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

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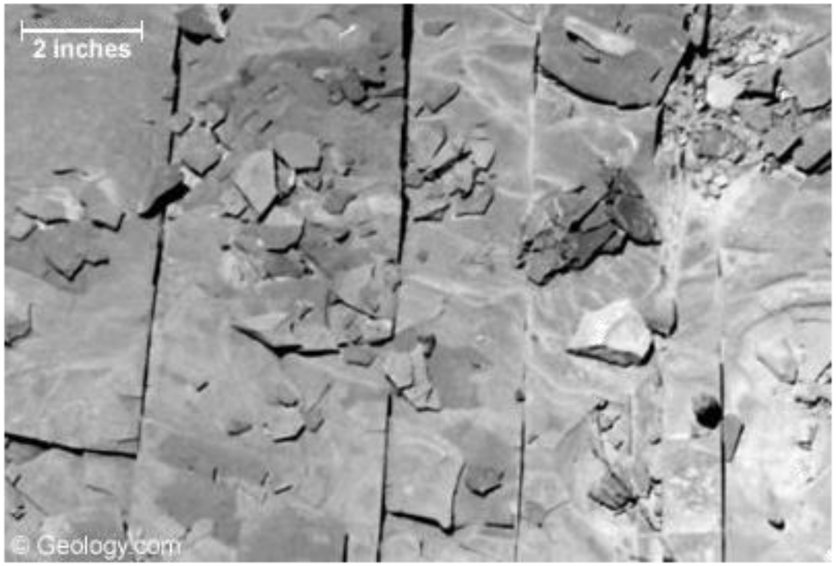
Examples of Fractured Shales

Marcellus shale



Geology.com

Whitby Mudstone (NE England)

Durham University

Plan view

Examples of Fractured Shales

Hanover gray-green shale (NY)

SUNY Fredonia

Utica shale

AAPG (photo taken by Bob Jacobi)

Examples of Fractured Shales

Eagleford shale

FLICKR (photo taken by Aikko Heiwa)

Devonian Black shale

Geology.com

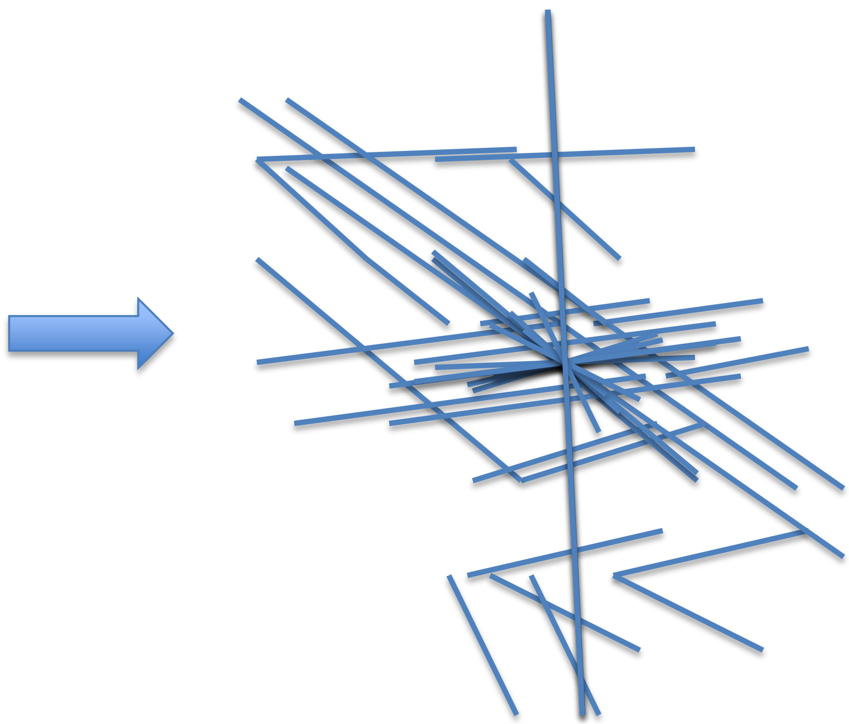
Plan view

Simple Fracture Interpretation

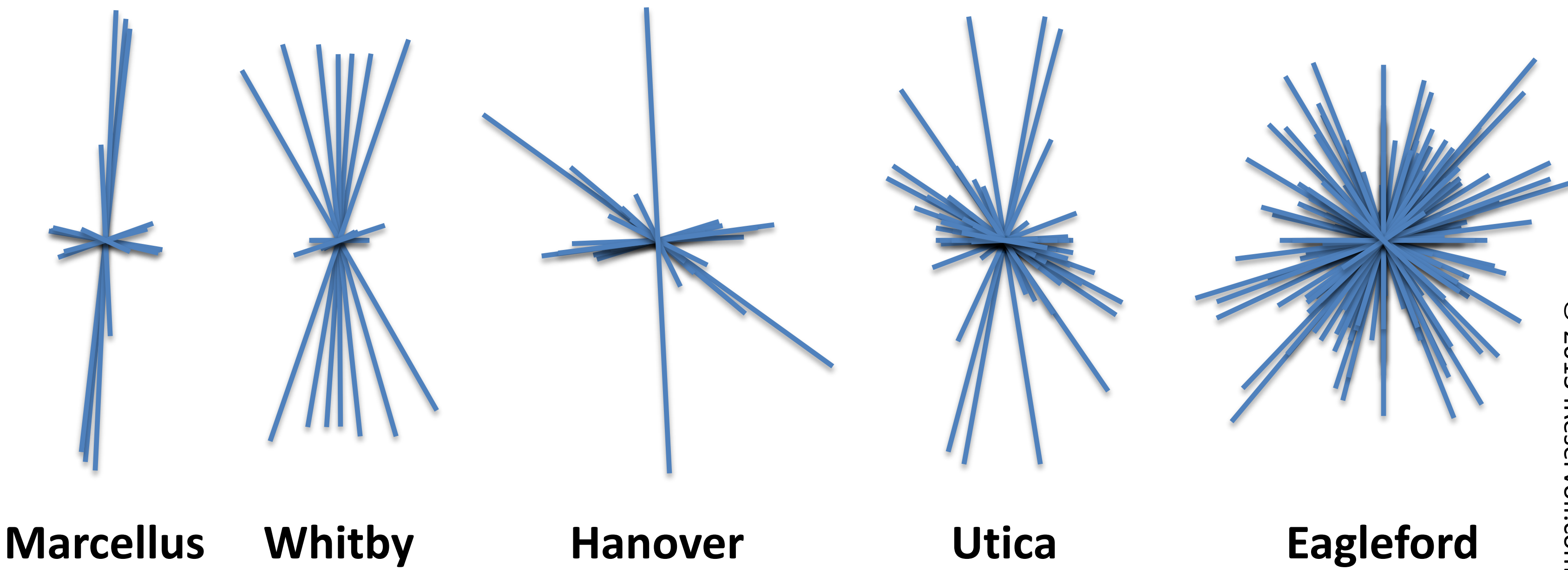
Hanover gray-green shale (NY)

SUNY Fredonia

Fracture lengths and orientations



Fracture Lengths and Orientations



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

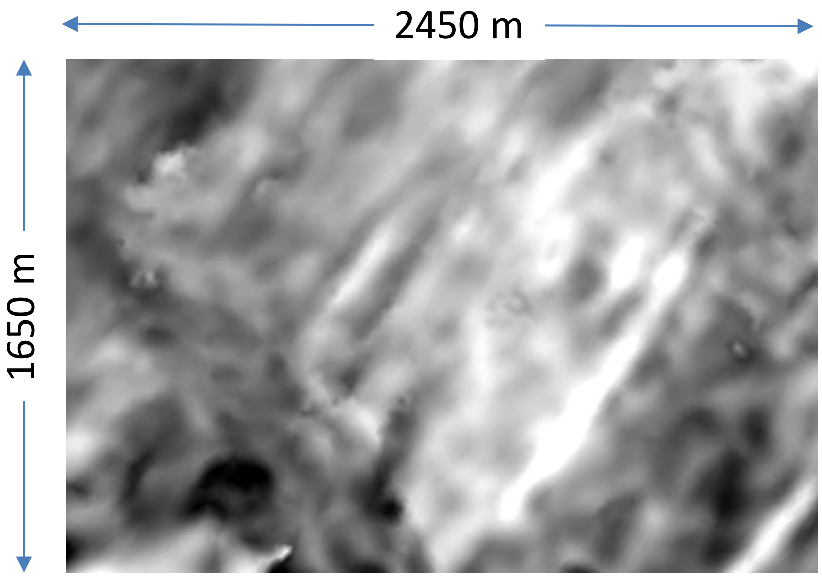
Seismic Scale Fracture Geometry

- 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)

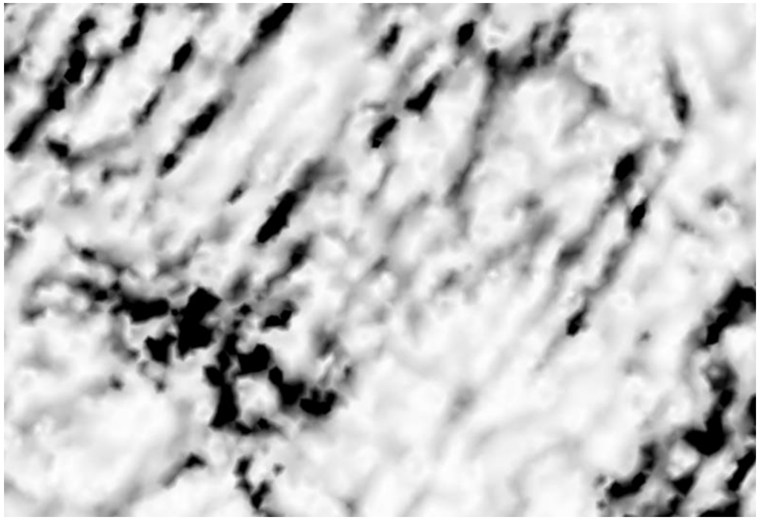
How can we estimate the different components of the fracture geometry from seismic data?

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



Amplitude

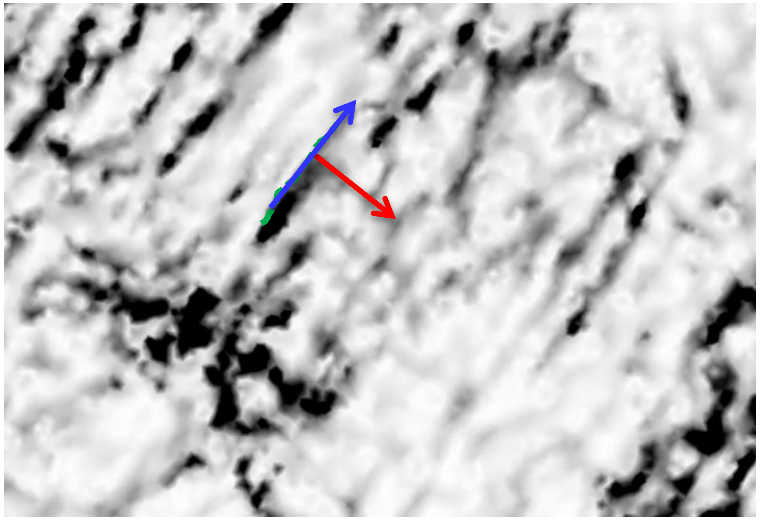


Maximum 3D Curvature

N

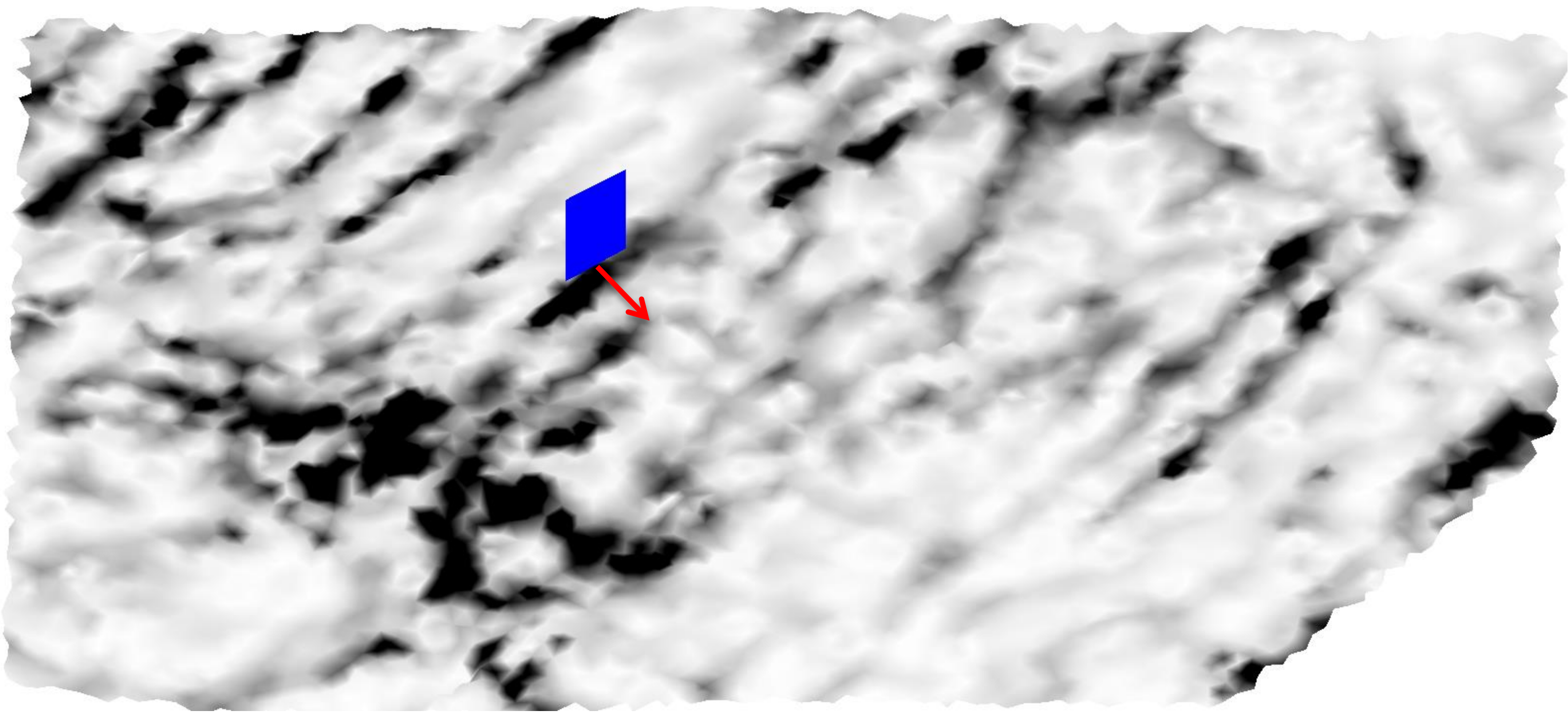
Fracture Geometry: Orientation

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



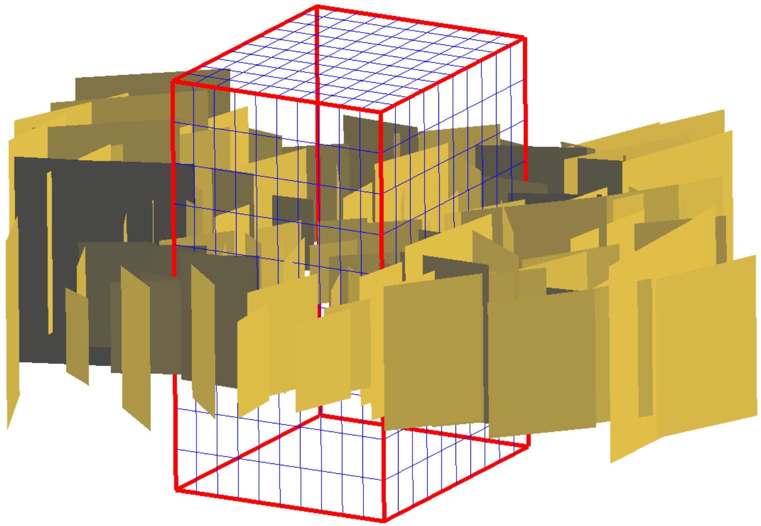
Trick: eliminate the direction information by referring all angles to the interval [0, 180) degrees

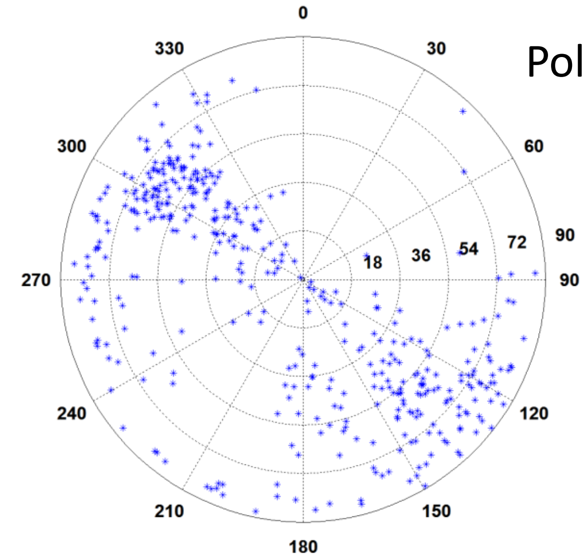
From Curvature to Orientations



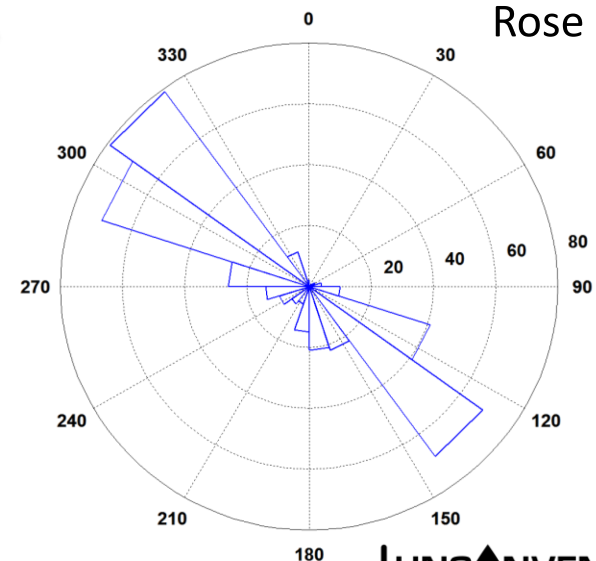
Curvature weighted orientation map

Statistics of fracture angles





Polar plot



Rose diagram

Basic fracture statistics:

- ~~Mean~~
- Mode
- Variance

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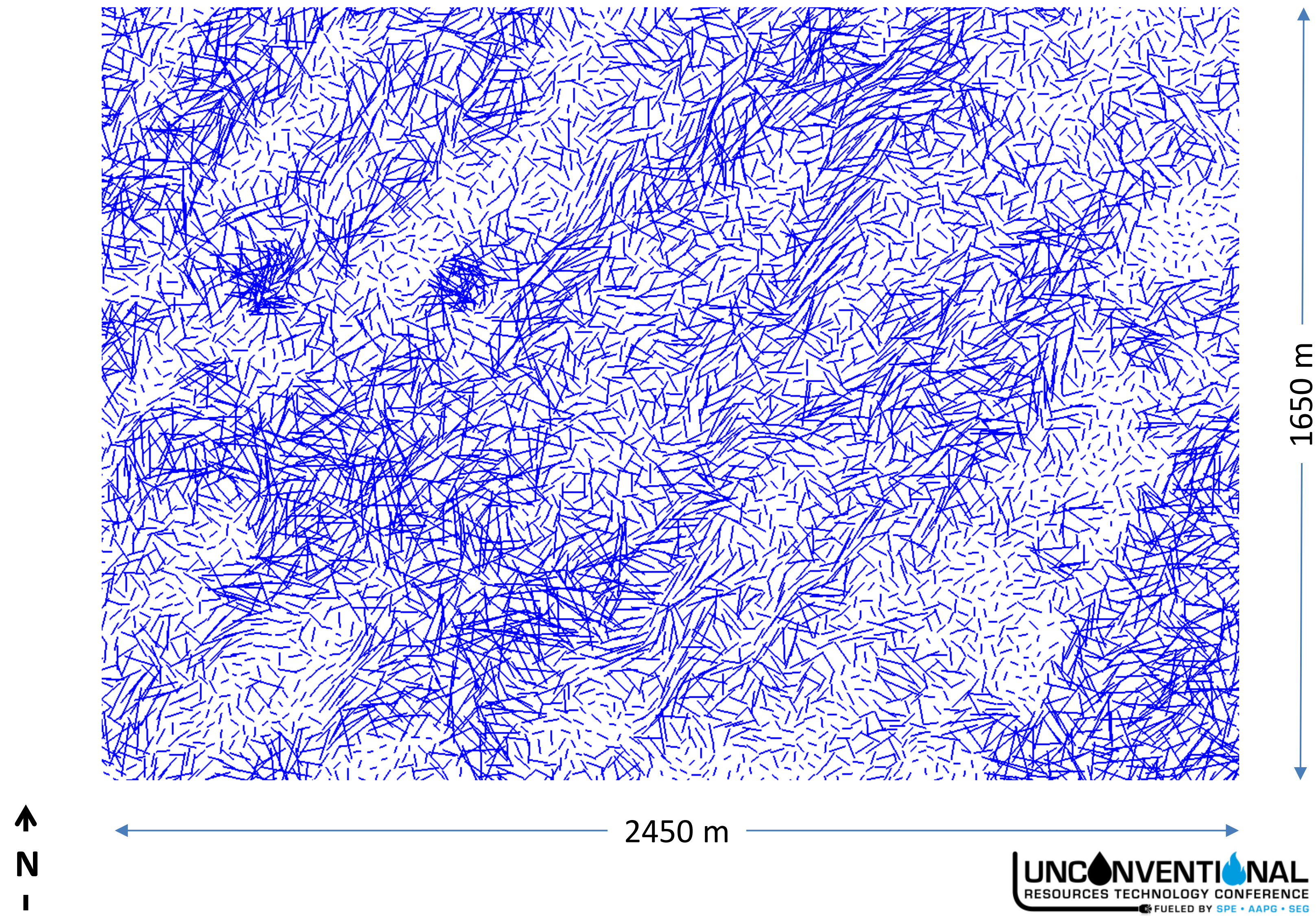
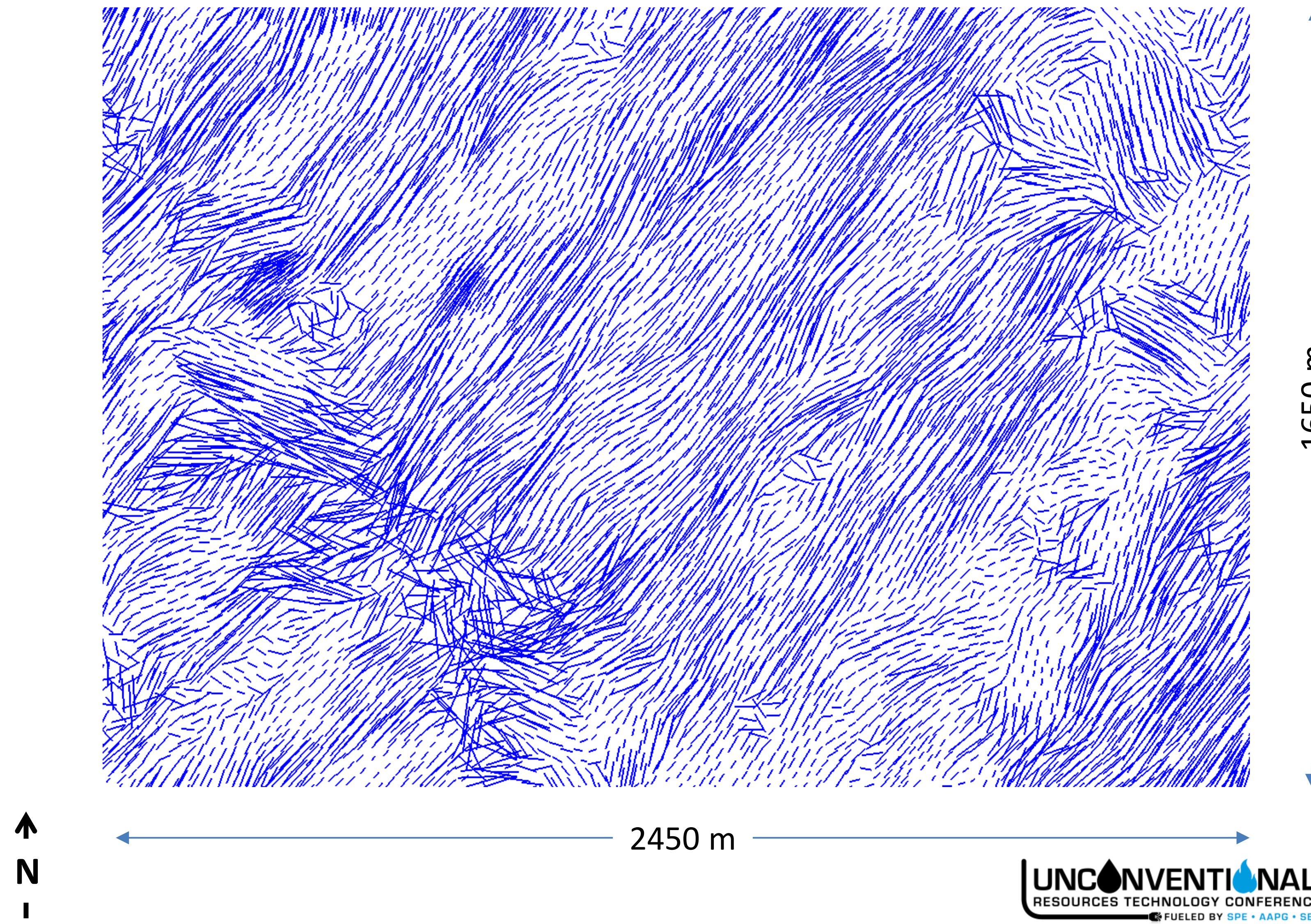
Original Orientations



Dominant Orientations



Circular variance

- The circular variance of $\boldsymbol{V}$ of $\boldsymbol{N}$ unit vectors $\widehat{\boldsymbol{U}_n}$ is defined as:

$$\boldsymbol{V} = 1 - \boldsymbol{R}/\boldsymbol{N} \quad \text{where}$$

$$\boldsymbol{R} = |\sum_{n=1}^{N} \widehat{\boldsymbol{U}_n}| \quad \text{and} \quad \boldsymbol{V} \in [0,1]$$

- Commonly used in DFN modeling as the Fisher coefficient $\boldsymbol{K}$

$$\boldsymbol{K} = 1/\boldsymbol{V} \quad \text{where}$$

$$\boldsymbol{K} \in [1, \infty)$$

Circular variance: properties

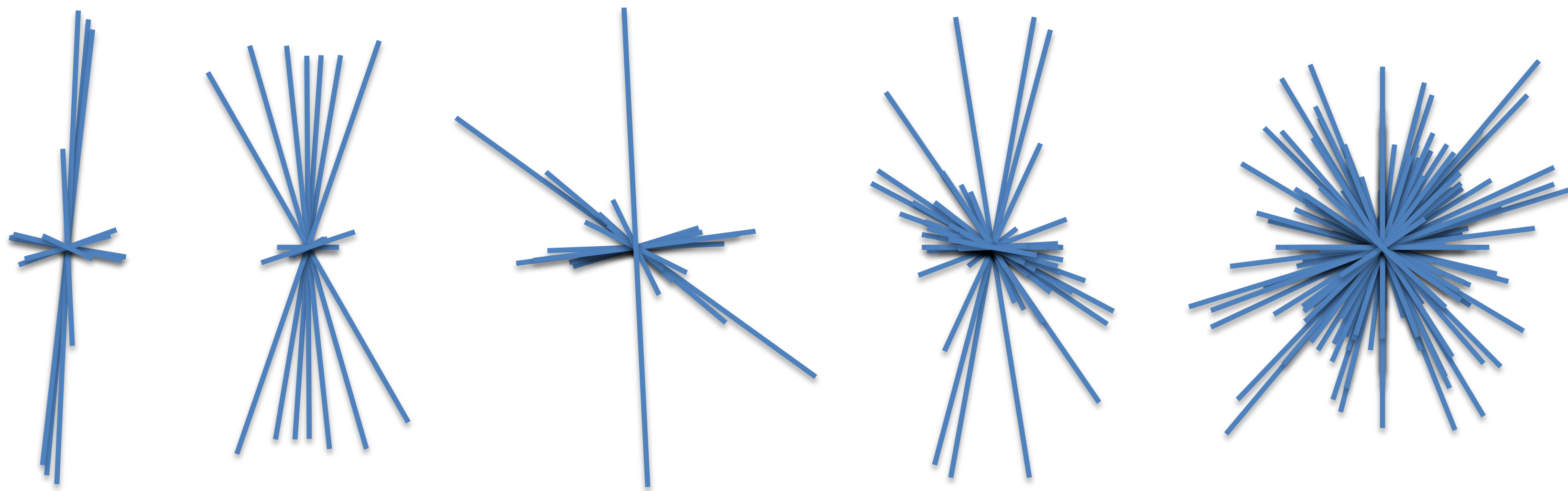
In theory, circular variance is …

- 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

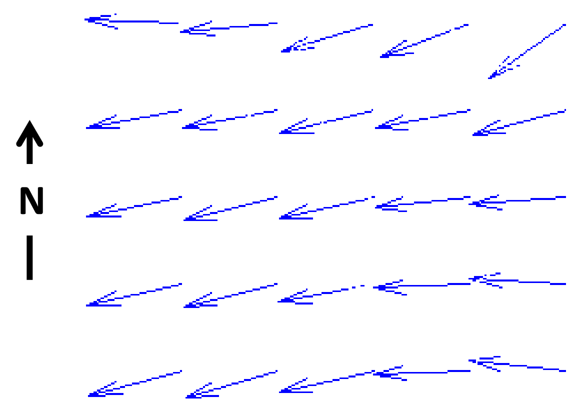


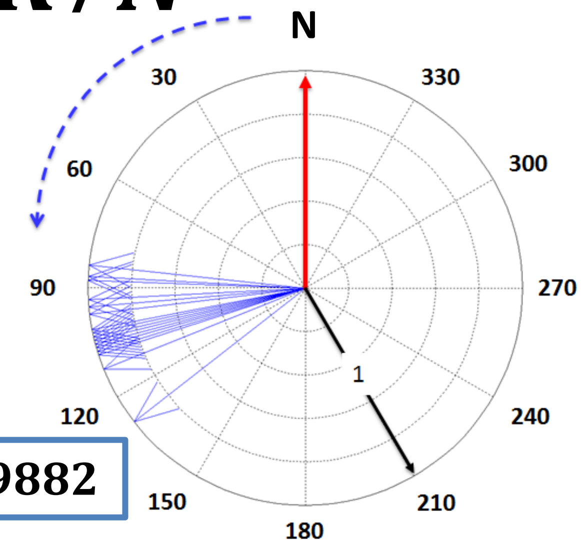
Small Variance, High Fisher → Large Variance, Small Fisher

Increase complexity in fracture orientations

Warning : very qualitative!

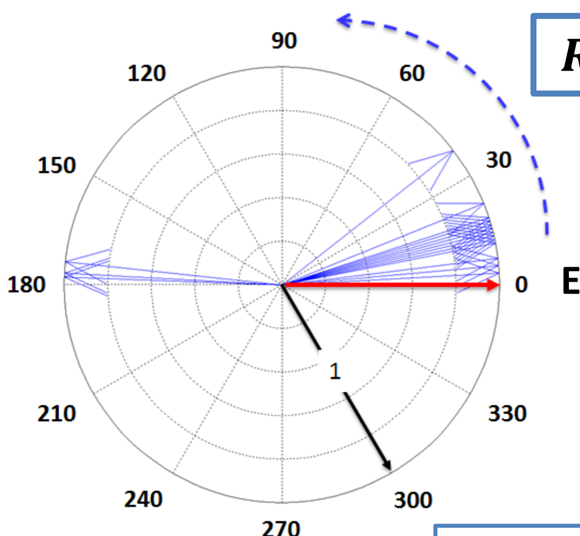
Estimation of R/N



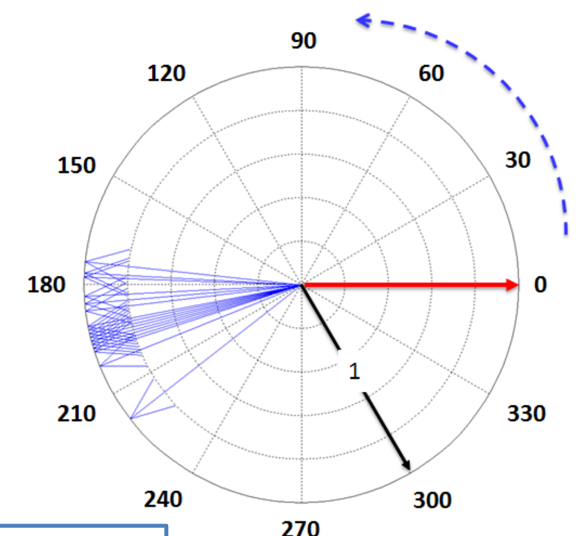


$R/N = 0.9882$

$R/N = 0.6863$



[0,180)
trick



R/N depends on the selection of the reference axis

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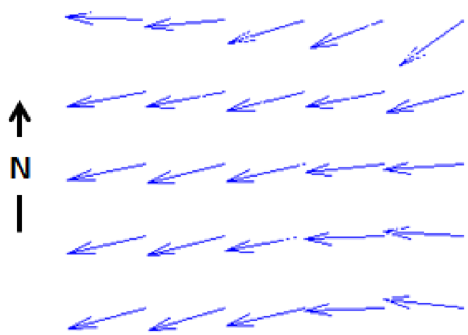
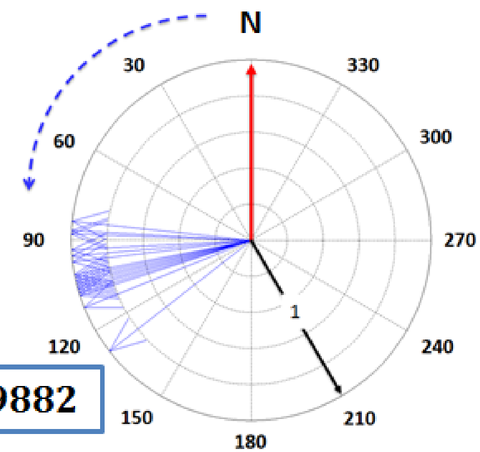
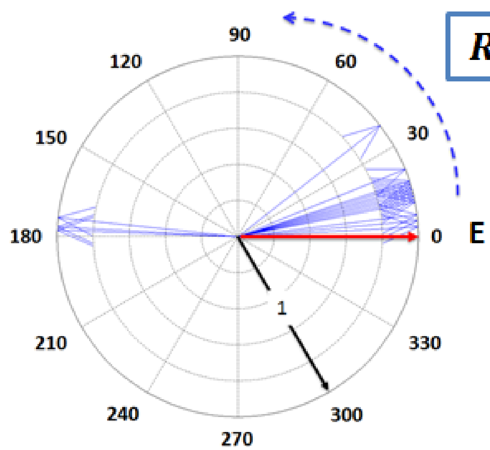
Estimation of Fracture Dispersion

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





$R/N = 0.9882$



$R/N = 0.6863$

Actual fracture orientation dispersion M

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From Dispersion to Fisher Coeff.

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

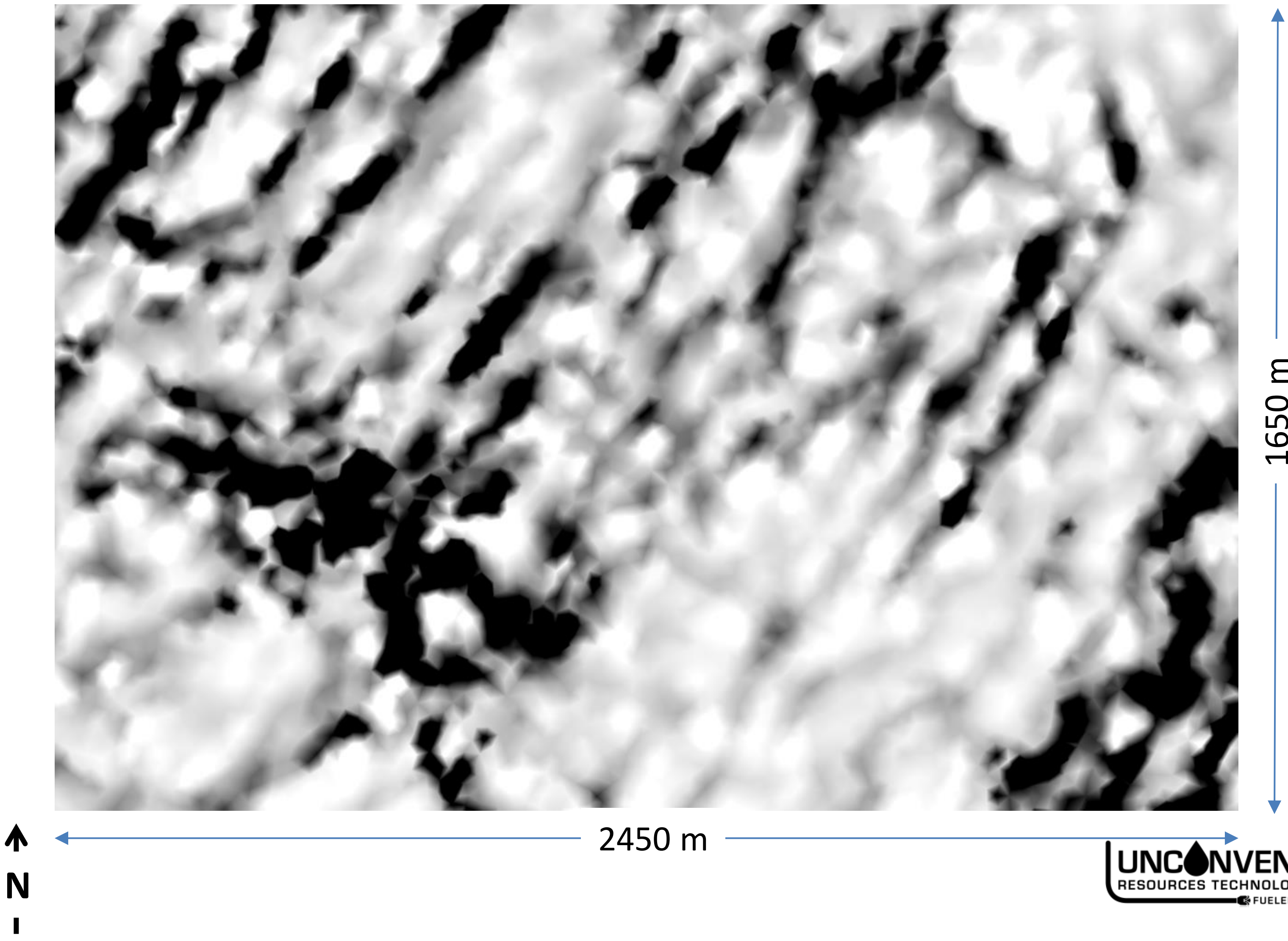
- The Fisher coefficient $\boldsymbol{K}$ needed for DFN modeling can be estimated from dispersion $\boldsymbol{M}$ as

$$\boldsymbol{K} = \frac{1 - 2/\pi}{1 - \boldsymbol{M}}$$

$$\boldsymbol{K} \in [1, \infty)$$

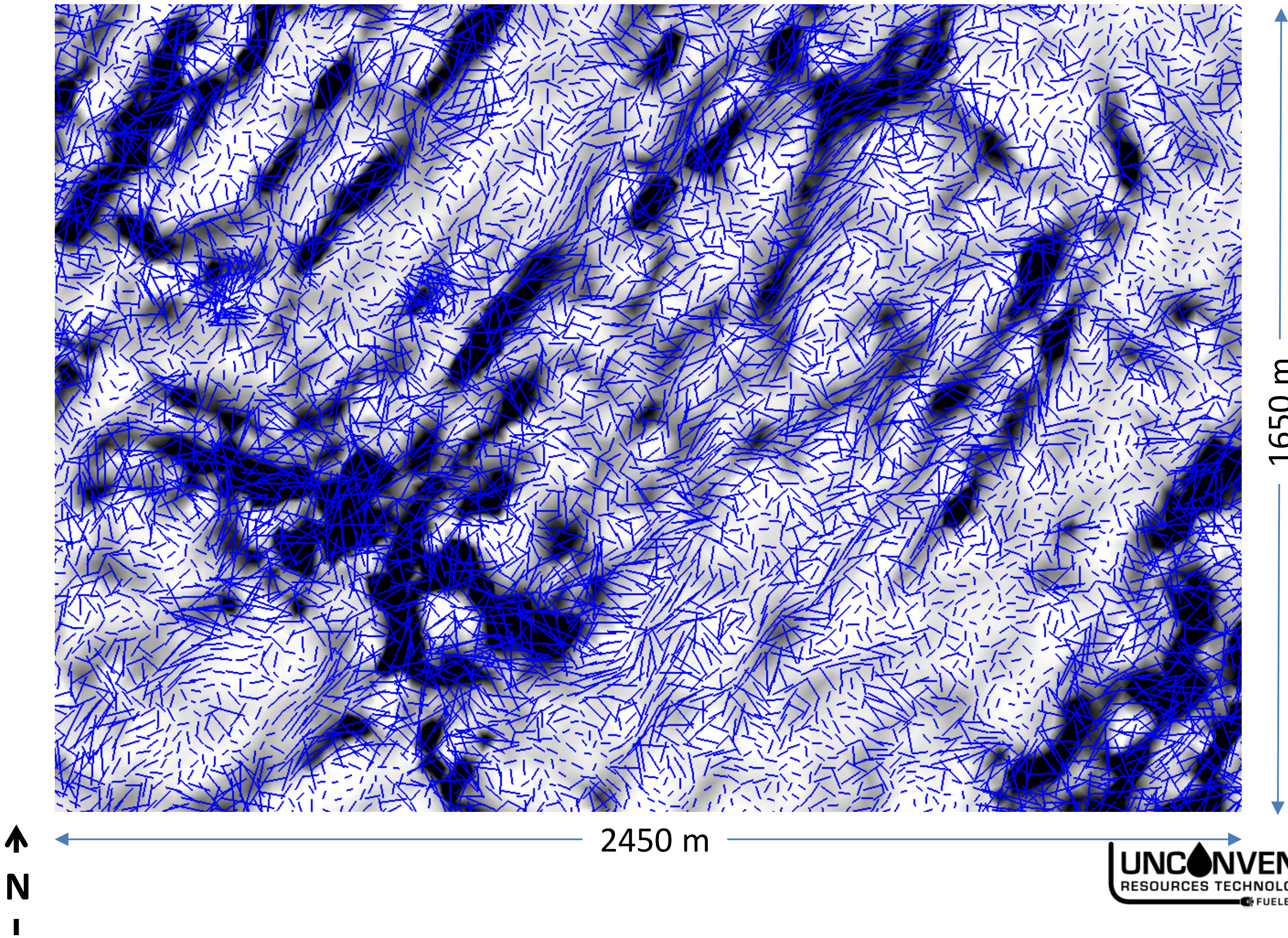
From Curvature to Dispersion

Maximum Curvature



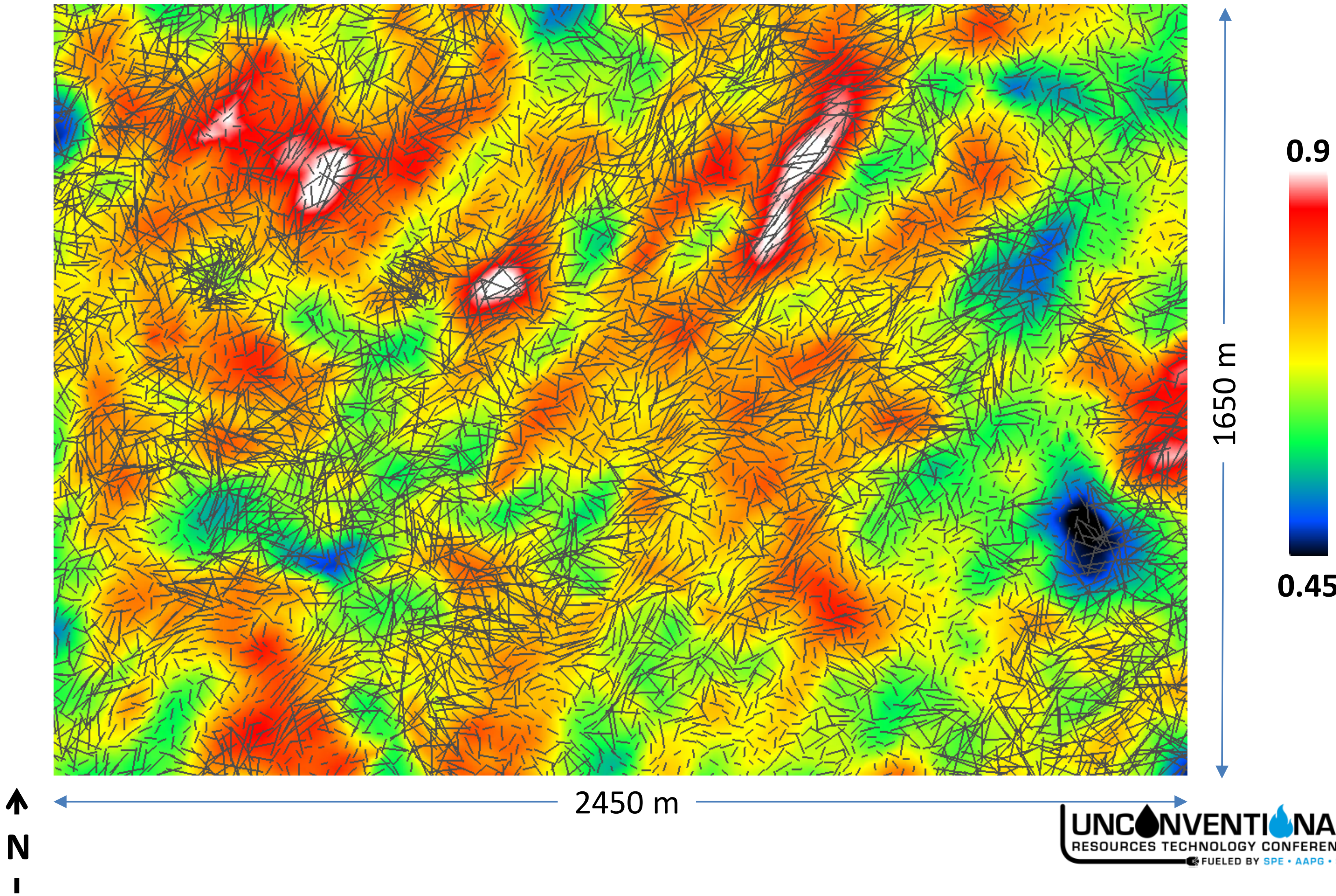
From Curvature to Dispersion

Maximum Curvature and Orientations



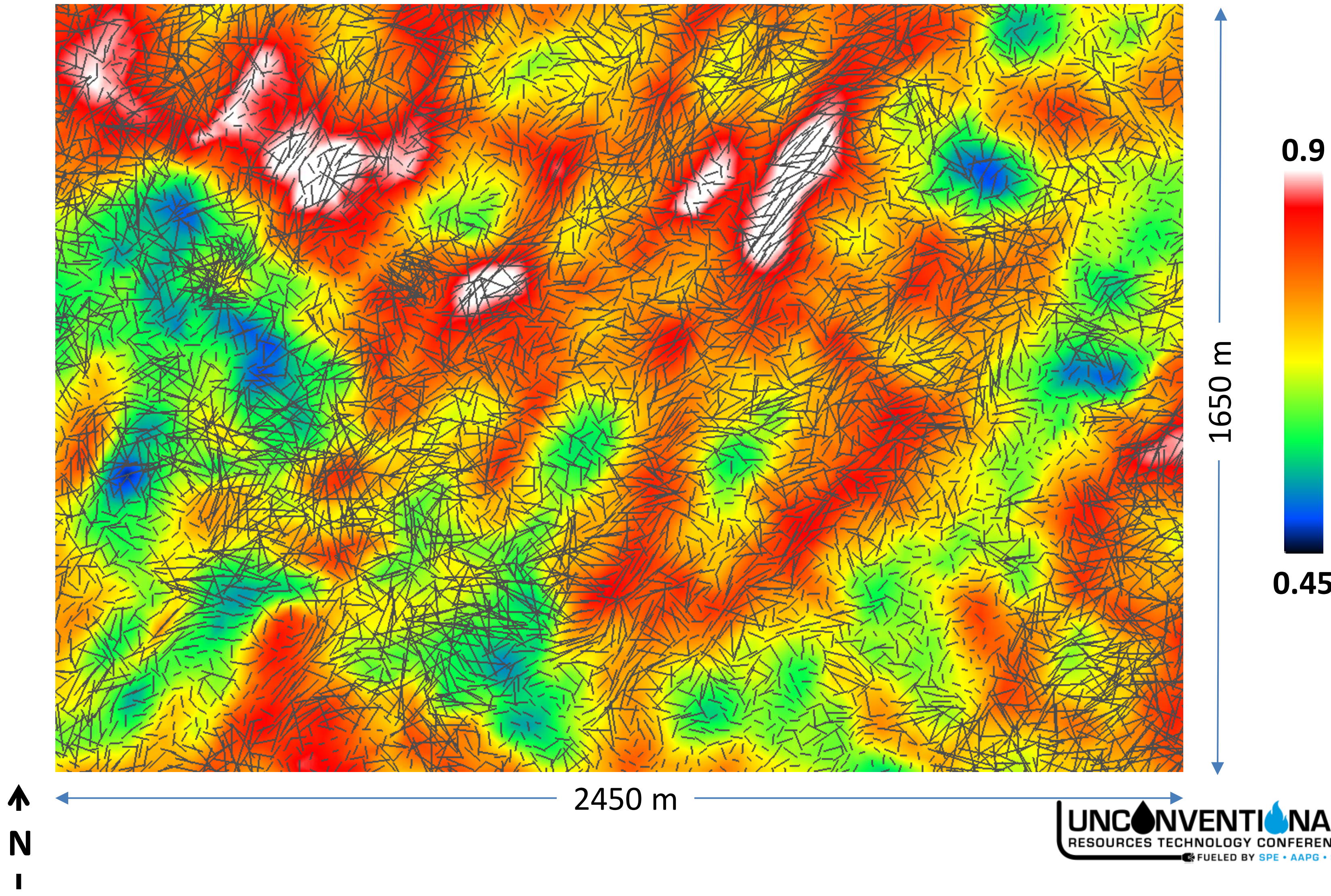
From Curvature to Dispersion

R/N with respect to East



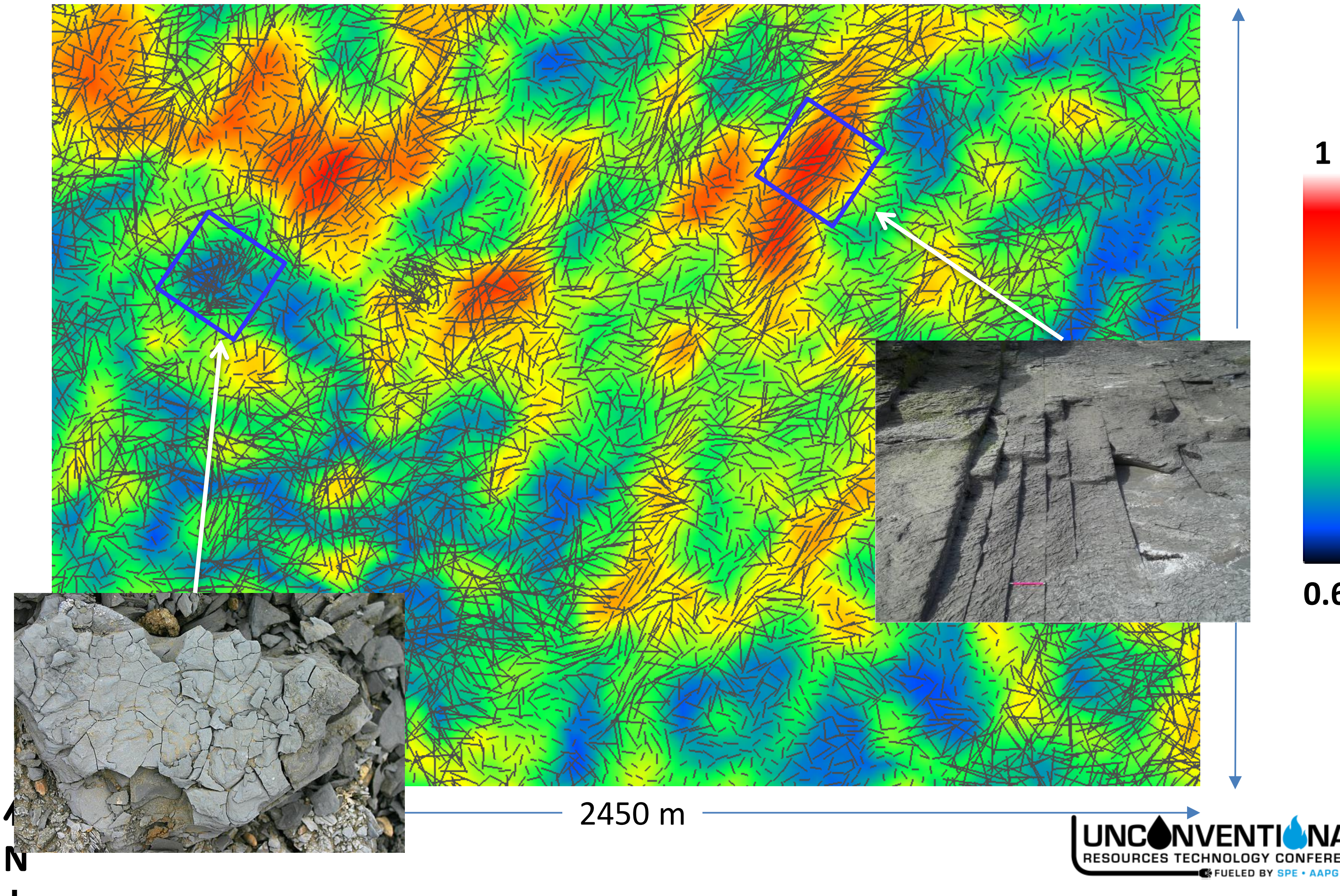
From Curvature to Dispersion

R/N with respect to North

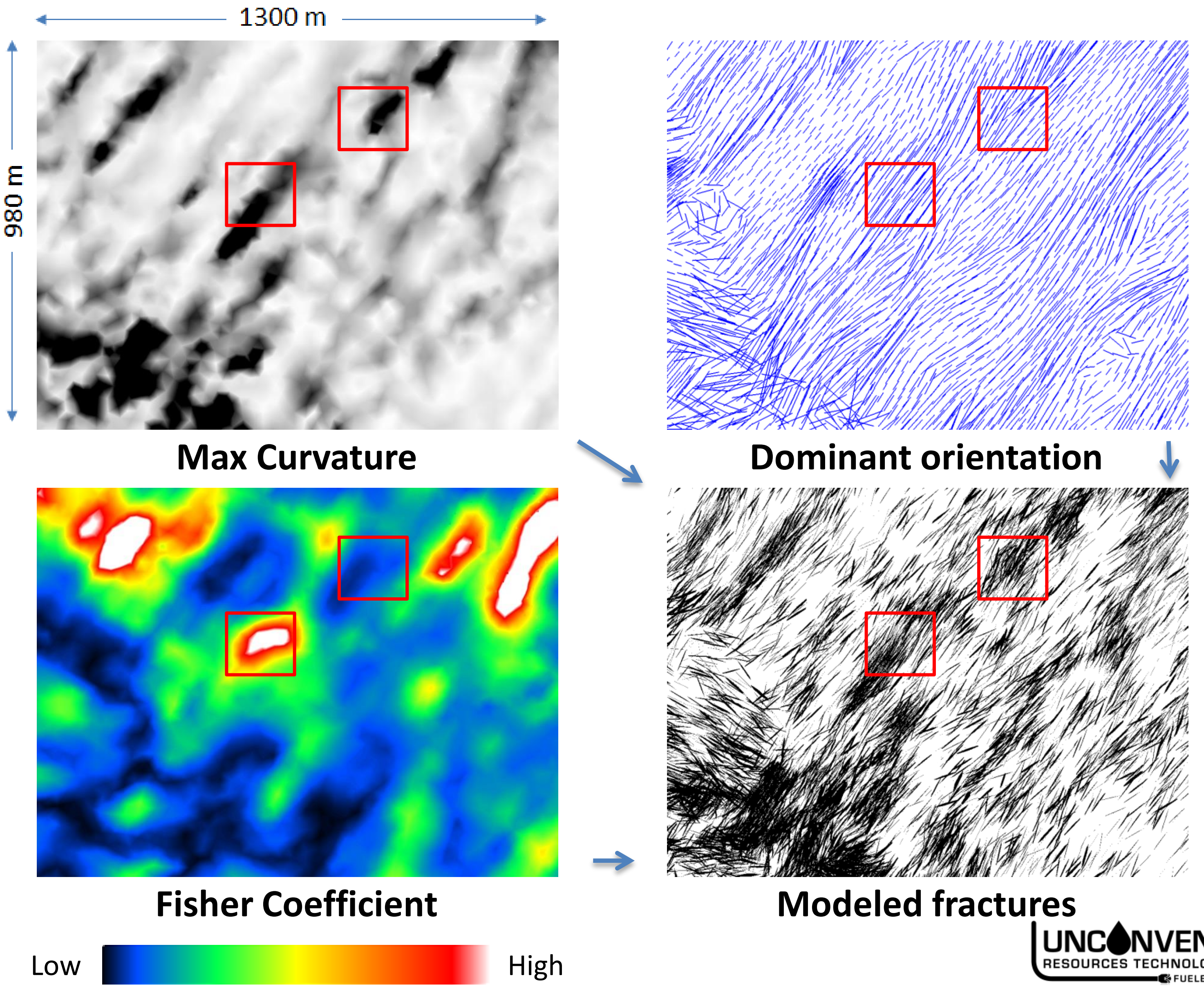


Fracture Dispersion

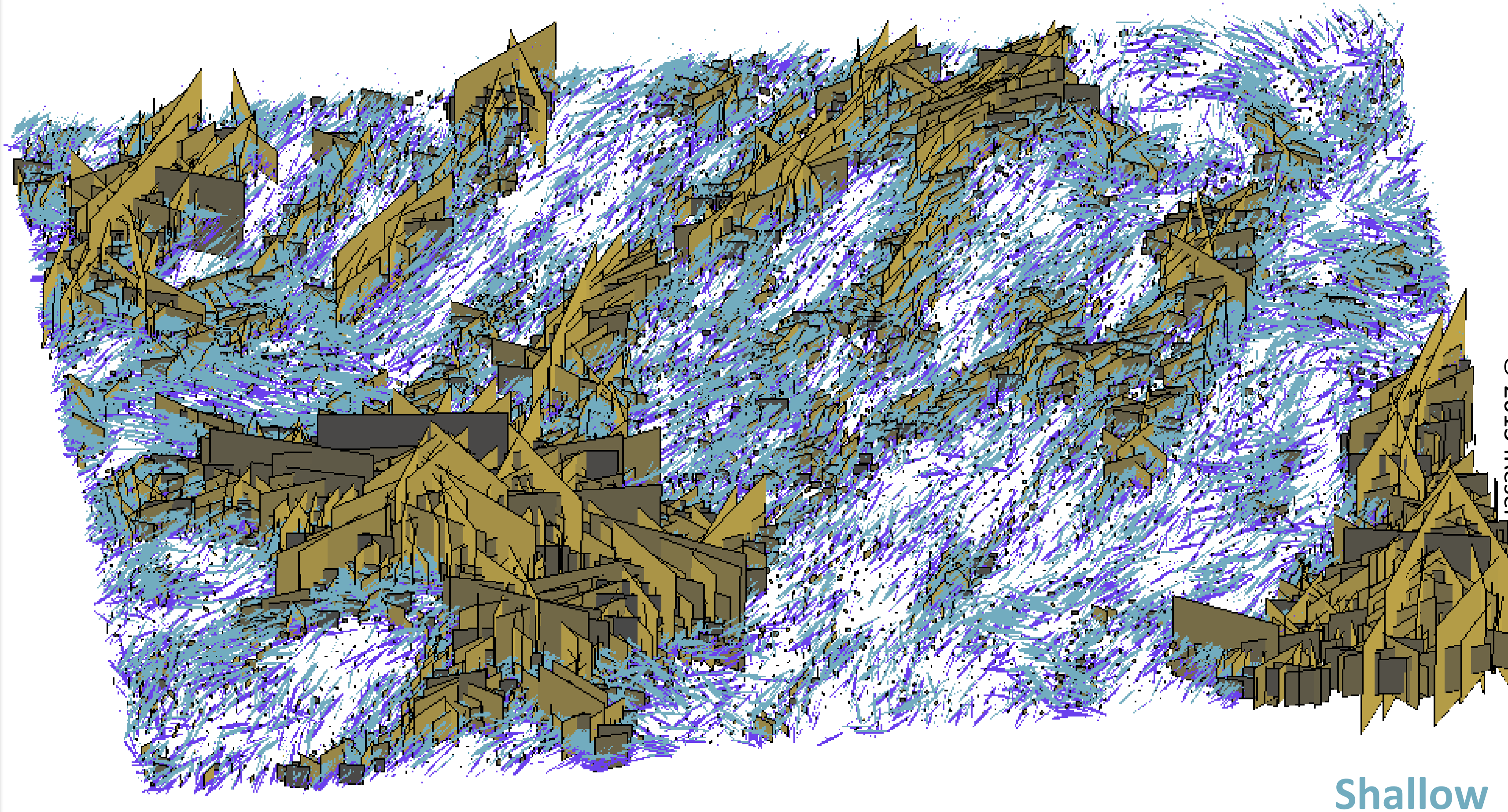
Maximum of R/N

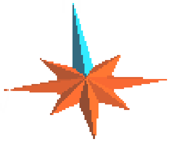


From Seismic to DFN



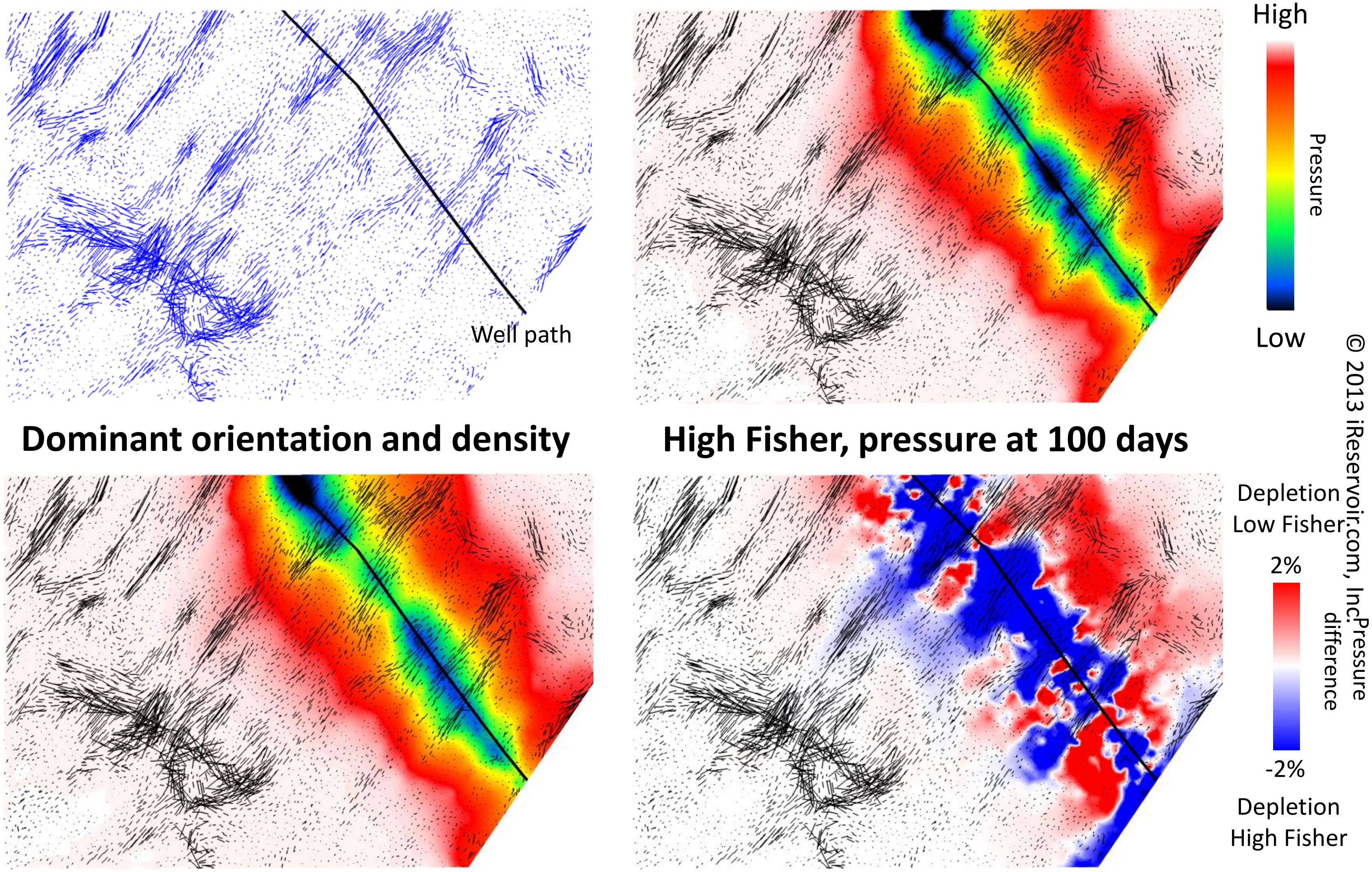
Seismic constraints & DFN





~ 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