Stratigraphic and Facies Control on Porosity and Pore Types of Mississippian Limestone and Chert Reservoirs: An Example from North-Central Oklahoma*

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Abstract

Mississippian limestone and chert reservoirs in north-central Oklahoma include lithofacies that form upward-shallowing cycles that commonly transition from more mud- to grain-dominated and are typically capped by deposits indicative of subaerial exposure. Mississippian-age rocks in the study area consist of 17 lithofacies that were deposited on a distally steepened ramp. Vertical lithofacies stacking reveals 28 higher order cycles, and cycle thickness varies from 1 ft (0.3 m) to 100 ft (30.5 m). Most cycles (22 of 28) are asymmetric, regressive cycles with an average thickness of 21 ft (6.4 m).

Digital-image analysis (DIA) illustrates that most lithofacies exhibit nanopores (1 nm² < A < 62.5 μm²) and micropores (62.5 μm² < A < 500 μm²) with five major pore types including interparticle, intraparticle, vuggy, channel, and microfracture. DIA-porosity quantification yields a reliable result to predict porosity with somewhat higher values as compare to core-measured porosity. The discrepancy is likely due to several factors including the internal pore network, diagenetic alteration, unconnected microfracture network, and isolated pores. The combination of thickness and high reservoir quality make most grain-dominated lithofacies the most prospective. Moreover, reservoirs with higher porosity and permeability are commonly associated with the upper intervals of higher order regressive cycles.

References Cited

Blakey, 2013, Paleography Map of North America during Early Mississippian (Kinderhookian): Colorado Plateau Geosystems, Phoenix, AZ.


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Reservoir Characterization and Modeling Laboratory

University of Oklahoma
Mid-Continental “Mississippian Limestone and Chert Reservoirs” Play Potential
Integrated Reservoir Characterization

Wireline Logs

Core and Thin Sections

Pore Architecture

Depositional Model

Sequence Stratigraphy
Paleogeography and Stratigraphy

Early Mississippian (~345Ma)

Modified After Mazzullo 2011, Mazzullo et al., 2011, and Mazzullo et al., 2016
Core Location and Data

- Devon Energy Frieouf 1-7 SWD
- Anadarko Ramp
- Thickness 528 ft (~161m)
- Depth 4780 ft SS (~1457 m)

- Wireline logs
- Porosity and Permeability
- 57 Thin Sections
- ~23500 SEM photomicrographs
St. Joe Group
- GR: 60 – 100 GAPI
- 22 ft (~6.7 m)
- Light color mudstone to shaly mudstone

Kinderhook Shale
- GR: 100 – 190 GAPI
- 38 ft (~12 m)
- Structureless shale
Lithofacies Characterization - Meramecian

Cowley Formation
- GR: 15 – 50 GAPI
- 268 ft (~ 81 m)
- Glauconitic sandstone at the base
- Subaerial exposure atop of the Cowley Formation
Lithofacies Characterization - Meramecian

Undivided Meramecian

1. Chert breccia in greenish shale matrix
2. Structureless skeletal-grainstone
3. Chert breccia
4. Skeletal mudstone-wackestone
5. Bioturbated skeletal-peloidal packstone-grainstone
6. Skeletal-peloidal packstone-grainstone
7. Splotchy packstone-grainstone
8. Nodular packstone-grainstone
9. Bedded skeletal packstone-grainstone
10. Bioturbated mudstone-wackestone

Depth

- 4760
- 4770
- 4780
- 4790
- 4800
- 4810
- 4820
- 4830
- 4840
- 4850
- 4860
- 4870
- 4880
- 4890
- 4900
- 4910
- 4920
- 4930
- 4940
- 4950
- 4960
- 4970
- 4980
- 4990
- 5000
- 5010
- 5020
- 5030
- 5040
- 5050
- 5060
- 5070
- 5080
- 5090
- 5100
- 5110
- 5120
- 5130
- 5140
- 5150
- 5160
- 5170
- 5180
- 5190
- 5200
- 5210
- 5220
- 5230
- 5240
- 5250
- 5260
- 5270
- 5280
- 5290
- 5300
- 5310

RCML
Spatial Distribution of Lithofacies

1. Chert breccia in greenish shale matrix
2. Skeletal grainstone
3. Chert breccia
4. Skeletal mudstone-wackestone
5. Bioturbated skeletal peloidal packstone-grainstone
6. Skeletal peloidal packstone-grainstone
7. Splotchy packstone-grainstone
8. Nodular packstone-grainstone
9. Bedded skeletal peloidal packstone-grainstone
10. Bioturbated mudstone-wackestone
11. Brecciated spiculitic mudstone-wackestone
12. Intraclast mudstone-wackestone
13. Spiculitic mudstone-wackestone
14. Shale
15. Argillaceous spiculitic mudstone-wackestone
16. Glauconitic sandstone
17. Shaly mudstone

1 - 10: Undivided Meramecian
11 - 16: Cowley Formation
14* and 17: Kinderhook
Mississippian – Sequence Stratigraphy

- 32 relatively high frequency cycles
- 1 – 100 ft (0.3 – 30.5m)
- 24 of 32 = asymmetric
- regressive > transgressive
- Kinderhook = 5 cycles, avg thickness 12 ft
- Cowley = 12 cycles, thickness > 60 ft
- Undivided Meramecian = 15 cycles, avg thickness 13 ft

Idealized vertical lithofacies succession (Meramecian):

- Exposure
  - Skeletal Grainstone
  - Bedded Skeletal Peloidal Packstone-Grainstone
  - Bioturbated Skeletal Peloidal Packstone-Grainstone
  - Bioturbated Mudstone-Wackestone
  - Spiculitic Mudstone-Wackestone
  - Argillaceous Spiculitic Mudstone-Wackestone
  - Glauconitic Sandstone

- 32 relatively high frequency cycles
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- 24 of 32 = asymmetric
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Quantifying Pores – Digital Image Analysis

Modified after Loucks et al., 2012

Photomicrograph acquisition

Segmentation

Pore extraction and measurement

\[
\text{Circularity} = \frac{4\pi A}{P^2}
\]

<table>
<thead>
<tr>
<th>Size</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m</td>
<td>Megapore</td>
<td>Solid/Matrix</td>
</tr>
<tr>
<td>1 cm</td>
<td>Macropore</td>
<td>Solid/Matrix</td>
</tr>
<tr>
<td>1 mm</td>
<td>&lt; 564 μm</td>
<td>Nano pore (1 mm &lt; ECR &lt; 12.5 μm)</td>
</tr>
<tr>
<td>1 mm</td>
<td>Mesopore</td>
<td>Nano pore (1 mm &lt; ECR &lt; 12.5 μm)</td>
</tr>
<tr>
<td>1 μm</td>
<td>&lt; 12.5 μm</td>
<td>Micro pore (5 μm &lt; ECR &lt; 12.5 μm)</td>
</tr>
<tr>
<td>1 μm</td>
<td>Micropore</td>
<td>Micro pore (5 μm &lt; ECR &lt; 12.5 μm)</td>
</tr>
<tr>
<td>1 nm</td>
<td>&lt; 1 nm</td>
<td>Nano pore (1 mm &lt; ECR &lt; 12.5 μm)</td>
</tr>
<tr>
<td>1 nm</td>
<td>Picopore</td>
<td>Nano pore (1 mm &lt; ECR &lt; 12.5 μm)</td>
</tr>
</tbody>
</table>

Modified after Loucks et al., 2012
# Pore Types

## Matrix Pores

**Pores between or within particles**

<table>
<thead>
<tr>
<th>Intraparticle Pores</th>
<th>Interparticle Pores</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>A</strong> Intercrystalline pores within pyrite framboid</td>
<td><strong>B</strong> Crystal-form pores</td>
</tr>
<tr>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>C</strong> Particle-rim pores</td>
<td><strong>D</strong> Moldic pores after crystals</td>
</tr>
<tr>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>E</strong> Pores within crystals</td>
<td><strong>F</strong> Microfractures within crystals</td>
</tr>
</tbody>
</table>

## Non Fabric Selective Pore not controlled by any particles

| ![Image](image7.png) | ![Image](image8.png) |
| **G** Pores between crystals | **H** Pores between grains |
| ![Image](image9.png) | ![Image](image10.png) |
| **I** Vuggy | **J** Channel |
| ![Image](image11.png) | ![Image](image12.png) |
| **K** Microfracture |

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*Not to Scale*
Pore Types

Particle-rim pores

20 μm
DIA: Quantitative Analysis - Porosity

R² = 0.82

- Sampling bias
- Grayscale/color threshold subjectivity
- Grain plucking
- $\phi_{\text{tot}} >\!< \phi_{\text{eff}}$

Lithofacies: 1 2 3 4 5 6 7 8 9 10 13 15
Lithofacies: 1 2 3 4 5 6 7 8 9 10 13 15
DIA: Quantitative Analysis – Pore Size Distribution

- $\phi_{\text{nanopore}} = 13.24\%$
- $\phi_{\text{micropore}} = 2.73\%$
- $\phi_{\text{mesopore}} = 7.96\%$
- $\phi_{\text{macropore}} = 0.26\%$
- $\phi_{\text{DIA}} = 23.94\%$
DIA : Quantitative Analysis – Pore Size Distribution

\[ \phi_{\text{nanopore}} = 13.24\% \]

\[ \phi_{\text{mesopore}} = 7.96\% \]

\[ \phi_{\text{nanopore}} = 3.81\% \]

\[ \phi_{\text{mesopore}} = 0.24\% \]
DIA: Pore Size Distribution
Devon Energy Frieouf 1-7 SWD:

- Predictable correlation with sequence-stratigraphic framework, porosity, and permeability.
- Best reservoir quality at the top of high-order regressive cycles.
Conclusions

• Pore Architecture Characterization - DIA:
  • DIA porosity vs. Laboratory Measured Porosity - positive
  • Pore shape vs. porosity and permeability - indeterminate
  • PSD: fine-grained vs. coarse-grained dominated lithofacies

• Reservoir quality – regressive cycles

• Sequence-stratigraphic analysis – best reservoir quality intervals
Acknowledgments
Thank You