Quick-Look Technique for Quantifying Shale Distribution Types using Total Porosity versus Shale Volume Crossplots

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GCAGS Explore & Discover Article #00236*
Posted October 30, 2017.

*Article based on an extended abstract published in the GCAGS Transactions (see footnote reference below), which is available as part of the entire 2017 GCAGS Transactions volume via the GCAGS Bookstore at the Bureau of Economic Geology (www.beg.utexas.edu) or as an individual document via AAPG Datapages, Inc. (www.datapages.com), and delivered as an oral presentation at the 67th Annual GCAGS Convention and 64th Annual GCSSEPM Meeting in San Antonio, Texas, November 1–3, 2017.

EXTENDED ABSTRACT

Shale distribution in a sandstone reservoir can be broadly described in terms of three components: shale laminations interlayered within the overall sandstone interval, dispersed shale within the overall sandstone pore network, and structural shale comprised of sand-sized particles of shale composition (e.g., Thomas and Stieber, 1975; Juhasz, 1986) (Fig. 1). Total porosity versus shale volume crossplots offer a tool for quantifying shale distribution components (Fig. 2). We expand upon previous work by describing a full three-component equation of total porosity based on the individual partial porosity contributions of each potential component—we plan to publish the full mathematical derivations in a separate publication and instead show here graphical representations of analysis. Due primarily to limitations of traditional triple-combination log data, previous studies focused on two-component models (either laminar-dispersed [Fig. 3] or laminar-structural [Fig. 4]), assuming the third component is entirely absent, and we ourselves describe an additional two-component model (dispersed-structural) [Fig. 5], which appears to be an especially relevant model in the cleanest reservoirs. Because the dispersed shale component plays a critical role in calculating effective sandstone porosity, a crucial parametric of reservoir quality, we considered the influence on dispersed shale volumetric calculations from two-component models when considering the potential presence of all three components in a reservoir sandstone. Importantly, we found that considering the potential occurrence of the third component in the previous dispersed-laminar model, likely underestimated dispersed shale volume and therefore overestimated effective sandstone porosity—an optimistic rather than conservative result (Fig. 9). Rather, our methodology constrains the actual range in dispersed shale volume and thus the range in effective porosity when using triple-combination log data. Additional datasets (e.g., 3D resistivity, core, image logs, etc.) can help more fully quanti-

fy the shale distribution.

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Overview

- INTRODUCTION
- PREVIOUS METHODOLOGY
- PROPOSED METHODOLOGY
- APPLICATION OF PROPOSED METHODOLOGY
- FUTURE RECOMMENDATIONS
- CONCLUSIONS

- Shale Distribution Types
Overview

- INTRODUCTION
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- Total Porosity versus Shale Volume Distribution Models
- Did not consider Dispersed-Structural Model, or Three-Type Distribution Model
Overview

• INTRODUCTION
  • PREVIOUS METHODOLOGY
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  • APPLICATION OF PROPOSED METHODOLOGY
  • FUTURE RECOMMENDATIONS
  • CONCLUSIONS

• Dispersed-Structural Model
• Three-Type Distribution Model
Overview

- Case Studies

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• $\phi_D$ vs. $\phi_N$ and $\phi_{\text{effective}}$ vs. $V_{\text{sh}}$
• Models
• Alternative Techniques
Overview

• We believe the previous methodologies are flawed.
• These 2 type distribution models may not fully describe the system, and represent the most optimistic scenario in terms of reservoir quality.
Shale Distribution Types

Clean Sandstone  Laminar Shale  Dispersed Shale  Structural Shale
Thomas and Stieber (1975) introduced the concept of shale distribution within a sand as dispersed, laminar, and structural, or any combination of the three. Simplified the quantification by assuming the amount of structural shale is too small to be significant, therefore ignoring it all together.
Juhasz (1986) built upon the work of Thomas and Steiber (1975) and acknowledged the potential implications of structural shale.

- Expanded methodology to include mixture of laminar and structural shale.
Proposed Methodology

- Previous deterministic methodologies did not consider the possibility of a Dispersed-Structural Distribution, or a Three-Type Distribution.
- Aquino-López et al. (2016) used a parametric inversion process with three homogenization levels to constrain the three distribution types—homogenization level 1 is the pore space that contains fluids and dispersed shale, level 2 is the sandstone that contains quartz and structural shale grains, and level 3 is the formation that contains sand and shale laminations.
Effect of Shale Distribution on Total Porosity

\[ V_{sh_{total}} = 0 \]
\[ \phi_{total} = \phi_{ss_{clean}} \]

\[ V_{sh_{total}} = V_{sh_{laminar}} \]
\[ \phi_{total} = \phi_{ss_{clean}} \times (1 - V_{sh_L}) + (V_{sh_L} \times \phi_{sh_L}) \]

\[ V_{sh_{total}} = V_{sh_{laminar}} + V_{sh_{dispersed}} \]
\[ \phi_{total} = \phi_{ss_{clean}} \times (1 - V_{sh_L}) + (V_{sh_L} \times \phi_{sh_L}) - V_{sh_{D}} + (V_{sh_D} \times \phi_{sh_D}) \]

\[ V_{sh_{total}} = V_{sh_{laminar}} + V_{sh_{dispersed}} + V_{sh_{structural}} \]
\[ \phi_{total} = \phi_{ss_{clean}} \times (1 - V_{sh_L}) + (V_{sh_L} \times \phi_{sh_L}) - V_{sh_D} + (V_{sh_D} \times \phi_{sh_D}) + (V_{sh_{S}} \times \phi_{sh_{S}}) \]
Total Porosity vs. Shale Volume Crossplot

1) Maximum Porosity in and Shale Free Matrix
   - $\phi_{total} = \phi_{ss\text{clean}}$
   - $V_{sh} = 0\%$

2) 100% Shale (No Matrix)
   - $\phi_{total} = \phi_{shale}$
   - $V_{sh} = 100\%$

3) Matrix porosity occupied completely by Dispersed Shale
   - $\phi_{total} = \phi_{ss\text{clean}} \times \phi_{shale}$
   - $V_{sh} = \phi_{ss\text{clean}}$

4) Matrix composed entirely of Structural Shale
   - $\phi_{total} = \phi_{ss\text{clean}} + (V_{shale} \times \phi_{shale})$
   - $V_{sh} = 1 - \phi_{ss\text{clean}}$
Single-Type Distribution

Laminar Shale

\[ V_{sh_{total}} = V_{sh_{laminar}} \]
\[ \phi_{total} = \phi_{ss_{clean}} \ast (1 - V_{sh_{L}}) + (V_{sh_{L}} \ast \phi_{sh_{L}}) \]
\[ V_{sh_{L}} = \frac{\phi_{ss_{clean}} - \phi_{total}}{\phi_{ss_{clean}} - \phi_{sh}} \]

Dispersed Shale

\[ V_{sh_{total}} = V_{sh_{dispersed}} \]
\[ \phi_{total} = \phi_{ss_{clean}} - V_{sh_{D}} + (V_{sh_{D}} \ast \phi_{sh_{D}}) \]
\[ V_{sh_{D}} = \frac{\phi_{ss_{clean}} - \phi_{total}}{1 - \phi_{sh}} \]

Structural Shale

\[ V_{sh_{total}} = V_{sh_{structural}} \]
\[ \phi_{total} = \phi_{ss_{clean}} + (V_{sh_{S}} \ast \phi_{sh_{S}}) \]
\[ V_{sh_{S}} = \frac{\phi_{total} - \phi_{ss_{clean}}}{\phi_{sh}} \]

[Graphs showing total porosity versus shale distribution model for different shale types]
2-Type Distribution Models

Laminar and Dispersed Shale Distribution Model
Thomas-Stieber

- Clean SS
- Laminar Shale
- Pore-Filled
- 100% Shale
2-Type Distribution Models
2-Type Distribution Models
2-Type Distribution Models

LAMINAR-DISPERSED

LAMINAR-STRUCTURAL MODEL

DISPERSED-STRUCTURAL MODEL
Existing Methodology

• Juhasz (1986)

• Points BELOW the laminar line invoke the LAMINAR-DISPERSED model. ➞ GREEN POINT
  • BUT, the same input data may be described in the DISPERSED-STRUCTURAL model.
  • We now call this the “Dispersed-Required Field”

• Points ABOVE the laminar line invoke the LAMINAR-STRUCTURAL model. ➞ RED POINT
  • BUT, the same input data may be described in the DISPERSED-STRUCTURAL model.
  • We now call this the “Structural-Required Field”

• Points ALONG the laminar line invoke the LAMINAR ONLY model. ➞ YELLOW POINT
  • May not have any Dispersed or Structural but it could.
Quantifying Two-Type Distribution: Laminar/Dispersed Only

\[ V_{sh\text{total}} = V_{sh\text{laminar}} + V_{sh\text{dispersed}} + V_{sh\text{structural}} \]

\[ \phi_{total} = \phi_{ss\text{clean}} \ast (1 - V_{shL}) - V_{shD} + (V_{shD} \ast \phi_{sh}) + (V_{shL} \ast \phi_{sh}) + (V_{shS} \ast \phi_{sh}) \]

\[ V_{sh\text{total}} = V_{sh\text{laminar}} + V_{sh\text{dispersed}} + 0 \]

\[ \phi_{total} = \phi_{ss\text{clean}} \ast (1 - V_{shL}) - V_{shD} + (V_{shL} \ast \phi_{sh}) + (V_{shD} \ast \phi_{sh}) + 0 \]

\[ V_{sh\text{dispersed}} = V_{sh\text{total}} - V_{sh\text{laminar}} \]

\[ \phi_{total} = \phi_{sh} \ast (1 - V_{shL}) - (V_{shT} - V_{shL}) + (V_{shT} - V_{shL}) \ast \phi_{sh} + (V_{shL} \ast \phi_{sh}) \]

\[ V_{shL} = \frac{\phi_{ss\text{clean}} - \phi_{total} + V_{shT} - (V_{shT} \ast \phi_{sh})}{1 - \phi_{ss\text{clean}}} \]
Quantifying Two-Type Distribution: Laminar/Dispersed Only

**LAMINAR-DISPERSED CALCULATION**

\[
V_{sh_{total}} = V_{sh_{laminar}} + V_{sh_{dispersed}}
\]

\[
V_{sh_{dispersed}} = V_{sh_{total}} - V_{sh_{laminar}}
\]

\[
V_{sh_L} = \frac{\phi_{ss\text{clean}} - \phi_{total} + V_{sh_T} - (V_{sh_T} \times \phi_{Sh})}{1 - \phi_{ss\text{clean}}}
\]

**STRUCTURAL-DISPERSED CALCULATION**

\[
V_{sh_{total}} = V_{sh_{dispersed}} + V_{sh_{structural}}
\]

\[
V_{sh_{structural}} = V_{sh_{total}} - V_{sh_{dispersed}}
\]

\[
V_{sh_D} = \phi_{ss\text{clean}} - \phi_{total} + (V_{sh_T} \times \phi_{Sh})
\]

**LAMINAR-STRUCTURAL CALCULATION**

\[
V_{sh_{total}} = V_{sh_{laminar}} + V_{sh_{structural}}
\]

\[
V_{sh_{structural}} = V_{sh_{total}} - V_{sh_{laminar}}
\]

\[
V_{sh_L} = \frac{\phi_{ss\text{clean}} - \phi_{total} + (V_{sh_T} \times \phi_{Sh})}{\phi_{ss\text{clean}}}
\]
Inconsistencies between Models

Laminar-Dispersed

\[ V_{sh_L} = 34\% \]
\[ V_{sh_D} = 6\% \]
\[ V_{sh_S} = 0\% \]

Green Point

\[ V_{sh_{total}} = 40\% \]

Dispersed-Structural

\[ V_{sh_L} = 0\% \]
\[ V_{sh_D} = 14\% \]
\[ V_{sh_S} = 26\% \]
Quantifying Shale Distribution: Dispersed-Required System

\[ V_{sh_{total}} = V_{sh_{laminar}} + V_{sh_{dispersed}} + V_{sh_{structural}} \]

\[ R = \frac{V_{sh_S}}{V_{sh_L}} \rightarrow R \cdot V_{sh_L} = V_{sh_S} \]

\[ V_{sh_T} = V_{sh_L} + V_{sh_D} + (R \cdot V_{sh_L}) \]

\[ V_{sh_L} = \frac{V_{sh_T} - V_{sh_D}}{1 + R} \]

\[ V_{sh_T} = \left( \frac{V_{sh_T} - V_{sh_D}}{1 + R} \right) + V_{sh_D} + (R \cdot V_{sh_L}) \]

\[ \phi_{total} = \phi_{ss_{clean}} \cdot \left( 1 - \left( \frac{V_{sh_T} - V_{sh_D}}{1 + R} \right) \right) - V_{sh_D} + \left( \phi_{sh} \left( \frac{V_{sh_T} - V_{sh_D}}{1 + R} \right) \right) + (V_{sh_D} \cdot \phi_{sh}) + \left( R \cdot \phi_{sh} \left( \frac{V_{sh_T} - V_{sh_D}}{1 + R} \right) \right) \]

\[ V_{sh_D} = \frac{\phi_{total} - \phi_{ss} + \frac{\phi_{ss} \cdot V_{sh_T}}{(1 + R)} - V_{sh_T} \cdot \phi_{sh}}{\phi_{sh}} \]

\[ \frac{1}{(1 + R) - 1} \]
Quantifying Shale Distribution: Dispersed-Required System

<table>
<thead>
<tr>
<th>$\frac{V_{shS}}{V_{shL}} = R$</th>
<th>$V_{shS} = R \times V_{shL}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{V_{shS}}{V_{shL}} = 0/1$</td>
<td>$V_{shS} = \frac{0}{1} \times V_{shL}$</td>
</tr>
<tr>
<td>$\frac{V_{shS}}{V_{shL}} = 1/3$</td>
<td>$V_{shS} = \frac{1}{3} \times V_{shL}$</td>
</tr>
<tr>
<td>$\frac{V_{shS}}{V_{shL}} = 1/1$</td>
<td>$V_{shS} = \frac{1}{1} \times V_{shL}$</td>
</tr>
<tr>
<td>$\frac{V_{shS}}{V_{shL}} = 3/1$</td>
<td>$V_{shS} = \frac{3}{1} \times V_{shL}$</td>
</tr>
<tr>
<td>$\frac{V_{shS}}{V_{shL}} = 1/0$</td>
<td>$V_{shS} = \frac{1}{0} \times V_{shL}$</td>
</tr>
</tbody>
</table>
# Implications of 3-Type Distribution Model

<table>
<thead>
<tr>
<th></th>
<th>Laminar-Dispersed Model</th>
<th>V(<em>{shS}):V(</em>{shL}) = 1:3 Model</th>
<th>V(<em>{shS}):V(</em>{shL}) = 1:1 Model</th>
<th>V(<em>{shS}):V(</em>{shL}) = 3:1 Model</th>
<th>Dispersed-Structural Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>V(_{sh})</strong></td>
<td><strong>V(_{shL})</strong></td>
<td><strong>V(_{shD})</strong></td>
<td><strong>V(_{shS})</strong></td>
<td><strong>V(_{shL})</strong></td>
<td><strong>V(_{shD})</strong></td>
</tr>
<tr>
<td><strong>%</strong></td>
<td>34%</td>
<td>6%</td>
<td>0</td>
<td>24%</td>
<td>8%</td>
</tr>
</tbody>
</table>

### Graphs

1. **Laminar-Dispersed Model (Juhász, 1986)**
   - Laminar
   - Structural
   - Dispersed

2. **Dispersed-Structural Model (Juhász, 1986)**
   - Laminar
   - Dispersed
   - Structural
## Implications of 3-Type Distribution Model

<table>
<thead>
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<tr>
<td>20.0%</td>
<td>8.0%</td>
<td>0.0%</td>
<td>12.0%</td>
<td>3.4%</td>
<td>1.2%</td>
<td>15.4%</td>
<td>1.6%</td>
<td>1.6%</td>
<td>16.8%</td>
<td>0.6%</td>
<td>1.9%</td>
<td>17.5%</td>
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<tr>
<td>18.0%</td>
<td>2.0%</td>
<td>2.0%</td>
<td>18.0%</td>
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<td>18.0%</td>
<td>0.0%</td>
<td>2.0%</td>
<td>18.0%</td>
</tr>
</tbody>
</table>

### Laminar-Structural Model

- Vsh$_D$:Vsh$_L$ = 1:3 Model
- Vsh$_D$:Vsh$_L$ = 1:1 Model
- Vsh$_D$:Vsh$_L$ = 3:1 Model

### Dispersed-Structural Model
### Implications of 3-Type Distribution Model

<table>
<thead>
<tr>
<th>Vsh</th>
<th>Vsh&lt;sub&gt;L&lt;/sub&gt;</th>
<th>Vsh&lt;sub&gt;D&lt;/sub&gt;</th>
<th>Vsh&lt;sub&gt;S&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Laminar-Structural Model</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vsh&lt;sub&gt;D&lt;/sub&gt;:Vsh&lt;sub&gt;L&lt;/sub&gt; = 1:3 Model</td>
<td>20.0%</td>
<td>8.0%</td>
<td>12.0%</td>
</tr>
<tr>
<td>Vsh&lt;sub&gt;D&lt;/sub&gt;:Vsh&lt;sub&gt;L&lt;/sub&gt; = 1:1 Model</td>
<td>8.0%</td>
<td>12.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Vsh&lt;sub&gt;D&lt;/sub&gt;:Vsh&lt;sub&gt;L&lt;/sub&gt; = 3:1 Model</td>
<td>12.0%</td>
<td>3.4%</td>
<td>15.4%</td>
</tr>
<tr>
<td><strong>Dispersed-Structural Model</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Graphs

- **Laminar**
- **Structural**
- **Dispersed**

![Graphs showing distribution models](image-url)
Implications of 3-Type Distribution Model

Total Porosity Versus Shale Distribution Model
Thomas-Stieber, Juhasz

- Clean SS
- Dispersed Shale
- Structural Shale
- Grain-Replaced
- Pore-Filled

End of Document
Implications of 3-Type Distribution Model

<table>
<thead>
<tr>
<th></th>
<th>Laminar Line Model</th>
<th>Vsh&lt;sub&gt;S&lt;/sub&gt;:Vsh&lt;sub&gt;L&lt;/sub&gt; = 1:3 Model</th>
<th>Vsh&lt;sub&gt;S&lt;/sub&gt;:Vsh&lt;sub&gt;L&lt;/sub&gt; = 1:1 Model</th>
<th>Vsh&lt;sub&gt;S&lt;/sub&gt;:Vsh&lt;sub&gt;L&lt;/sub&gt; = 3:1 Model</th>
<th>Dispersed-Structural Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vsh&lt;sub&gt;L&lt;/sub&gt;</td>
<td>66.7%</td>
<td>66.7%</td>
<td>28.6%</td>
<td>13.3%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Vsh&lt;sub&gt;D&lt;/sub&gt;</td>
<td>0.0%</td>
<td>0.0%</td>
<td>9.5%</td>
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<tr>
<td>Vsh&lt;sub&gt;S&lt;/sub&gt;</td>
<td>46.2%</td>
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<td>40.0%</td>
<td>50.0%</td>
</tr>
<tr>
<td>Vsh</td>
<td>66.7%</td>
<td>66.7%</td>
<td>28.6%</td>
<td>13.3%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

Graphs show the distribution of Vsh<sub>S</sub> and Vsh<sub>L</sub> for different models:

- **Laminar**
- **Structural**
- **Dispersed**

Graphs indicate the percentage distribution of Vsh across different Vsh<sub>S</sub>:Vsh<sub>L</sub> ratios for each model type.
Effective Porosity

\[ \phi_{total} = \phi_{ss\,clean} \ast (1 - Vsh_L) + (Vsh_L \ast \phi_{sh}) - Vsh_D + (Vsh_D \ast \phi_{sh}) + (Vsh_S \ast \phi_{sh}) \]

\[ \phi_{effective} = \phi_{total} - (Vsh_T \ast \phi_{sh}) \]

\[ \phi_{ess} = \phi_{e} \frac{1}{1 - Vsh_L} \]

\[ \phi_{ess} = \frac{\phi_{ss\,clean} \ast (1 - Vsh_L) + (Vsh_L \ast \phi_{sh}) - Vsh_D + (Vsh_D \ast \phi_{sh}) + (Vsh_S \ast \phi_{sh}) - (Vsh_L \ast \phi_{sh}) - (Vsh_D \ast \phi_{sh}) - (Vsh_S \ast \phi_{sh})}{1 - Vsh_L} \]

\[ \phi_{ess} = \phi_{ss\,clean} - \frac{Vsh_D}{1 - Vsh_L} \]
Shale Distribution Implications toward Effective Porosity

\[ \phi_{e,SS} \]

- Previous Methodology (Juhasz, 1986)
- Three-Type Distribution Models
- Dispersed-Structural Model

\[ \frac{V_{ShS}}{V_{ShL}}, \frac{V_{ShS}}{V_{ShL}}, \frac{V_{ShD}}{V_{ShL}} \]
Application of Revised Methodology on Sandstone Case Studies

Case 1: Show Permission Denied
Case 2: Onshore Louisiana
Case 3: Deepwater GOM
Case Study 2
Onshore Louisiana

Diagram showing scatter plot of $V_{sh}$ vs $\phi$, with different zones identified as ZONE 1, ZONE 2, and ZONE 3.
\( \phi_d \text{ vs. } V_{\text{sh-gr}} \)

(TOP) Zones 1-3
Shale Point has higher porosity and GR versus original zone 1-5 average

(BOTTOM) (Zone 5)
Shale Point has lower porosity and GR versus original 1-5 average.
### Ratio Analysis and Effective Porosity

<table>
<thead>
<tr>
<th>LS or LD Trigger</th>
<th>1:3</th>
<th>1:1</th>
<th>3:1</th>
<th>DS Model</th>
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<tbody>
<tr>
<td>0.0% D</td>
<td>0.3% D</td>
<td>0.4% D</td>
<td>0.5% D</td>
<td>0.5% D</td>
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<tr>
<td>1.9% L</td>
<td>0.9% L</td>
<td>0.4% L</td>
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</tr>
<tr>
<td>2.3% S</td>
<td>3.0% S</td>
<td>3.4% S</td>
<td>3.5% S</td>
<td>3.6% S</td>
</tr>
<tr>
<td>29.3% $\phi_{eff}$-ss</td>
<td>29.0% $\phi_{eff}$-ss</td>
<td>28.9% $\phi_{eff}$-ss</td>
<td>28.8% $\phi_{eff}$-ss</td>
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</tr>
<tr>
<td>6.2% L</td>
<td>4.2% L</td>
<td>2.6% L</td>
<td>1.2% L</td>
<td>0.0% L</td>
</tr>
<tr>
<td>0.0% S</td>
<td>1.4% S</td>
<td>2.6% S</td>
<td>3.6% S</td>
<td>4.4% S</td>
</tr>
<tr>
<td>25.2% $\phi_{eff}$-ss</td>
<td>24.5% $\phi_{eff}$-ss</td>
<td>24.0% $\phi_{eff}$-ss</td>
<td>23.5% $\phi_{eff}$-ss</td>
<td>23.1% $\phi_{eff}$-ss</td>
</tr>
</tbody>
</table>
Ongoing Research

Density Porosity versus Volume of Shale

Effective Porosity versus Volume of Shale
NMR Case Study
Deepwater GOM

Graph showing the relationship between VshCBW and ΦE.
Additional Techniques

3D Resistivity

Image Logs
Summary

Juhasz’s (1986) method provides one endmember for shale volumetrics and interpretation, and that endmember just so happens to be the most optimistic with respect to reservoir quality.

Using triple-combo data with our method, we can quickly provide the range of possible scenarios, from most optimistic to most pessimistic.

As additional datasets are added, the range can be more accurately constrained.