Unconventional Carbonate Reservoir Characterization Using Sonic Velocity and Characterization of Pore Architecture: An Example From the Mid-Continent Mississippian Limestone

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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 makes it crucial to understand the petrophysical characteristics to target producing intervals. Sonic velocity, or acoustic response, in carbonate rocks has predictable trends based on porosity, pore architecture, and location within a sequence stratigraphic framework. Previous work has shown that quantification of primary reservoir pore types (macro- vs. micro-) may increase the predictability of reservoir permeability within a basin. Facies are characterized by a hierarchy of shoaling-upward packages defined by planar-beded mudstone at the base, followed by bioturbated, very fine- to fine-grain sand size crinoid-brachiopod skeletal wackestones, and massively bedded, peloidal-skeletal wackestone to grainstones at the top. A sequence stratigraphic hierarchy of shoaling-upward cycles are observed in core and wireline logs at third-, fourth-, and fifth-order scale. Acoustic response (compressional and shear wave) for a sub-set of samples from the Mississippian Limestone varies from 6500 to 5000m/sec (Vp) and 4500-2500m/sec (Vs). Overall trends of the data confirm observations from previous studies regarding the expected range of acoustic response for low-porosity, low-permeability carbonates. Porosity in the horizontal direction, in the current data set, ranges from 0.5-7%, although locally, porosity values may be as high as 20%. Pore diameter ranges in size from the mesopore (4mm-62.5 μm) to nanopore (1μm-1nm) size, with the majority of the porosity in the micro- to nanopore scale. Pores viewed with SEM show that the largest pores are mostly oblong- to oval-shaped intercrystalline to vuggy mesopores, with a diameter of 100μm x 25μm, whereas the smallest are circular-shaped, intercrystalline to vuggy nanopores, with diameters of 5-10μm and 50-100nm pore throats. Petrophysical analyses have been integrated into high-resolution sequence stratigraphic analyses of core and outcrops from Oklahoma, Missouri, and Arkansas. Sonic velocity, coupled with characterization of macro- to nanoscale pore architecture, wireline logs and high-resolution sequence stratigraphic analyses, shows promise of predicting both key reservoir facies and key producing intervals within an unconventional carbonate reservoir.
References Cited


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Integrate Reservoir Characterization

- Wireline Logs
- Core and Thin Sections
- Analogs
- Sequence Stratigraphy
- Geologic Modeling
- 3-D Seismic
- Sonic Velocity/K

Grammer, 2013

- Carbonate rocks
- Compacted mud samples
- Time-average equation
- Woods equation (for suspension)
- Theoretical maximum
Porosity and Permeability Relationships

Total Porosity

Acoustic Response

Acoustic Response

Primary & Secondary Porosity

Pore Architecture

Permeability
Velocity – Porosity Relationship in Carbonates

Modified from Eberli et al. 2003
Velocity - Pore Type Relationship

Anselmetti and Eberli 1999
Velocity Correlation to Pore Type

From Anselmetti and Eberli 1999

- microporosity
- interpart./crystalline por.
- densely cemented, low porous
- moldic porosity
- moldic porosity
- intraframe porosity

Time Average Equation for Dolomite

Time Average Equation for Calcite
Velocity – Permeability Relationship

Modified from Anselmetti and Eberli 1999
Digital Image Analysis and Permeability Prediction

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

Predictable Permeability

Weger et al. 2004
Mississippian Limestone Reservoir Data Location Map

Outcrop ⭐
Public Cores ⬤
Consortium Cores ●
Mudrock Pore Classification

Modified from Loucks et al. 2012

\[ \phi = 9\% \]
\[ k = 0.02 \text{ mD} \]
Pore Architecture:
Thin Section Photomicrographs

\[
\phi = 3.01\% \\
k = 0.0216 \text{ mD}
\]

\[
\phi = 19.96\% \\
k = 1.49 \text{ mD}
\]

\[
\phi = 3.23\% \\
k = 0.0134 \text{ mD}
\]

\[
\phi = 2.5\% \\
k = 0.0026 \text{ mD}
\]
Pore Architecture:
Thin-Section Photomicrographs

Intercrystalline, Vuggy, Pin-point

$\phi = 2.5\%$
$k = 0.0026 \text{ mD}$
$\text{DIA } \phi = 3.5\%$
Total porosity over-estimated
Pore Architecture
SEM Photomicrographs – Core #1

Vuggy, Dissolution, Intercrystalline Pores
\( \phi = 19.96\% \)  
\( k = 1.49 \text{ mD} \)

Loucks et al., 2012
Pore Architecture
SEM Photomicrographs – Core #1

Loucks et al., 2012
Pore Architecture
SEM Photomicrographs – Core #1

Loucks et al., 2012

Intercrystalline, Vuggy
\( \phi = 4.42\% \)
\( k = 0.004 \) mD
98% Microporosity

Intercrystalline, Vuggy
\( \phi = 5.23\% \)
\( k = 0.008 \) mD
98% Microporosity
Pore Architecture
SEM Photomicrographs – Core #2

Loucks et al., 2012
Pore Size, Porosity, and Permeability Relationship

-- Larger pores ≠ greater permeability
-- Smaller pores can have greater connectivity
Porosity and Permeability (1” Plugs)

Data from 4 cores
N = 423
Velocity – Porosity Relationship in Carbonates

Modified from Eberli et al. 2003
Velocity – Porosity Relationship in Carbonate Mudrocks

**Velocity (m/sec)** vs. **Porosity %**

- **Mississippian Core #1**
- **Mississippian Core #2**

Key Points:
- 5200 m/s at 1%
- 5600 m/s at 5.5%
- 6600 m/s at 5.5%
Velocity – Porosity Relationship Classified by Primary Pore Type

![Graph showing the relationship between velocity and porosity. The graph includes a trend line with an R² value of 0.4029.](image-url)

- **Velocity (m/sec)**
- **Porosity (%)**

Interparticle Porosity
Macropore vs. Nanopore Velocity – Porosity Relationship

- Macropore Carbonates
- Mississippian Core #1
- Mississippian Core #2
Macropore vs. Nanopore Velocity – Porosity Relationship

- Macropore Carbonates
- Mississippian Core #1
- Mississippian Core #2

*Velocity (m/sec)*

*Porosity*

- Time Average Equation
- Woods Equation
- Theoretical Maximum
Digital Image Analysis: Pore Size

Pore Length/Width:
- Most Pores are <200µm x 20µm
- Class size: Mesopore to Nanopore
  - Most: Micro- to Nanopore

Average Pore Size

Pore Size

Width (µm) vs. Length (µm)

Core 1
Core 2
Digital Image Analysis: Pore Shape and Pore-Size Distribution

Macro- and Microporosity Contribution:
10% Macroporosity
90% Meso-, Micro- and Nanoporosity

Pore Shape (1 = perfect sphere):

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

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

Eqn. from (Anselmetti et al. 1998)

Geometry: Oval to oblong

Greater irregularity correlates with greater connectivity (permeability) in macropore systems

Mesopore (4mm-62.5μm)
Micropore (62.5μm - 1μm)
Digital Image Analysis: Accuracy of Porosity Prediction

Porosity Prediction

DIA Estimated Porosity

Laboratory Porosity

N=30
Preliminary Conclusions

• Pores in carbonate mudrocks are meso- to nanoscale size but primarily micro- to nanoscale size.
• Sonic velocity response has a predictable relationship to porosity in carbonate mudrocks, with a relationship similar to what is observed in carbonates with predominantly macropore systems.
• Current data indicates carbonate mudrock sonic velocity response is less than the velocity predicted by the time average equation.
• Based on porosity prediction from DIA, permeability prediction is possible with multivariate statistics.
Continued Research

• Additional sonic velocity response from core and outcrop samples.
• Argon milling coupled with SEM and digital image analysis to characterize the pore architecture.
• High resolution CT-scans to view the pore architecture in 3-D.
• Correlate porosity, permeability and acoustic response to high-resolution sequence stratigraphic analysis of core and outcrops in Northern Oklahoma, Southern Kansas, Arkansas and Missouri.
• Create a static 3-D model to test the predictability of petrophysical properties in carbonate mudrocks.
Acknowledgement

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Questions?