Natural Fracture Characterization and Prediction of the “Mississippian Limestone” Play, North-Central Oklahoma, U.S.A.*

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Abstract

Natural Fractures are ubiquitous in several unconventional carbonate reservoirs in both the U.S. and around the world and these natural fractures, even when sealed, can facilitate the propagation of induced fractures during hydraulic fracturing. This study is focused on correlation of fracture types and fracture density to specific petrophysically-significant facies and to an established sequence stratigraphic framework in the unconventional carbonate reservoirs of the “Mississippian Limestone” of the U.S. Mid-Continent region. Four fracture types are observed in several cores from north-central Oklahoma: ptygmatic (folded) fractures, vertical extension fractures, shear fractures, and zones of mixed types of fractures. Most of the fractures have been completely filled with predominantly calcite cement derived from basinal fluids based upon both d¹⁸O and d¹³C values as well as fluid inclusion homogenization temperatures and strontium values. Fractured zones are vertically heterogeneous at various scales, indicating the variability of rock mechanical properties. At the millimeter scale, fractures are commonly discontinuous and exhibit variable width. At the centimeter scale, ptygmatic fractures exhibit variable termination modes in relation to bedding planes, suggesting mineralogical control of rock mechanical properties. At the meter scale, the highest fracture abundance corresponds to facies with the highest calcite content. Such mineralogical control of fracture distribution, which is corroborated by the positive correlation between calcite content and fracture density in a “fourth-order” sequence, further contributes to the general correlation of fracture abundance with regressive phases of “third-order” sequences at the whole core scale, indicating the value of sequence stratigraphic approach in characterizing fracture distribution.

References Cited


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Abstract
Natural fractures are common in several unconventional reservoirs in both the U.S. and around the world. Although many are induced during hydraulic fracturing and, therefore, are important components for characterizing and producing from these reservoirs. This study is focused on correlating fracture types and their productivity to petrophysically significant factors and to an established sequence stratigraphic framework in the accretional “Mississippian Limestone” in north-central Oklahoma.

Four types of natural fracture are observed: planar, vertical, and horizontal, clear, and mixed types of fractures, with the planar fractures being the most abundant type. Most of the fractures are sealed with calcium carbonate. Fractures are both lateral and vertically heterogeneous in certain scales, including variability in fault mechanisms. While hydraulic fractures can extend across lithology and scale vectors, and they can exhibit micro and meso-fracturing. At the macro scale, the highest fracture abundance corresponds to facies with the highest calcite content, and consequently, to the regression phase of higher-order sequences which are commonly defined by these facies. Laterally, fracture abundance varies among individual rocks, likely attributed to variations in the proportion of petrophysically significant factors, variations structural settings throughout the region, and variable tectonic stress fields at the time of the faulting related to the regional stress field. The rate of fracture forming is controlled by the production rate of rock mechanics, and the effective stress. The micro- and meso-fracturing of petrophysically significant factors and interactions of effective stress and rock mechanics, can provide insight that may enhance the prediction of natural fracture distribution in these other unconventional mineral-carbonate reservoirs.

Significance and Objectives

Why Care About These Natural Fractures?
1. Provide porosity and permeability to unconventional reservoirs
2. May provide pathways of weakness, even when isolated, that may facilitate propagation of induced fractures

Knowledge Gaps
1. Integration of fracture and mechanical stratigraphy into a high-resolution sequence stratigraphic framework is lacking, resulting in limited understanding of the controlling factors of fracture distribution and a need for minimal application of relevant datasets in predicting fracture behavior in unconventional reservoirs on an exploration or production scale.
2. The impact of structural diagenesis on rock mechanical properties, from both a temporal and spatial perspective, adds additional uncertainty when interpreting the mechanical stratigraphy during the formation of the natural fractures in the present-day distribution of natural fractures.

Objectives
1. Examine the natural fractures in terms of type, abundance, and attributes (e.g., height, width, terminal spacing) with a multi-scale approach to model the character and distribution of the fractures
2. Tie key attributes (e.g., abundance, average intensity, spacing) to an established sequence stratigraphic framework to examine the controlling factors of fracture distribution, and to enhance the prediction of naturally fractured zones

Data and Methodology

Geologic Setting

Oklahoma during Early Mississippian (a)
- Four types of fractures are observed: planar, vertical, and horizontal, clear, and mixed types of fractures, with the planar fractures being the most abundant type. Most of the fractures are sealed with calcium carbonate. Fractures are both lateral and vertically heterogeneous in certain scales, including variability in fault mechanisms. While hydraulic fractures can extend across lithology and scale vectors, and they can exhibit micro and meso-fracturing. At the macro scale, the highest fracture abundance corresponds to facies with the highest calcite content, and consequently, to the regression phase of higher-order sequences which are commonly defined by these facies. Laterally, fracture abundance varies among individual rocks, likely attributed to variations in the proportion of petrophysically significant factors, variations structural settings throughout the region, and variable tectonic stress fields at the time of the faulting related to the regional stress field. The rate of fracture forming is controlled by the production rate of rock mechanics, and the effective stress. The micro- and meso-fracturing of petrophysically significant factors and interactions of effective stress and rock mechanics, can provide insight that may enhance the prediction of natural fracture distribution in these other unconventional mineral-carbonate reservoirs.

Idealized Vertical Facies Succession & Regional Depositional Model

Regional Depositional Model - Mixed Carbonate-siliciclastic, Distally Steepened Ramp
- Depositional setting: Mixed carbonate-siliciclastic, distally steepened ramp
- Depositional architecture: Mixed carbonate-siliciclastic, distally steepened ramp
- Depositional process: Mixed carbonate-siliciclastic, distally steepened ramp

Correlation of P-Facies

Figure 1: Regional Depositional Model - Mixed Carbonate-siliciclastic, Distally Steepened Ramp

Fracture Type and Attributes - Abundance, Width, Height, Termination, and Spacing

- Total Fracture Count
- Fracture Area
- Fracture Height
- Estimated Fracture Width
- Fracture Type
- Measured Fracture Height
- Measured Fracture Spacing

Figure 2: Fracture Type and Attributes - Abundance, Width, Height, Termination, and Spacing

- Fracture Type
- Estimated Fracture Width
- Fracture Height
- Measured Fracture Height
- Measured Fracture Spacing

Figure 3: Fracture Type and Attributes - Abundance, Width, Height, Termination, and Spacing

- Fracture Type
- Estimated Fracture Width
- Fracture Height
- Measured Fracture Height
- Measured Fracture Spacing

Figure 4: Fracture Type and Attributes - Abundance, Width, Height, Termination, and Spacing

- Fracture Type
- Estimated Fracture Width
- Fracture Height
- Measured Fracture Height
- Measured Fracture Spacing

Figure 5: Fracture Type and Attributes - Abundance, Width, Height, Termination, and Spacing

- Fracture Type
- Estimated Fracture Width
- Fracture Height
- Measured Fracture Height
- Measured Fracture Spacing

Figure 6: Fracture Type and Attributes - Abundance, Width, Height, Termination, and Spacing

- Fracture Type
- Estimated Fracture Width
- Fracture Height
- Measured Fracture Height
- Measured Fracture Spacing

Figure 7: Fracture Type and Attributes - Abundance, Width, Height, Termination, and Spacing

- Fracture Type
- Estimated Fracture Width
- Fracture Height
- Measured Fracture Height
- Measured Fracture Spacing

Figure 8: Fracture Type and Attributes - Abundance, Width, Height, Termination, and Spacing

- Fracture Type
- Estimated Fracture Width
- Fracture Height
- Measured Fracture Height
- Measured Fracture Spacing

Figure 9: Fracture Type and Attributes - Abundance, Width, Height, Termination, and Spacing

- Fracture Type
- Estimated Fracture Width
- Fracture Height
- Measured Fracture Height
- Measured Fracture Spacing

Figure 10: Fracture Type and Attributes - Abundance, Width, Height, Termination, and Spacing

- Fracture Type
- Estimated Fracture Width
- Fracture Height
- Measured Fracture Height
- Measured Fracture Spacing

Figure 11: Fracture Type and Attributes - Abundance, Width, Height, Termination, and Spacing

- Fracture Type
- Estimated Fracture Width
- Fracture Height
- Measured Fracture Height
- Measured Fracture Spacing

Figure 12: Fracture Type and Attributes - Abundance, Width, Height, Termination, and Spacing

- Fracture Type
- Estimated Fracture Width
- Fracture Height
- Measured Fracture Height
- Measured Fracture Spacing

Figure 13: Fracture Type and Attributes - Abundance, Width, Height, Termination, and Spacing

- Fracture Type
- Estimated Fracture Width
- Fracture Height
- Measured Fracture Height
- Measured Fracture Spacing

Figure 14: Fracture Type and Attributes - Abundance, Width, Height, Termination, and Spacing

- Fracture Type
- Estimated Fracture Width
- Fracture Height
- Measured Fracture Height
- Measured Fracture Spacing

Figure 15: Fracture Type and Attributes - Abundance, Width, Height, Termination, and Spacing

- Fracture Type
- Estimated Fracture Width
- Fracture Height
- Measured Fracture Height
- Measured Fracture Spacing

Figure 16: Fracture Type and Attributes - Abundance, Width, Height, Termination, and Spacing

- Fracture Type
- Estimated Fracture Width
- Fracture Height
- Measured Fracture Height
- Measured Fracture Spacing

Figure 17: Fracture Type and Attributes - Abundance, Width, Height, Termination, and Spacing

- Fracture Type
- Estimated Fracture Width
- Fracture Height
- Measured Fracture Height
- Measured Fracture Spacing

Figure 18: Fracture Type and Attributes - Abundance, Width, Height, Termination, and Spacing

- Fracture Type
- Estimated Fracture Width
- Fracture Height
- Measured Fracture Height
- Measured Fracture Spacing
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Fracture Intensity in Sequence Stratigraphic Framework

- Fractures Measured: 414
- Intensity
- PNN

Core #3
Depositional Dip (Basinward)
Core #3
Depositional Strike
Core #3

Legend

Natural Fractures: In Core and Petrography:

1. Occurrence
2. In Relation to Ductile Layers
3. Potential Reactions to Localized Stress and/or Structural Diagnosis

Pyramidal Fractures
- Highly faulted morphology along fracture length
- Occurring in singular (a) and sets of fractures (b)
- May contain thin bundles (c)
- Commonly discontinuous at mm-scale (d)

Pyramidal Fractures:
- Pyramidal fractures
- May be associated with highly faulted morphology along fracture length
- Occurring in singular or sets of fractures
- May contain thin bundles
- Commonly discontinuous at mm-scale

Pyramidal Fractures: Pyramidal fractures

Vertical Extension Fractures
- Characterized by relatively straight fracture walls
- Occur as singular (a) and sets (b) of fractures
- Rare tall fractures contain void space related to partial mineralization (c) - reservoir permeability?

Vertical Extension Fractures:
- Vertical extension fractures
- Characterized by relatively straight fracture walls
- Occur as singular or sets of fractures
- Rare tall fractures contain void space related to partial mineralization

Mixed Fractures
- Co-existence of multiple types along one fracture (this example: pyramidal and vertical extension) suggests variability and evolution of rock mechanics (i.e., structural diagnosis)

Origin of Fractures

- The pyramidal fractures commonly occur in many of the unconventional reservoirs currently being explored in the continental U.S. (Gale et al., 2014), with a poorly understood formation mechanism.
- These fractures may be formed in a critical condition where the rock is brittle enough to break but ductile to deform in a relatively easy mode.
- Ductile deformation of the mineralized fractures is evidenced by the intense distortion along the fracture length. In this sense, the formation of the fractures may serve as a measurement of compressive strain.

- The vertical extension fractures, which are characterized by the relatively straight fracture walls, are inferred to be formed at both relatively early (post-depositional) and late (post-burial) stage in the rock obtaining sufficient strength to break via eductile stress (Olson et al., 2007), reflecting a sense of displacement perpendicular to fracture wall and a pure opening mode (mode e.g., Olson et al., 2006).
- The mixed fractures, the “pyramidal-planar” structure may reflect mode e folding with lateral shear stress being oblique to fracture wall (e.g., Olson et al., 2006).
- Although the dominant stress regime can be difficult to determine for the mixed type of fractures, difference in rock mechanical properties (e.g., strength) and stress regimes can be inferred where transformation of the fracture type occurs.
Fracture Count, Average Intensity, and Average Spacing In Relation To Facies and Sequence Stratigraphy

<table>
<thead>
<tr>
<th>Facies Type</th>
<th>Fracture Count</th>
<th>Average Intensity</th>
<th>Average Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>54</td>
<td>6.2</td>
<td>19.1</td>
</tr>
<tr>
<td>F2</td>
<td>22</td>
<td>7.8</td>
<td>15.7</td>
</tr>
<tr>
<td>F3</td>
<td>12</td>
<td>9.3</td>
<td>10.5</td>
</tr>
<tr>
<td>F4</td>
<td>8</td>
<td>11.2</td>
<td>8.2</td>
</tr>
<tr>
<td>F5</td>
<td>5</td>
<td>13.3</td>
<td>6.8</td>
</tr>
</tbody>
</table>

### Limited Information

#### Key Points
- Naturally fractured zones are vitrally heterogeneous and are controlled by F1 facies types and relative position within the sequence stratigraphic framework.
- Fracture count and average fracture intensity correlate with:
  - Roughness phase (F1) and post-erosional phase (F2).
  - Fracture intensity increases from F1 to F5.

#### Interpretation

1. **Natural Fracture Characterization and Prediction of the “Mississippian Limestone” Play, North-Central Oklahoma, U.S.A**
   - A detailed comparison between fracture count and well-log karst index (Køhl) intervals of Core 42 does not reveal any correlation relative, likely attributed to the variable sampling protocols (one per interval with variable sampling frequencies from 1 cm to 1 m). This correlation results in insufficient statistical significance in determining highly fractured intervals.
   - To overcome this sampling issue, high-frequency syn-fracture (KRD) data were collected from a “North-side” core in Core 42. The results show a highly constrained positive correlation between fracture intensity and calcite content, suggesting increasing calcite content leads to increased stress, even in higher frequency sequences.

2. **Fractured Related to Mineralogy and Bedding Structures**
   - Fractures related to bedding structures occur in the micro-fracture frame and are associated with changes in rock properties.
   - Fracture intensity varies among sequences and individual facies, indicating differences in fracture density.
   - Fracture intensity varies as a function of sequence and individual facies, indicating differences in fracture density.

### Limitations
- 1. Geographic separation of cores (seven to five km) results in a scattered fracture dataset.
- 2. Nearer core width (65 m) limits hundreds of spacing fractures, resulting in an insufficient picture of fracture distribution.
- 3. Measurements of the fracture attributes can be complex.

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#### Fractures in Micro-CT Imaging

- **Strength & Elastic Properties**
  - Three-dimensional and high-resolution (up to 40 micron) micro-CT imaging of fractured samples provides a detailed understanding of the fracture matrix structure.
  - Strength enhancement, including the development of the fracture skin surface, is supplemented by the 3-D scan-based fracture simulation.

- **Mineralogy**
  - Mineralogy of fracture filling cement and its position in distinguishing between induced and naturally fractured minerals.

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#### Fractures in Core Samples

- **Core Cross-Sections**
  - Core images from 5.5 inch diameter core plugs from Core 42.
  - Variable sizes of grey reflection density of minerals, higher the density, the darker the grey (e.g., mica, 2004).
  - Single fractures (F1) and F2 are imaged in situ with no aware interference (e.g., well, horizontal fractures) in 3-D and 2-D.
  - Fractures are associated with enhanced core surface roughness, indicating a highly roughened interface.

- **Core-2, P-Facies 5**
  - Figure shows the relationship between fracture intensity and calcite content in a “North-side” core in Core 42.