PSNatural Fracture Characterization and Prediction of the "Mississippian Limestone" Play, North-Central Oklahoma, U.S.A.*

Yulun Wang[1], Taylor Thompson[1], and G. Michael Grammer[1]

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[1]Oklahoma State University, Stillwater, Oklahoma, United States (marcowang1989@hotmail.com)

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 $d^{18}O$ and $d^{13}C$ 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.

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Yulun Wang*, Taylor Thompson, and G. Michael Grammer
Boone Pickens School of Geology, Oklahoma State University, Stillwater, OK, USA

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Abstract

Natural fractures are common in several unconventional carbonate reservoirs in both the U.S. and around the world. Although many are sealed, these natural fractures may assist in the propagation of induced fractures during hydraulic fracturing and, therefore, are an important component for characterizing and producing from these reservoirs. This study is focused on correlating fracture types and intensity to petrophysically-significant facies and to an established sequence stratigraphic framework in the unconventional "Mississippian Limestone" in north-central Oklahoma.

Four types of natural fractures are observed: ptygmatic, vertical extension, shear, and mixed types of fractures, with the ptygmatic fractures being the most abundant type. Most of the fractures are sealed with calcite cement. Fractured zones are both laterally and vertically heterogeneous at various scales, indicating variability in rock mechanics. Within individual cores, fractures are commonly discontinuous and exhibit variable widths at the millimeter scale, as revealed by thin sections and micro-CT imaging. At the centimeter scale, ptygmatic fractures exhibit variable termination patterns in relation to bedding planes, suggesting a mineralogical control on fracture propagation and rock mechanics. At the meter scale, the highest fracture abundance corresponds to facies with the highest calcite content, and consequently, to the regressive phases of "third-order" sequences which are commonly defined by these facies. Laterally, fracture abundance varies among individual cores, likely attributed to variations in the proportion of petrophysically significant facies, variations in structural settings throughout the region, variable patterns in the evolution of rock mechanics, and clustered fracture distribution related to the geographic separation of the cores. Although there is a potential mismatch between the present-day fracture stratigraphy and the mechanical stratigraphy at the time of fracturing related to evolution of rock mechanics (e.g., structural diagenesis), the sequence stratigraphic framework, which governs the distribution of petrophysically significant facies and impacts the evolution of diagenesis and rock mechanics, can provide insight that may enhance the prediction of natural fracture distribution in these and other unconventional mixed carbonate-siliciclastic reservoirs.

Significance and Objectives

Why Care About These Natural Fractures?

1. Provide porosity and permeability to unconventional reservoirs
2. May provide planes of weakness, even when cemented, 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 a limited understanding of the controlling factors of fracture distribution, and a more limited application of relevant datasets in predicting subsurface fractured zones 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 via the present-day distribution of natural fractures.

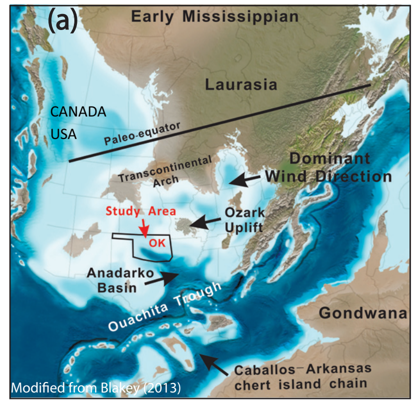
Objectives

1. Examine the natural fractures in terms of type, abundance, and attributes (e.g., height, width, termination, spacing) with a multi-scale approach to reveal 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.

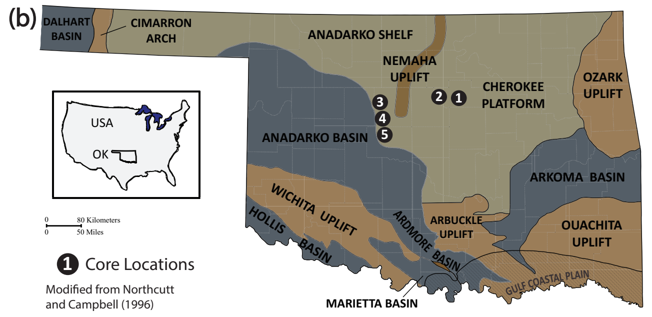
Data and Methodology

- **Five subsurface cores** (2091 ft in total) - facies, sequence stratigraphy, fractures at core scale
- **Thin sections** - facies, mineralogy, fractures and fracture attributes at petrographic scale
- **Micro-CT imaging** (2 core plugs) - three-dimensional view of fracture attributes up to 40 microns
- **X-ray diffraction** (calcite, quartz, bulk clay) - mineralogical control of fracture distribution

Geologic Setting



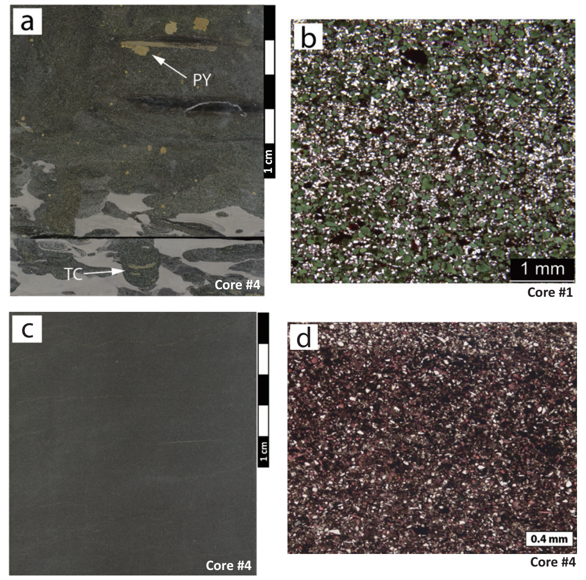
Oklahoma during Early Mississippian (a)
- Subtropical epeiric sea - a mixed carbonate-siliciclastic system



Study Area (b) - North-Central Oklahoma (OK)
- Depositional Setting: Cherokee Platform to the edge of Anadarko Basin – relatively shallow & deep water
- Structural Setting: adjacent to Nemaha Fault Zone – complex fault distribution

Petrophysically Significant Facies (P-Facies)

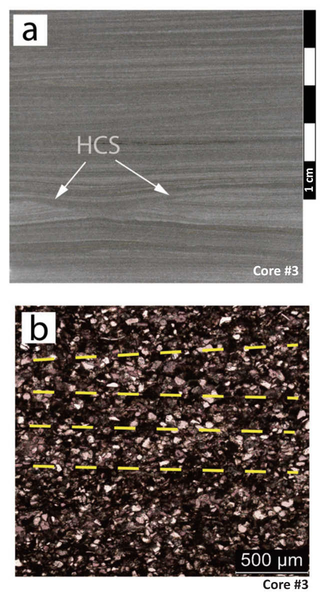
P-Facies 1: Glauconitic Siltstone - Fine Sandstone (a, b) & Massive-bedded Siltstone (c, d)



[P-Facies 1.1] Glauconitic Siltstone - Fine Sandstone (a, b)
- Mostly at Mississippian base; dark green in color;
- Glauconite, quartz, dolomite, phosphatic grains, pyrite;
- Distal outer ramp to basin

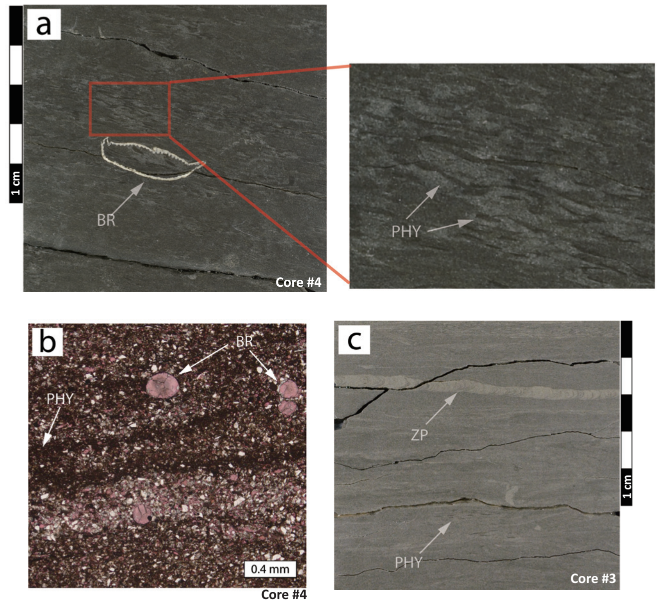
[P-Facies 1.2] Massive-bedded Siltstone (c, d)
- Black in color; massive-bedded structure;
- Quartz, feldspar, clay;
- Distal outer ramp to basin

P-Facies 2: Laminated Siltstone



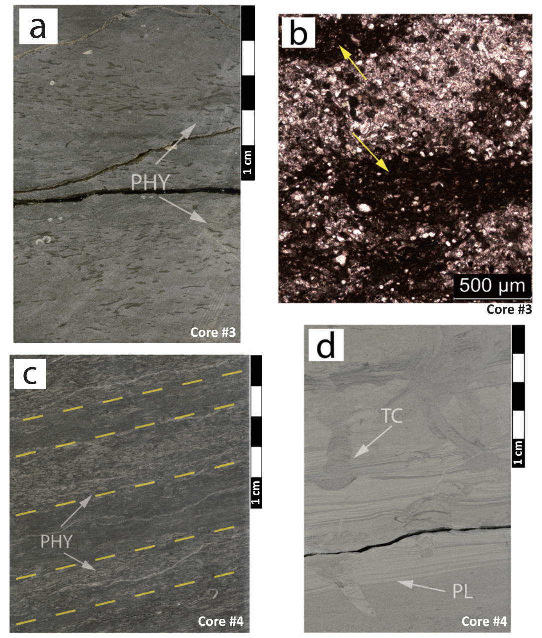
[P-Facies 2] Laminated Siltstone
- Alterations of mud- and calcite-rich laminae;
- Scattered hummocky cross-stratification (HCS) points to storm;
- Quartz, feldspar, clay;
- Outer ramp

P-Facies 3: Burrowed Siltstone



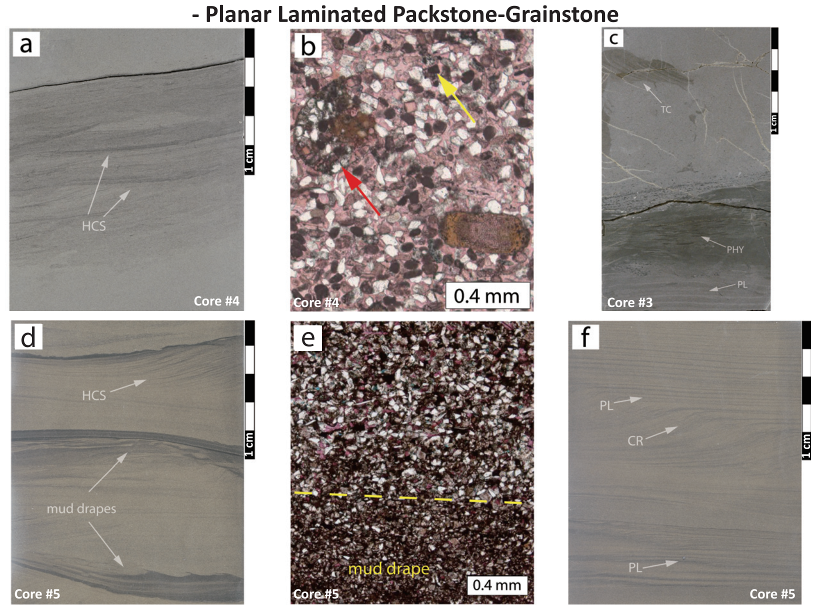
[P-Facies 3] Burrowed Siltstone
- Scattered mm-scale burrows (*Phycosiphon incertum*, PHY; *Zoophycos*, ZP);
- Occasionally clustered burrows (a) indicate variable energy / water condition;
- Brachiopod (BR), crinoid; quartz, feldspar, clay;
- Proximal outer ramp to distal middle ramp

P-Facies 4: Bioturbated Siltstone



[P-Facies 4] Bioturbated Siltstone
- Abundant mm-scale burrows (*Phycosiphon incertum;* PHY) forming interconnected burrow network;
- Variable mineralogy and bioturbation extent, and scattered HCS beds burrowed by *Techichnus* (TC) and planar lamination (PL) indicate fluctuations in energy / water condition;
- Proximal outer ramp to distal middle ramp

P-Facies 5: Massive-bedded and Hummocky Cross-stratified (HCS) - Planar Laminated Packstone-Grainstone

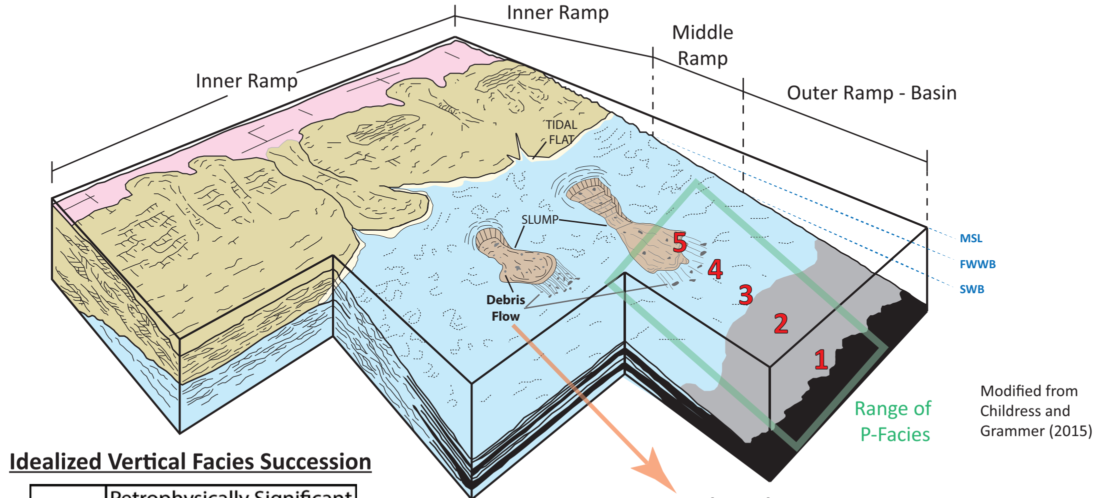


[P-Facies 5.1] Massive-bedded packstone-grainstone (a, b, c)
- Grayish-brownish in color; Massive-bedded with rare biogenic structure;
- Peloids, bioclasts, quartz, feldspar;

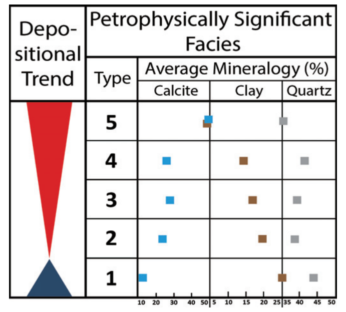
[P-Facies 5.2] HCS - planar laminated packstone-grainstone (c, d, e)
- Abundant HCS and planar laminations (PL), and rare climbing ripples (CR) point to rapid sedimentation associated with frequent storm events;
- Scattered mud-rich and burrowed laminae/beds suggest energy fluctuation;
- Sand bodies in proximal outer ramp to distal middle ramp

Idealized Vertical Facies Succession & Regional Depositional Model

Regional Depositional Model – Mixed Carbonate-siliciclastic, Distally Steepened Ramp

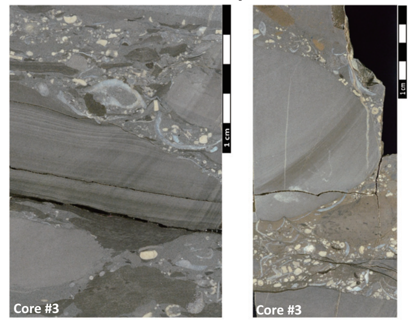


Idealized Vertical Facies Succession



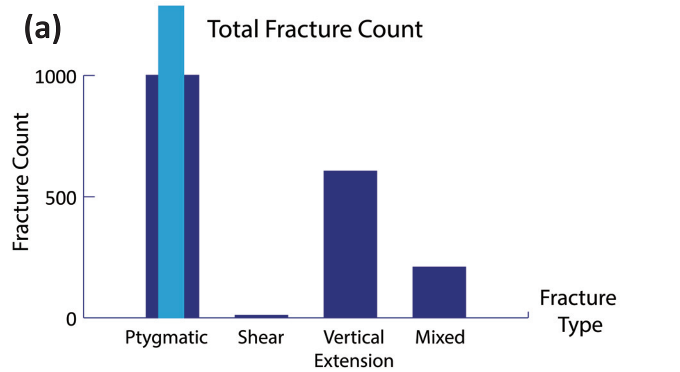
- P-Facies 1 to 5 – generally increasing calcite and decreasing clay-quartz content indicate increasing energy during deposition and increasing rock strength
- A guide for defining sequence stratigraphic framework which is the basis for data integration

Debris Flow Deposits

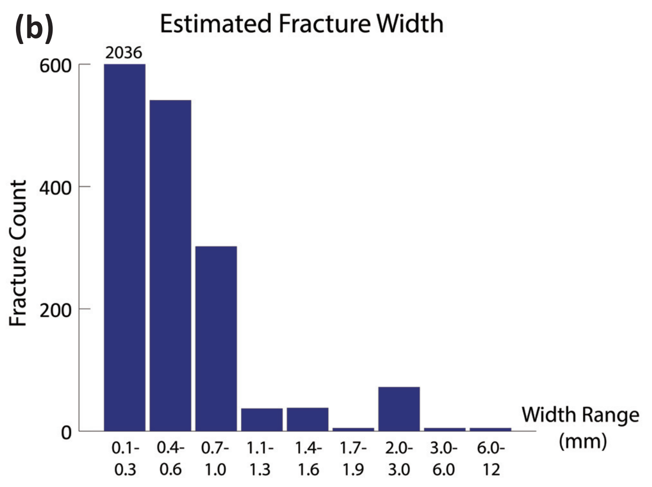


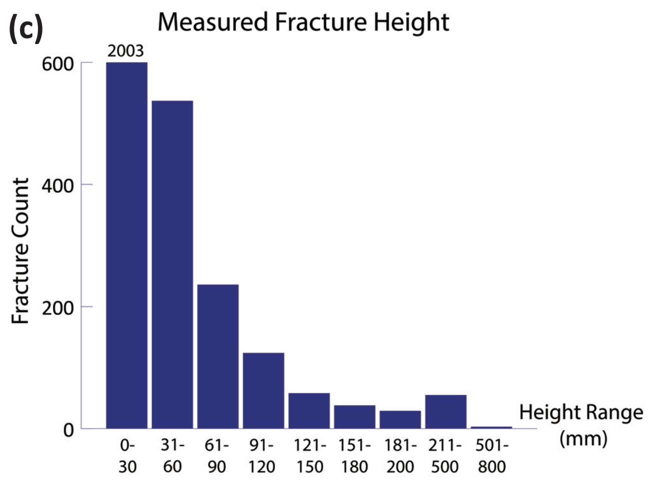
- 5 facies belts generally from middle to outer ramp-basin
- Debris flow deposits suggest slope ("distally steepened")

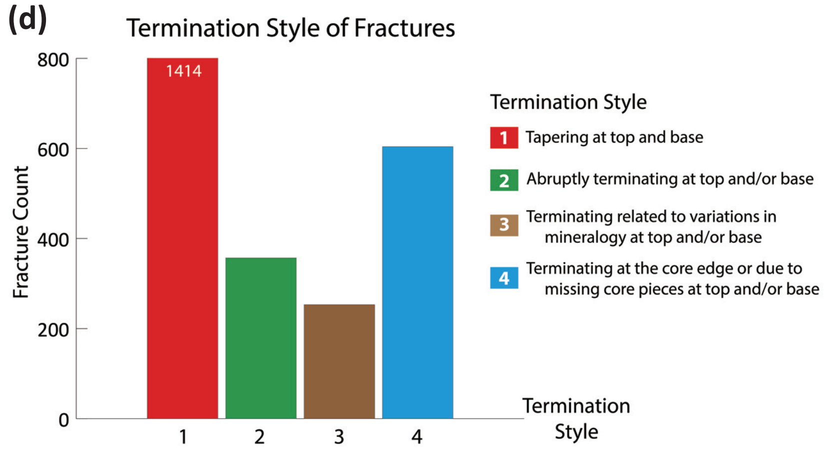
Fracture Type and Attributes - Abundance, Width, Height, Termination, and Spacing

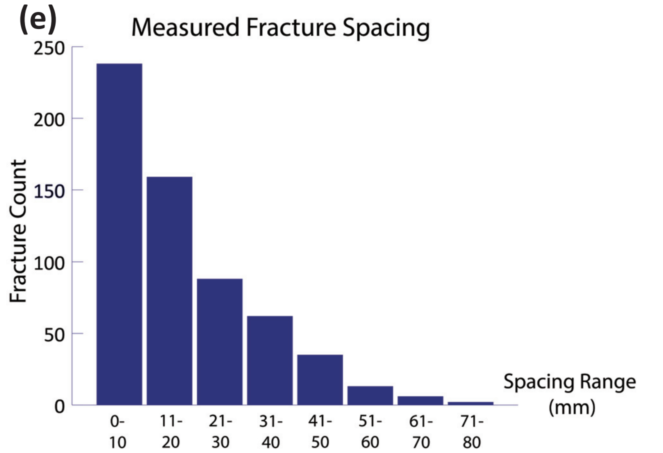


- **4 types of fractures** – ptygmatic, vertical extension, shear, mixed
- Mostly (sub)vertical and sealed with calcite cement
- Ptygmatic fracture – most abundant type (a)









- A large proportion of fractures exhibit an estimated width of 0.1 to 0.3 mm (b), a measured height up to 30 mm (c), and a tapering termination style (d)
- Termination due to core edge and/or missing core pieces in core (d), suggesting the limitation of measured height as compared to "true" height
- In fracture sets, measured spacing commonly ranges up to 10 mm (e), but **sampling bias due to narrow width of individual cores** should be considered

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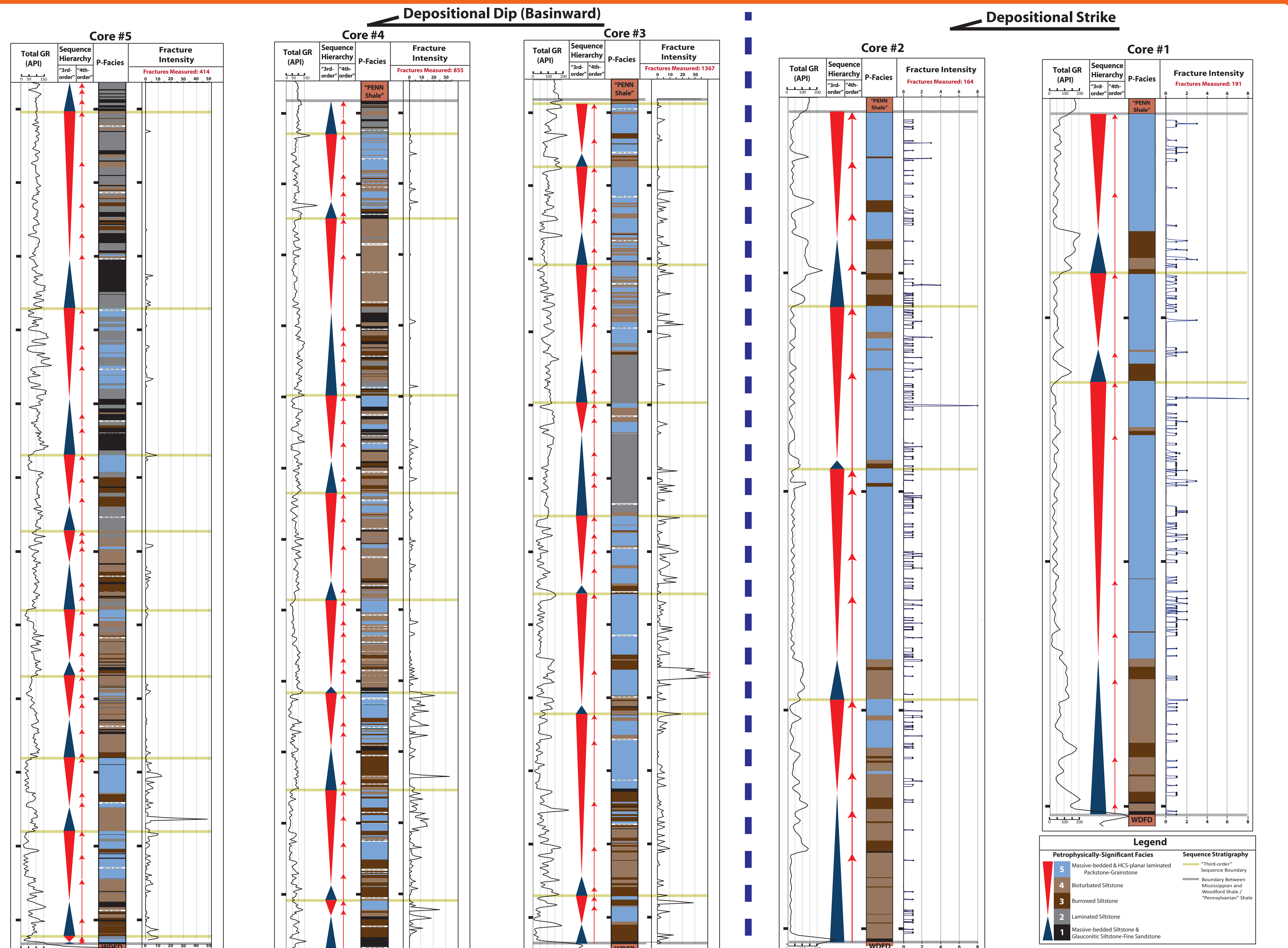
Fracture Intensity in Sequence Stratigraphic Framework

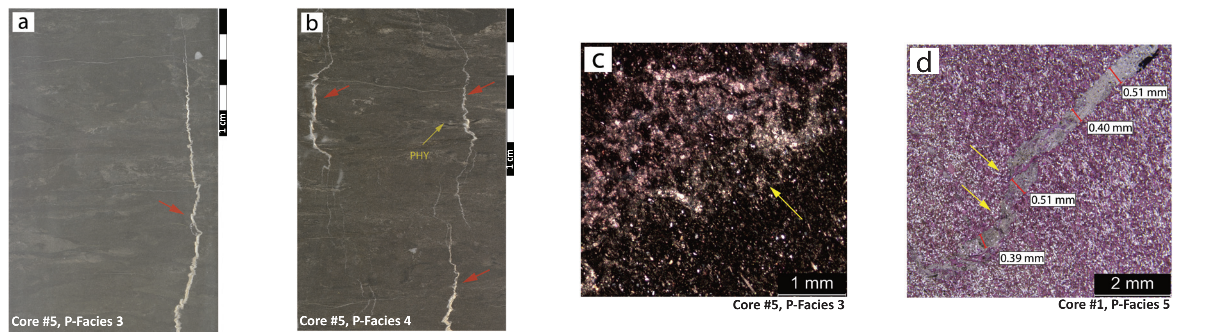


***Vertical Scale in 50 ft**
"WDFD" - Woodford Shale; "Penn Shale" - "Pennsylvanian" Shale

Natural Fractures In Core and Petrography

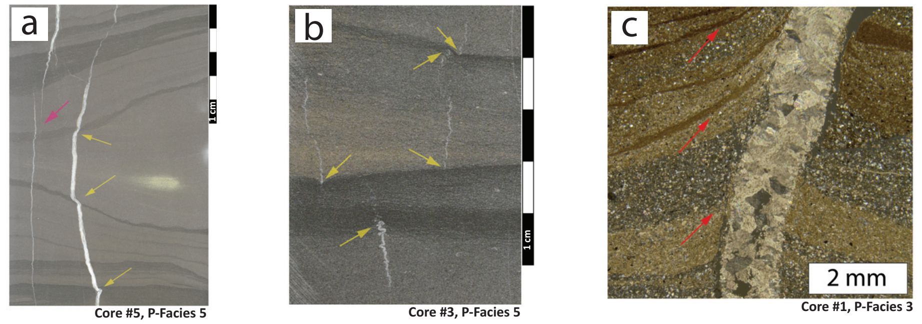
Ptygmatic Fractures

1. Occurrence



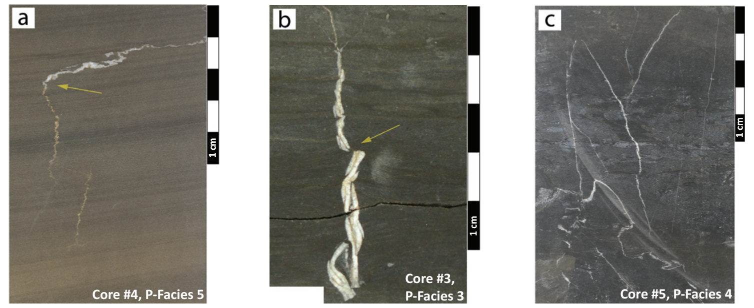
Ptygmatic fractures
- Highly folded morphology along fracture length occurring as singular (a) and sets of fractures (b)
- May contain thin bundles (c)
- Commonly discontinuous at mm-scale (d)

2. In Relation to Ductile Layers



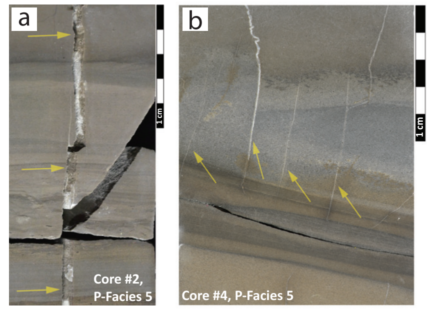
Ptygmatic fractures
- **Ductile deformation** is suggested by increasing distortion along fracture length when cutting through thin mud-rich, ductile layers (a) and by scattered micro-tepee (b, c) when protruding into these layers.

3. Potential Reactions to Localized Stress and/or Structural Diagenesis



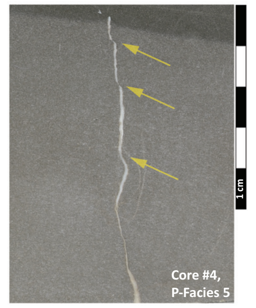
Ptygmatic fractures
- **Evidence of localized stress and/or structural diagenesis** is suggested by variations in the direction of fracture propagation (a), brittle failure of fracture (b), and abrupt occurrence of highly fractured intervals (c).

Vertical Extension Fractures



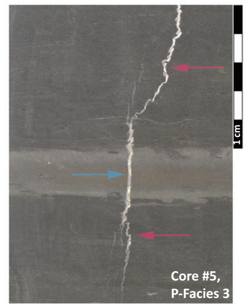
- Characterized by relatively straight fracture walls
- Occur as singular (a) and sets (b) of fractures
- A few tall fractures contain void space related to partial mineralization (a) - reservoir permeability?

Shear Fractures



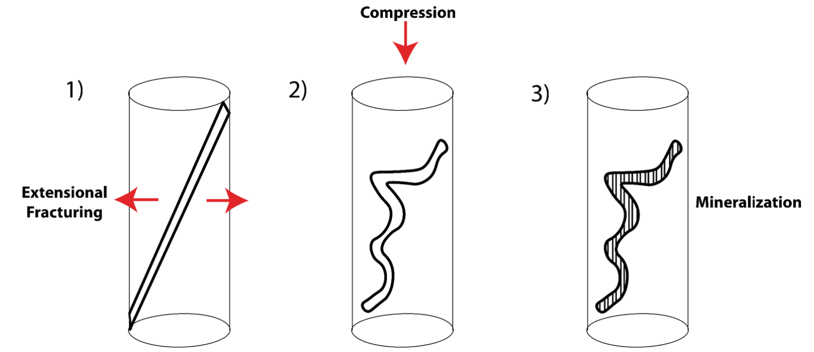
- Pinch-and-swell structure indicated by thinning at point of shearing

Mixed Fractures



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

Origin of Fractures



- The ptygmatic fractures commonly occur in many of the unconventional reservoirs currently being worked in the continental U.S. (Gale et al., 2014), with a poorly understood formation mechanism.
  - These fractures may be formed at a critical condition when the rock was **brittle enough to break but ductile to deform** at a relatively early stage.
  - Ductile compaction of the mineralized fractures is evidenced by the intense distortion along the fracture length. In this sense, the tortuosity of the fractures may serve as a measurement of compressive strain (Ramberg, 1959; Shelley, 1968).
- The vertical extension fractures, which are characterized by the relatively straight fracture walls, are inferred to be formed at both a **relatively early (post-deposition) and late (post-burial) stage** as the rock obtains sufficient strength to break via tensile stress (Olson et al., 2007), reflecting a sense of displacement perpendicular to fracture wall and a pure opening mode (mode I; e.g., Olson et al., 2009).
- In the shear fractures, the "pinch-and-swell" structure may reflect mode II sliding with lateral shear stress being oblique to fracture wall (e.g., Olson et al., 2009).
- 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.

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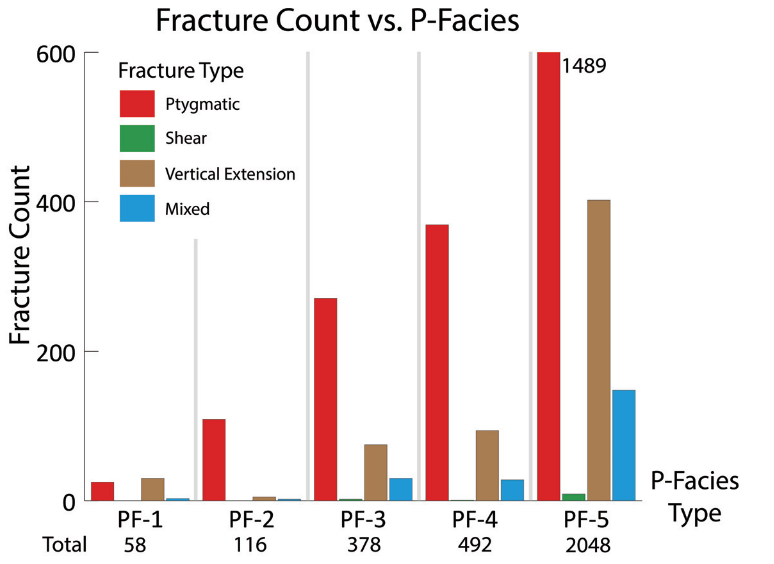
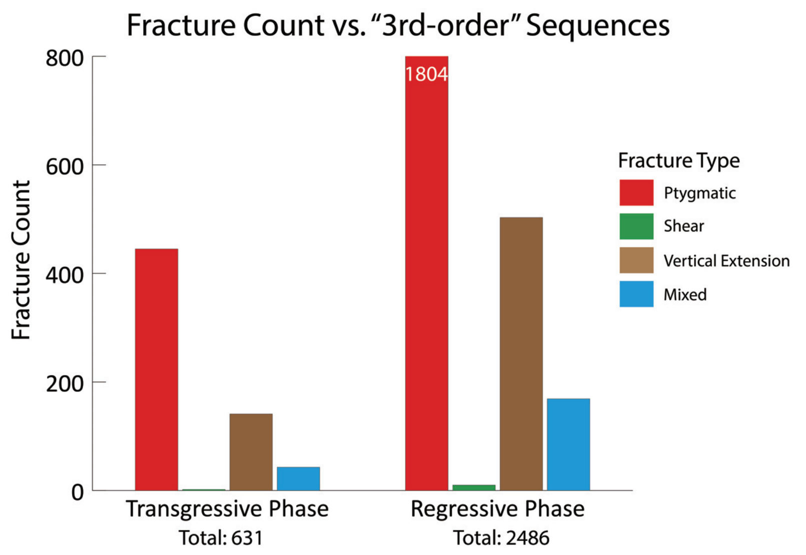
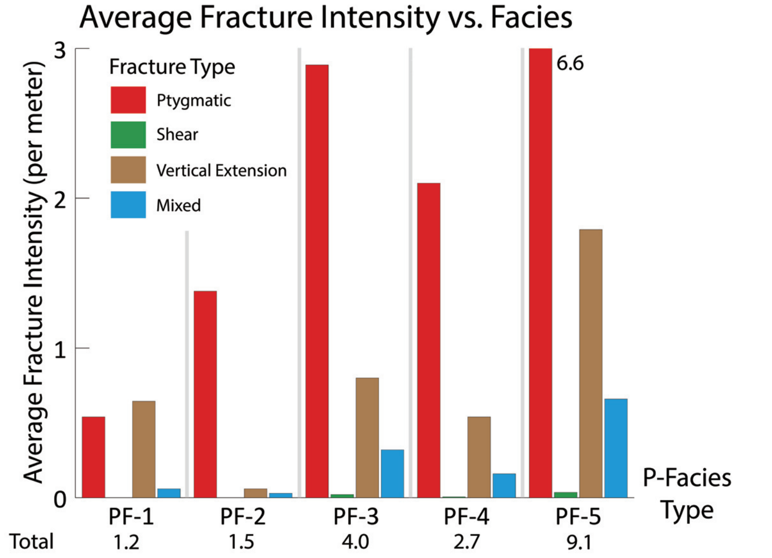
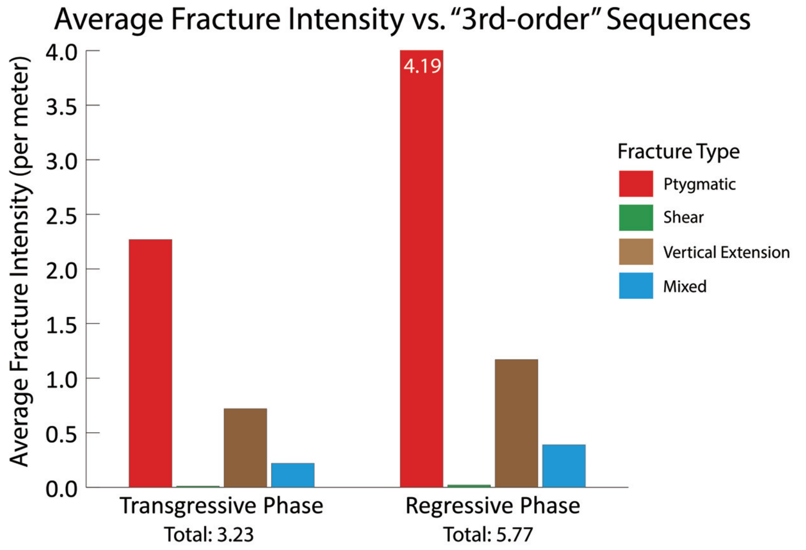
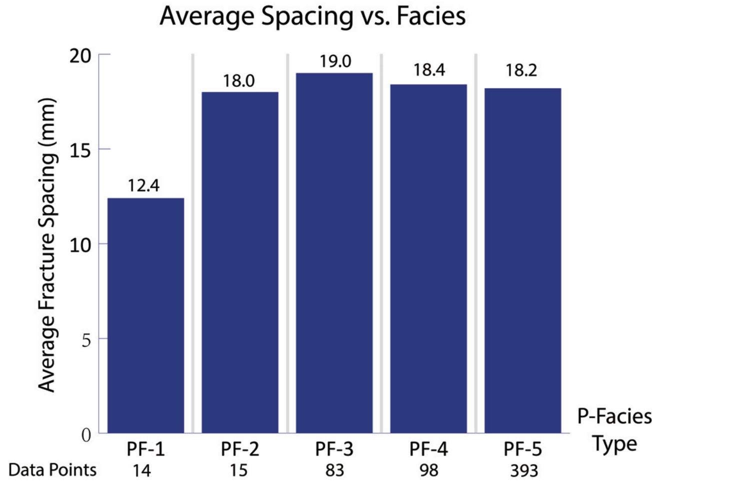
Fracture Count, Average Intensity, and Average Spacing In Relation To Facies and Sequence Stratigraphy

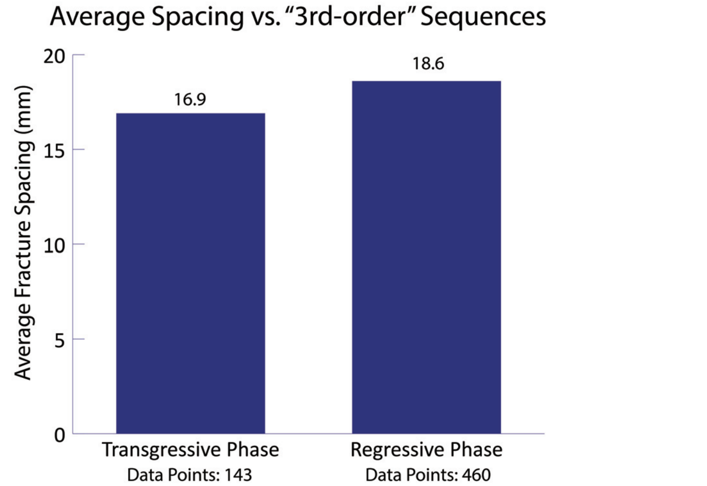








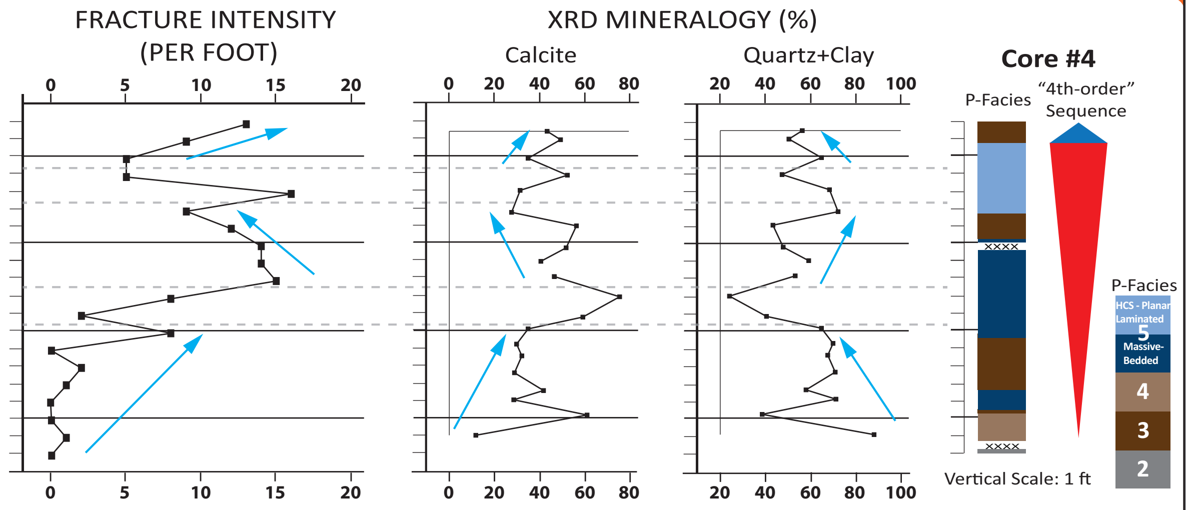




- Naturally fractured zones are vertically heterogeneous and are controlled by P-Facies types and relative position within the sequence stratigraphic framework.
- Higher fracture count and average fracture intensity correlates to:
  (1) **P-Facies 5** with highest average calcite content, related to the higher strength due to higher carbonate content (e.g., Gale et al., 2007; Zahm et al., 2010).
  (2) **regressive phases of "third-order" sequences**. Because *these sequences can be correlated sub-regionally with cleaning upward gamma-ray patterns*, the tie between fracture intensity and sequences provides a valuable tool to assist in the prediction of fractures in the subsurface away from cored wells.
- There are **exceptions to this pattern**, illustrating the importance of rock data in predicting fracture distribution.
  The exception is mostly seen when the sequences are not capped by P-Facies 5, or when relatively abundant P-Facies 5 occur in the transgressive phases, most likely due to significant storm deposition.
  Highly fractured intervals may occur within P-Facies 3/4 in the transgressive phases, probably related to structural diagenesis and localized structural activities.
- Average fracture spacing does not show distinct correlation with facies and sequence stratigraphy, reflecting a complex relationship among fracture attributes.

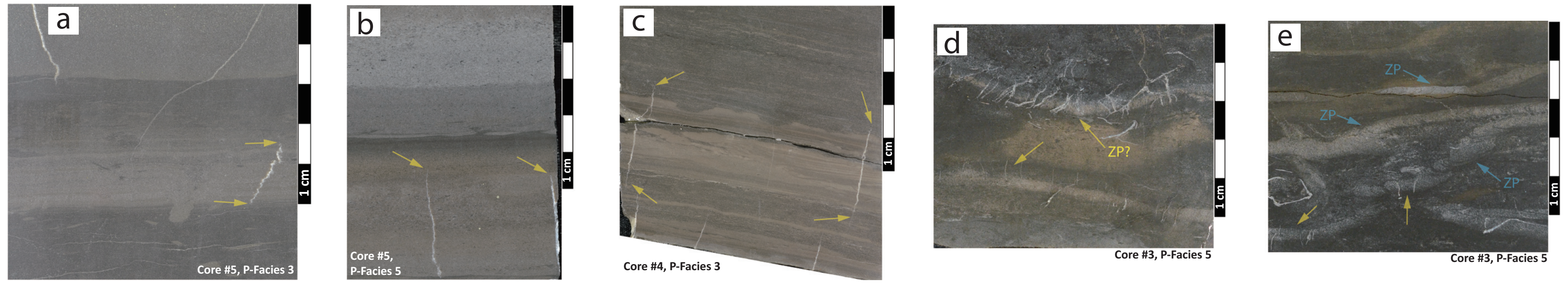
Fractures Related to Mineralogy

- A detailed comparison between fracture count and whole-core XRD mineralogy of Core #2 does not reveal any correlative relation, likely attributed to poorly defined sampling protocol (once per interval with variable sampling frequencies from <1 m to >2 m). This commonly results in insufficient data in thinly bedded and highly fractured intervals.
- To overcome this sampling issue, high-frequency x-ray diffraction (XRD) data were collected from a "fourth-order" sequence in Core #4. The results show a loosely constrained positive correlation between fracture intensity and calcite content, suggesting increasing calcite content leads to increased strength, even in higher frequency sequences.



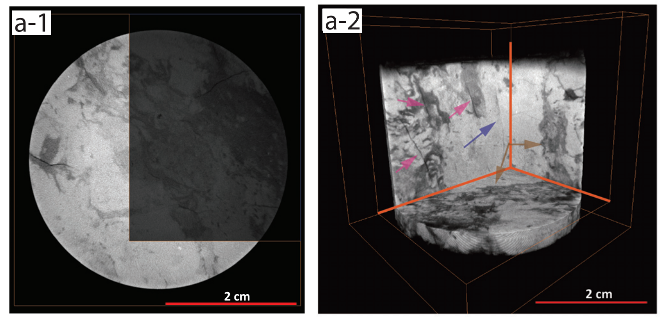
Comparison between x-ray diffraction (XRD) mineralogy and fracture intensity in a "fourth-order" sequence in Core #4

Fractures Related to Bedding Structures

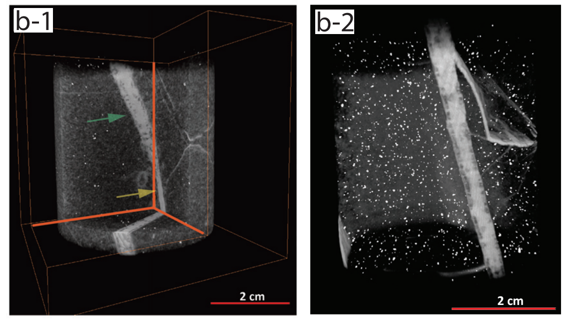


- In addition to mineralogy, attributes of mechanical units and interfaces (e.g., thickness) may control fracture height, termination, and spacing.
- The ptygmatic fractures exhibit variable relations to bedding, indicating variability of rock mechanics and its effect on affecting fracture propagation.
  The fractures are occasionally confined (a) within bed, but more commonly terminate within beds (b) and span across boundaries (c).
  Rarely, densely arrayed short fractures span across thin laminae seemingly related to chertified *Zoophycos* trace fossils (ZP in d, e).
- Confinement of fractures within relatively thin brittle laminae/beds (a, b) is related to internal deformation of ductile layers and the local opening/sliding of weak bedding planes, the latter of which reduces the stress singularity at the fracture tip and results in subcritical crack growth (e.g., Olson et al., 2009).
  Waning propagation impetus at the fracture tip may be indicated by the decreasing width along the fracture length (b, c).
- More commonly, step-over of fractures into adjacent mud-rich, relatively ductile intervals (c) may be related to the strongly bonded nature of the contact which promotes fracture propagation (Cooke and Underwood, 2001), and with the non-elastic deformation within the ductile interval (Rijken and Cooke, 2001).
  Decreasing rate of fracture propagation and decreasing effective confining pressure (Friedman et al., 1994), the latter of which may even transform the brittleness to ductility in mudrocks (Nygård et al., 2006), may also be a responsible factor.
- Although affecting mineralogy of facies, alteration of brittle and ductile layer can play a key role in determining the mechanical behavior of mudrocks (Gross and Engelder, 1995).

Fractures In Micro-CT Imaging



Core #2; P-Facies 4



Core #2; P-Facies 5

Strength & implication of micro-CT imaging
- Three-dimensional and higher-resolution (up to 40 micron in this study) imaging of fractures beneath the core surface supplement the 2-D core surface-based fracture dataset
- Reveals mineralogy of fracture-filling cement and aids in distinguishing between induced and naturally mineralized fractures

Fractures in micro-CT imaging (two 1.5 inch-diameter core plugs from Core #2)
- Variable hues of gray reflect density of minerals - higher the density, lighter the gray color (e.g., Hu et al., 2014).
  Some fractures in a-1 & 2 are likely induced fractures filled with less dense material (e.g., drilling mud) as compared to fractures in b-1 & 2 which are filled with minerals with higher density (e.g., calcite).
- Fractures commonly terminated beneath core surface (a-2) and showing variable width in three-dimensional views (b-1).

Structural Diagenesis

- Temporal variations of rock mechanical properties (i.e., structural diagenesis) may result in the present-day fracture distribution not reflecting the rock mechanical properties when the fractures initially formed (e.g., Gale et al., 2004; Shackleton et al., 2005; Laubach et al., 2010).
- Fracture intensity varies among sequences and individual cores (i.e., clustering of fractures), partly due to **variable proportions of P-Facies** related to different parts (e.g., proximal vs. distal) of the depositional system, leading to variable potential for structural diagenesis from a ***spatial*** perspective and, consequently, to variable fracture distribution. **Various intensities of structural activities** and **different burial histories of the rock** may also be responsible.
- Co-existence of abundant "early" ptygmatic and "early-to-late" vertical extension fractures in P-Facies 5 suggests ***temporal*** evolution of rock mechanical properties.
- Because of high initial porosity-permeability, high-energy P-Facies 5 is susceptible to extensive calcite cementation following deposition which adds rock strength at a relatively early stage and facilitates the formation of ptygmatic and "early" vertical extension fractures. As the rock further gains rock strength following burial, "late" vertical extension fractures formed.
- Despite the potential offset between the present-day fracture distribution and the mechanical stratigraphy at the time of fracturing, and a challenge in predicting an exact fracture count due to a clustered fracture distribution, the correlative trend between fracture intensity and facies, and relative positions in the sequence stratigraphic framework, the latter of which can guide the prediction of grain texture, initial porosity, and mineralogy, can provide insight for predicting the relative fracture abundance in the "Mississippian Limestone" play in this area.

Limitations

1. Geographic separation of cores (several to 10's of km) results in a clustered fracture dataset.
2. Narrow core width (85 mm) omits widely spaced fractures, resulting in an incomplete picture of lateral fracture distribution.
3. Measurements of the fracture attributes can be equivocal.
   "True" fracture height is underestimated when the fractures terminate due to missing core pieces and/or at the core edge. This effect can be worsened by an orthogonal orientation of the core.
   Examination of "true" fracture width is limited by a 2-D view of the core surface and occasional breakage of core along fractures and the angle of core surface intersecting the fracture plane.
4. Poorly developed bedding structures and complex fracture arrangement result in a poorly constrained relationship among fracture attributes (e.g., height, spacing) and bed thickness.
5. Fractures terminating beneath the core surface cannot be captured in a core surface-based investigation, illustrating the necessity of incorporating 3-D imaging techniques in reinforcing the comprehensiveness of a core surface-based fracture dataset.
6. Detailed understanding of the mineralogical control of the fracture distribution is hampered by the non-systematic sampling protocol.

Key Points

1. Natural fractures are common in the "Mississippian Limestone" play in north-central Oklahoma.
2. The fractures exhibit concentrated populations in certain attributes, although sampling bias related to narrow width in individual core should be considered.
3. Four types of natural fractures are identified, with the ptygmatic fractures being most common.
4. Fractures are commonly terminated beneath the core surface and exhibit variable width, illustrating the value of 3-D imaging in producing a comprehensive fracture dataset.
5. Fracture abundance correlates with facies and sequence stratigraphy, illustrating the value of sequence stratigraphic approach in characterizing and predicting natural fracture distribution.
6. Integrating fracture data at various scales from seismic data, outcrop, core surface, thin-sections, and micro-CT imaging, accompanied with high-resolution mineralogy data would be most applicable to developing a comprehensive, scale-independent natural fracture dataset.

On-going work: micro-CT imaging; higher frequency sampling for mineralogy; tying fracture abundance with rock mechanical data; measuring the natural fractures in a highly fractured Mississippian outcrop; modelling the formation of ptygmatic fractures (laboratory); comparative study with other unconventional reservoirs (e.g., Bakken play).

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