Estimation of Dispersion in Orientations of Natural Fractures from Seismic Data: Application to Discrete Fracture Network Modeling

Reinaldo J Michelena*, Kevin S. Godbey, Huabing Wang, James R. Gilman and Chris K. Zahm
Examples of Fractured Shales

Marcellus shale

Whitby Mudstone (NE England)

Plan view

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Durham University
Examples of Fractured Shales

Hanover gray-green shale (NY)

SUNY Fredonia

AAPG (photo taken by Bob Jacobi)

Utica shale
Examples of Fractured Shales

Eagleford shale

Devonian Black shale

FLICKR (photo taken by Aikko Heiwa)

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Plan view
Simple Fracture Interpretation

Hanover gray-green shale (NY)

Fracture lengths and orientations

SUNY Fredonia
Fracture Lengths and Orientations

Marcellus  Whitby  Hanover  Utica  Eagleford

Increase complexity in fracture geometry

Warning: very qualitative!
Motivation

• Fracture geometry may vary significantly between (and within) shale plays

• Existing natural fractures strongly influence the effectiveness (drainage) of any stimulation program

• Depending on in-situ stress anisotropy and fracture geometry, induced fractures may reactivate, cross, dilate or be arrested by existing natural fractures
Seismic Scale Fracture Geometry

- Density: number of fractures per unit volume
- Dominant orientation: most frequent orientation in a given volume of rock
- Orientation dispersion: variability of orientations in a given volume (circular variance)

How can we estimate the different components of the fracture geometry from seismic data?
Fracture Geometry: Density

- Typically estimated from structural seismic attributes, azimuthal seismic AVO, or 3C data
- Careful calibration with log derived density information can help select the most appropriate attribute
Fracture Geometry: Orientation

• Typically estimated from structural seismic attributes, azimuthal seismic AVO, or 3C data
• We estimate orientations by computing the local gradient on selected structural attributes

**Trick:** eliminate the direction information by referring all angles to the interval \([0, 180)\) degrees
From Curvature to Orientations

Curvature weighted orientation map
Statistics of fracture angles

Basic fracture statistics:
- Mean
- Mode
- Variance

Polar plot
Rose diagram
Original Orientations

2450 m

1650 m

N
Dominant Orientations
Circular variance

• The circular variance of $V$ of $N$ unit vectors $\mathbf{U}_n$ is defined as:
  
  $$V = 1 - \frac{R}{N}$$

  where

  $$R = \left| \sum_{n=1}^{N} \mathbf{U}_n \right|$$

  and

  $$V \in [0, 1]$$

• Commonly used in DFN modeling as the Fisher coefficient $K$
  
  $$K = \frac{1}{V}$$

  where

  $$K \in [1, \infty)$$
Circular variance: properties

In theory, circular variance is ...
- Intrinsically a 3D, spatially varying parameter
- Designed to measure spread in directions, not orientations
- Dependent on the selection of the origin for angles

In practice, circular variance is typically ...
- Estimated from FMI data along the well path (1D data with sample bias)
- Assumed constant in the interwell region for DFN modeling
- Estimated separately for different fracture groups or families
Fracture Lengths and Orientations

- Marcellus
- Whitby
- Hanover
- Utica
- Eagleford

Small Variance, High Fisher
Large Variance, Small Fisher

Increase complexity in fracture orientations

Warning: very qualitative!
Estimation of $R/N$

$R/N = 0.9882$

$R/N = 0.6863$

$R/N$ depends on the selection of the reference axis
Estimation of Fracture Dispersion

- Estimate variance for two orthogonal reference axes and select the maximum

Actual fracture orientation dispersion $M$
From Dispersion to Fisher Coeff.

- Limits of orientation dispersion $M$
  - $2/\pi$ (≈ 0.64) -> random fracture orientations
  - 1 -> constant fracture orientations

- The Fisher coefficient $K$ needed for DFN modeling can be estimated from dispersion $M$ as

\[
K = \frac{1 - 2/\pi}{1 - M}
\]

$K \in [1, \infty)$
From Curvature to Dispersion

Maximum Curvature

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From Curvature to Dispersion

Maximum Curvature and Orientations

2450 m

1650 m
From Curvature to Dispersion

$R/N$ with respect to East
From Curvature to Dispersion

\[ \frac{R}{N} \text{ with respect to North} \]
Fracture Dispersion

Maximum of $R/N$

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From Seismic to DFN

Max Curvature

Fisher Coefficient

Dominant orientation

Modeled fractures
Seismic constraints & DFN

~ 6,000 seismic control points
~ 60,000 DFN fracture planes
From DFN to Flow Simulation

Dominant orientation and density

High Fisher, pressure at 100 days

Low Fisher, pressure at 100 days

Depletion areas (difference)
Conclusions

• Seismic data can help in the characterization of fracture geometry, not only density and orientation but also orientation dispersion
• Orientation dispersion a modified version of the circular variance that is independent of direction
• Density, dominant orientation, and dispersion can be used to constrain DFN modeling
• High and low fracture dispersion flow simulation models show small differences in depletion
• More research is needed to understand the effect of dispersion in hydraulic fracturing as well as other issues such as fracturing scales, calibration with dispersion from log data, and seismic velocity anisotropy