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A Decade Monitoring Shale Gas Plays Using Microseismicity: Advances in the Understanding of Hydraulic Fracturing

17-Feb-15

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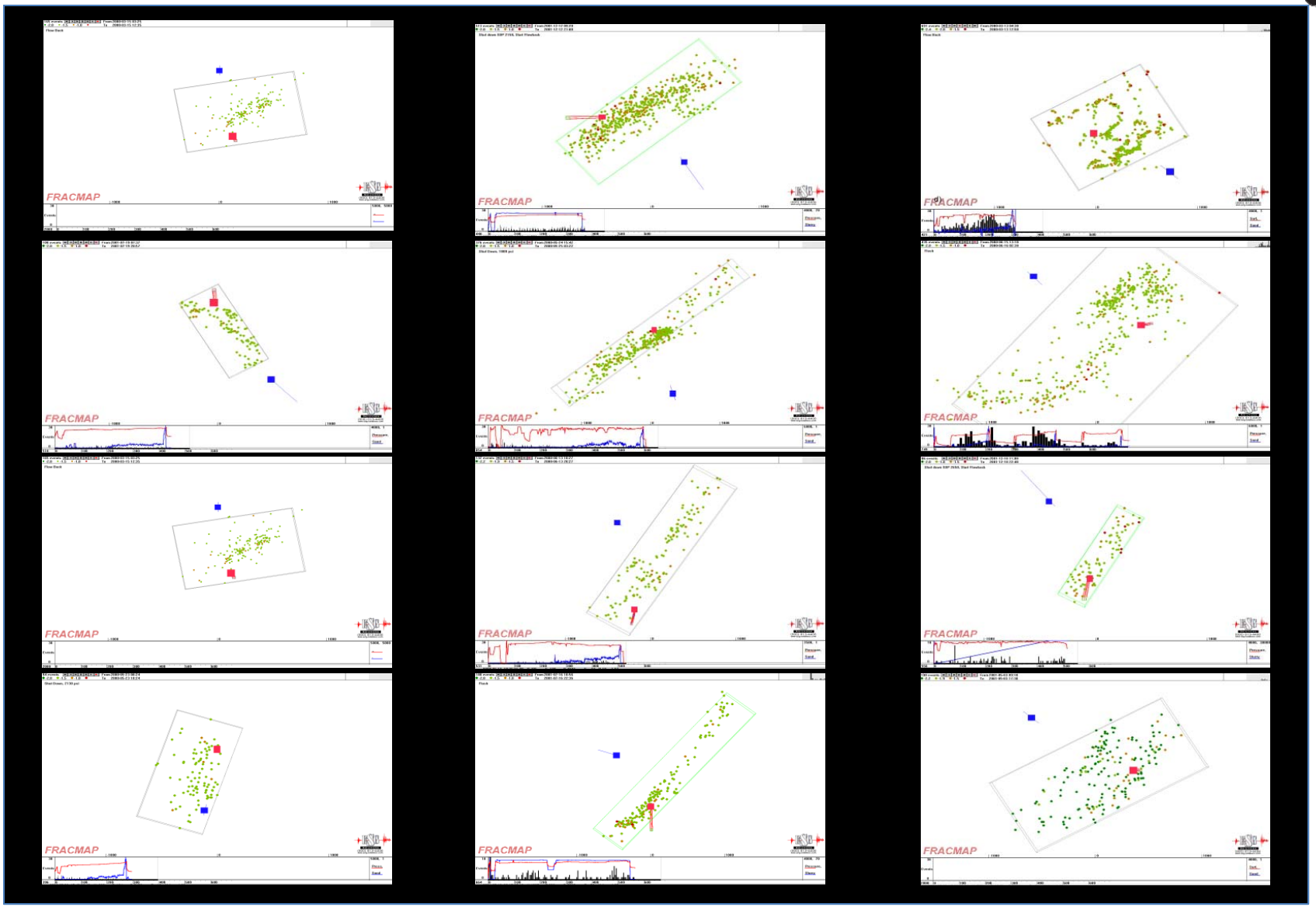
Introduction

- Early assumptions:
  - Rock is a homogeneous mass with no pre-existing structure
  - Hydraulic stimulation nucleates fractures which propagate through the rock
  - Fractures grow asymmetrically about the treatment zone
  - Fractures are vertical to sub-vertical
- Introduction of microseismic monitoring in ~2000 challenged a number of these assumptions
  - Fractures do not always grow symmetrically
  - Changes in treatment programs and completion styles can affect fracture growth
  - Not all fractures are vertical
  - Pre-existing structures such as natural fractures exist in many geological formations.
- We review the evolution of microseismic monitoring as it has been applied to hydraulic fracturing and how it has helped shape the current understanding of reservoirs and fracing.

Early Days of Monitoring

- Single, vertical, offset observation arrays
- Microseismics can identify stage dimensions only - Length, Height, Orientation
  - Draw a box/envelope around events to determine stimulated volume
- More events = more production
- Real-time geo-hazard avoidance

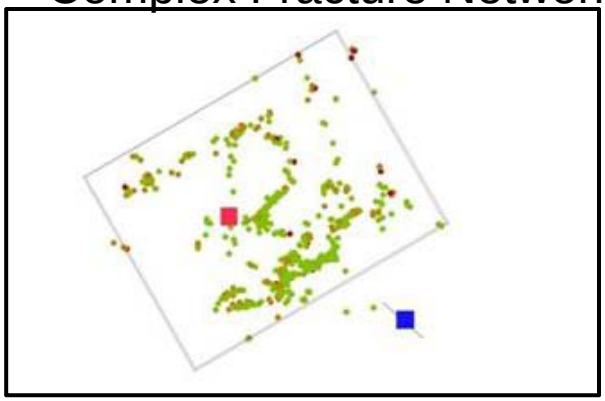
Fracture Variability, Barnett Shale, 2000



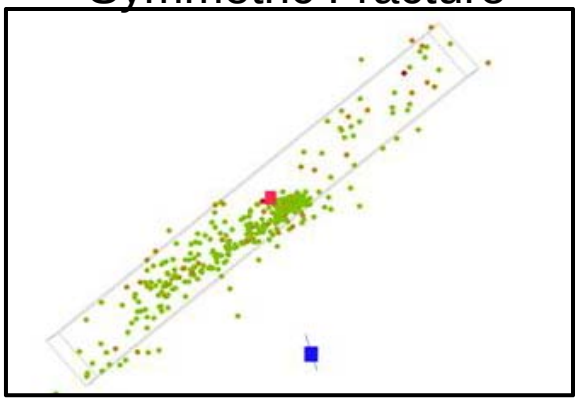
SPE 77440

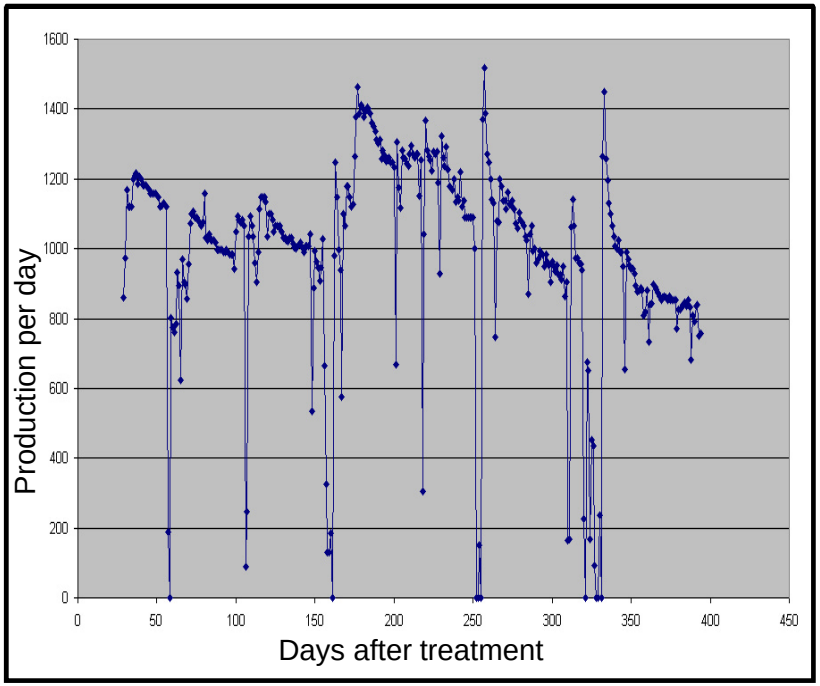
Role of Structure in Production

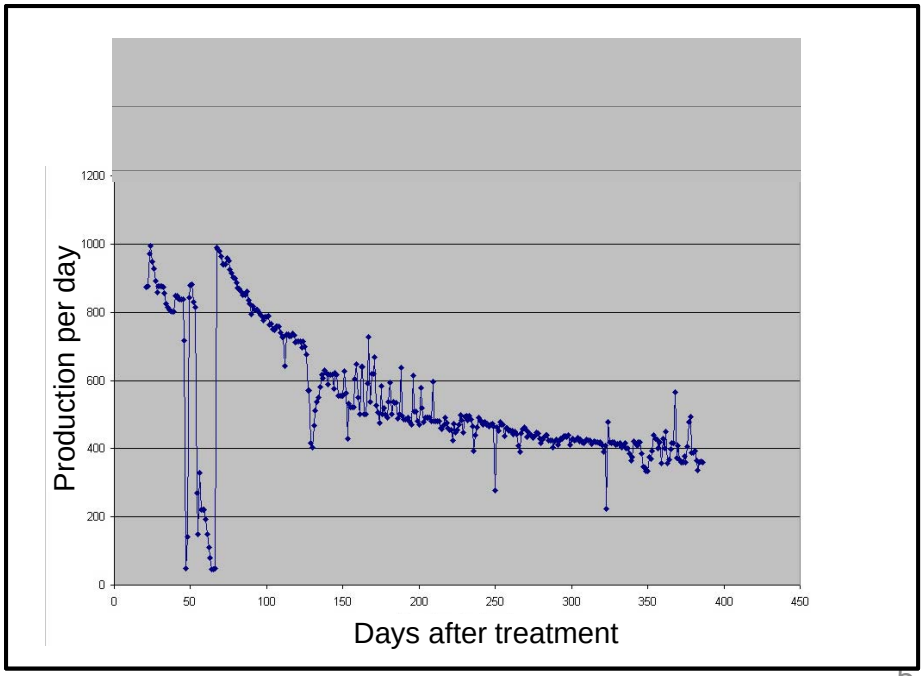
Complex Fracture Network



Symmetric Fracture







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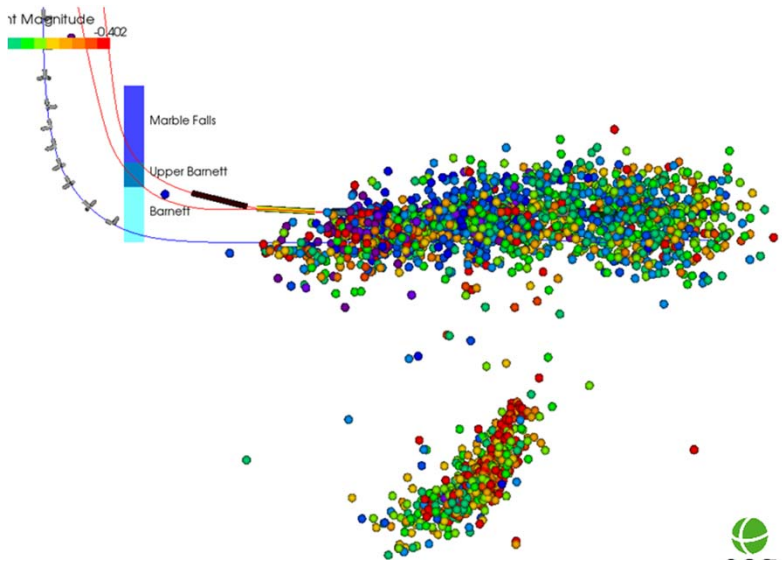
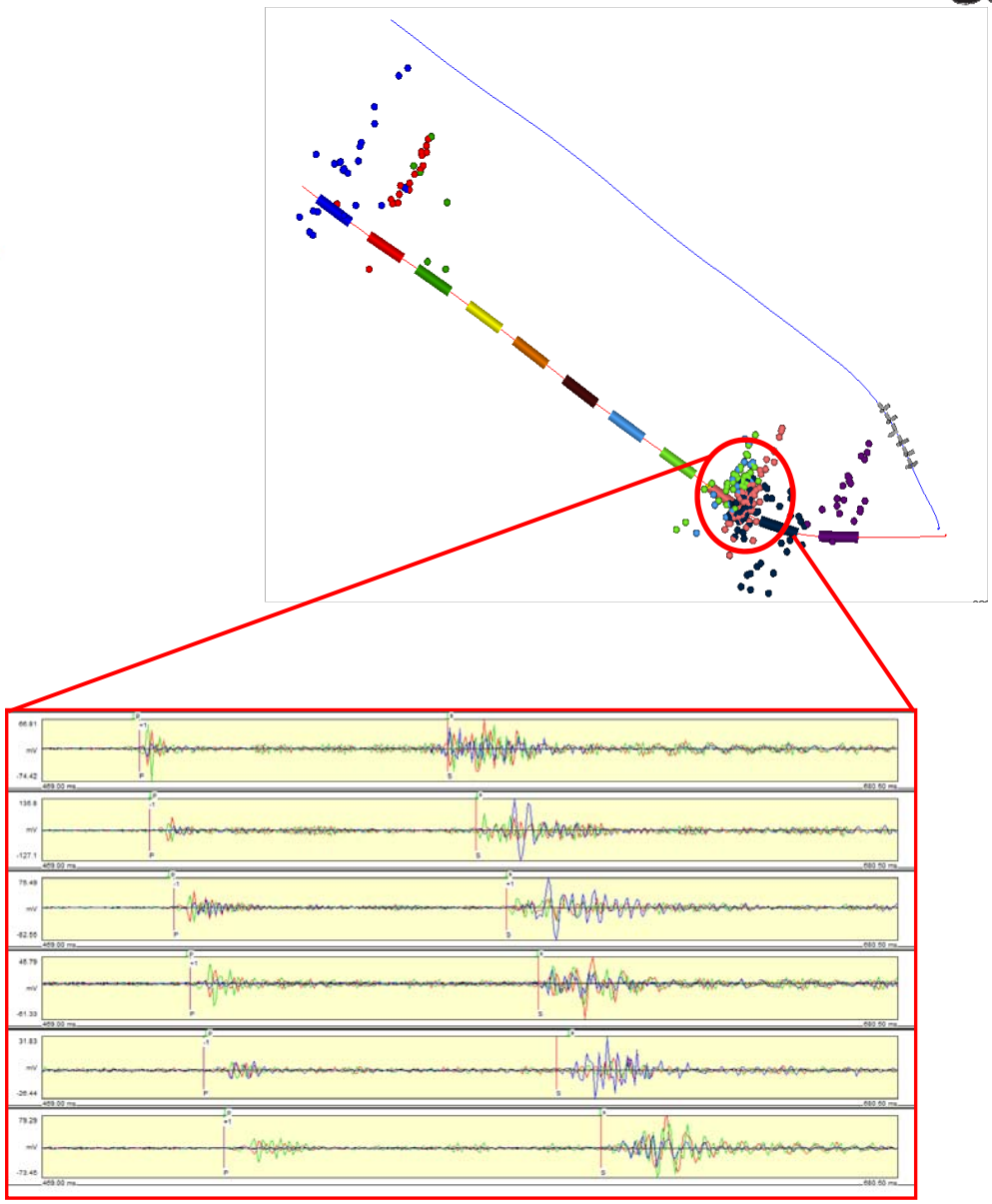
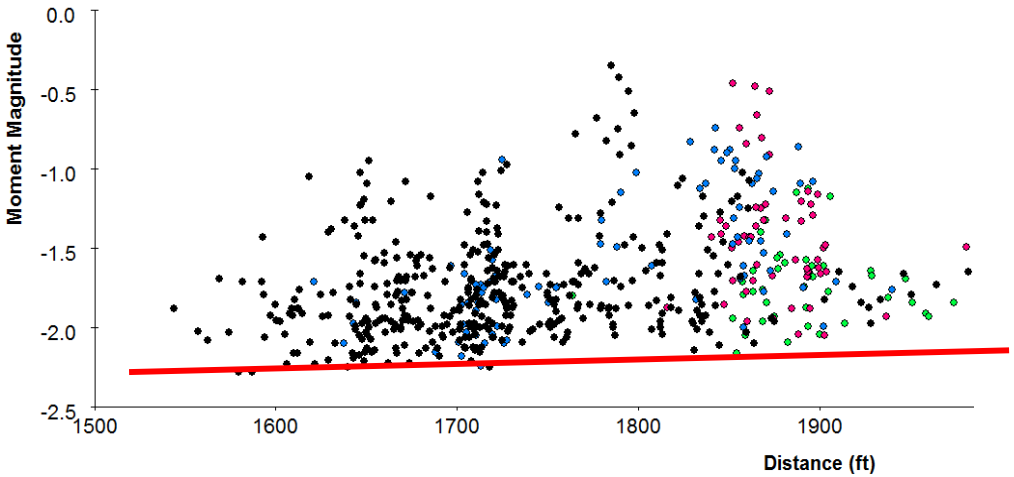
Real Time Geo-Hazard Avoidance

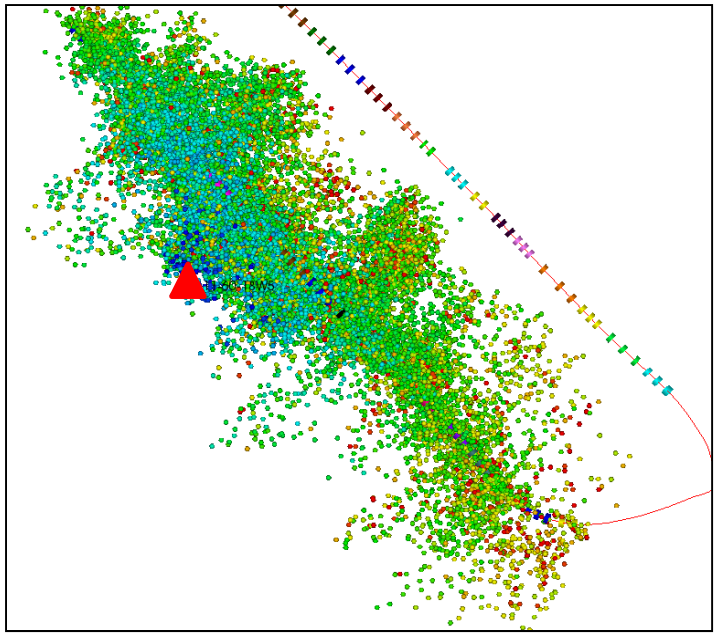


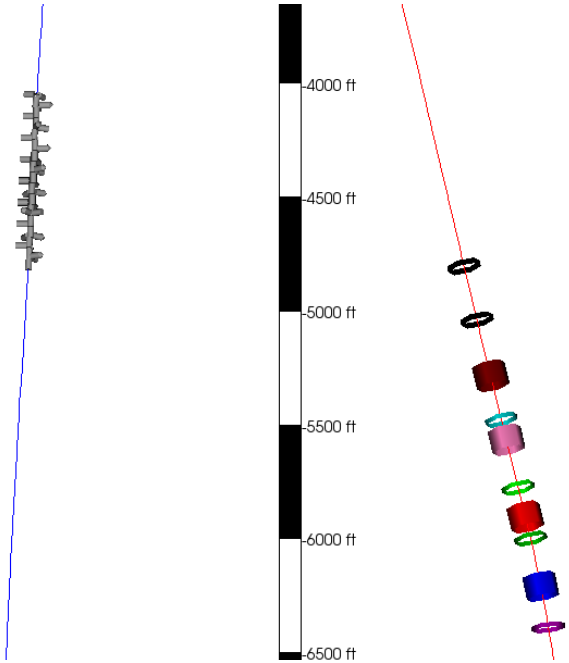


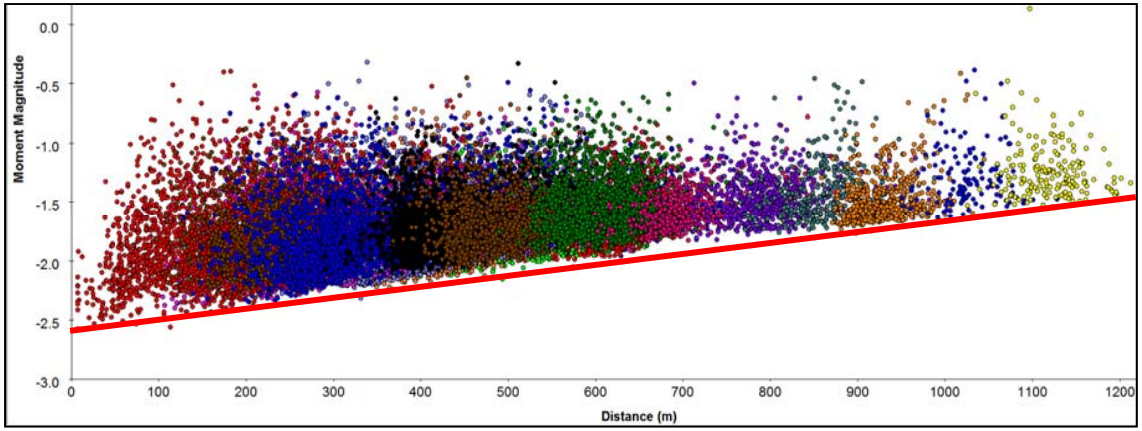
- Prevention of fracing into aquifers
- Identification of casing failures

Moving From Vertical to Horizontal Treatment Wells - Detectability

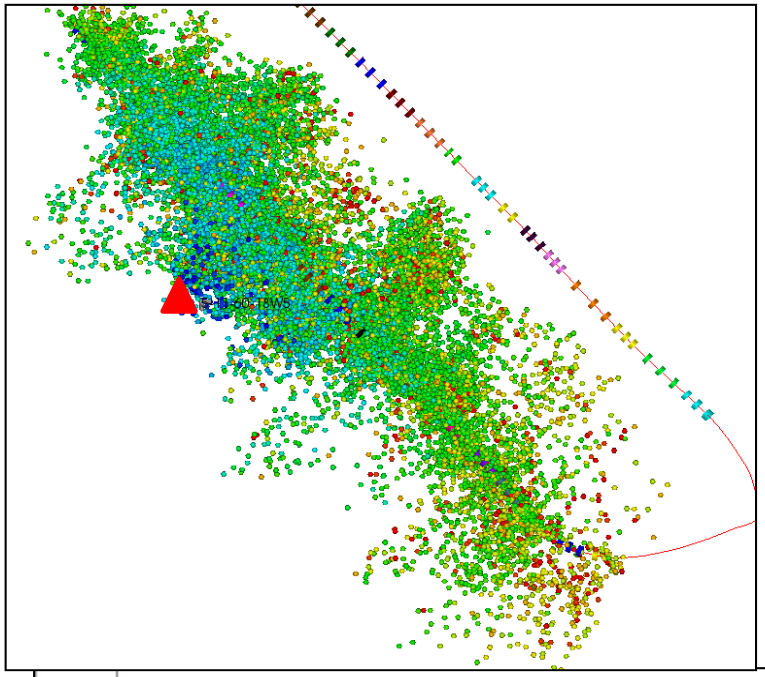






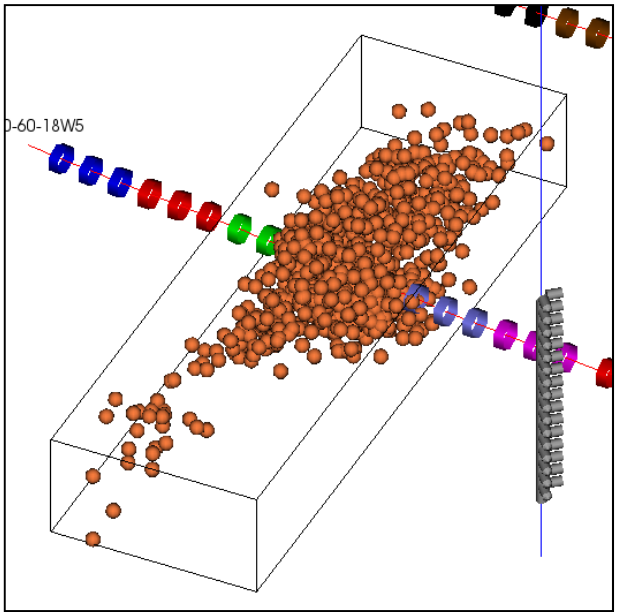


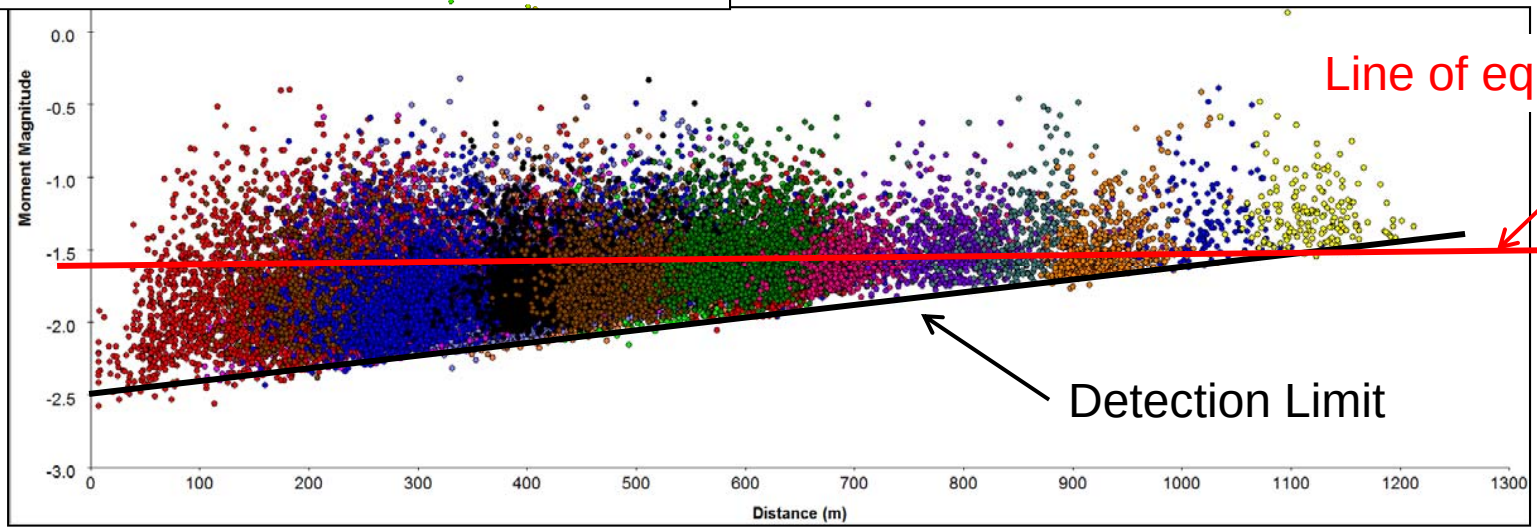
Fracture Dimensions and Detection Biases



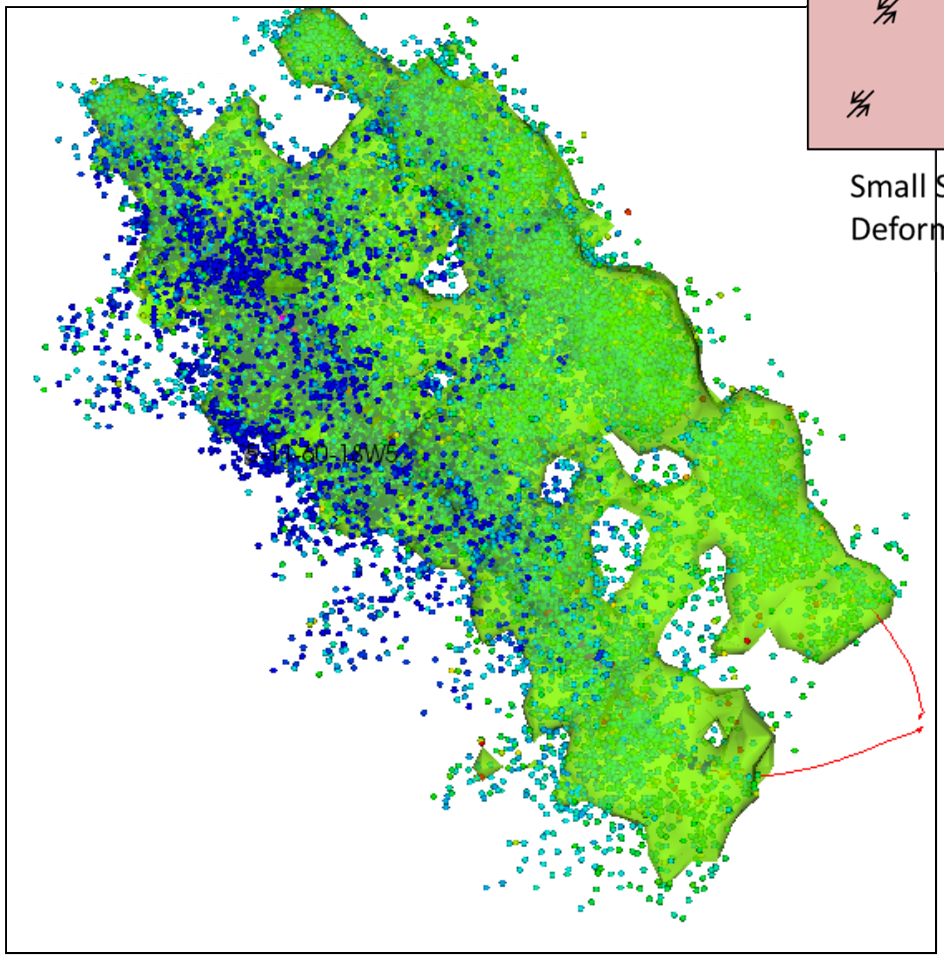
How to calculate fracture dimensions?

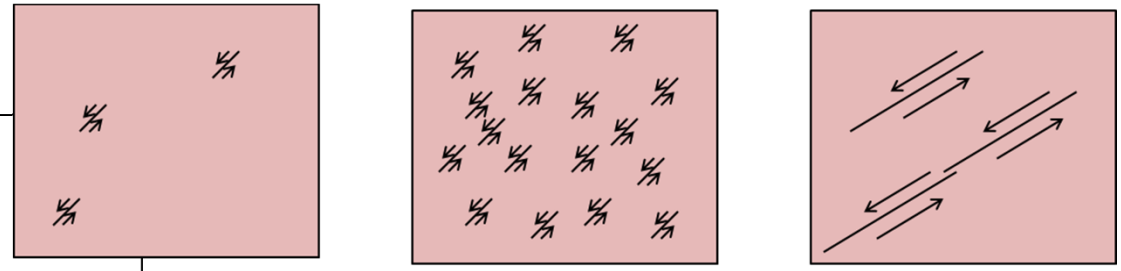
- 100% of events? 90%
- Envelop around events?
- Does every event contribute equally?





Stimulated Reservoir Volume





Small Seismic Deformation

Large Seismic Deformation

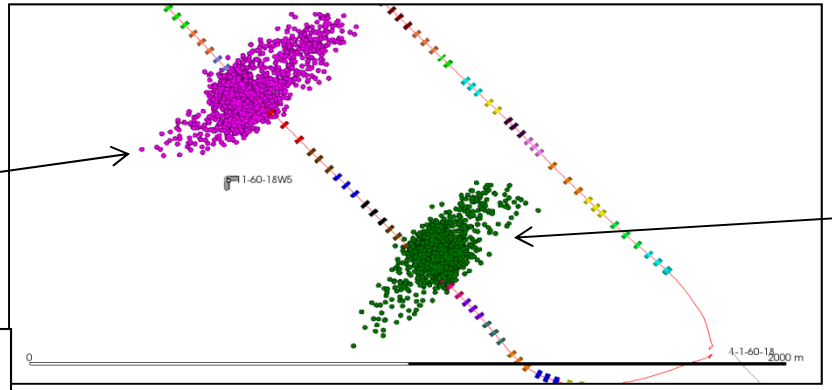
Large Seismic Deformation

Estimated Stimulated Reservoir Volume based on seismic deformation (SRV_D) aims to describe effective stimulation volume taking into account information available in the microseismic data.

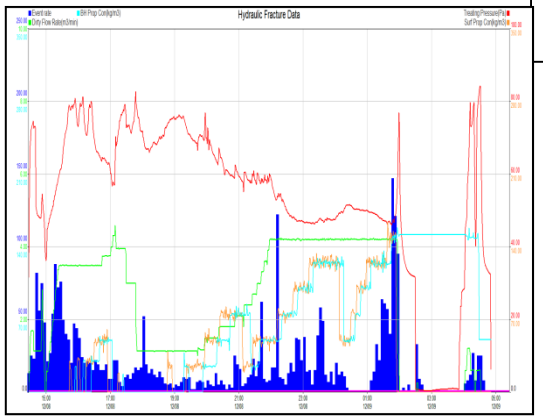
- Seismic Deformation in a volume is calculated based on the moment of the seismic events within that volume.
- Volumes that have small seismic deformation will not be extensively fractured.
- Areas of higher seismic deformation show increased fracture density and permeability and therefore, are expected to contribute more effectively to reservoir production.
- Large seismic deformation will either have a complex network of many small fractures, a number of large fractures, or both.

Using Source Parameters to Assess Treatment Plan

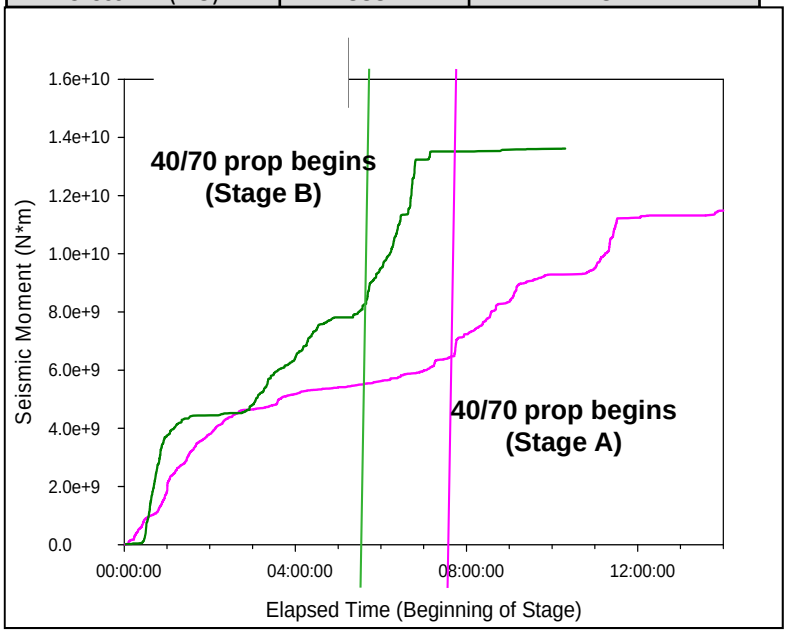
Stage A

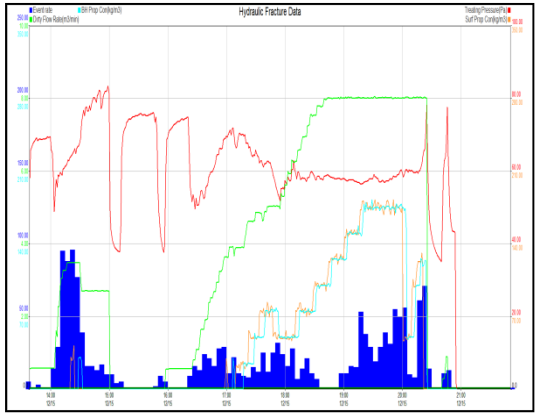


Stage B

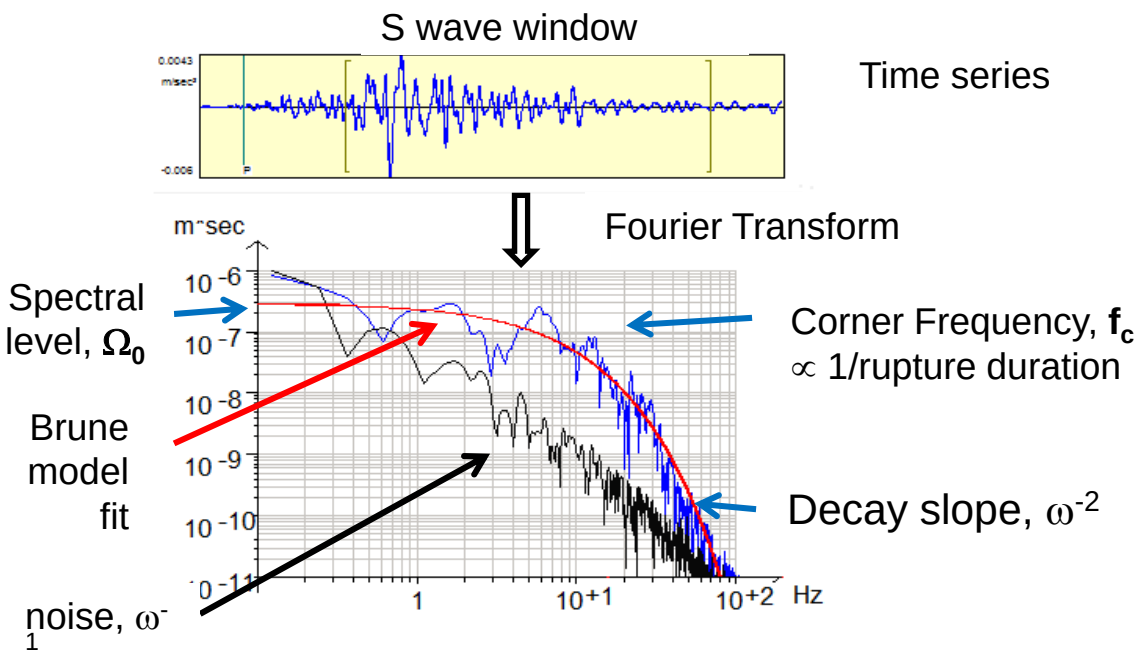


Stage:	Stage A	Stage B
Number of Events:	2416	1700
Fracture Length (m):	371	326
Type of Sand Used:	70/140, 40/70	70/140, 40/70, 40/80
Max Prop Conc. (kg/m3):	150	175
Crosslink (m3)	3331	1374





More Than Just Dots…

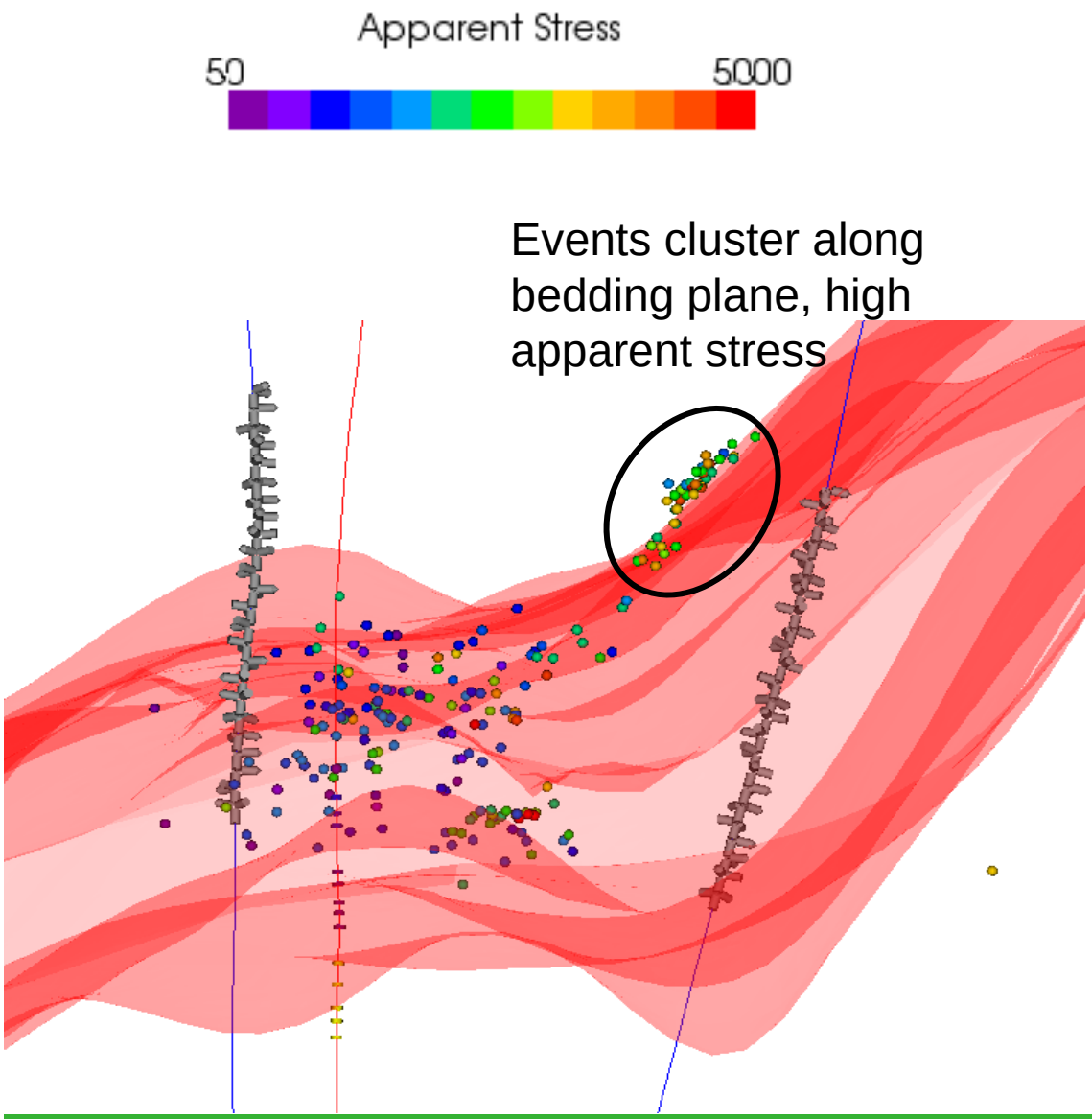


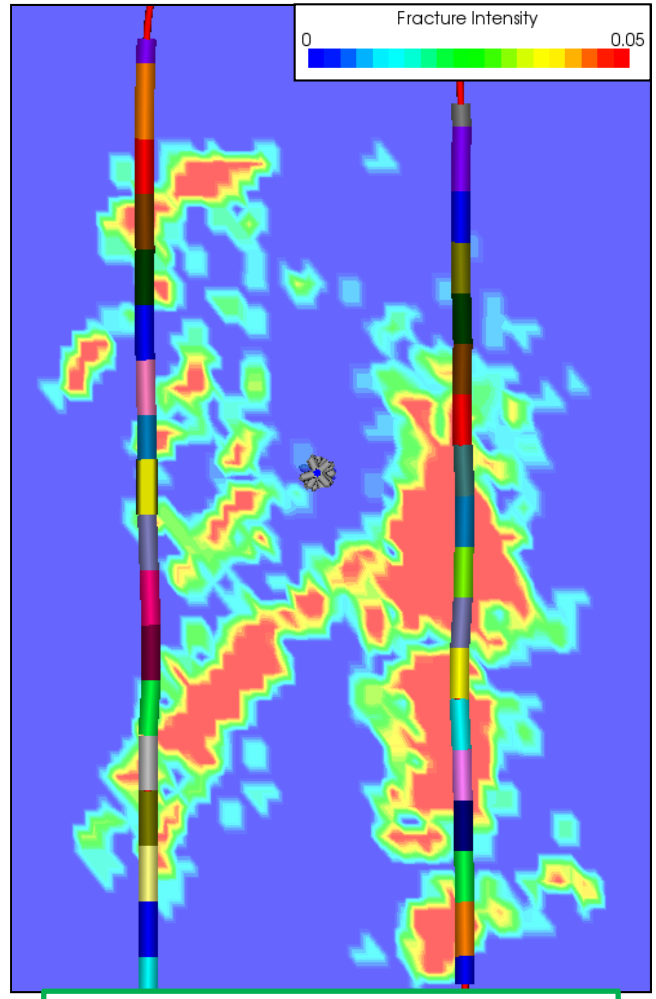
Ω_0	• Seismic Moment, M_0 • Moment Magnitude, M_W • Stress Drop, $\Delta\sigma$
f_c	• Fault Radius, r • Stress Drop, $\Delta\sigma$
$\Omega(f)$	• Radiated Energy, E_S • **Apparent Stress, σ_a**

Apparent Stress, σ_a, is a measure of how much energy the events are radiating relative to their moment:

- **Higher apparent stress**, events radiate energy more readily, can characterize unstable growth of events in **more brittle** regions of the reservoir
- **Lower apparent stress**, events invest more energy into deformation than radiation, **stable growth** of events

Apparent Stress and Fracture Intensity



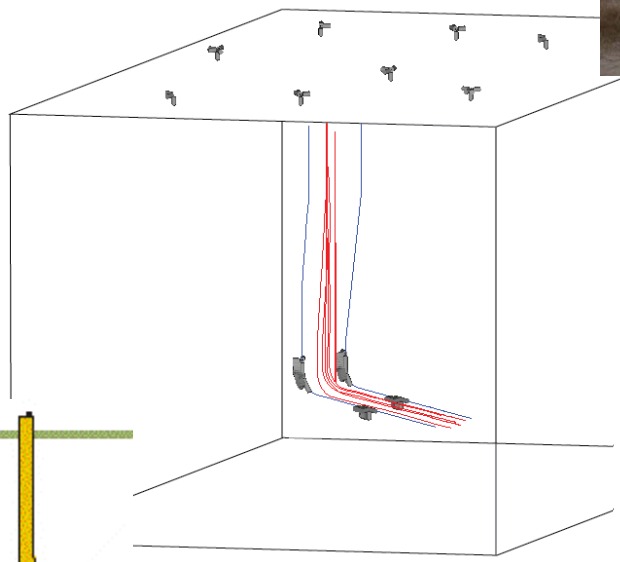


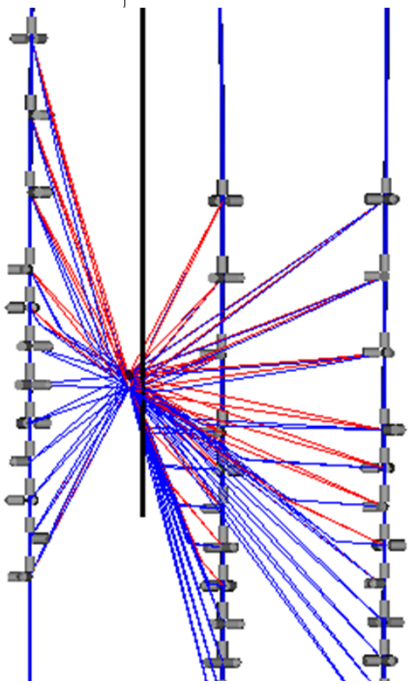
Fracture Intensity
Fracture intensity is the cumulative fracture length per unit area in each formation.

Using More Than One Array

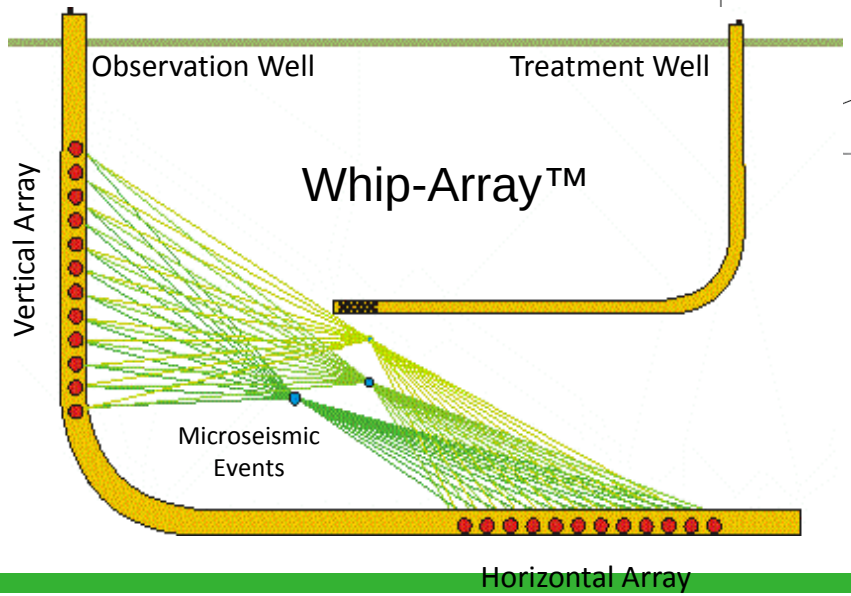
- Adding multiple arrays reduces detection bias
- Provides wider coverage of treatment wells
- Improves location accuracy
- Provides opportunity for more advanced analysis

Surface Arrays

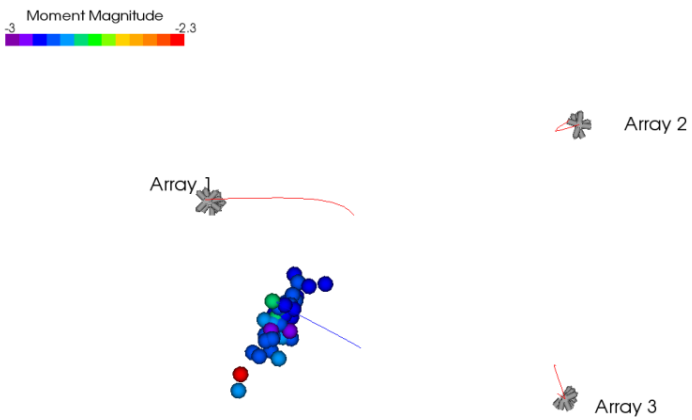




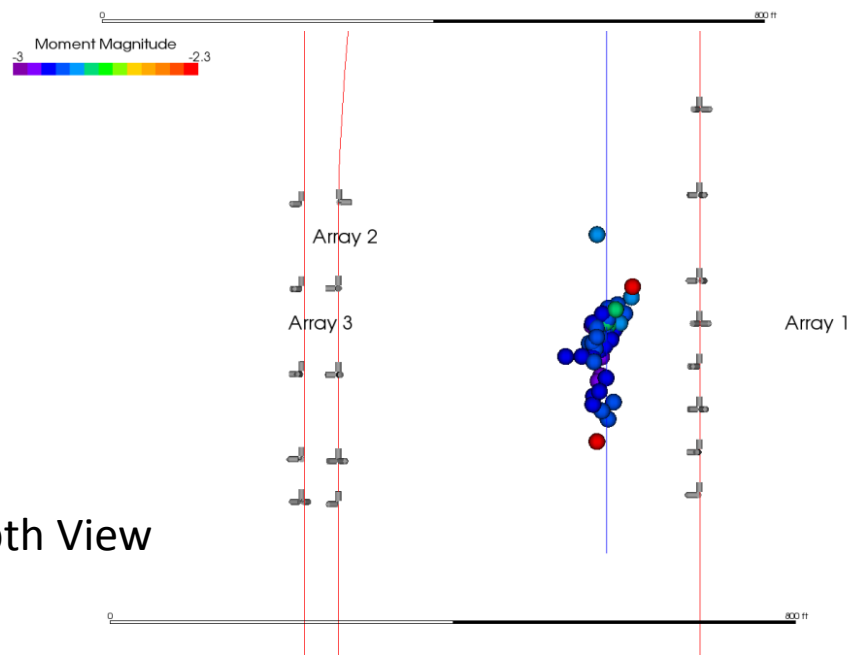
Multiple Vertical or Horizontal arrays



Benefit of Multiple Observation Arrays



Plan View



Depth View

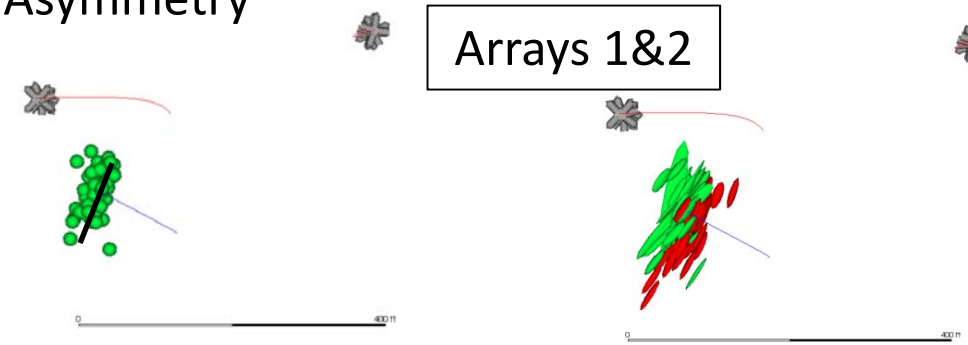
- All 52 events are
  - Individually locatable on all arrays (P- and S-waves detected on all arrays)

Dual-Array Event Locations

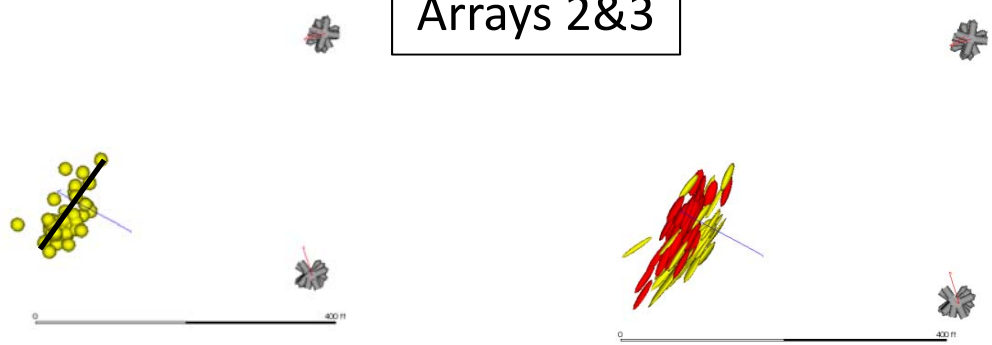
Array Locations & Asymmetry

Error Ellipsoids

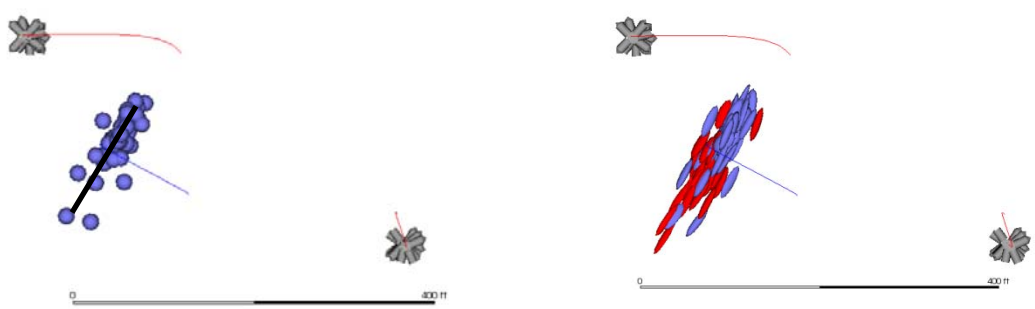
Arrays 1&2



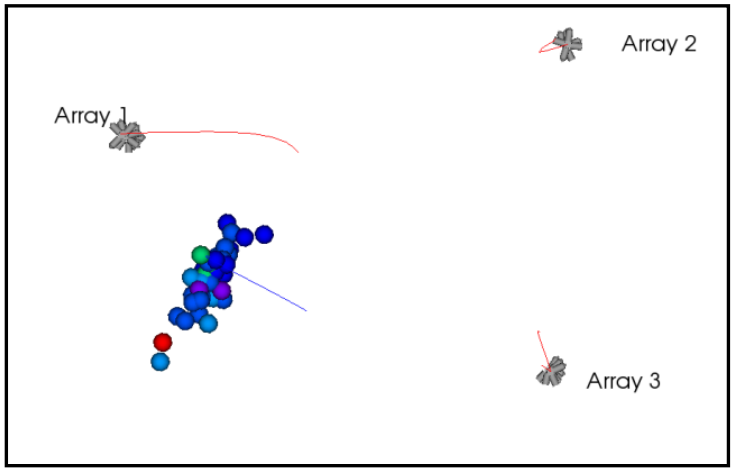
Arrays 2&3



Arrays 1&3



- Illustrate slightly more scatter
- Some array configurations show offset

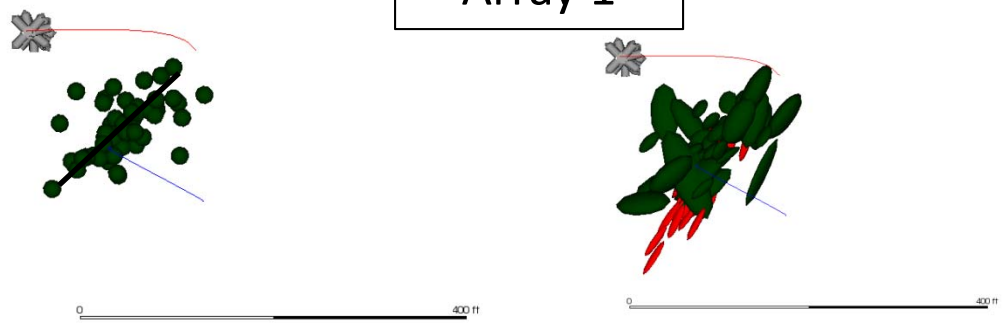


Single-Array Event Locations

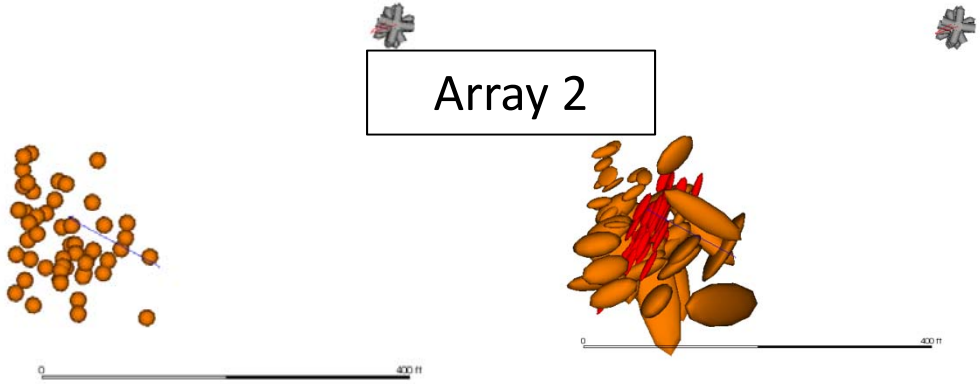
Array Locations & Asymmetry

Error Ellipsoids

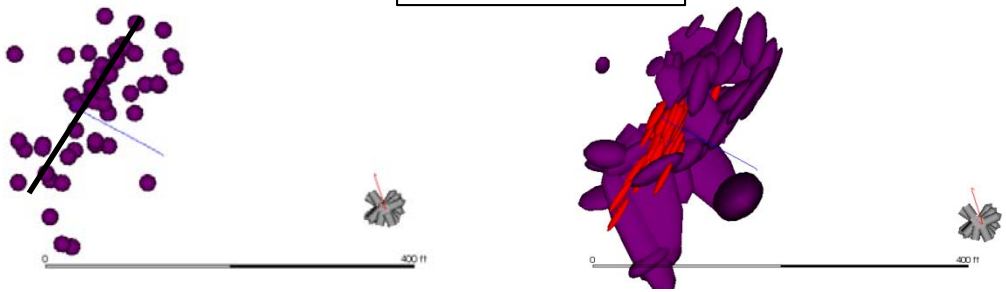
Array 1



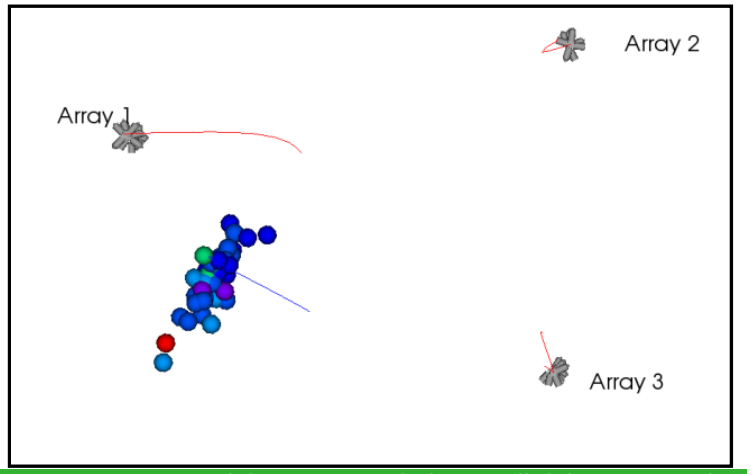
Array 2



Array 3



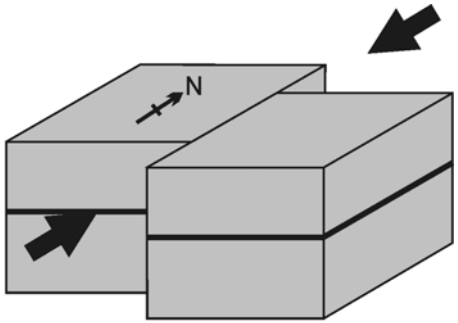
- Reveal increase scatter
- Larger error ellipsoids
- Loss of northeast-southwest azimuth in array 2 event solutions
- One array solutions rely more on azimuth



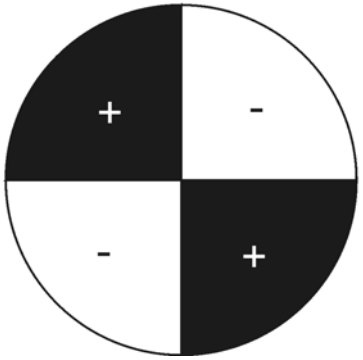
Challenges to Old Ideas

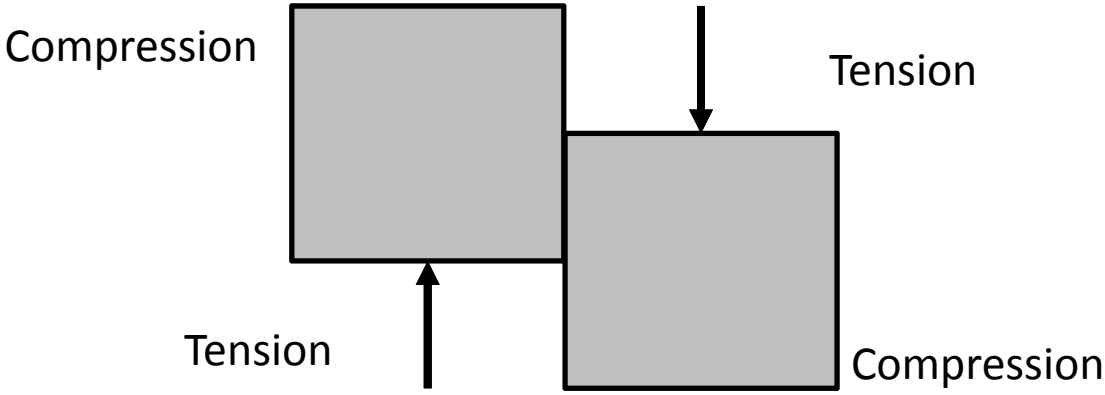
- How do fractures initiate and propagate?
- Are new fractures being created or are old fractures being activated?
- What is the role of pre-existing fractures and bedding planes?
- Are these fractures open or cemented prior to stimulation?
- Are some fracture sets preferentially activated during hydraulic stimulation?
- What is the interaction of fractures of different orientations?

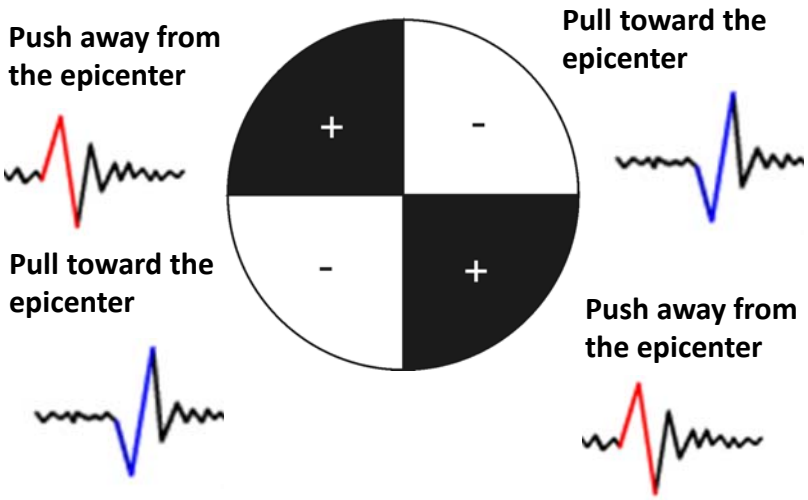
Moment Tensors



Strike-Slip Fault



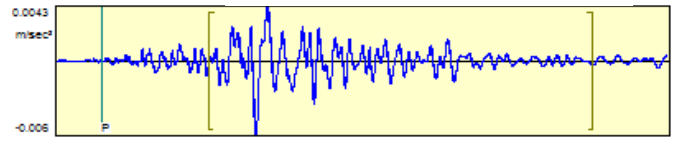




Bridging the Gap Using Microseismicity

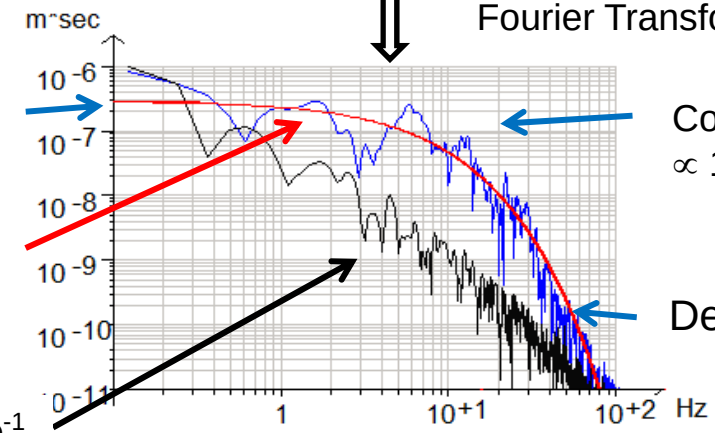
Microseismic waveforms include information about the source of the failure and the rock conditions leading to failure.

S wave window



Time series

Fourier Transform



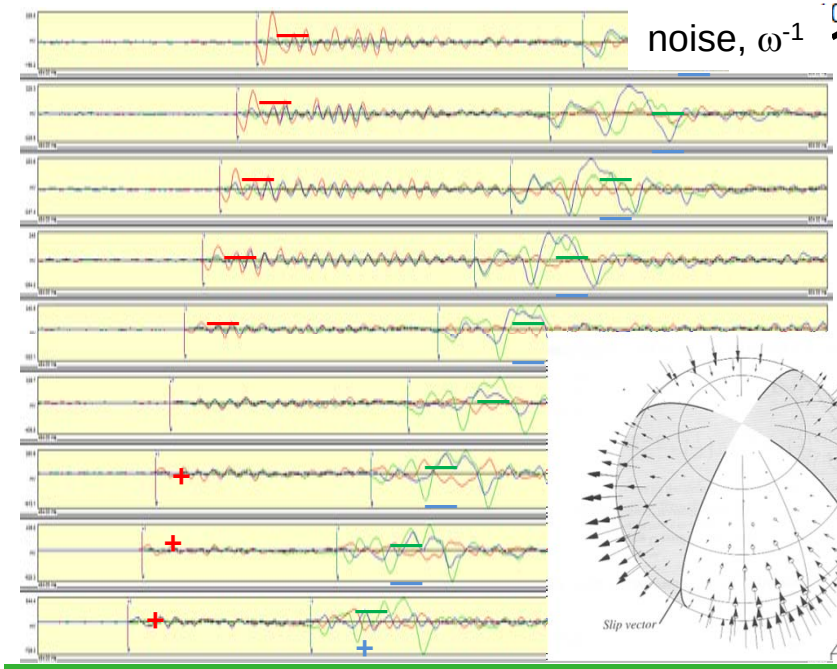
Spectral level, Ω_0

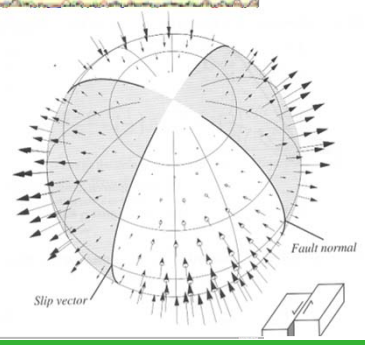
Brune model fit

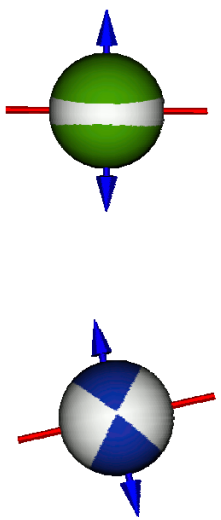
noise, ω^{-1}

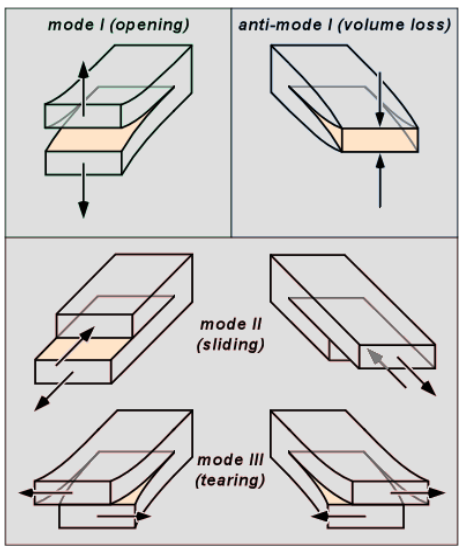
Corner Frequency, f_c $\propto$ 1/rupture duration

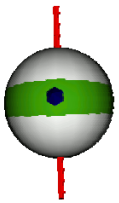
Decay slope, ω^{-2}





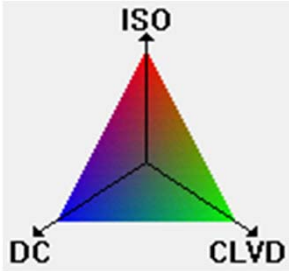




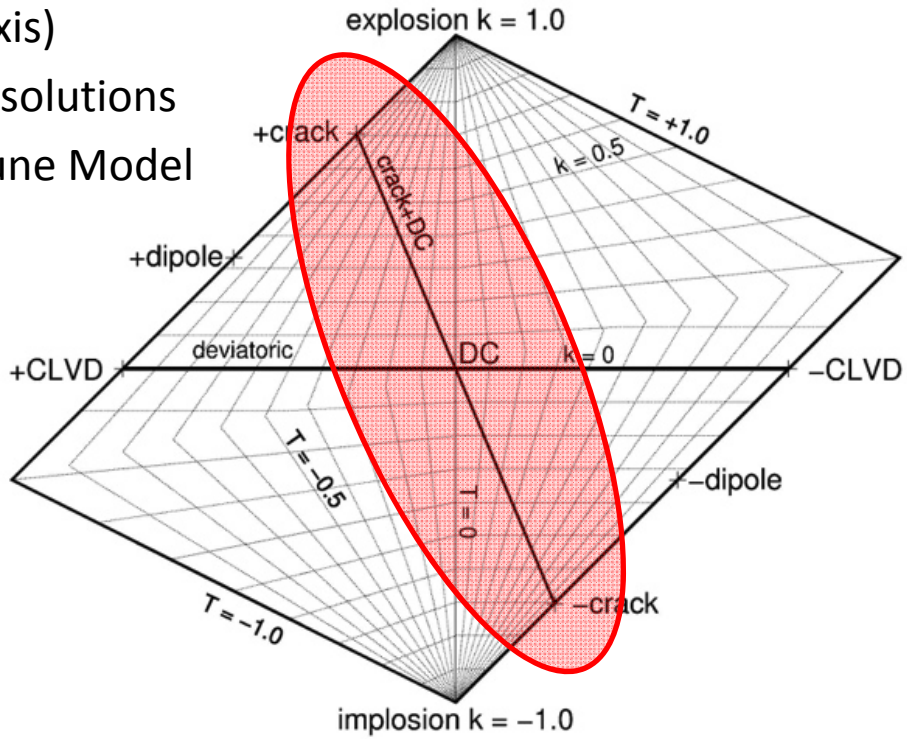


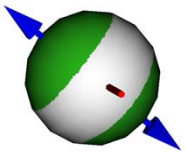
SMTI/DFN

- Modes of failure have three end-members:
  - isotropic
  - double-couple (DC) / shear
  - compensated linear vector dipole (CLVD)

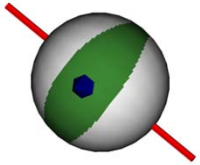


- Common modes of failure:
  - Tensile opening of a fracture (normal to tension axis)
  - Closure of a fracture (normal to pressure axis)
  - Slip on a fracture surface (DC) – resolvable solutions
  - Relative dimensions based on modified Brune Model (shear-tensional)

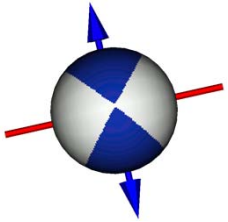




crack opening

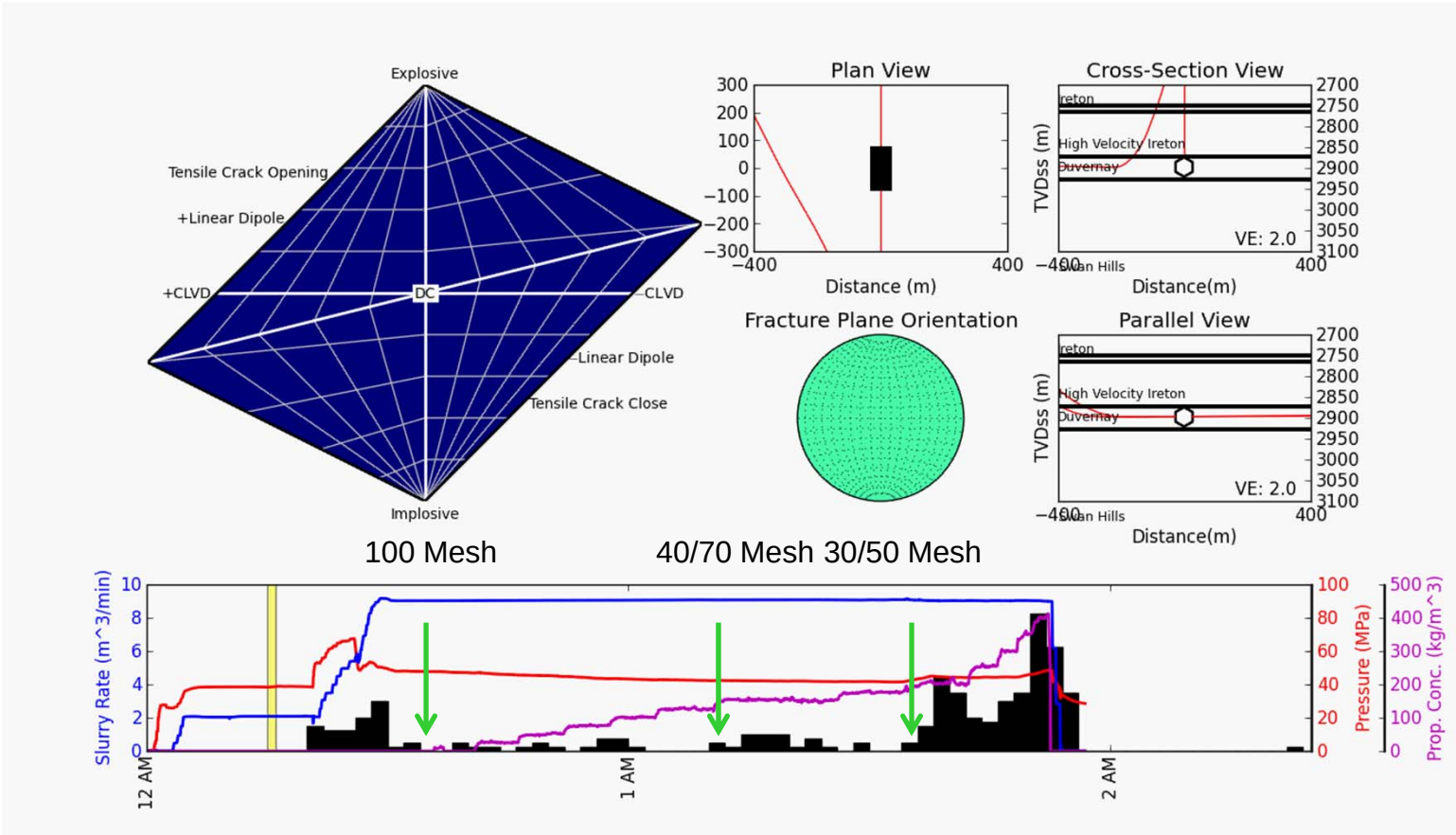


crack closing

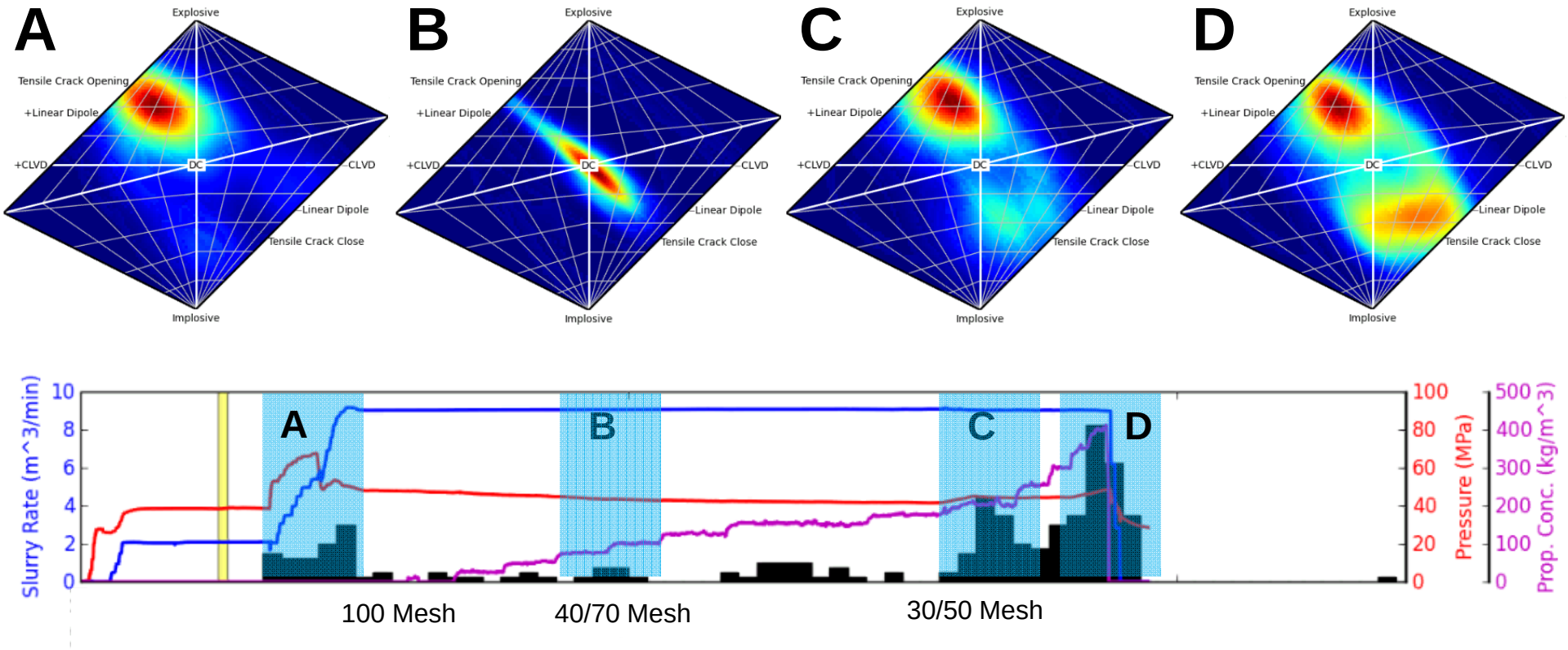


DC / shear

Response to Treatment

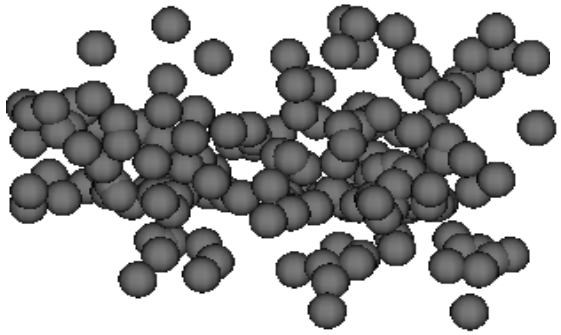


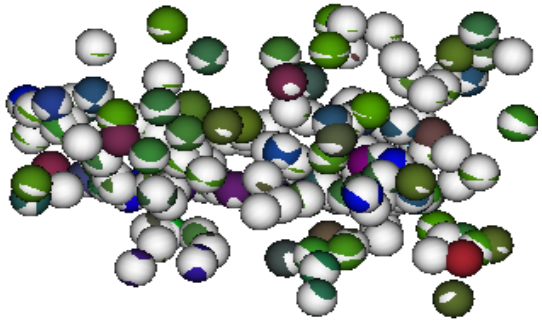
Response to Treatment

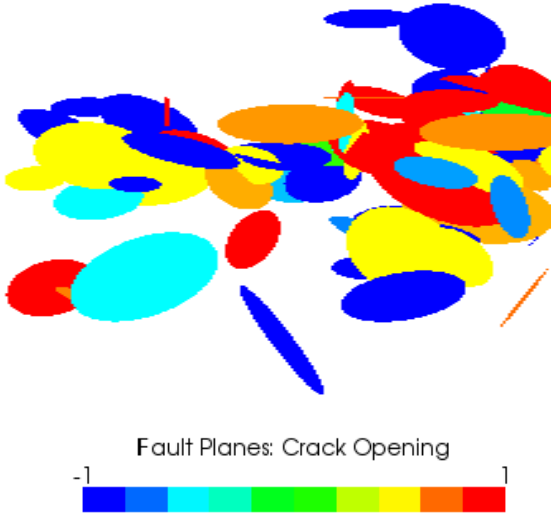


Building on SMTI
Discrete Fracture Network (DFN)

Microseismic Events (dots) → Moment Tensors (beachballs) → Discrete Fracture Networks (penny-shaped cracks)







Fracture orientations and extents are dimensions shown as discs, coloured by source type.

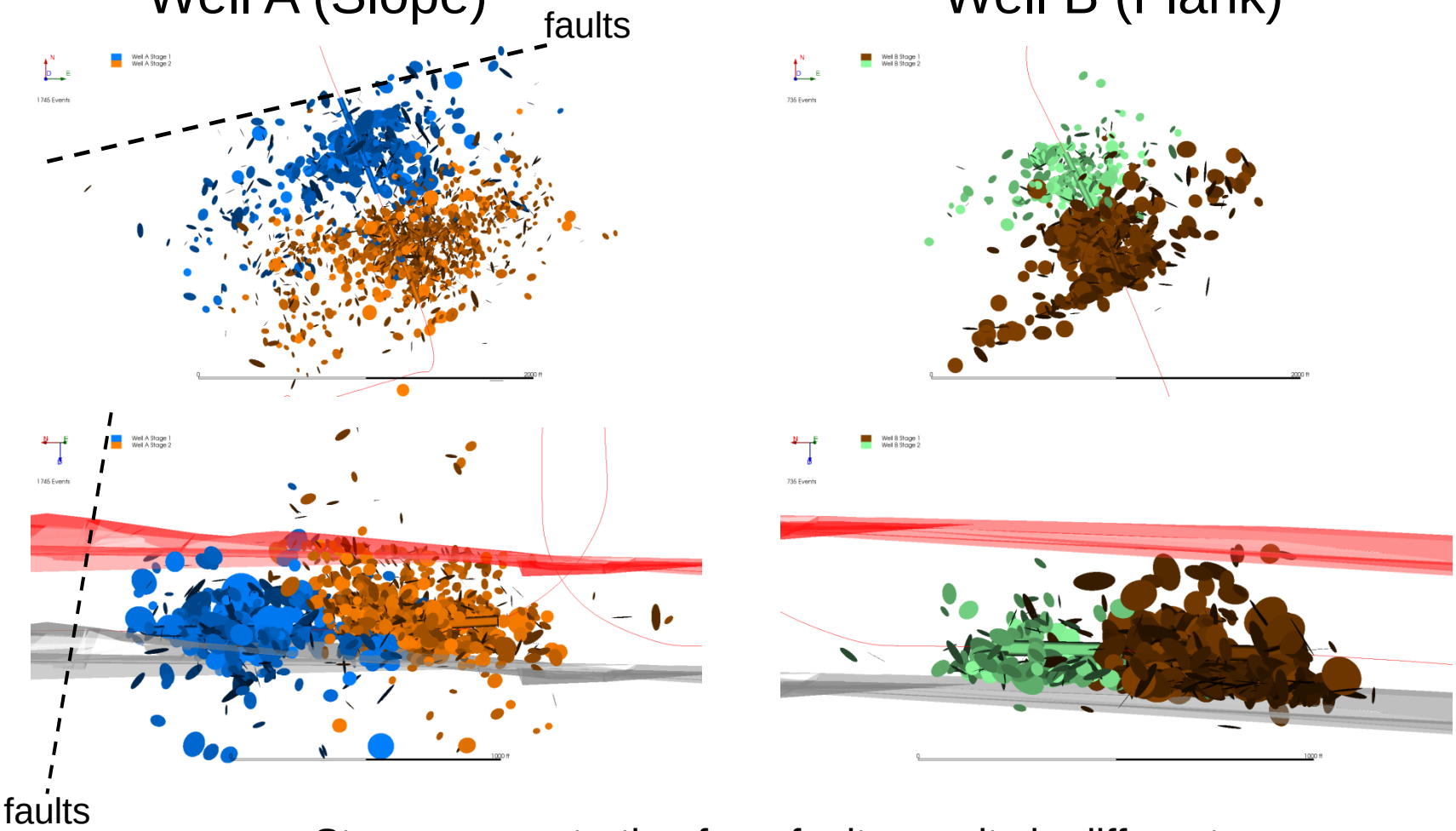
DFN: Marcellus - Role of Pre-existing Fractures in Shale

Well A (Slope)

Well B (Flank)

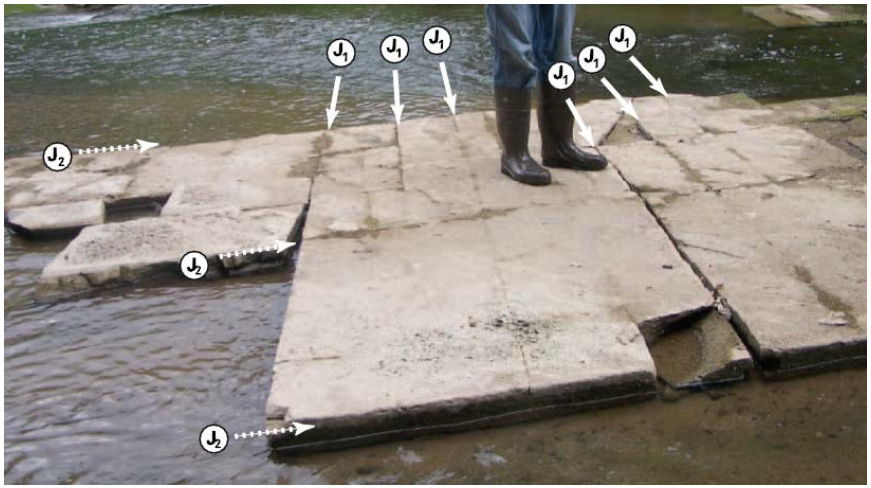
Plan View

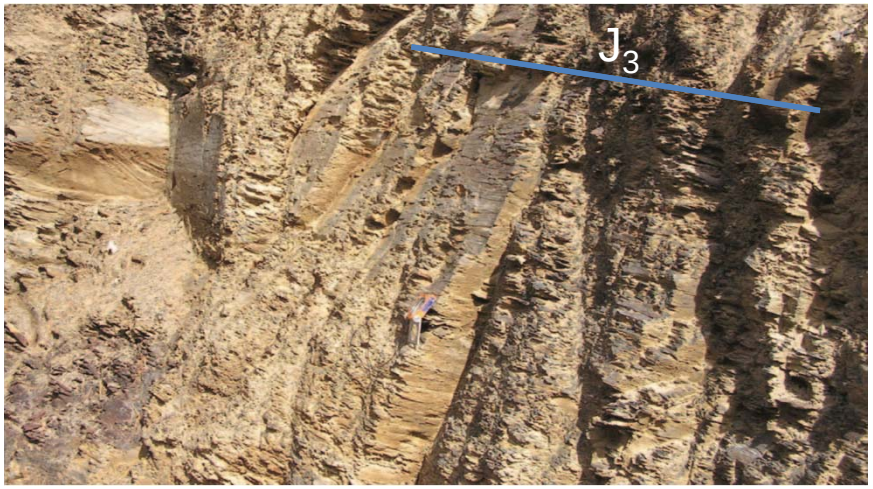
Depth View

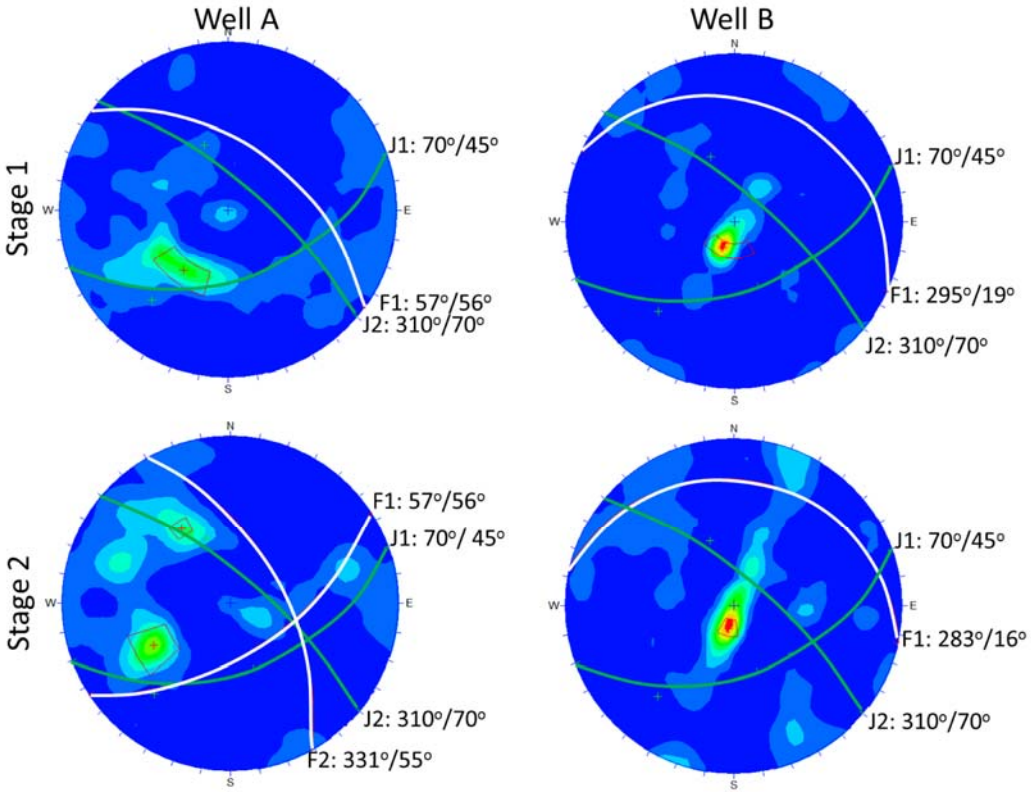


Stress concentration from faults results in different fracture sets activated on either side of the pad.

DFN Activation in the Marcellus Shale



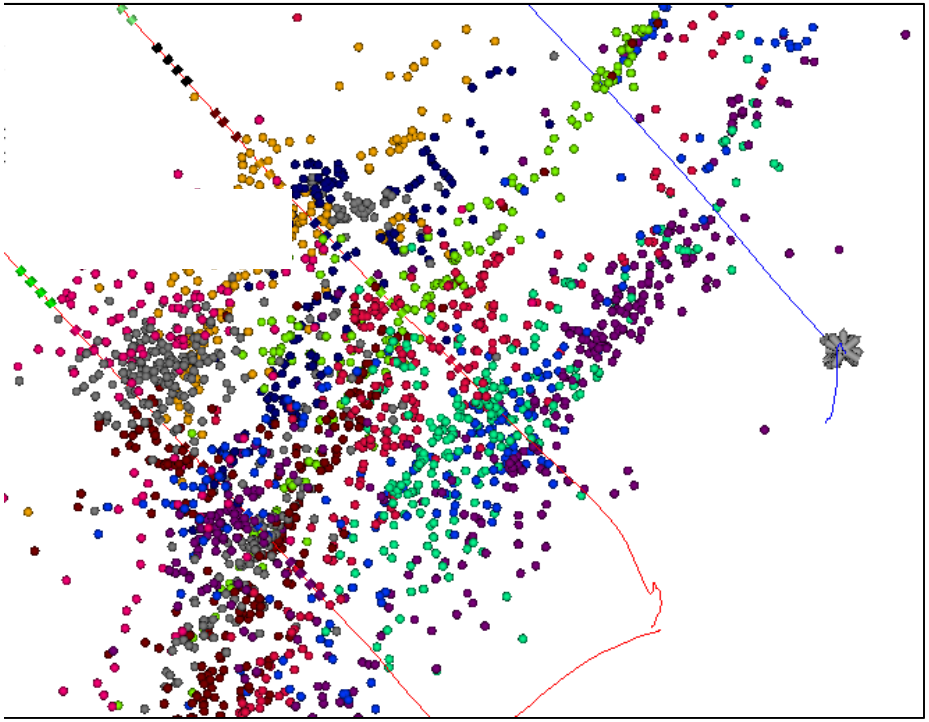




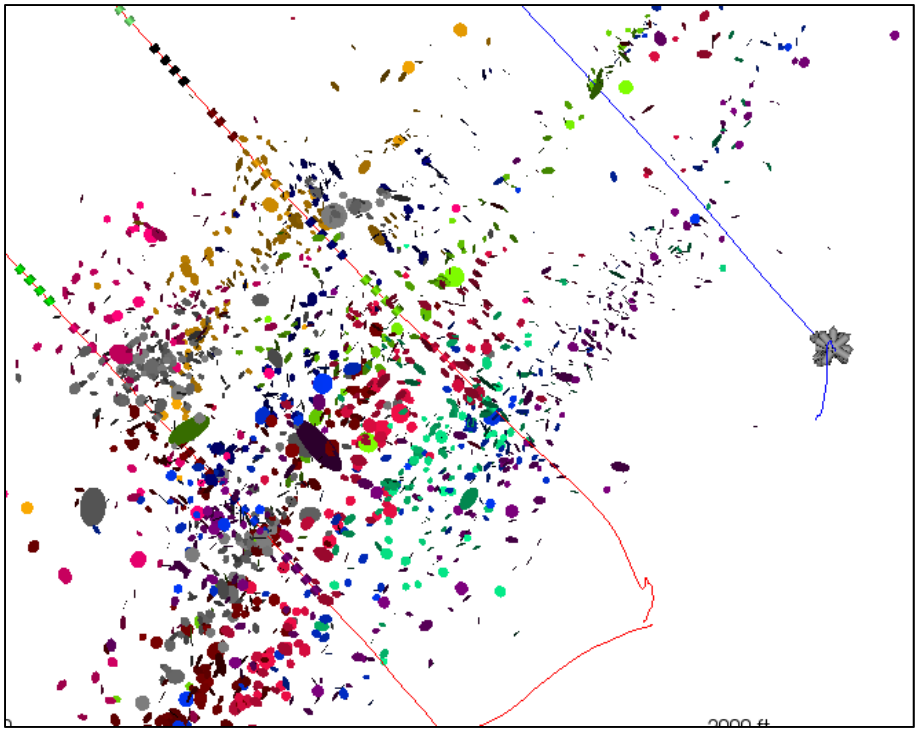
Engelder et al. (2009)

DFN Case Study #2

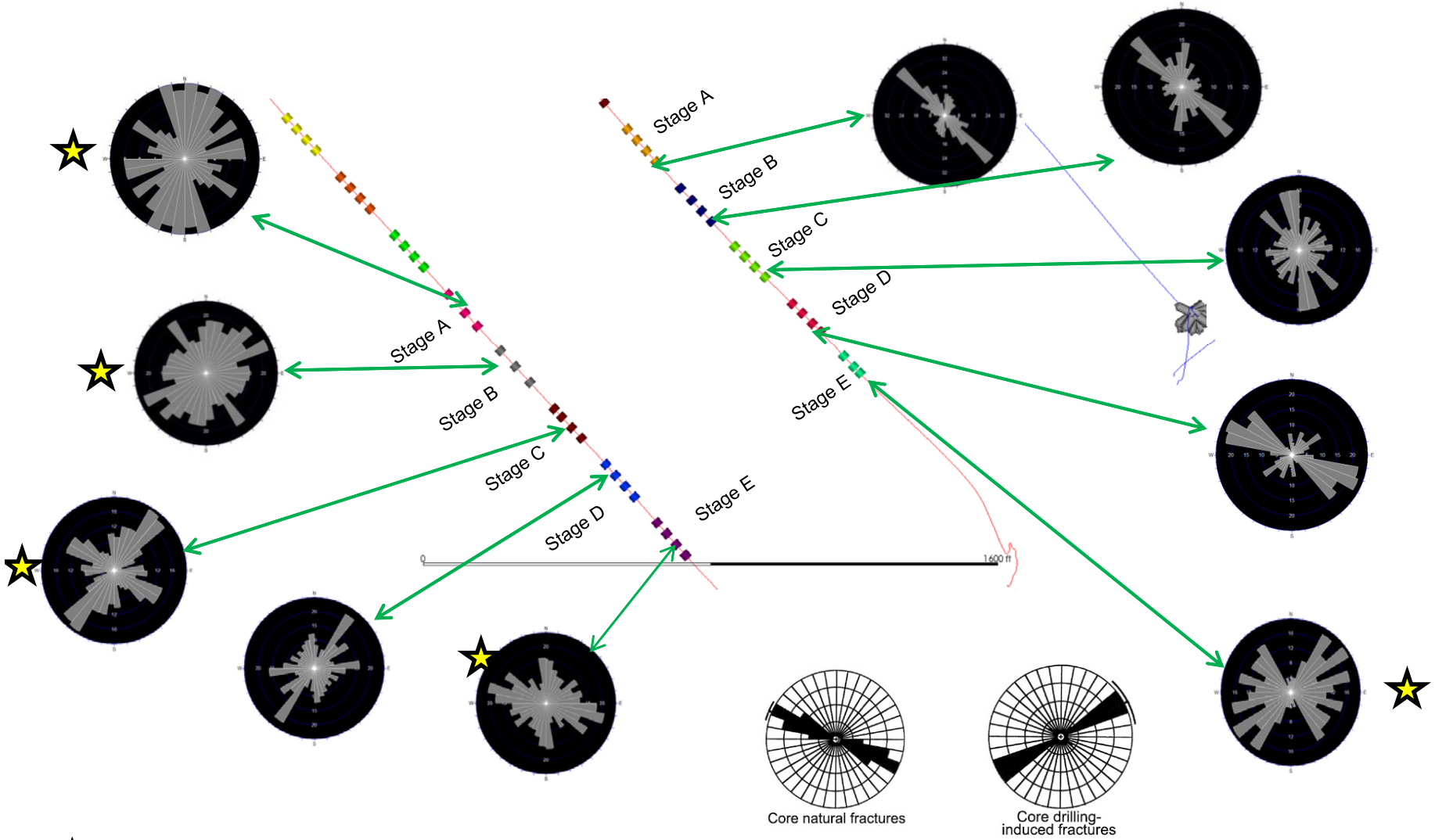
Event Locations



Fracture Planes

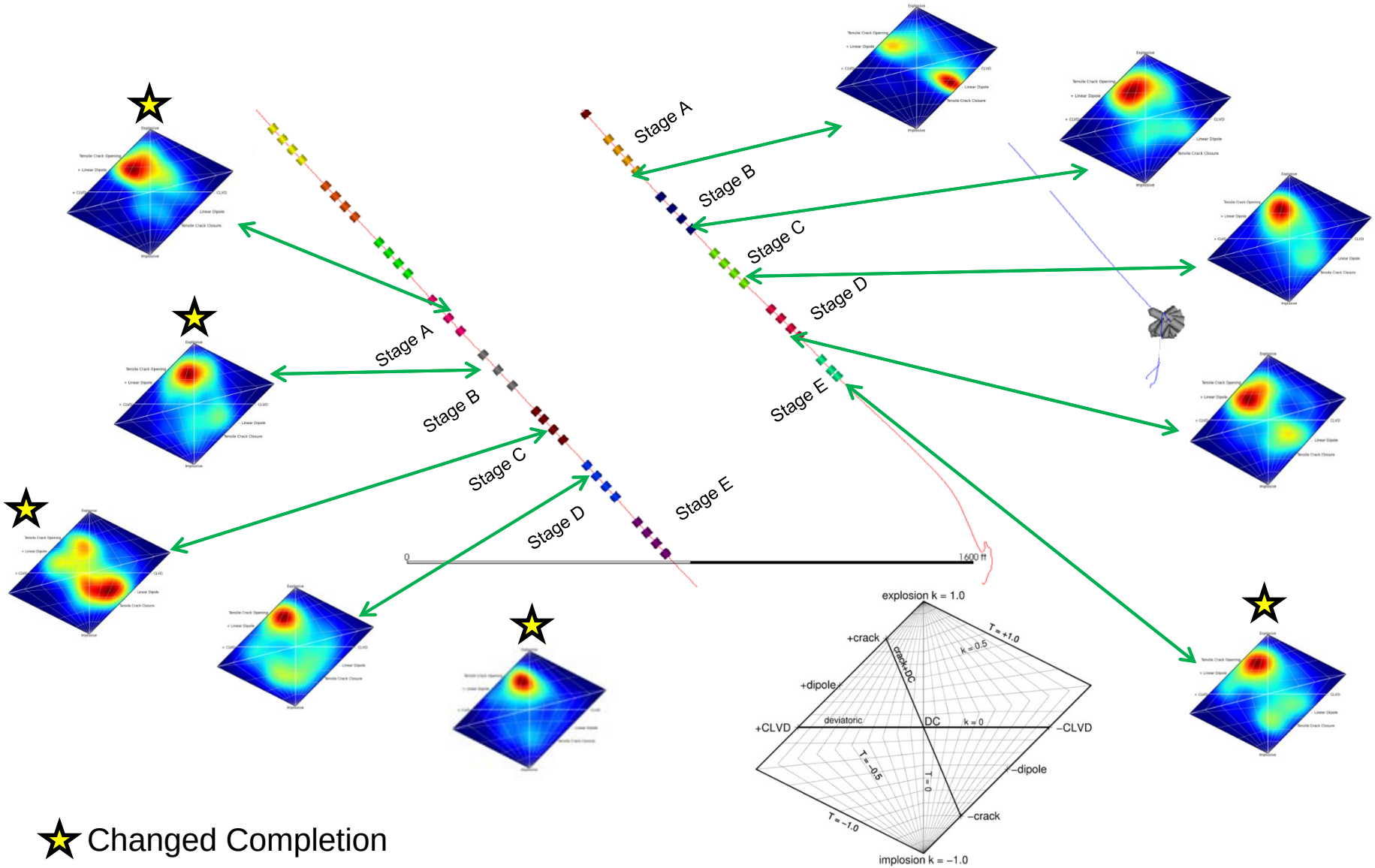


Stimulation Response: Fractures



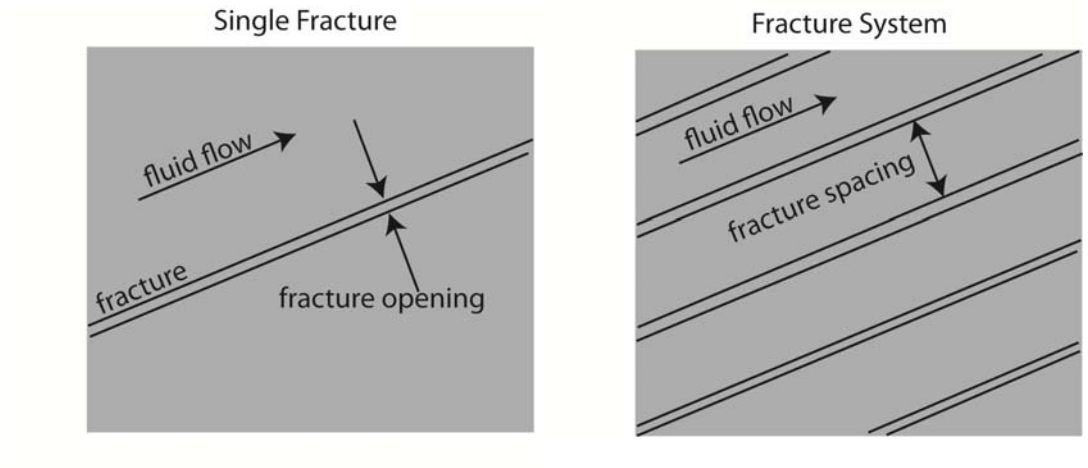
Changed Completion

Stimulation Response: Failure Types

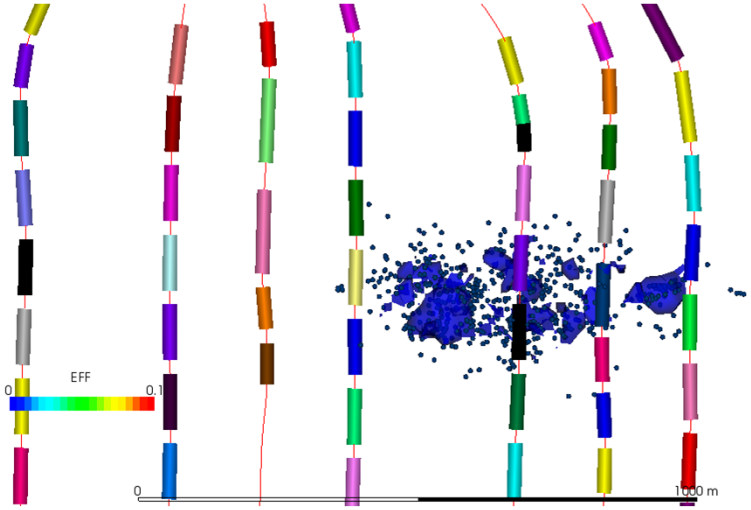


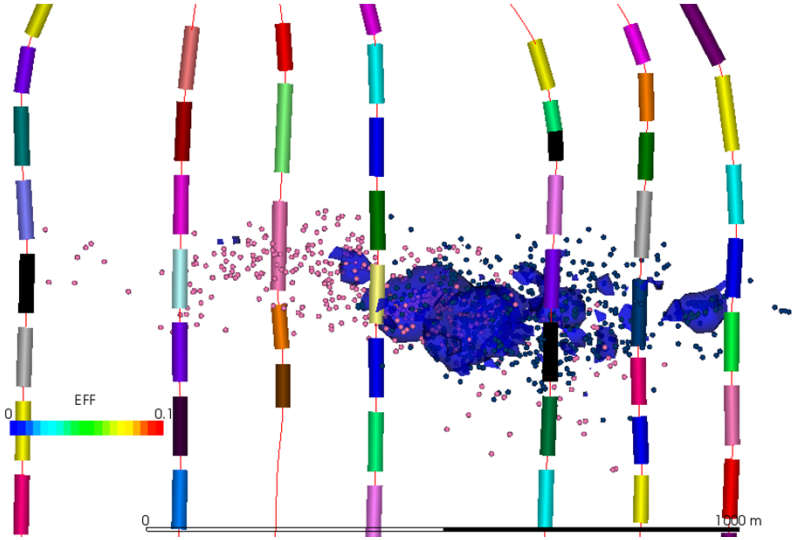
★ Changed Completion

Enhanced Fluid Flow - EFF

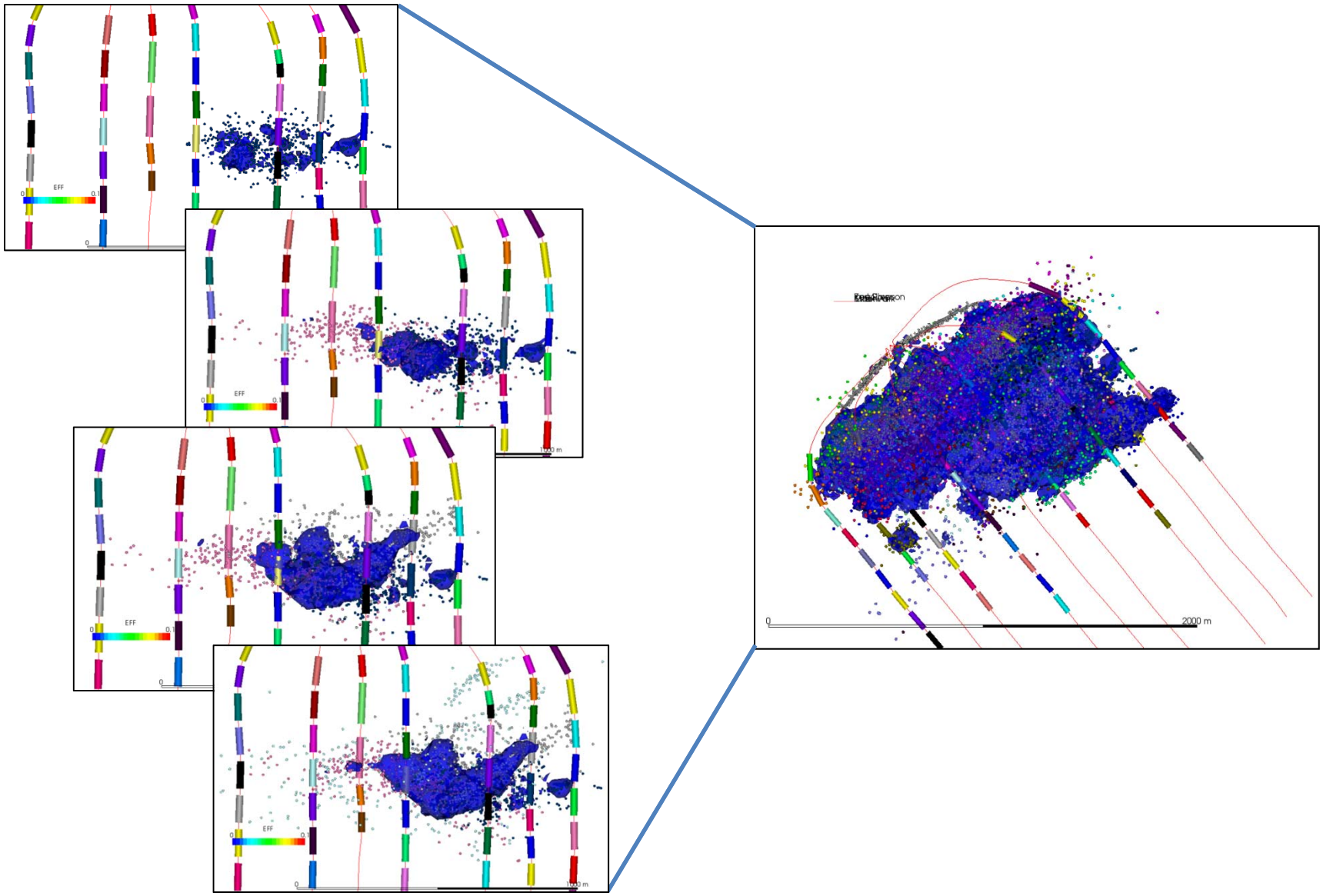


- Opening aperture is calculated based on the strain from the moment tensor factoring in the source dimensions.
- Average individual fracture openings over a neighbourhood (nearest neighbour statistical approach) of fractures with similar orientation





Building Fracture Complexity, EFF



Where Do We Go Next?

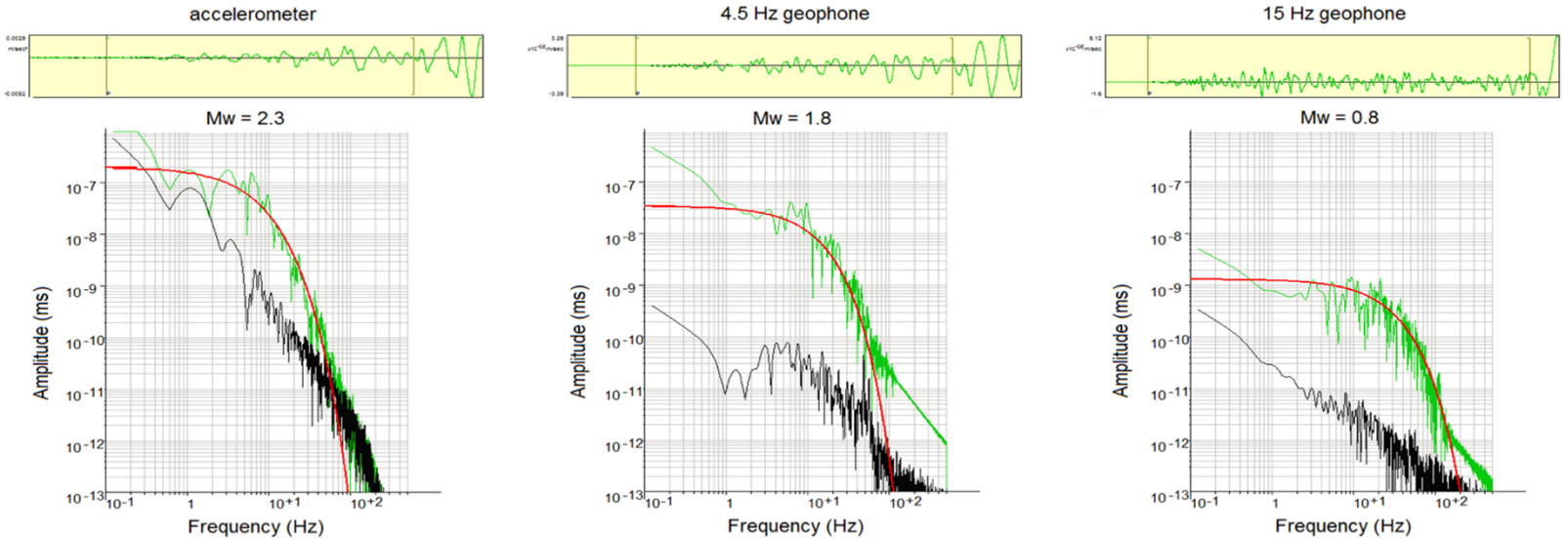
- Are we seeing the whole picture?
- Seismic vs. aseismic and the age old balance of energy question?
- Where did the proppant go?
- Relationship between rock properties (Poisson's ratio, Young's Modulus, Vp/Vs ratios, etc.) and fracability and production?
- Can we go into deeper and hotter wells?

New Tools, New Understandings

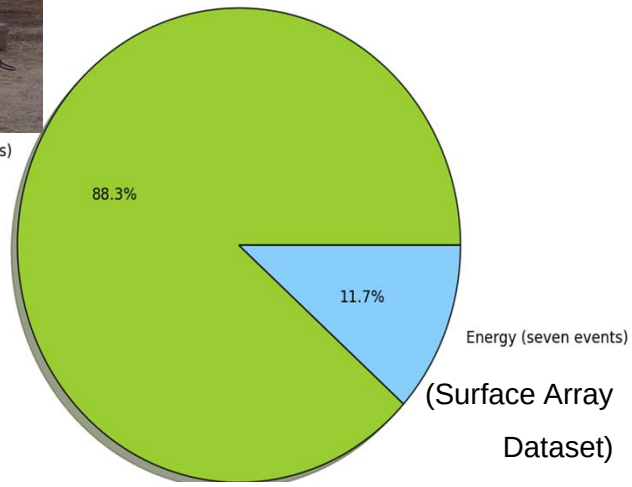
- Operators are in need of more robust monitoring solutions
  - High temperature tools
    - Deeper, higher temperature reservoirs are the “hot” plays
  - Longer lasting tools
    - Stimulations are moving away from single well pads to multi-well, zipper-fracing pads
- Integration is key
  - Geomechanics, geophysics, geology, engineering, all need to come together to answer the questions
- Broader range of monitoring equipment
  - Treatments are producing events with moment magnitudes > 0
  - Traditional downhole geophones underestimate the actual size of larger events.

Hybrid Solutions:

Combining Surface + Downhole + lower Freq. Geophones



Correct Event Radius based on ISM network (ft)	Event Fault Radius based on saturated downhole data (ft)
99	12
101	11
77	14
87	15
93	26
82	19
82	15

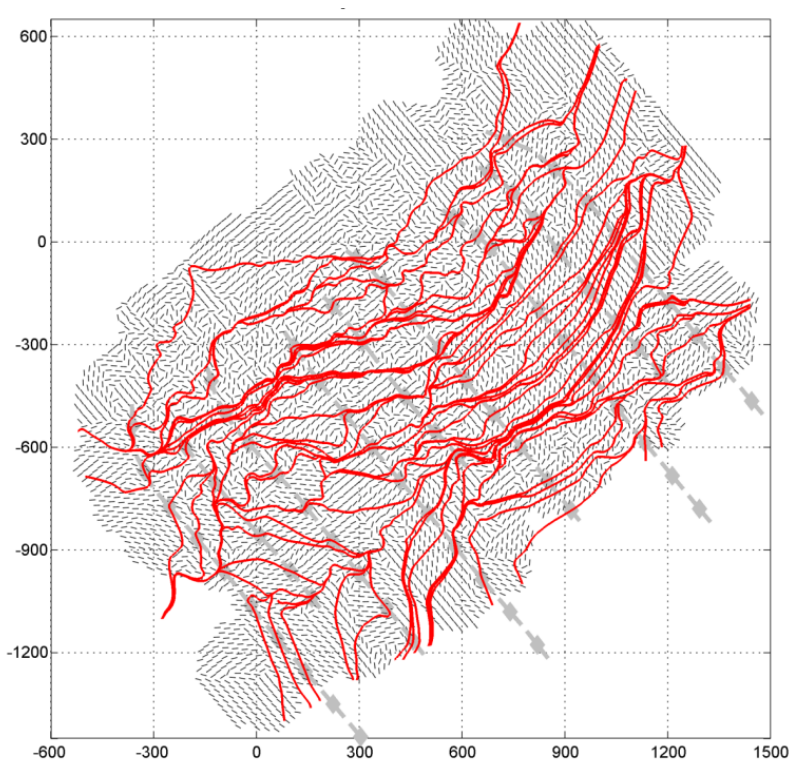


(Downhole Array Dataset)

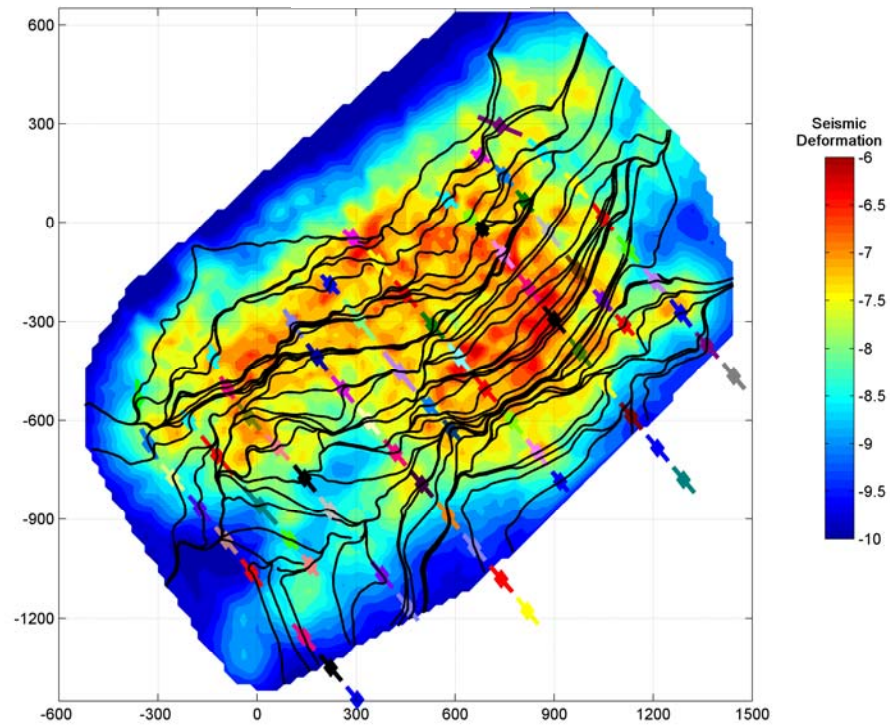
(Surface Array Dataset)

Connecting the dots…

- Possible Hydraulic Flow-units



- Stimulated Reservoir Volume layer unit with lateral flow connectivity



Putting It All Together