Burrowed, Mudstone to Peloidal Mud-rich Packstone
- Graptolite Mudstone to Wackestone
Sequence Stratigraphic Hierarchy in Niagaran Reefs (northern and southern trends)

Ritter and Grammer (2008)
Stratigraphic Control on Porosity and Permeability

- Increased $\phi$ & $k$
- Decreased $\phi$ & $k$
Sequence Boundaries – Ray Reef
(tie core to wireline logs and extrapolate)

Wold and Grammer (2008)
Sequence Framework – Ray Reef

• Skeletal Outline of the Model constrained by sequence boundaries

• Surfaces honor the geometry of the reef from reef crest to the off-reef position

• High Resolution porosity, permeability, and facies data incorporated into model
Algorithm for Modeling Surfaces (SGS)

Sequential Gaussian Simulation Algorithm

Model consists of three zones:
- 6.8 million 3-D cells per zone
- Cell size of 50 x 50 x 1 ft (x,y,z)
- 200 layers of data

Wold and Grammer (2008)
B - B’ Cross-Section

- Progradational vs. Aggradational Growth
- Windward vs. Leeward Margins
- Potential reservoir intervals along the windward margin of the reef complex.

Wold and Grammer (2008)
Characterization of Carbonate Pore Architecture and Relationship to Permeability
Carbonates have varying pore types that influence permeability.

Eberli, 2000
Velocity versus Porosity in Carbonates

![Graph showing the relationship between P-wave velocity (m/s) and porosity (%).](image)

- Black squares represent carbonate rocks.
- Red circles represent compacted mud samples.

### Theoretical Maximum
- 5000 m/s
- 43%

### Time-average equation

### Woods equation (for suspension)

### Porosity (%) vs. P-wave velocity (m/s)

- 2400 m/s
- 12%

Anselmetti and Eberli (1999)
Grammer et al. (2006)
Predicting Permeability from Sonic Velocity?

Core Plug Values

\[ \Phi = 10.59\% \]
\[ K = 66.5 \text{ mD} \]

Vp = 4866 m/s

Core Plug Values

\[ \Phi = 10.50\% \]
\[ K = 1.04 \text{ mD} \]

Vp = 6023 m/s

Thornton and Grammer (2010)
Pore Architecture tied to Petrophysical Properties – can we Predict Permeability???

1. Relate rock fabric to pore types by developing petrophysically significant facies

2. Relate pore architecture to pore connectivity (permeability) to determine reservoir quality

3. Use laboratory and log-measured sonic velocity to establish a first-order relationship between sonic velocity and pore type/pore network connectivity

4. Tie to Wireline Logs
Quantifying Pores: Digital Image Analysis

- ImagePro Plus
- Color-cube segmentation
- Can measure parameters for each pore
  - Area, length, width, roundness, perimeter
- Pore parameters (measures of pore architecture) are calculated
Image Analysis to characterize size, shape and distribution of pores in thin section

Thornton and Grammer (2010)
Average percent error between actual and predicted p-wave velocity = 5.31%

\[ V_P = 388.626 \gamma + 3.890 A_{\phi} - 85.650 \phi - 62.812 \frac{L}{W} - 270.858 \ln \frac{P}{A} + 5694.809 \]
Integrating porosity, P- and S-wave velocities, density and DIA parameters

\[
lnK = 3.906lnV_p + 2.263ln\Phi - 41.722ln\rho_g + 3.955lny - 0.926lnPOA \\
+ 1.005lnAR + 0.697lnV_s - 0.310lnDS - 7.013
\]

\[R^2 = 0.817\]
Summary – General Thoughts and Trends in Carbonate Reservoirs

1. Reservoir quality has a direct correlation to primary depositional facies.

2. Because of this, the predictability of reservoir distribution, both laterally and vertically, may be enhanced by the development of a sequence stratigraphic framework.

3. Porosity and permeability (i.e., reservoir quality) is a direct function of pore architecture, which again is often tied to primary depositional facies and/or position within a sequence stratigraphic framework.

4. Detailed characterization of pore architecture should lead to a better understanding of the 3-D distribution and connectivity of pores – image analysis and CT scans, along with laboratory-measured sonic velocity, may lend insight into the acoustic properties of different reservoir and non-reservoir facies.

5. Modern and ancient analogs may provide critical understanding of process, geometry and evolution of carbonate reservoirs.