Using Carbonate Mudrock Pore Architecture to Provide Insight into Porosity and Permeability Trends in Unconventional Carbonate Reservoirs: Examples from the Mid-Continent Mississippian Limestone*

Beth Vanden Berg¹ and G. Michael Grammer¹

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Editor’s note: Please refer to the following related articles by the authors and colleagues: Unconventional Carbonate Reservoir Characterization Using Sonic Velocity and Characterization of Pore Architecture: An Example From the Mid-Continent Mississippian Limestone,” Search and Discovery Article #50979 (2014) and “Combining Pore Architecture and Sonic Velocity Response to Predict Reservoir Quality: An Example from a Mid-Continent Mississippian Carbonate,” Search and Discovery Article #10547 (2013).

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¹Boone Pickens School of Geology, Oklahoma State University, Stillwater, Oklahoma (beth.vanden_berg@okstate.edu)

Abstract

The Mid-Continent Mississippian Limestone is an unconventional carbonate reservoir with a complex depositional and diagenetic history. Oil and gas have been produced from vertical wells for over 50 years, but recent horizontal activity in low porosity, low permeability zones have illustrated how crucial it is to understand the petrophysical characteristics to better target producing intervals. Because of the wide variability and complexity of pore systems in carbonate reservoirs, simple porosity and permeability transforms developed for siliciclastic reservoirs often provide erroneous results for carbonates. Recent research has only started to identify the complexity of the pore architecture observed in carbonate mudrocks and the applicability of conventional carbonate pore relationships to describing carbonate mudrock systems.

The current study shows examples of how fundamental relationships between pore shape, porosity, permeability, and acoustic response differ in carbonate mudrocks with micro- to pico-porosity (<62μm diameter) compared to conventional carbonates with primarily macropore (256-4mm diameter) systems. Quantitative data show positive correlations exist between porosity and permeability, but negative to no correlation between pore shape and associated porosity and permeability. In addition, there is a significant shift in the acoustic response relative to values calculated from empirically derived equations for porosity in
carbonate mudrocks. Deviations from quantitative data trends are explained through qualitative observations of the pore types and differing internal pore geometries. Visual observations of the pore morphology show how post-depositional cementation can increase the complexity of the internal pore network by sub-dividing pores. When correlated to facies, the internal pore geometry helps explain deviations to general relationships between basic quantitative pore architecture measurements, porosity, and permeability. Although there is an added level of complexity in the pore architecture of carbonate mudrocks, there are fundamental relationships that exist between the pore architecture, pore shape, porosity, permeability, acoustic response, facies, and sequence stratigraphic framework with variable levels of predictability that, when used as an integrated data set, can be used to enhance the predictability of key petrophysical properties within these types of reservoir systems.

References Cited


Using Carbonate Mudrock Pore Architecture to provide insight into porosity and permeability trends in Unconventional Carbonate Reservoirs: examples from the Mid-Continent Mississippian Limestone

Beth Vanden Berg
G. Michael Grammer
Integrated Reservoir Characterization

Wireline Logs

Core and Thin Sections

Analogs

Sequence Stratigraphy

Geologic Modeling

3-D Seismic

Sonic Velocity/K

Pore Architecture

Grammer, 2013
Predicting Reservoir Permeability

Total Porosity

- Acoustic Response
- Pore Architecture
- Primary & Secondary Porosity
- Permeability
Conventional Carbonate Acoustic Response

Figure Modified from Eberli et al. 2003
and used with permission from G. Eberli
Predictable Acoustic Response

Figure Modified from Eberli et al. 2003
Acoustic Response Relationship to Permeability

From Anselmetti and Eberli 1999
Acoustic Response Relationship to Permeability

From Anselmetti and Eberli 1999
Acoustic Response Relationship to Permeability

Anselmetti and Eberli 1999
Qualitative Permeability from Velocity

Modified from Anselmetti and Eberli 1999
Digital Image Analysis: Link to quantitative prediction

Color Segmentation to identify the pore space

Key Parameters:
- Length
- Width
- Perimeter (P)
- Area (A) [Pore Size]
- Perimeter/Area (P/A)
- Dominant Pore Size
- Pore Shape (γ)

Figure Thornton and Grammer 2012
Pore Architecture: Pore Size

\[
y = -0.00068x + 2.9 \\
y = -0.0012x + 3.6 \\
y = -0.0033x + 5
\]

**Figure and images used with permission from G. Eberli**
Quantitative Permeability Prediction

Quantified acoustic response
+Quantified pore architecture
+Quantified macro- and microporosity

Predictable Permeability

Figure from Anselmetti et al. 1998

Figure from Baechle et al. 2004
Quantitative Permeability Prediction

\[ \ln K = 3.906 \ln V_p + 2.263 \ln \Phi - 41.722 \ln \rho_b + 3.955 \ln y - 0.926 \ln POA + 1.005 \ln AR + 0.697 \ln V_g - 0.310 \ln DS - 7.013 \]

\[ R^2 = 0.817 \]
Mid-Continent “Mississippi Limestone” Oil and Gas Production History

- Production began in the early 1900’s
- Reservoir intervals vary from limestone, or dolomite-rich intervals to tripolitic, nodular and bedded chert intervals
- Horizontal drilling has revitalized production, but highlighted the need to better understand the reservoir architecture

Figure modified from Harris (1975)
Carbonate Mudrock porosity and permeability range

![Graph showing the distribution of porosity and permeability for Carbonate Mudrock. The x-axis represents porosity (%) ranging from 0 to 10, and the y-axis represents permeability (mD) ranging from 0.0001 to 1.0000. The data points are scattered across the graph, indicating a wide range of permeability values for the given porosity levels.](image-url)
Carbonate mudrock velocity – porosity relationship

![Graph showing the relationship between carbonate mudrock velocity and porosity. The graph has a scatter plot with data points indicating a general trend where velocity decreases as porosity increases. The graph has velocity values ranging from 4500 to 6500 m/sec and porosity values ranging from 0 to 8%. Key points include 5000 m/sec velocity at 1% porosity, 5900 m/sec velocity at 7% porosity.](image-url)
Unconventional carbonate mudrock vs. conventional carbonate velocity response
Pore Architecture: Thin Section Photomicrographs

Pore Size Classification

Loucks et al. (2012)  Rouquerol et al. (1994)

1 m
- 256 mm
- Macropore

1 cm
- <4 mm
- Mesopore

1 mm
- <62.5 μm
- Micropore

1 μm
- <1 μm
- Nanopore

1 nm
- <1 nm
- Picopore

Methane = 0.38 nm
Water = 0.28 nm
Basic Pore Types Observed

Interparticle

Interparticle/Matrix

Shrinkage

Intraparticle

Scale:
- 1 μm
- 200 nm
- 0.5 μm

Legend:
- ‘Matrix’ surrounding pores
- Pore filling clays
- Pore/void space
- Pore filling calcite
Pore Architecture: Pore types and size
SEM Photomicrographs

Interparticle pore wall. Pore is filled with kaolinite.

Interparticle pore with smectite/illite/montmorillonite coating pore

Loucks et al., 2012
Pore Architecture: Pore types and size

SEM Photomicrographs

Macropore

Mesopore

Micropore

Nanopore

Picopore

Interparticle pores

Interparticle pore with internal crystal growth

Calcite Crystals

Clay

Calcite

Loucks et al., 2012
Pore Architecture: Pore types and size
SEM Photomicrographs

- **Macropore**: >256 mm
- **Mesopore**: 4 mm - 62.5 μm
- **Micropore**: <1 mm
- **Nanopore**: <1 nm
- **Picopore**: <0.38 nm

Matrix pores: 500 nm
Interparticle/Matrix pores: 500 nm

Loucks et al., 2012
Pore Architecture: Pore types and size
SEM Photomicrographs

Loucks et al., 2012
Pore Architecture: Pore distribution
SEM Photomicrographs – Ion milled surface

Intergranular pore network.

Concentration of Intergranular pores

Matrix pores.

30µm

10µm

500 nm
Pore Architecture Data Summary

Analysis completed: Osage County core, North-Central Oklahoma
- 277 feet from 3147.10 – 3424.10ft bgs.
- 305 photomicrographs analyzed using digital image analysis
  • 47 thin sections, 420 photomicrographs, 175 images analyzed for DIA
  • 15 samples, 430 photomicrographs, 130 SEM images

Image analysis summary:
- Pores Identified: 140,330
- Image analysis porosity: 23-65% (biased samples)
- Length: Nanopore to Mesopore scale
- Width: Picopore to Micropore scale
- Shape: slightly elongate

Sonic velocity response:
- 80 samples: velocity response, dry
- 34 samples: velocity response, saturated in 35ppt NaCl brine solution
- Vp: 4852-6333
- Vs: 2768-3700

XRD analysis: 22 samples
Digital Image Analysis:

Pore size distribution

Perimeter/Area

Length (µm)

Macropore

Mesopore

Micropore

Nanopore

Picopore

Loucks et al. (2012)

Methane = 0.35 nm
Water = 0.28 nm
Digital Image Analysis: Pore size distribution (thin section)

- **Perimeter/Area vs. Length (μm)**

- **Classification of Pores**:
  - Macropore
  - Mesopore
  - Micropore
  - Nanopore
  - Picopore

- **Dimensions**:
  - Water: 0.28 nm
  - Methane: 0.38 nm

- **Reference**: Loucks et al. (2012)
Pore architecture:
Pore size distribution (ESEM images)

Loucks et al. (2012)

- Macropore: >256 mm
- Mesopore: 256 mm to 1 mm
- Micropore: 1 mm to 1 μm
- Nanopore: 1 μm to 1 nm
- Picopore: <1 nm

Water = 0.28 nm
Methane = 0.38 nm
Pore architecture:
Digital image analysis (thin section & ESEM images)

Loucks et al. (2012)

Methane = 0.38 nm
Water = 0.28 nm
**Pore Architecture:**

Thin section vs. ESEM Pore Size Distribution

- **Dominant Pore Size:** micro- to nanopore range.
- **Bi-modal distribution** between micro- and nanopores

### Thin Section Data: Average Percentage of Pores Per Size Category

(48 samples, 175 photos)

<table>
<thead>
<tr>
<th>Pore Type</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nanopores (0.001 μm - 1.0μm)</td>
<td>39%</td>
</tr>
<tr>
<td>Micropores (1.0 - 62.5 μm)</td>
<td>60%</td>
</tr>
<tr>
<td>Mesopores (62.5μm - 4 mm)</td>
<td>1%</td>
</tr>
</tbody>
</table>

### Pore Size Distribution

<table>
<thead>
<tr>
<th>Pore Type</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nanopores (0.001 μm - 1.0μm)</td>
<td>65%</td>
</tr>
<tr>
<td>Micropores (1.0 - 62.5 μm)</td>
<td>35%</td>
</tr>
<tr>
<td>Mesopores (62.5μm - 4 mm)</td>
<td>0.1%</td>
</tr>
<tr>
<td>Macropores (&gt;4mm)</td>
<td>0%</td>
</tr>
</tbody>
</table>
Pore Architecture:
ESEM Detailed Pore Size Distribution

- Dominant Pore Size: micro- to nanopore range.
- Bi-modal distribution within the micro- and nanopores
Facies Characterization

- **Facies 1**: Spiculitic Mudstone to Wackestone
- **Facies 2**: Mudstone to Skeletal Wackestone
- **Facies 3**: Peloidal-Skeletal-Ooid-Wackestone
- **Facies 4**: Skeletal-Peloidal Wackestone
- **Facies 5**: Wackestone
- **Facies 6**: Skeletal-Peloidal Wackestone
- **Facies 7**: Mudstone to Skeletal Wackestone
Predicting key petrophysical properties: Porosity and permeability, classified by facies.
Predicting key petrophysical properties: Porosity and permeability, classified by facies

\[ y = 0.0006x + 0.0027 \]
\[ R^2 = 0.2005 \]

\[ y = 0.0003x + 0.0017 \]
\[ R^2 = 0.0239 \]
Predicting key petrophysical properties: Porosity and permeability, classified by facies
Pore Architecture:
Pore shape relationship to porosity

Inverse relationship, except in facies 1 and 2

**Pore Shape (1 = perfect sphere):**

\[
\gamma = \frac{P}{2\sqrt{\pi A}}
\]

- \( P \) = perimeter
- \( A \) = Area

Eqn. from (Anselmetti et al. 1998)
Pore Architecture:
Pore shape relationship to permeability

Positive relationship, skewed perspective from 2 data points.

Outlier points removed shows no clear relationship.
Sequence Stratigraphy: Predicting Porosity and Permeability

Two unique correlations between porosity and permeability associated with the sequence stratigraphic framework

Correlation within the 3rd order transgressive and regressive sequences

Exceptions:
Post-deposition alteration
Regressive Phase:
Highest porosity & permeability

Within the regressive phase and at the top of 5\textsuperscript{th} order cycle.

Exceptions:
Extensive post-deposition silicification
Sequence Stratigraphy: Predicting Porosity and Permeability

**Transgressive Phase:**
Highest porosity & permeability

Within the transgressive phase and at the top of 5th order transgressive cycles.

*Exceptions:*
Post-deposition, hydrothermal brecciation.
Conclusions

• Sonic velocity data:
  – Significant shift in the acoustic response relative to values calculated from empirically derived equations for porosity in carbonate mudrocks
  – Data boundaries are the Wyllie Time Average equation and the Woods equation

• Image analysis data:
  – Post-depositional cementation can increase the complexity of the internal pore network by sub-dividing pores
  – Pore architecture correlation to facies: the internal pore geometry helps explain deviations to general relationships between basic quantitative pore architecture measurements, porosity, and permeability
  – Positive correlations between porosity and permeability
  – No clear relationship between pore shape and associated porosity or permeability

• Sequence stratigraphic framework:
  – Most predictable to locate highest porosity and permeability intervals

• The fundamental relationships that exist in conventional carbonates are not well defined in carbonate mudrocks

• An integrated data set enhances the predictability of key petrophysical properties within these types of reservoir systems
Continued Work

• Expand the data set using 4 Mid-Continent Mississippian Limestone cores
  Payne, County, OK; Logan County, OK; Reno County, Kansas
  – Sonic velocity response
  – Digital image analysis from thin section and ESEM photomicrograph
  – Qualitative and quantitative characterization of pore architecture
  – Identify relationships between sonic velocity, porosity, permeability, and pore architecture
  – Define multivariate algorithm to quantitatively predict permeability
  – Relate predictable relationships to sequence stratigraphic framework to reveal predictability of petrophysical properties

• CT-scanning to view permeability in 3-D
  – Relate 3-D images to 2-D data