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

11-Mar-14

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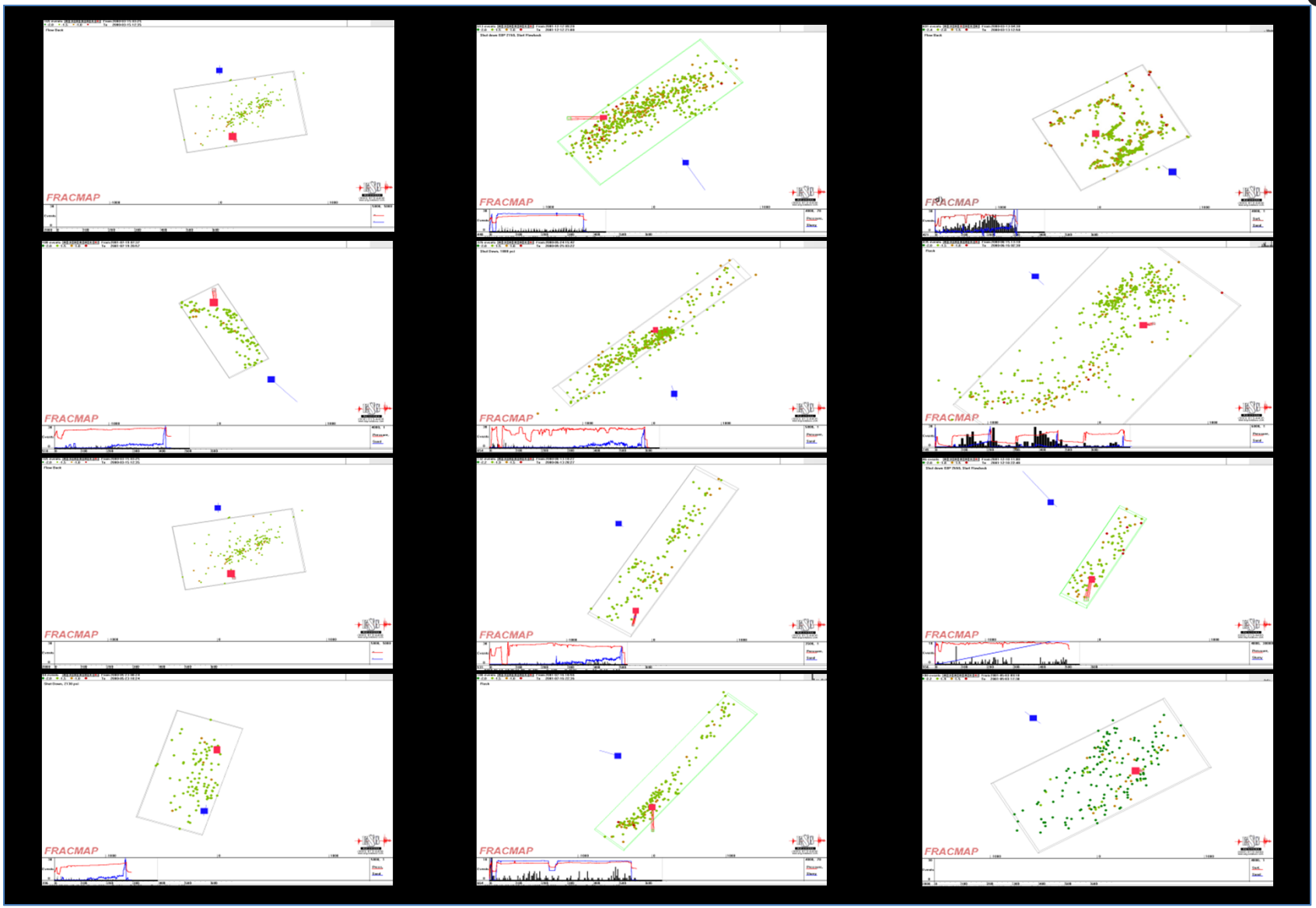
Introduction

- 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

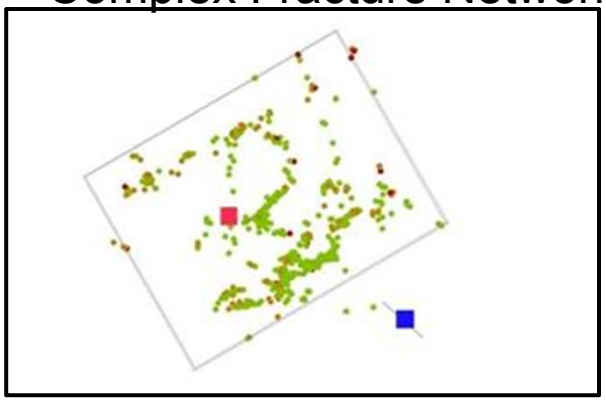
Fracture Variability, Barnett Shale, 2000



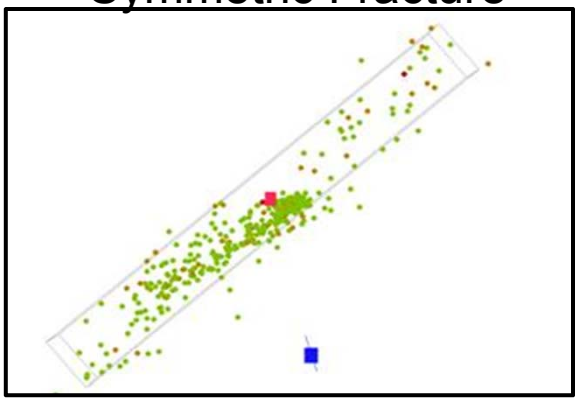
SPE 77440

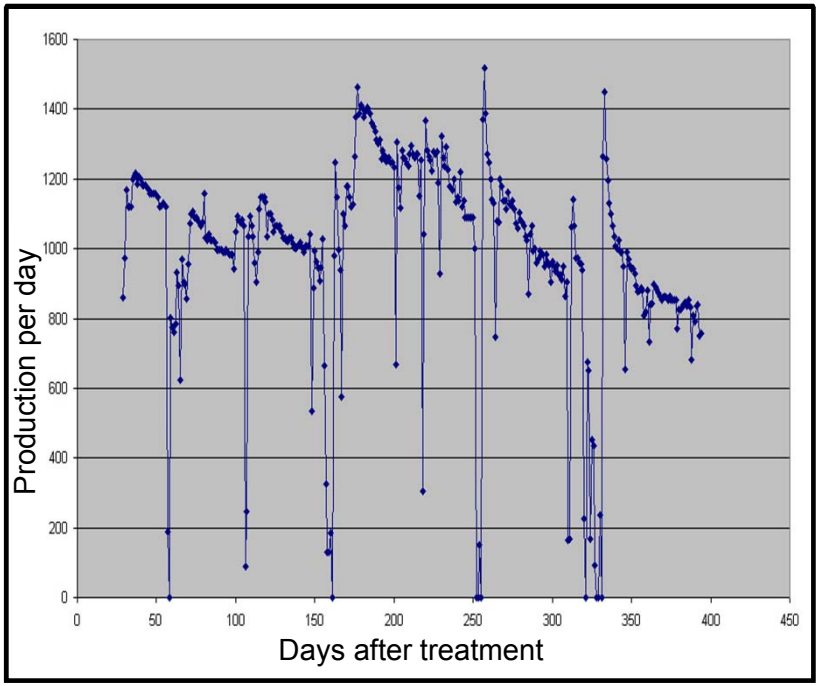
Role of Structure in Production

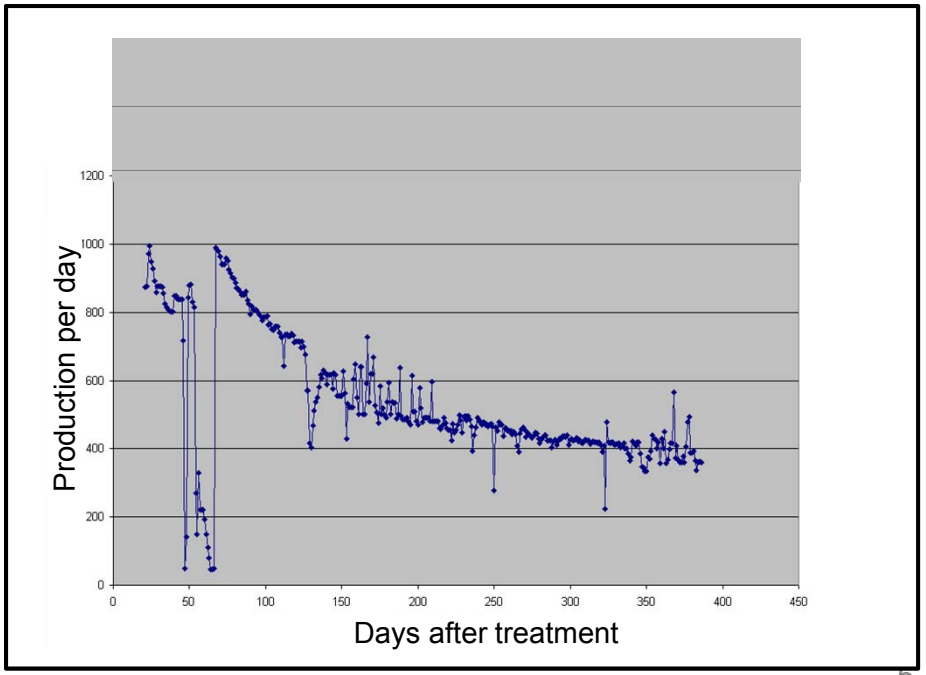
Complex Fracture Network



Symmetric Fracture







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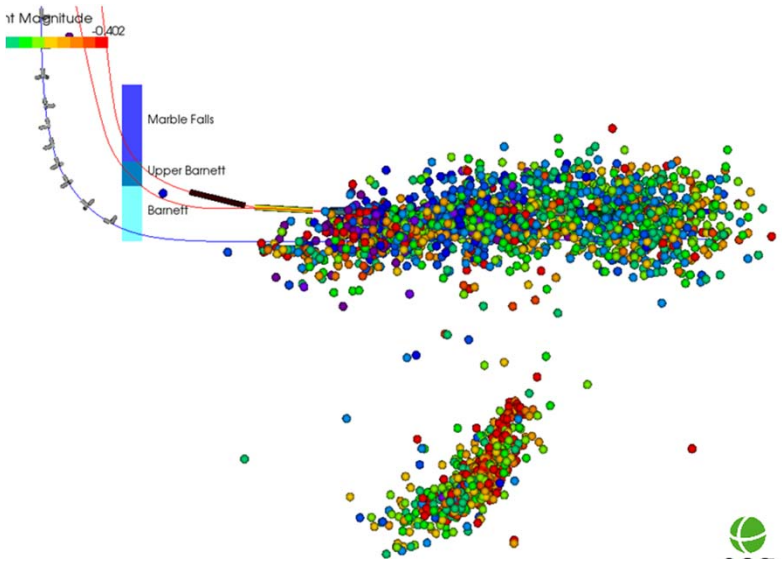
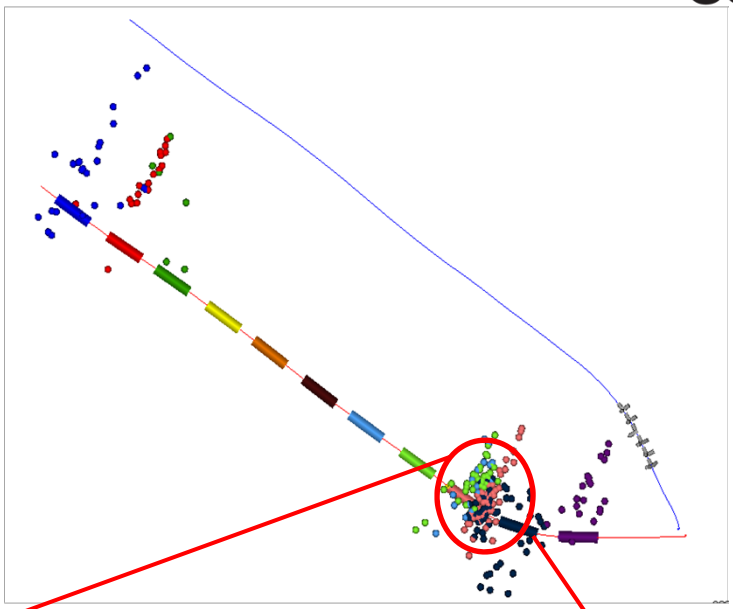
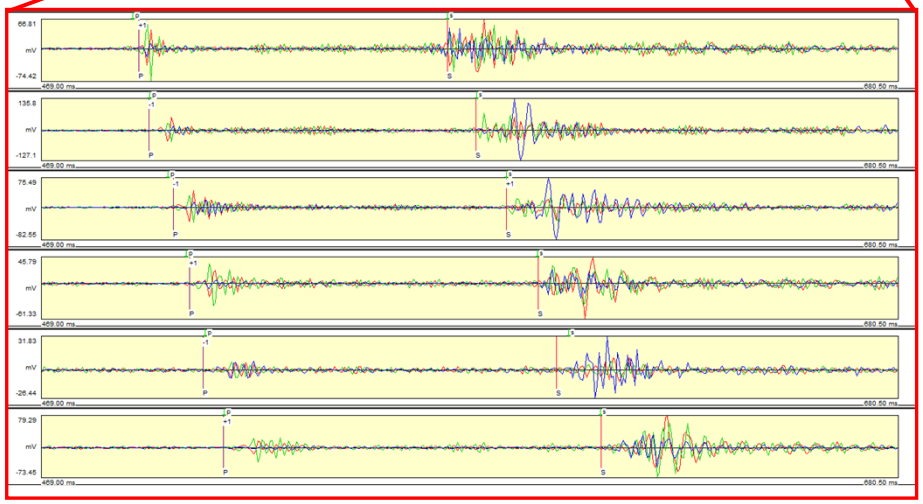
Real Time Geo-Hazard Avoidance

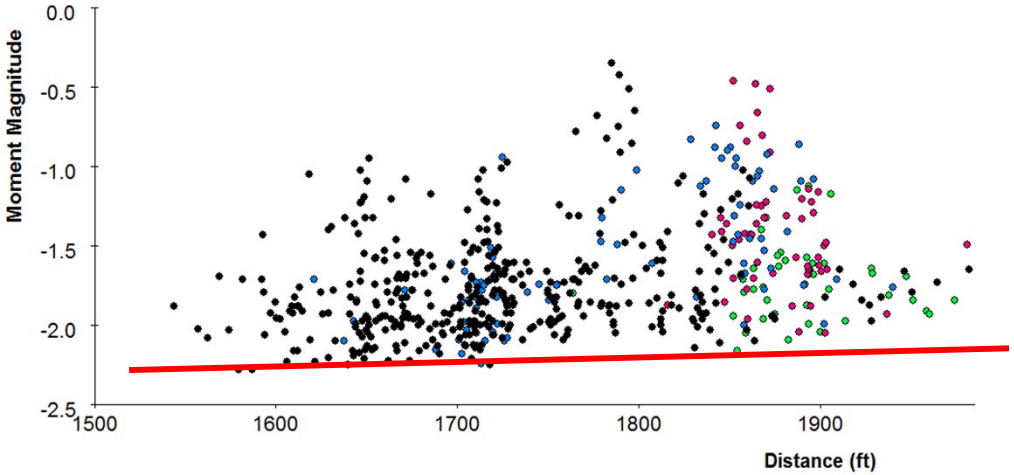


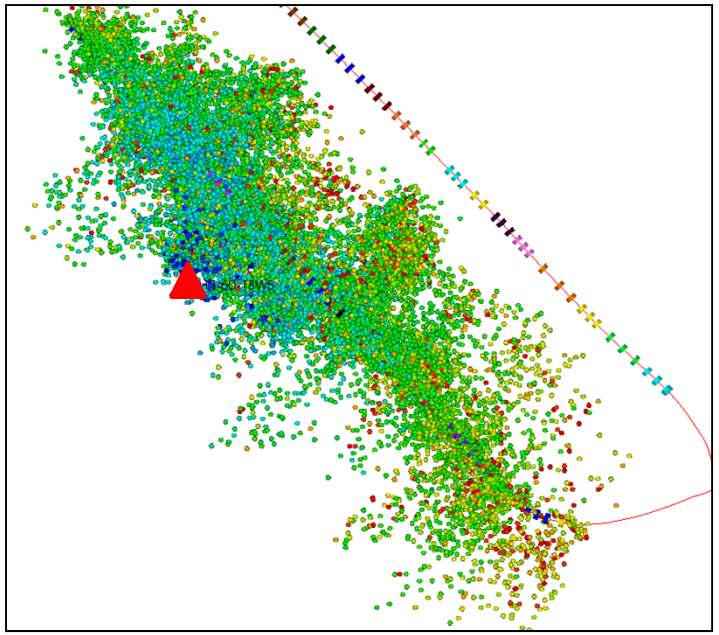


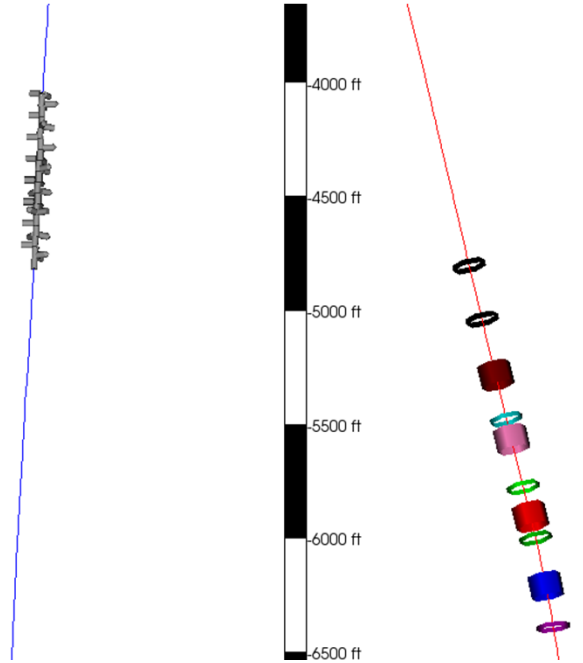


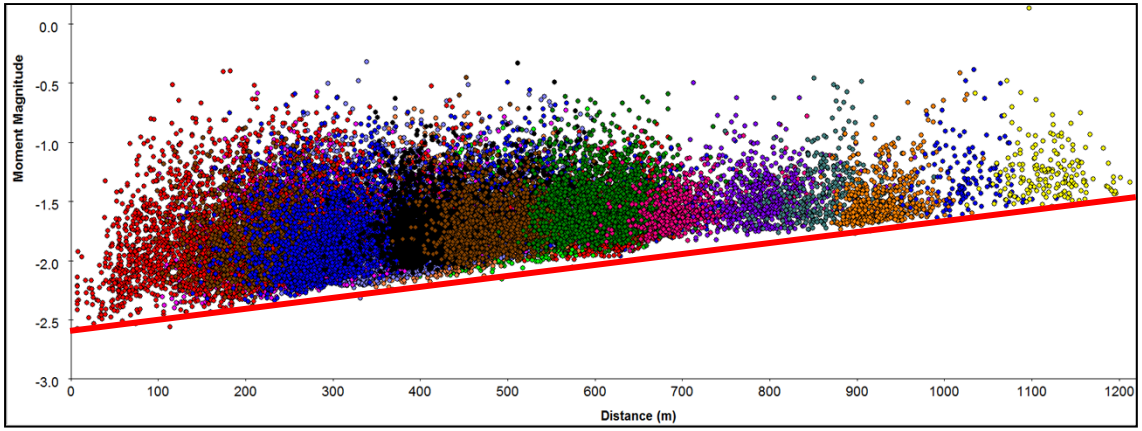
- Prevention of fracing into aquifers
- Identification of casing failures

Moving From Vertical to Horizontal Treatment Wells - Detectability

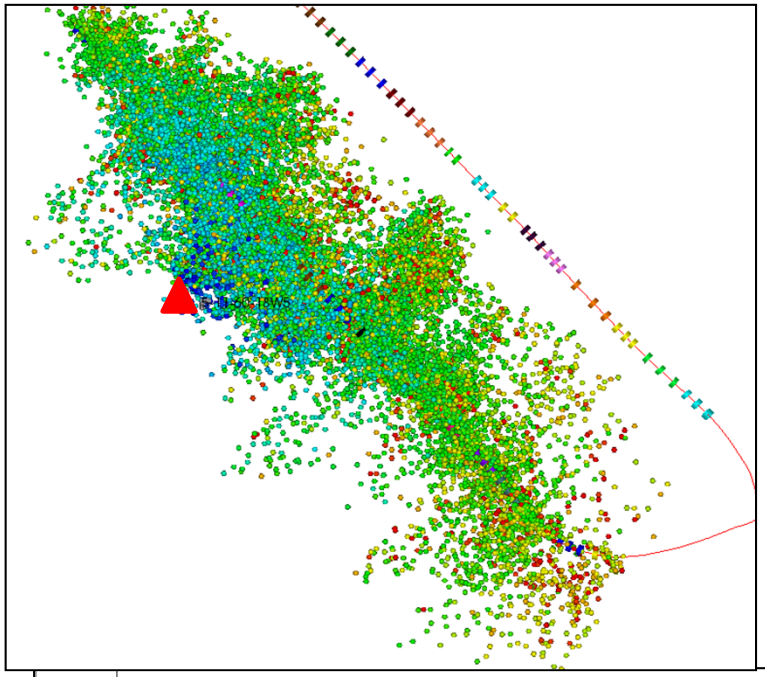






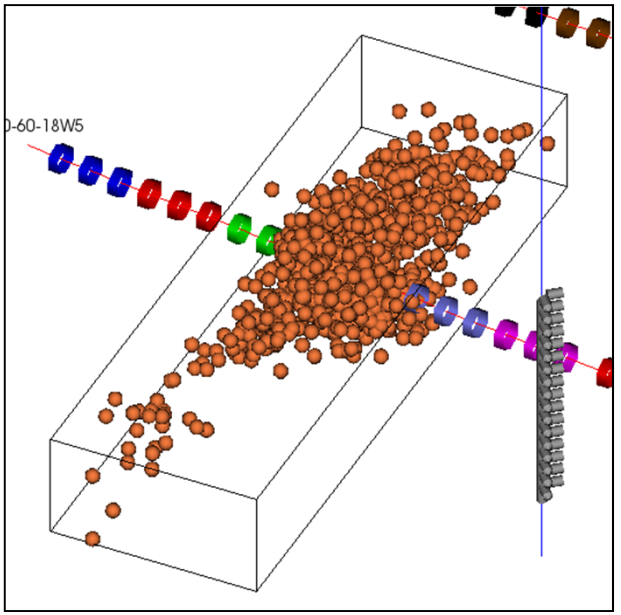


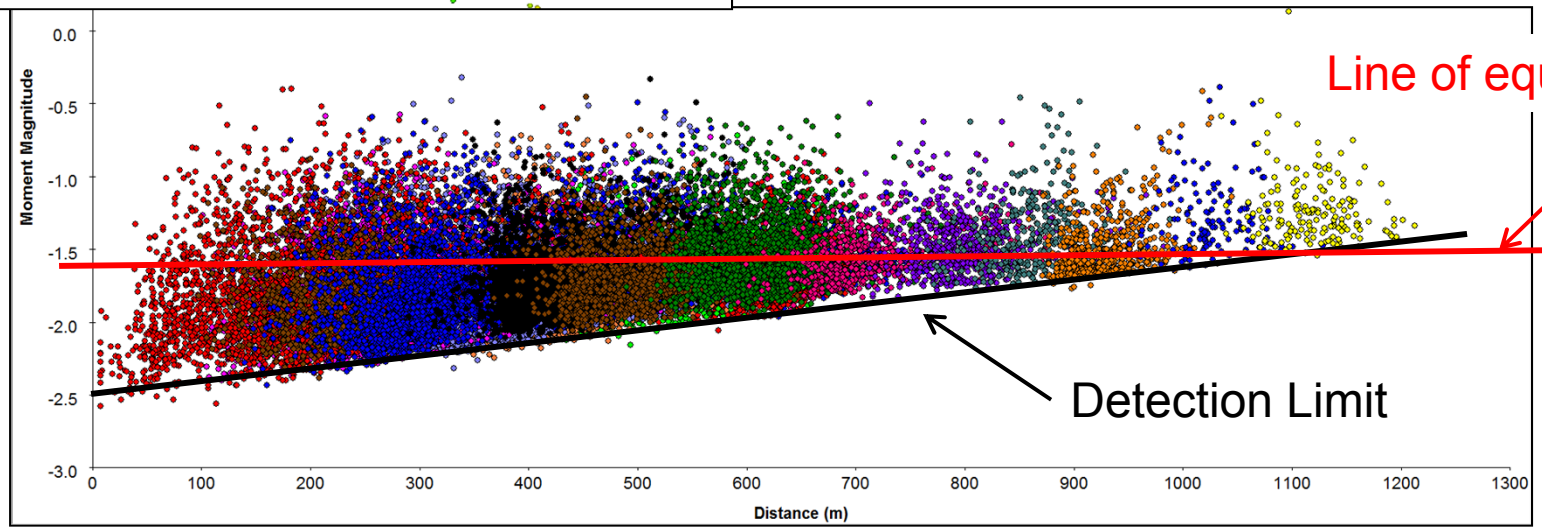
Fracture Dimensions and Detection Biases



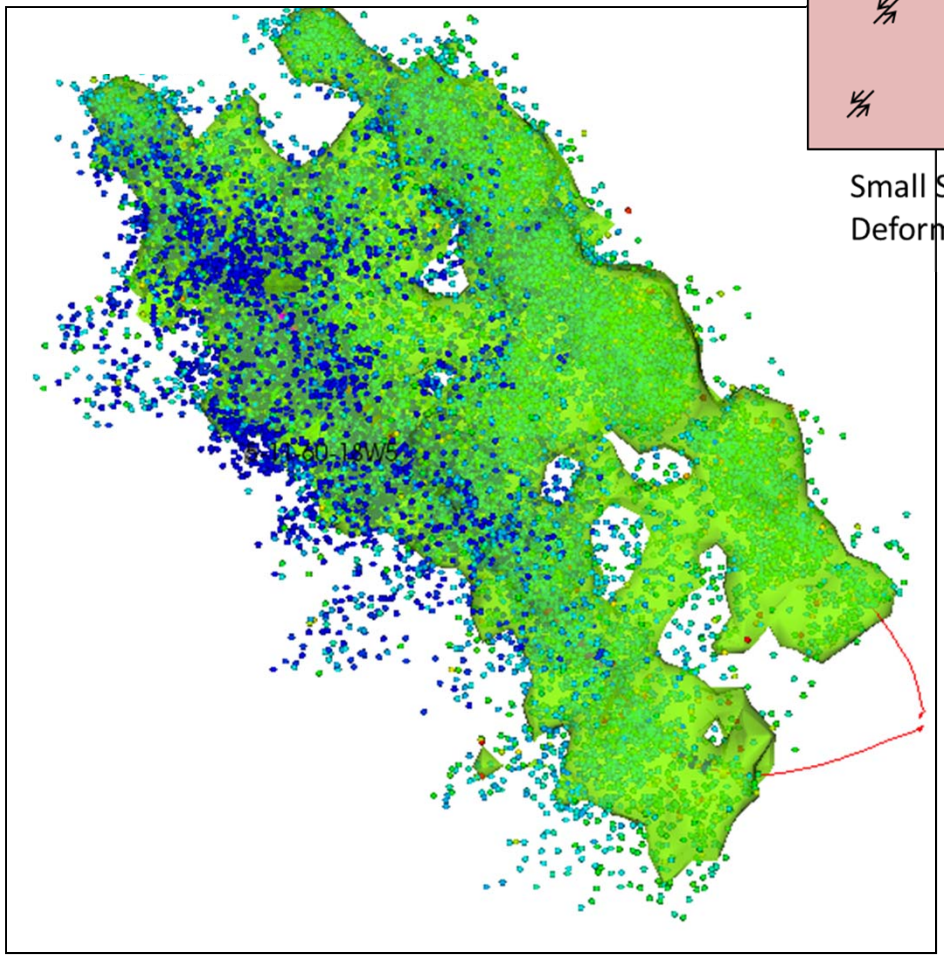
How to calculate fracture dimensions?

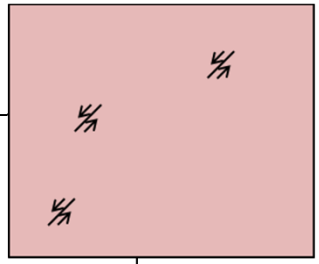
- 100% of events? 90%
- Envelop around events?
- Does every event contribute equally?



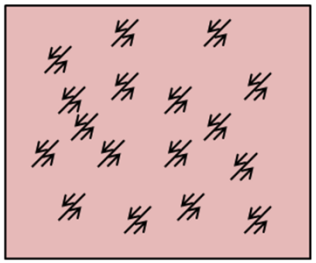


Stimulated Reservoir Volume

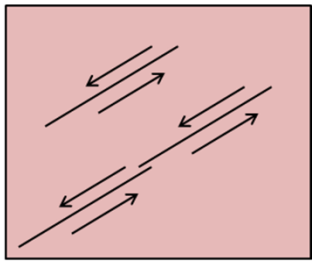




Small Seismic Deformation



Large Seismic Deformation



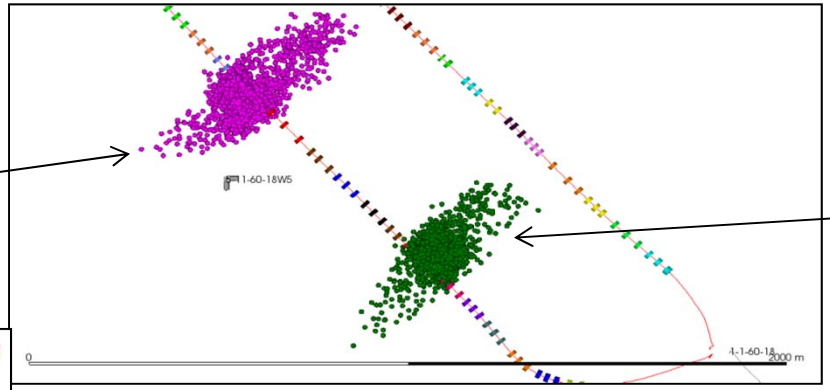
Large Seismic Deformation

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.

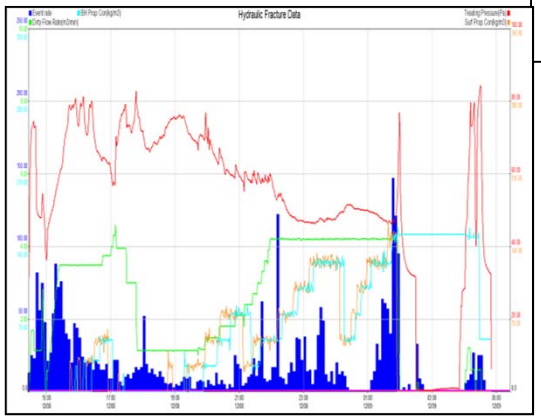
- Seismic Deformation in a volume is calculated based on the moment of the seismic events within that volume.
- Volumes that have small seismic deformation will not be extensively fractured.
- Areas of higher seismic deformation show increased fracture density and permeability and therefore, are expected 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

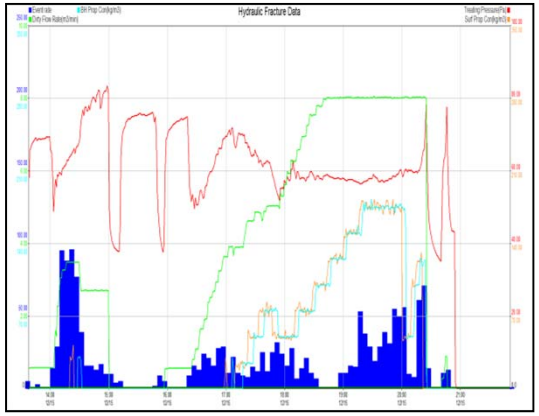
Stage A

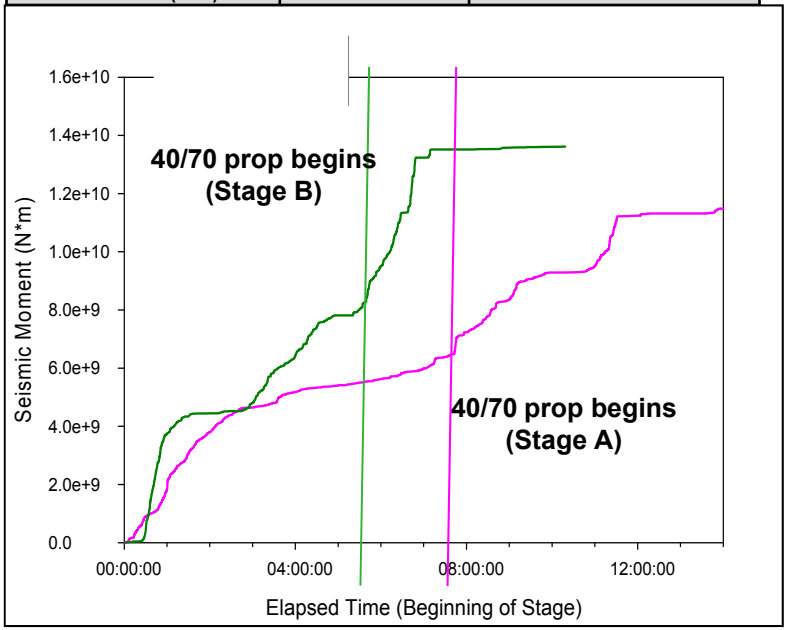


Stage B



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

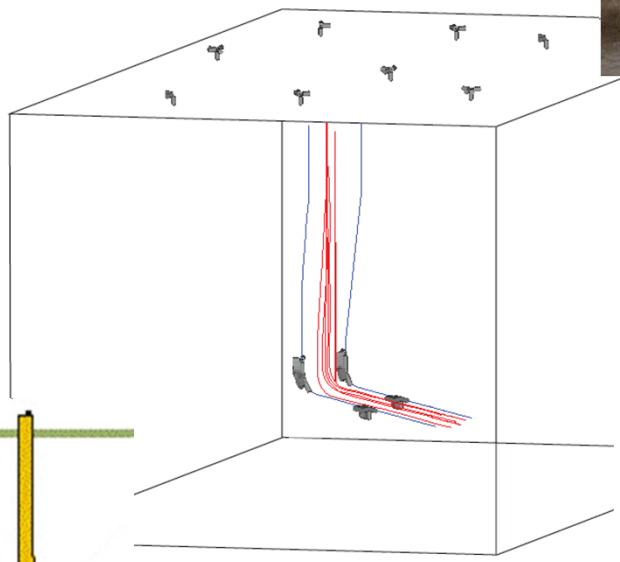


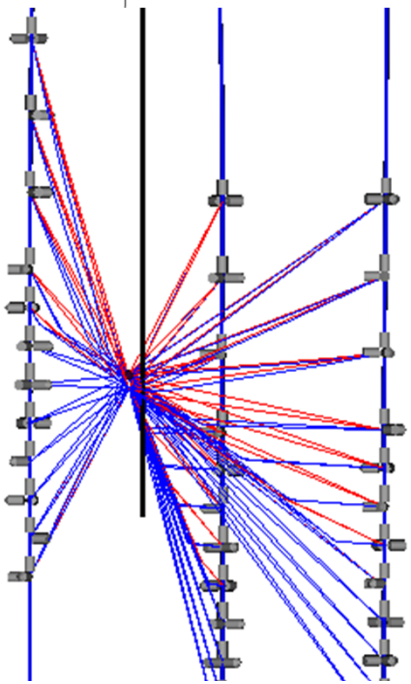


Using More Than One Array

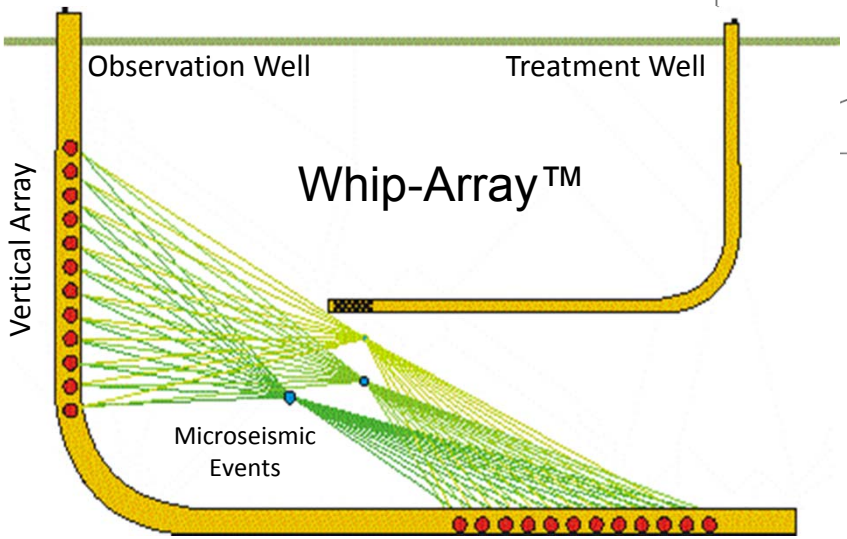
- Adding multiple arrays reduces detection bias
- Provides wider coverage of treatment wells
- Improves location accuracy
- Provides opportunity for more advanced analysis

Surface Arrays

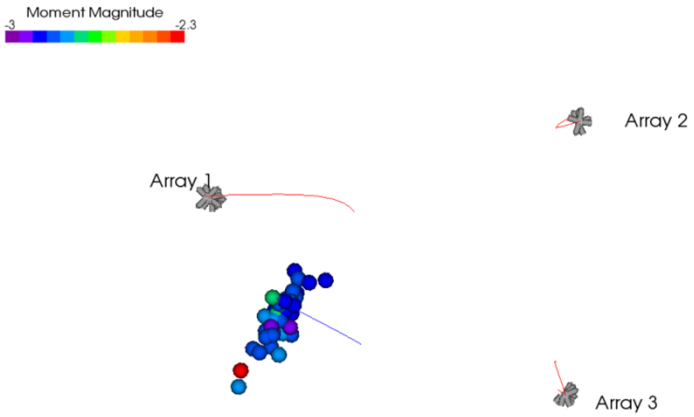




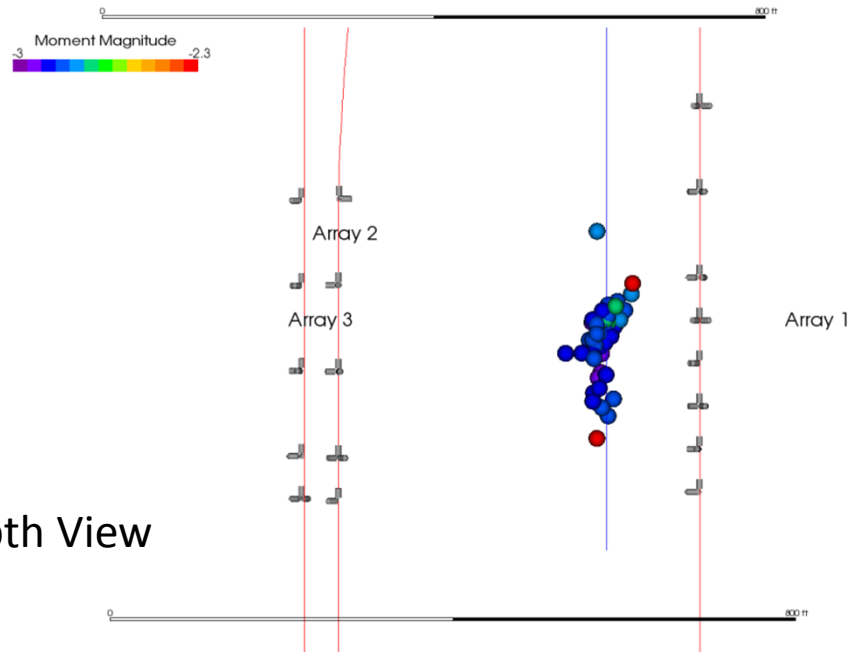
Multiple Vertical or Horizontal arrays



Benefit of Multiple Observation Arrays



Plan View



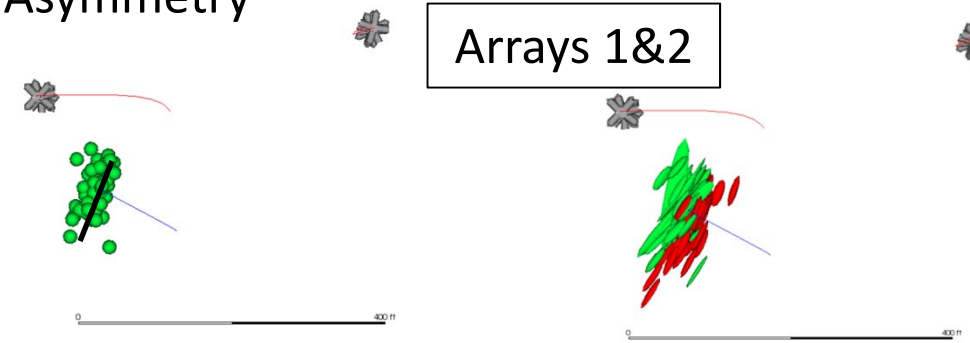
Depth View

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

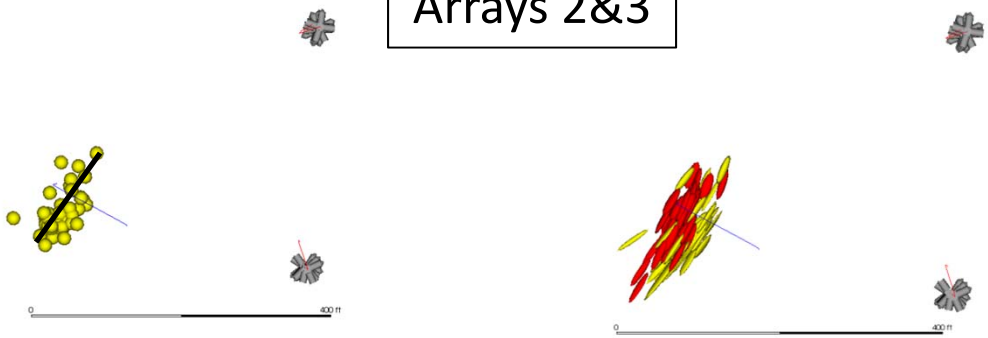
Array Locations & Asymmetry

Error Ellipsoids

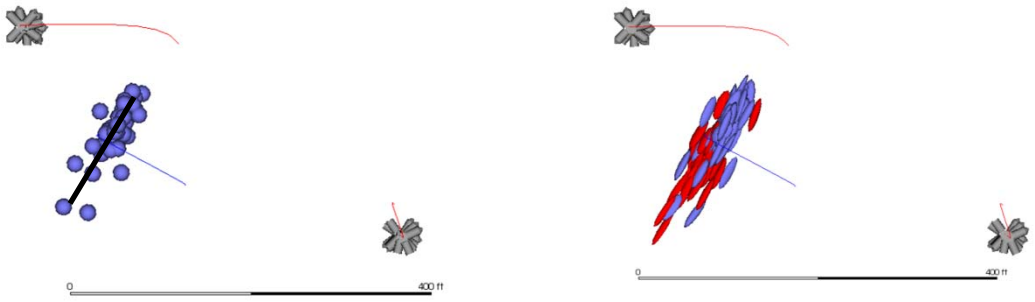
Arrays 1&2



Arrays 2&3

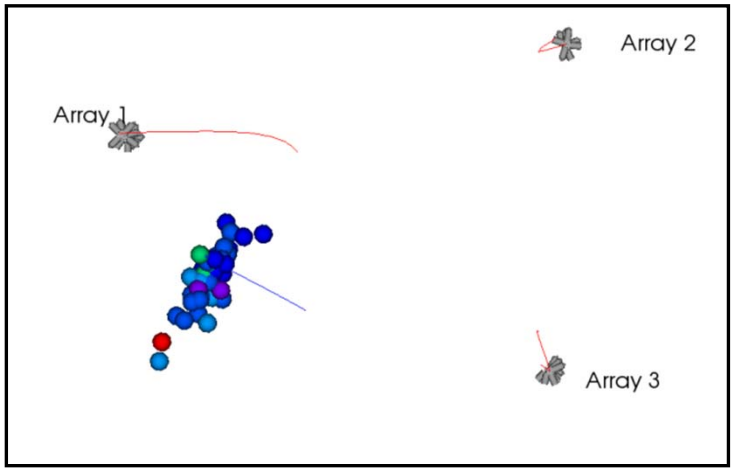


Arrays 1&3



Dual-Array Event Locations

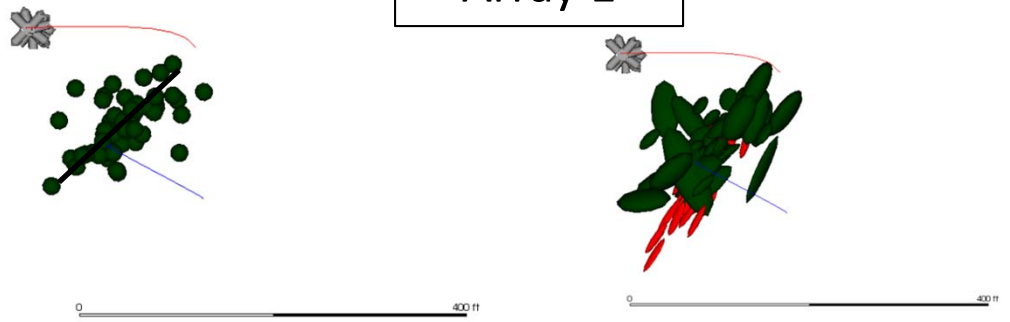
- Illustrate slightly more scatter
- Some array configurations show offset



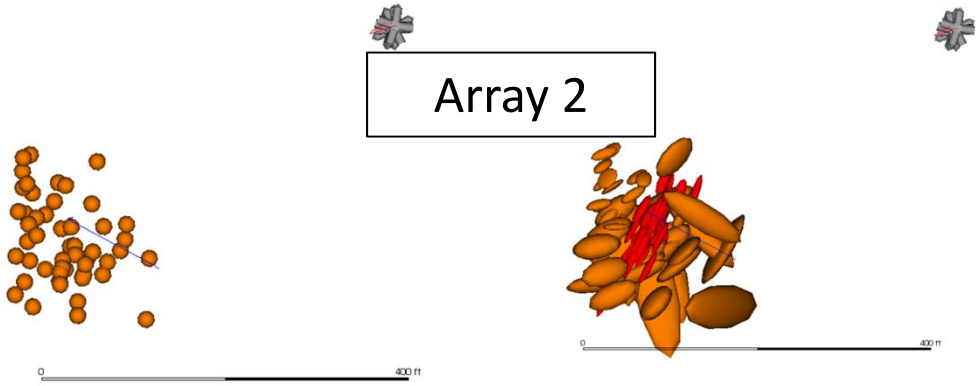
Array Locations & Asymmetry

Error Ellipsoids

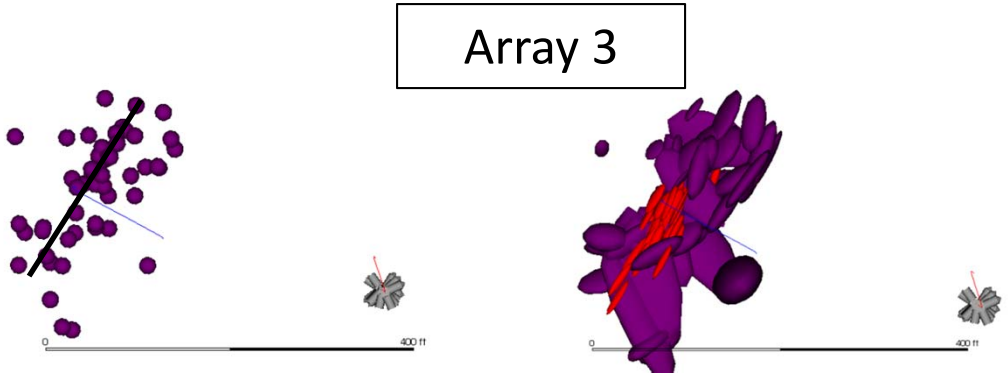
Array 1



Array 2

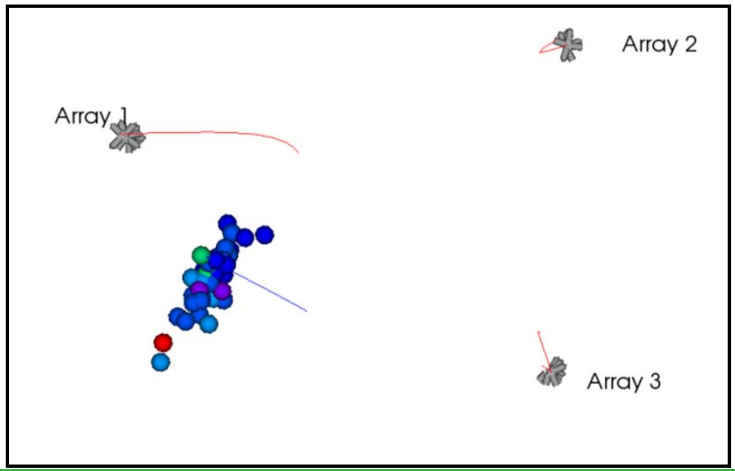


Array 3



Single-Array Event Locations

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

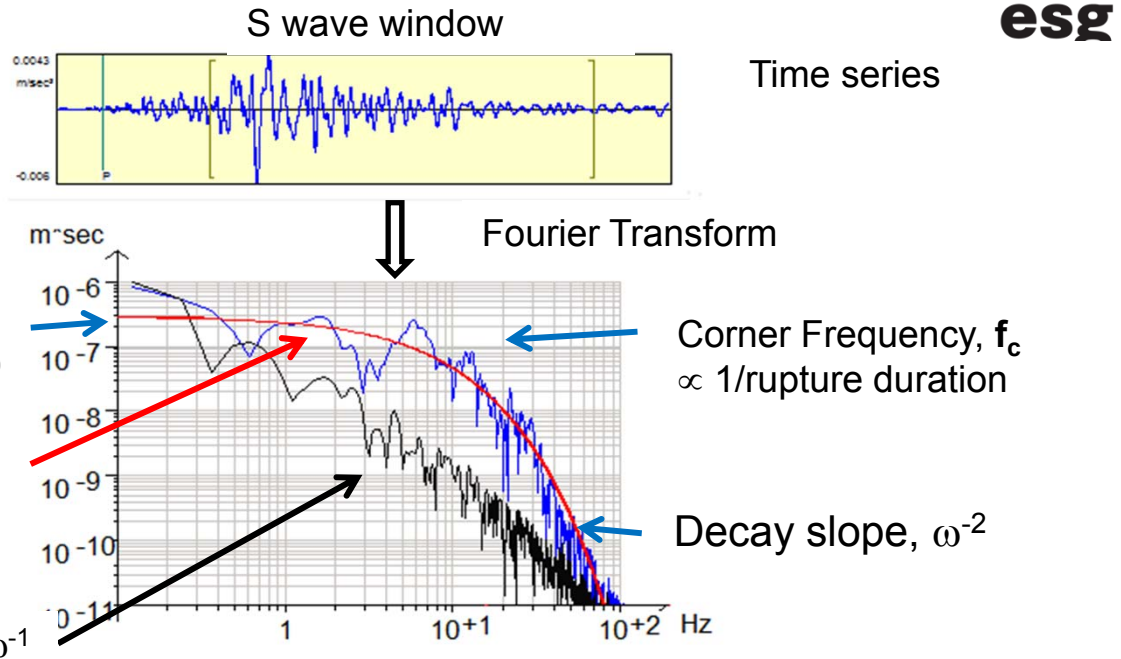


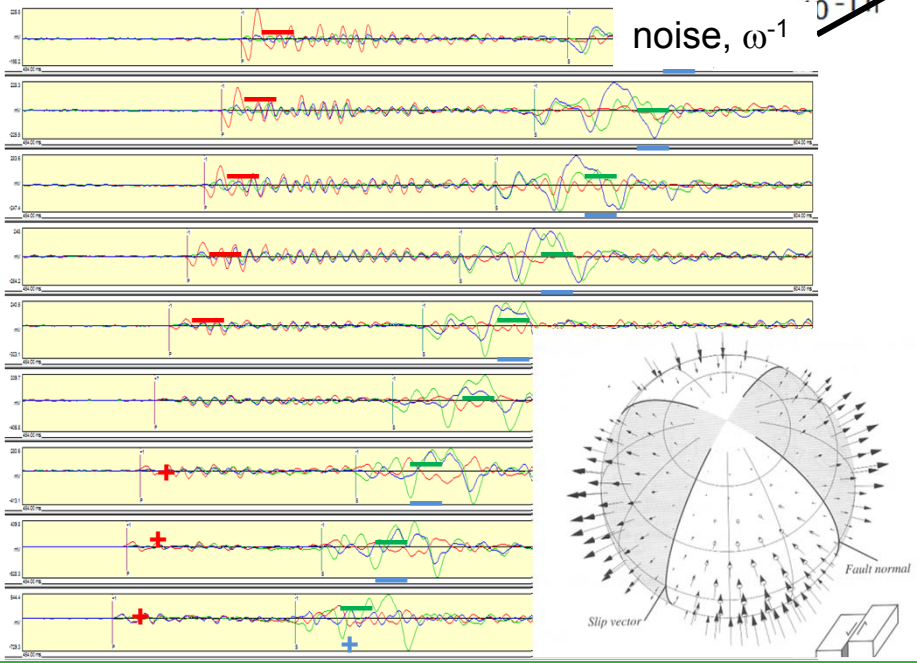
Challenges to Old Ideas

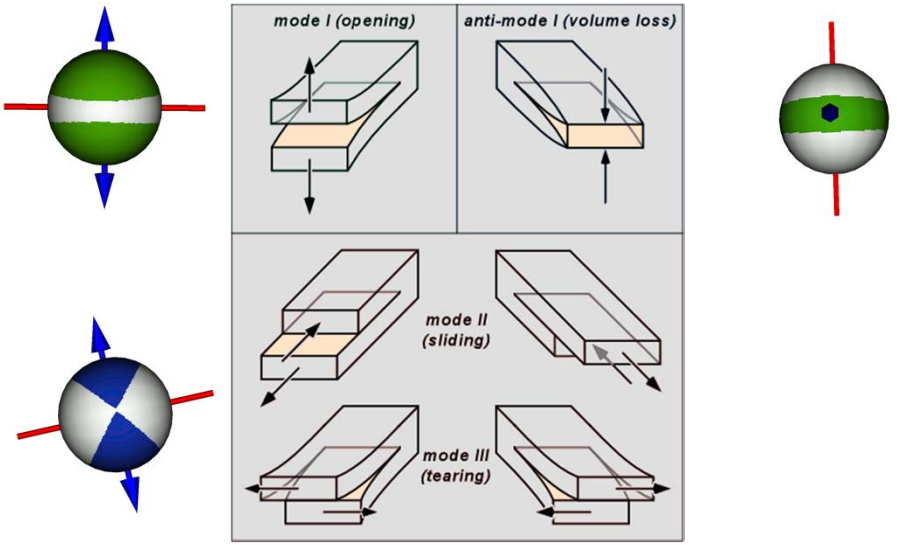
- How do fractures initiate and propagate?
- Are new fractures being created or are old fractures being activated?
- What is the role of pre-existing fractures and bedding planes?
- Are these fractures open or cemented prior to stimulation?
- Are some fracture sets preferentially activated during hydraulic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

Bridging the Gap Using Microseismicity

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

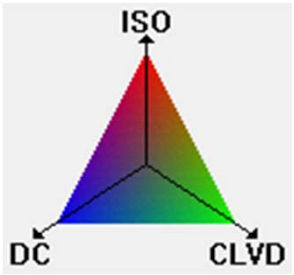




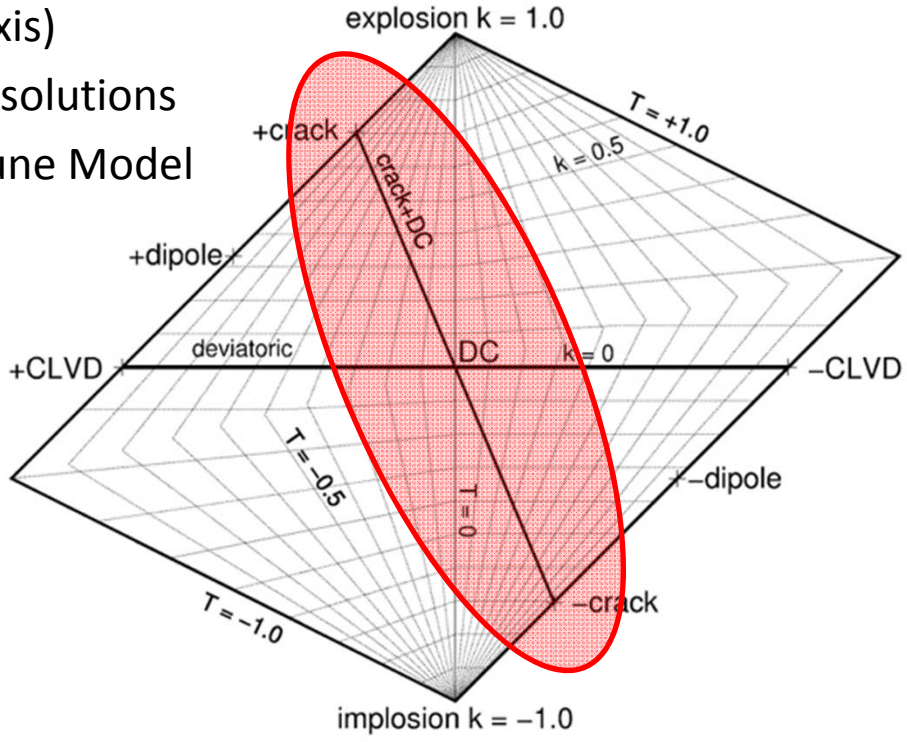


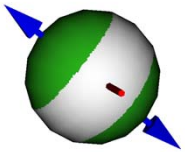
SMTI/DFN

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

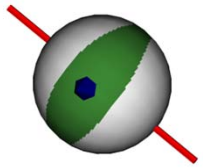


- Common modes of failure:
  - Tensile opening of a fracture (normal to tension axis)
  - Closure of a fracture (normal to pressure axis)
  - Slip on a fracture surface (DC) – resolvable solutions
  - Relative dimensions based on modified Brune Model (shear-tensional)

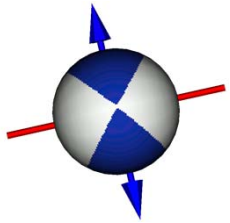




crack opening

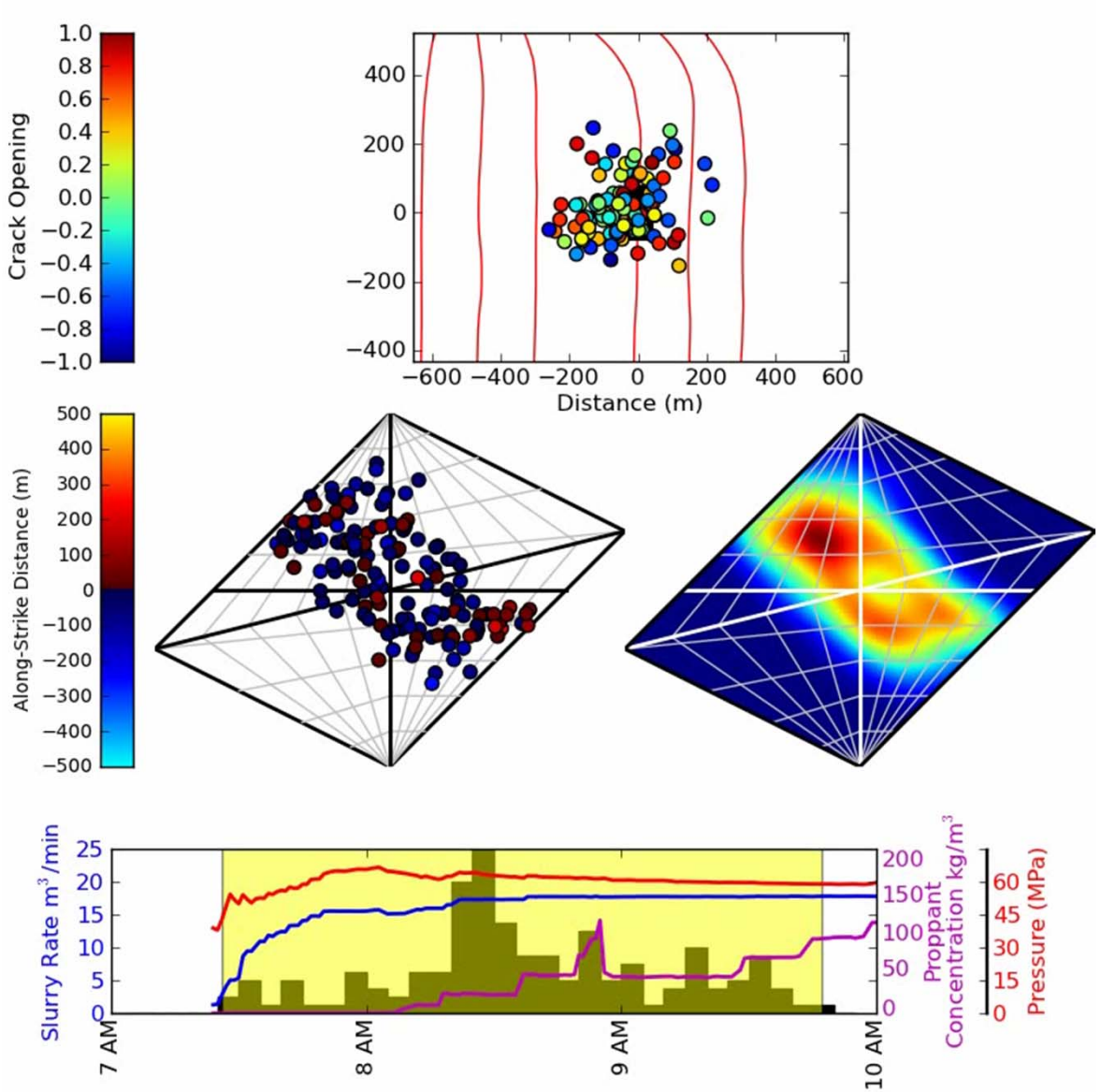


crack closing

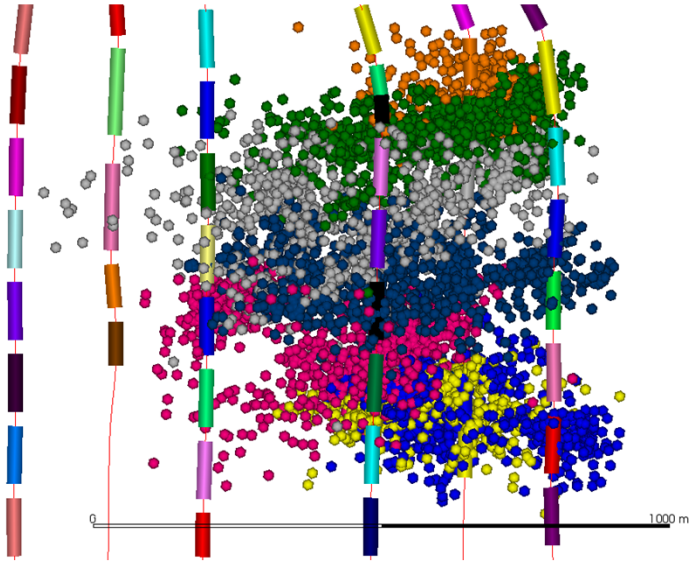


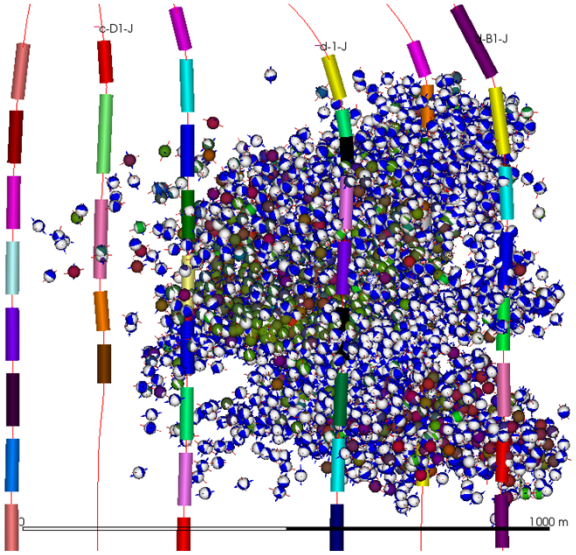
DC / shear

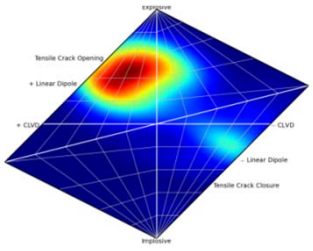
Source Types



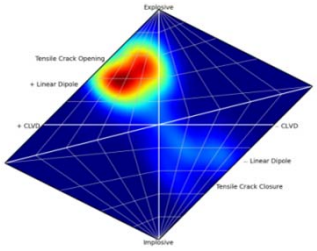
Effect of Overlapping Stages



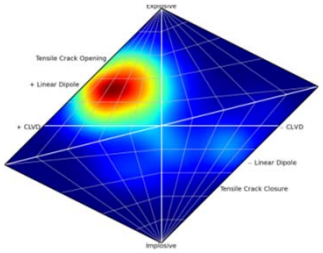




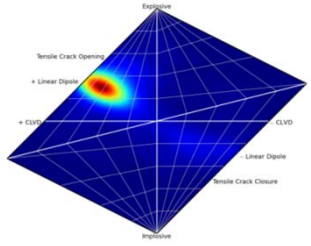
stage 11: 125 events



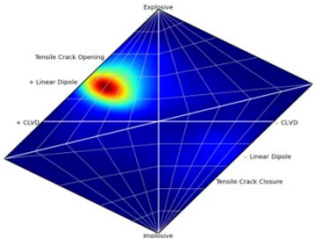
stage 12: 414 events



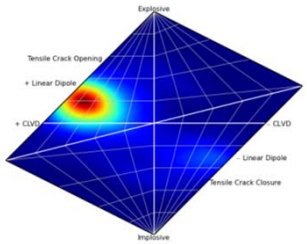
stage 13: 240 events



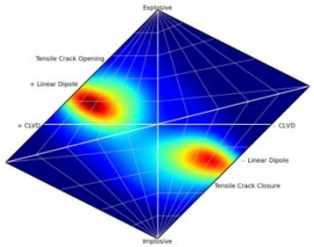
stage 14: 586 events



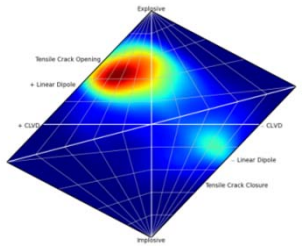
stage 15: 579 events



stage 16: 327 events



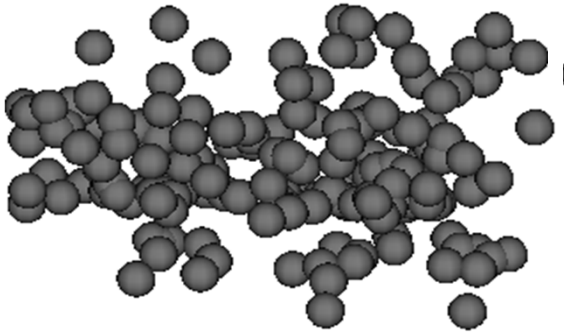
stage 17: 185 events

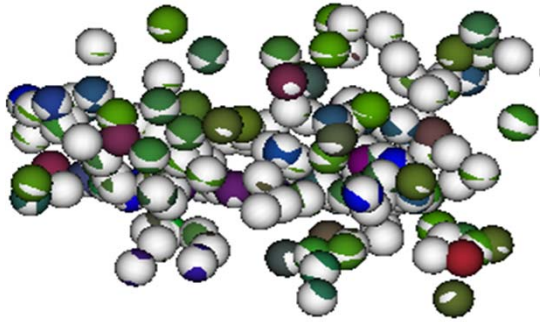


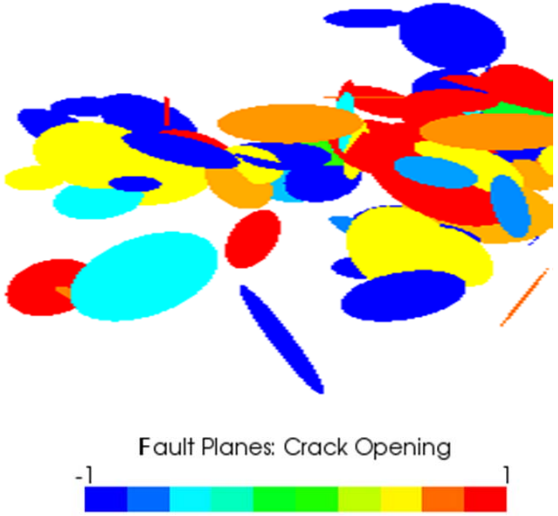
stage 18: 733 events

Building on SMTI
Discrete Fracture Network (DFN)

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

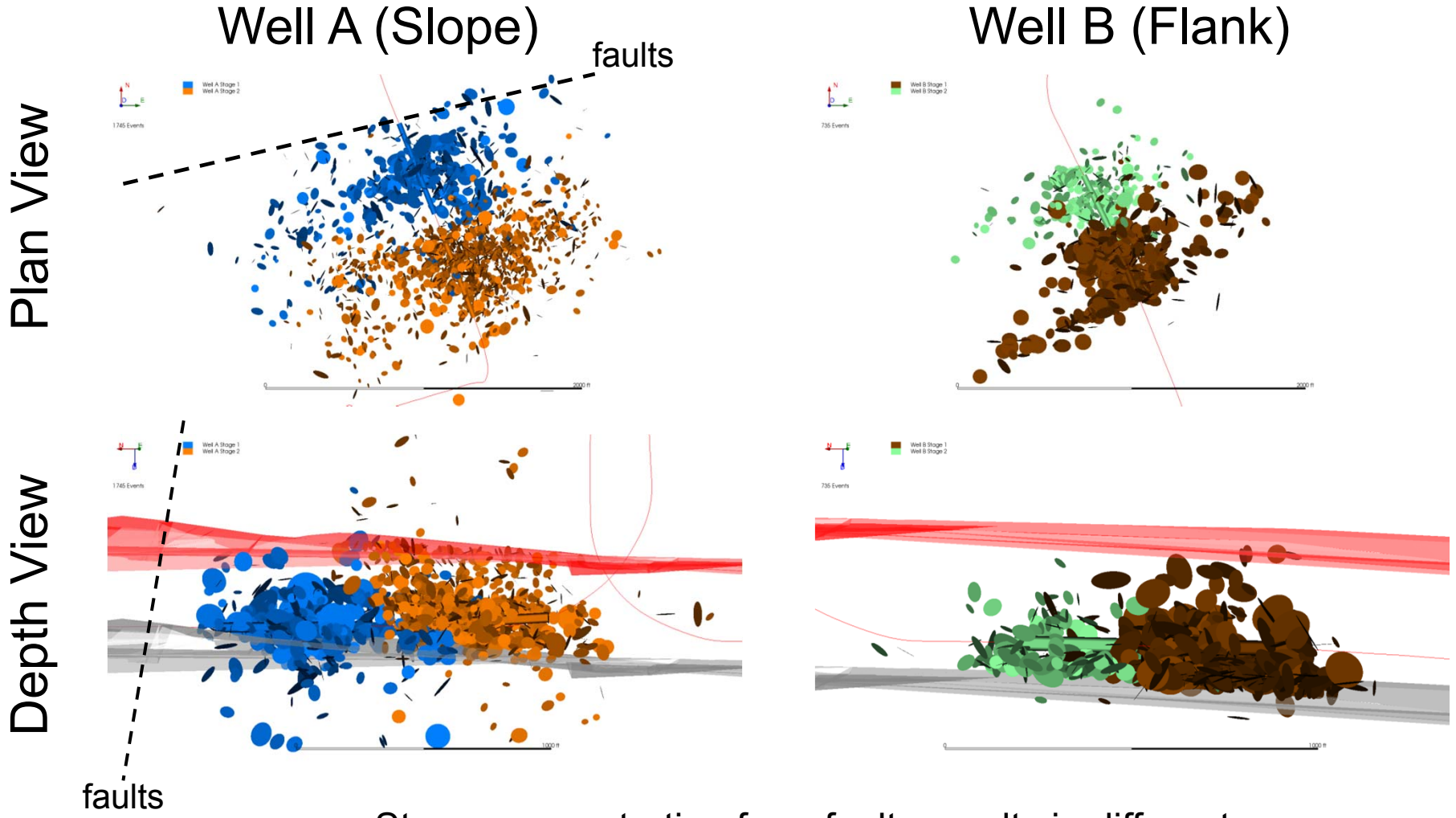






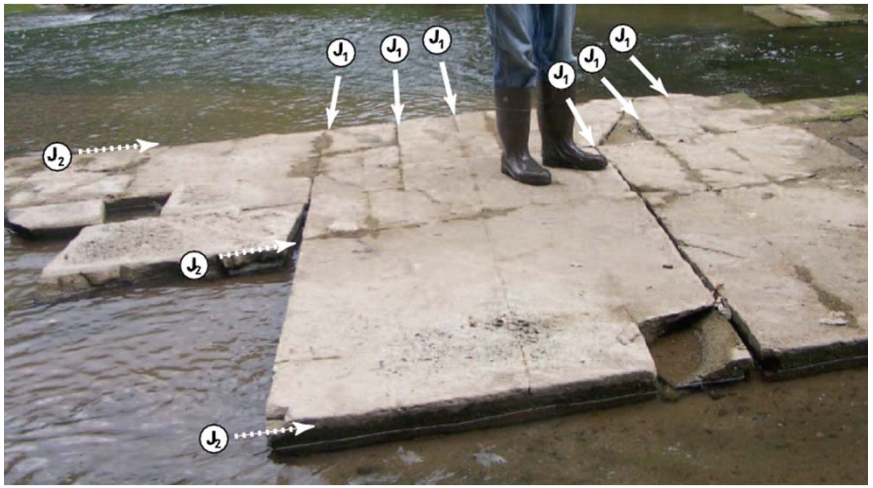
Fracture orientations and extents are dimensions shown as discs, coloured by source type.

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

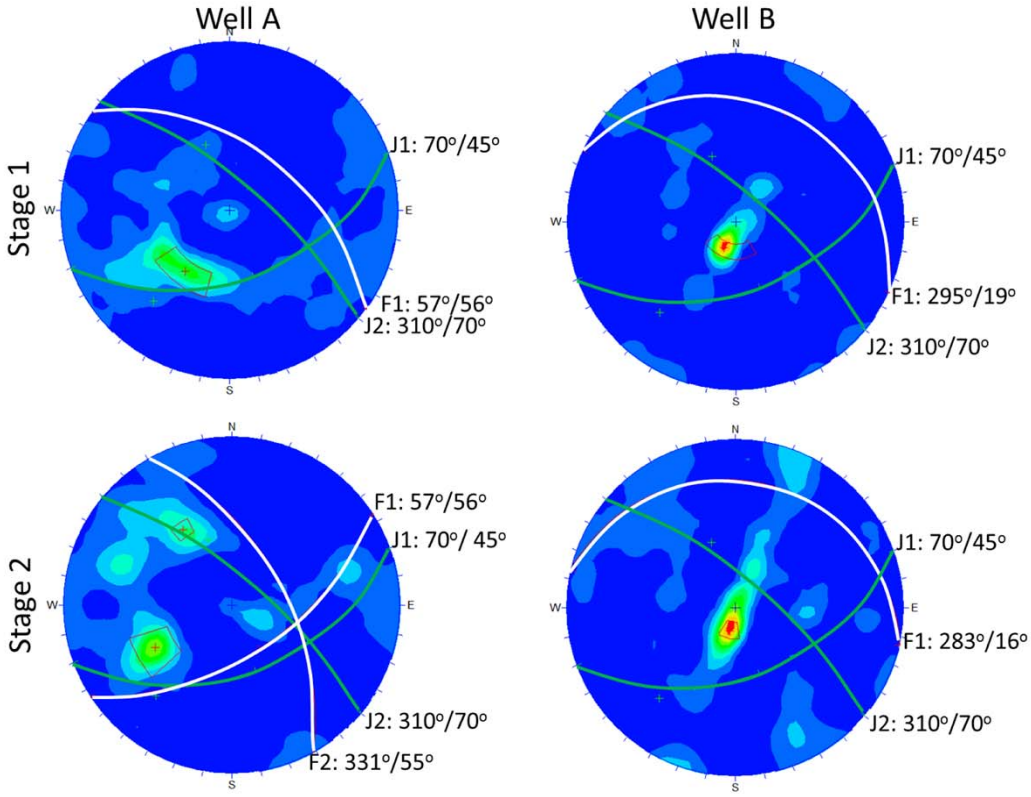


Stress concentration from faults results in different fracture sets activated on either side of the pad.

DFN Activation in the Marcellus Shale

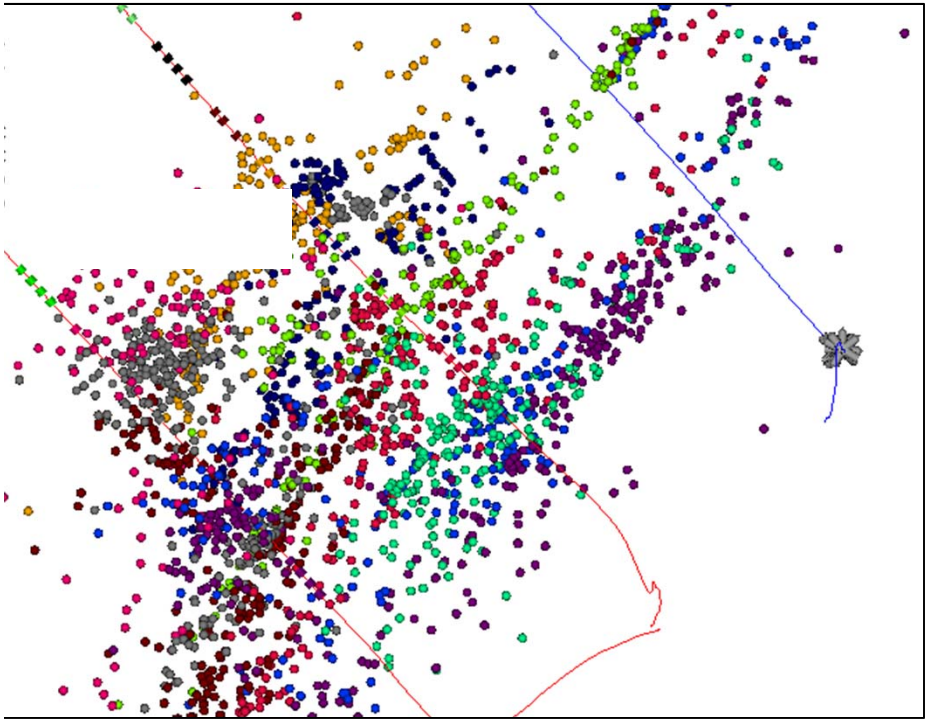


Engelder et al. (2009)

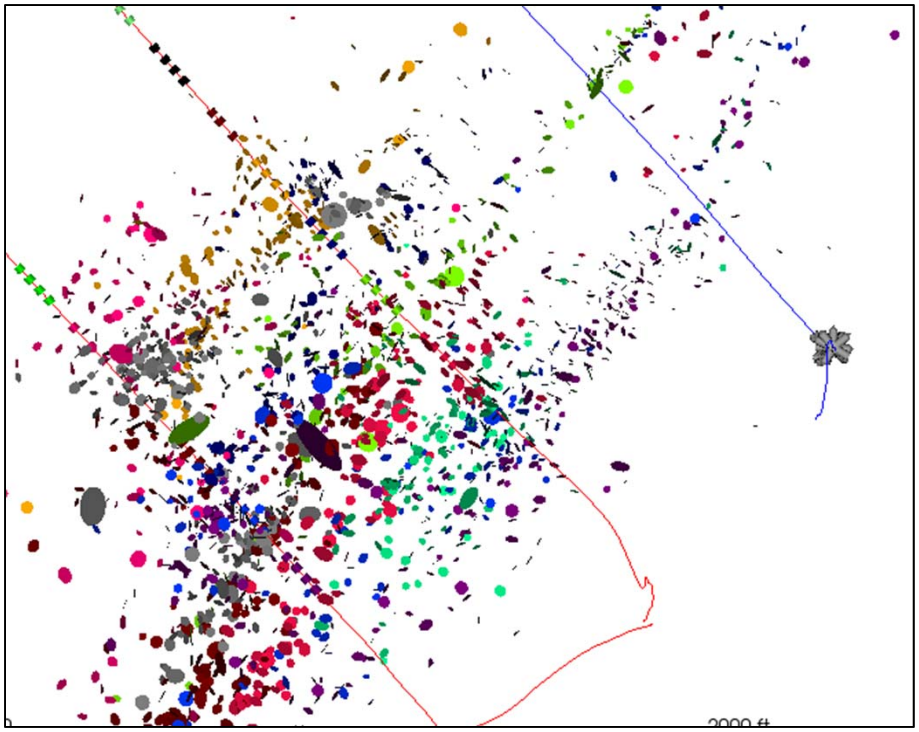


DFN Case Study #2

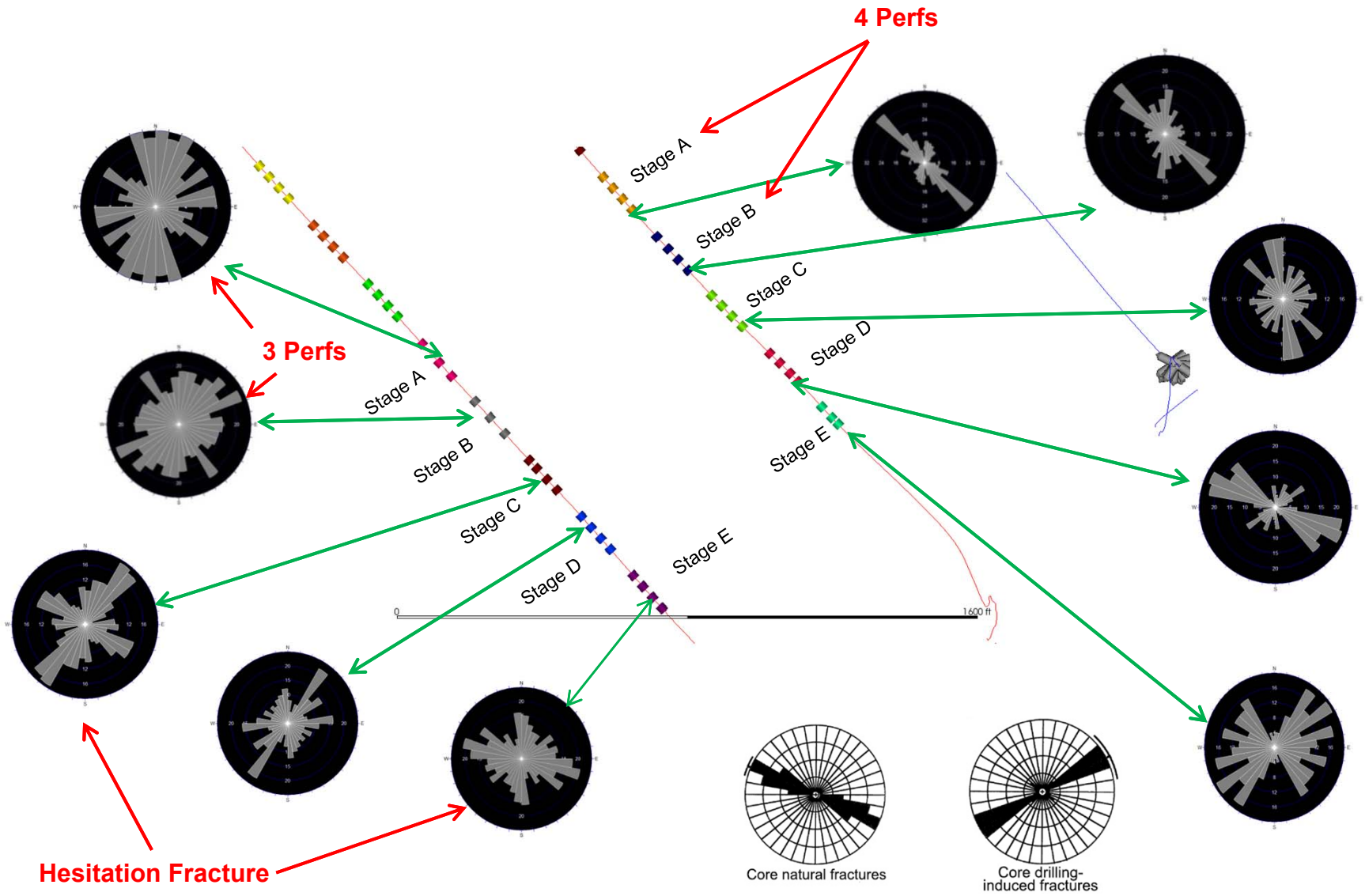
Event Locations



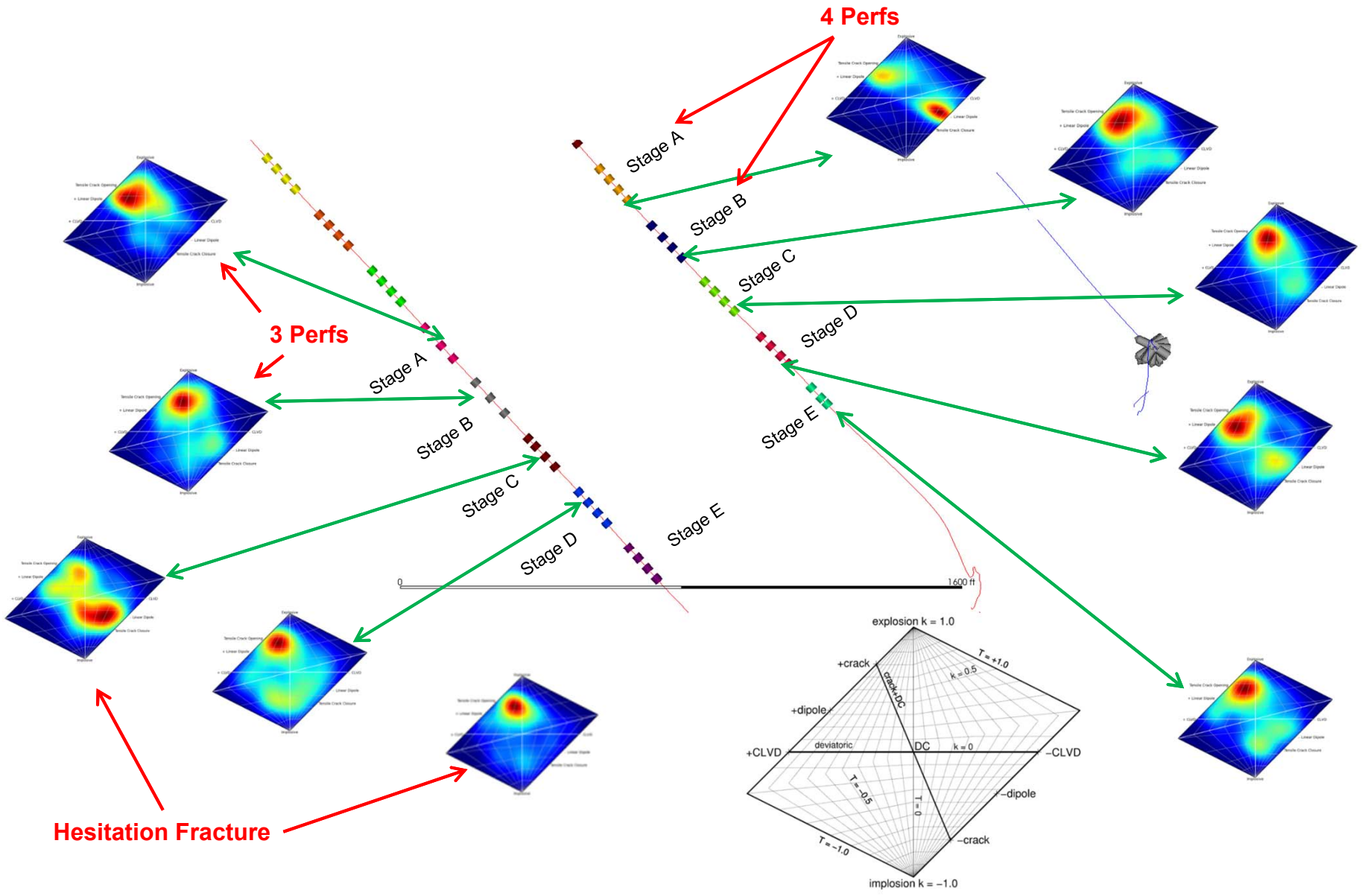
Fracture Planes



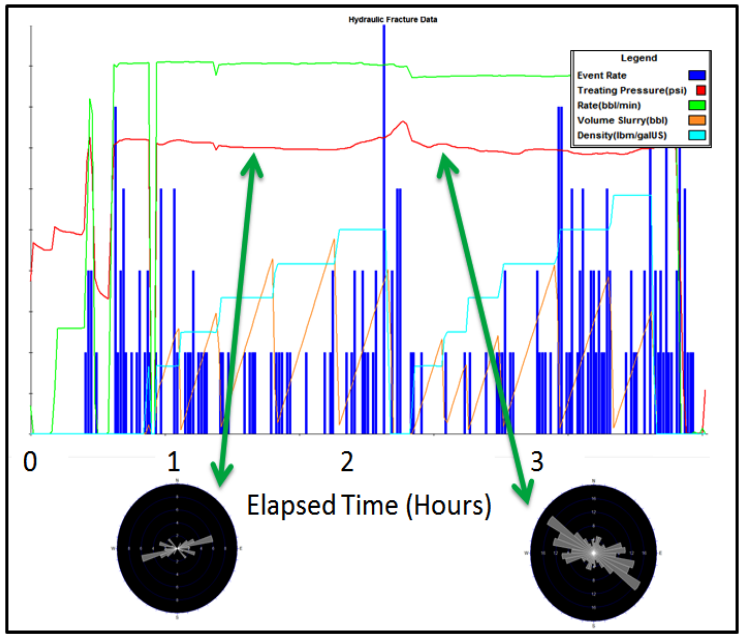
Stimulation Response: Fractures



Stimulation Response: Failure Types

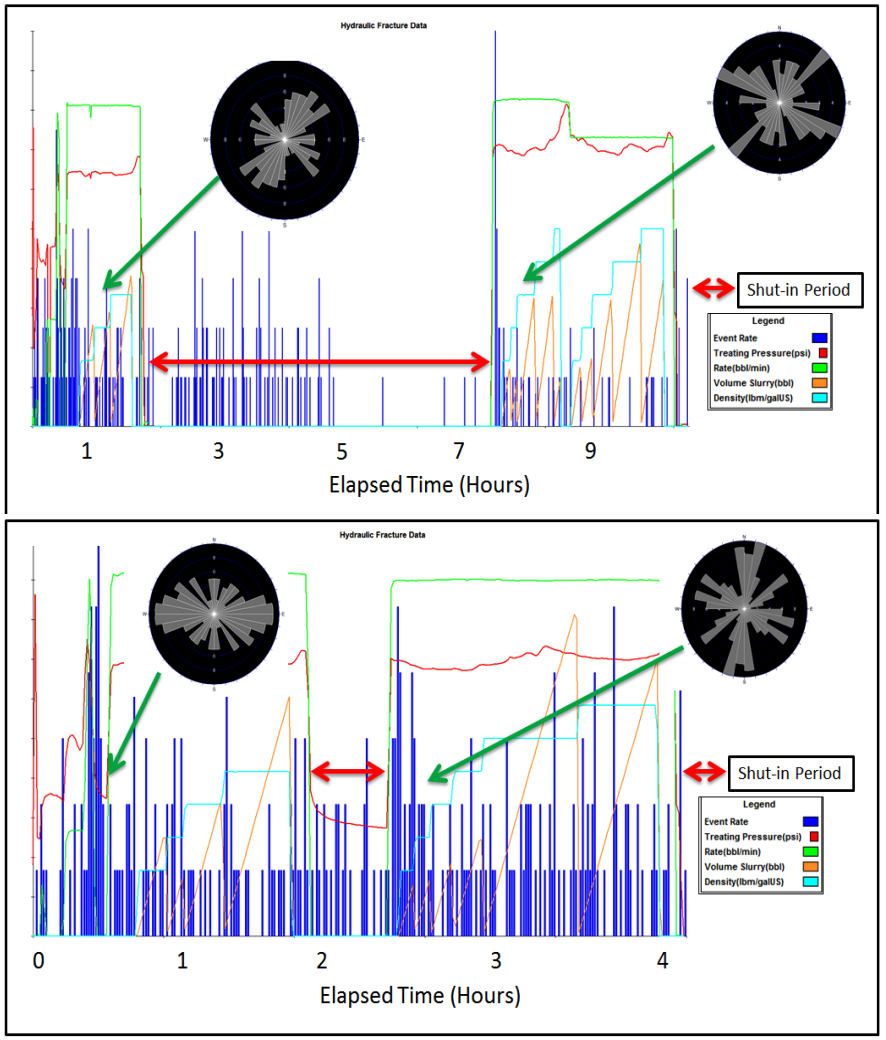


Fracture Re-orientation



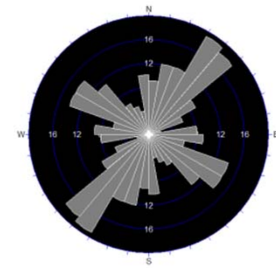
Pressure

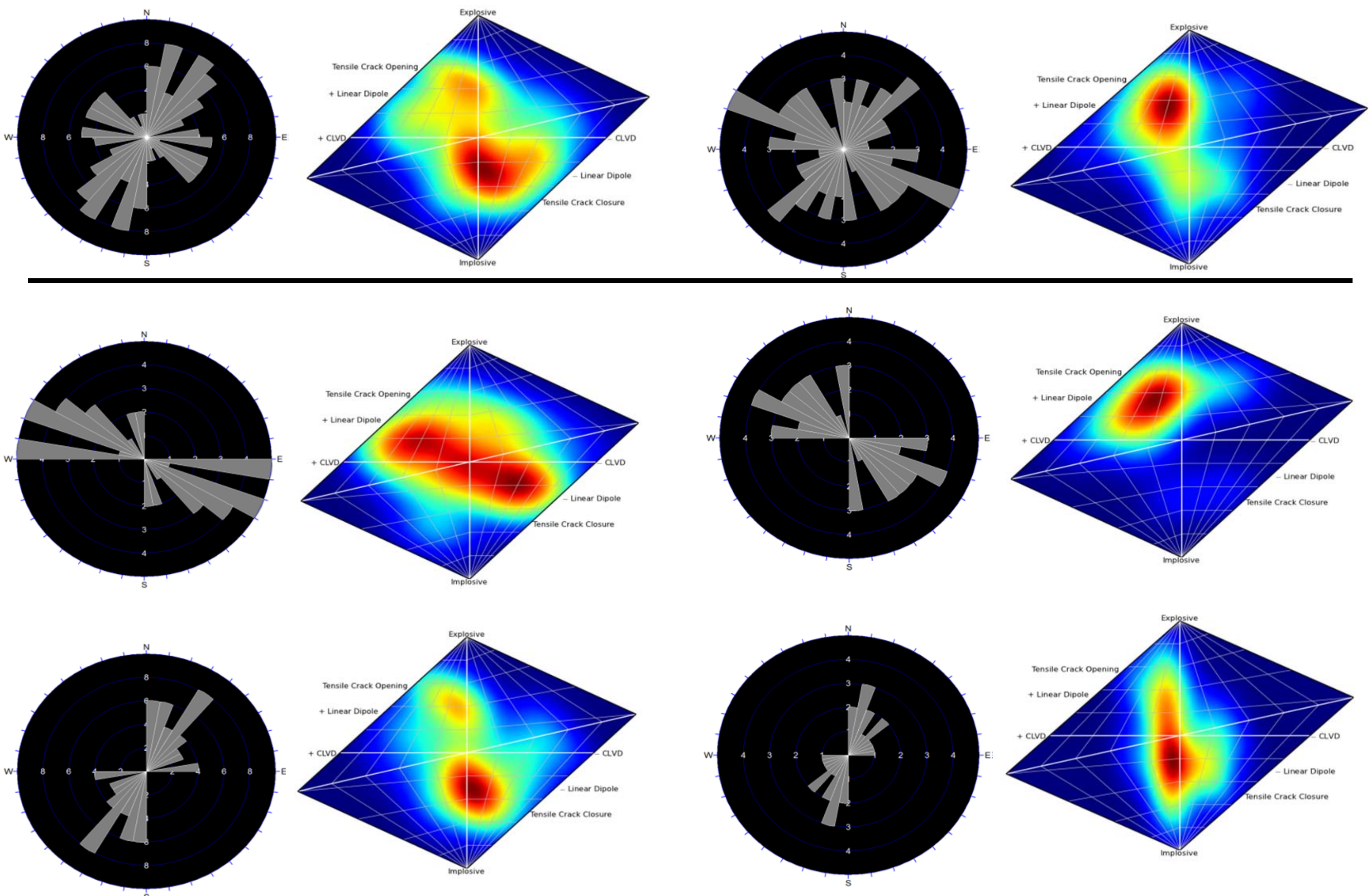
Well 2, Stage C



Well 2, Stage E

Hesitation Frac: Well 2, Stage C

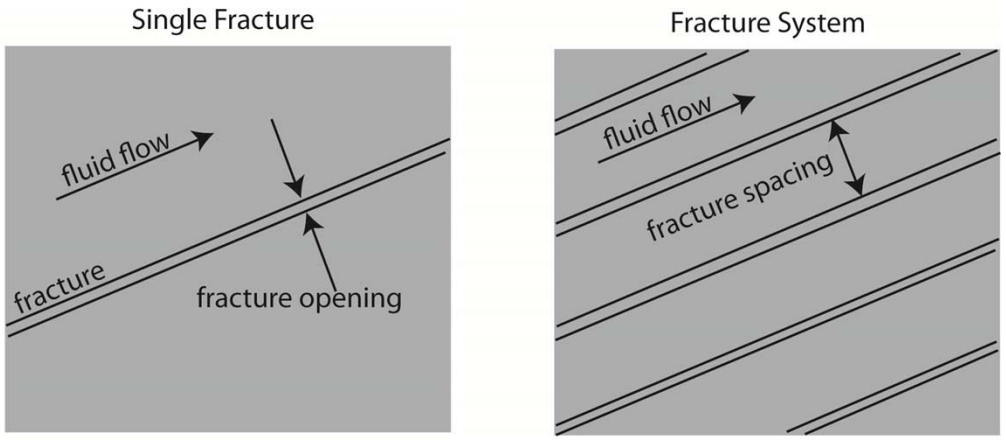




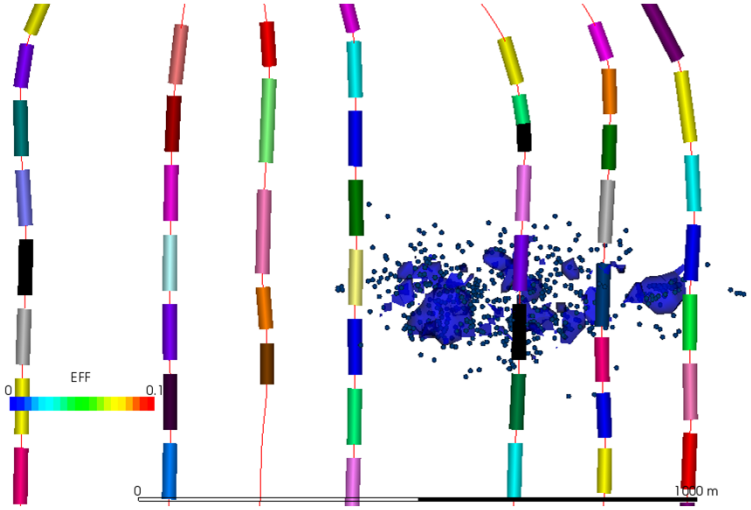
Pre Shut-In

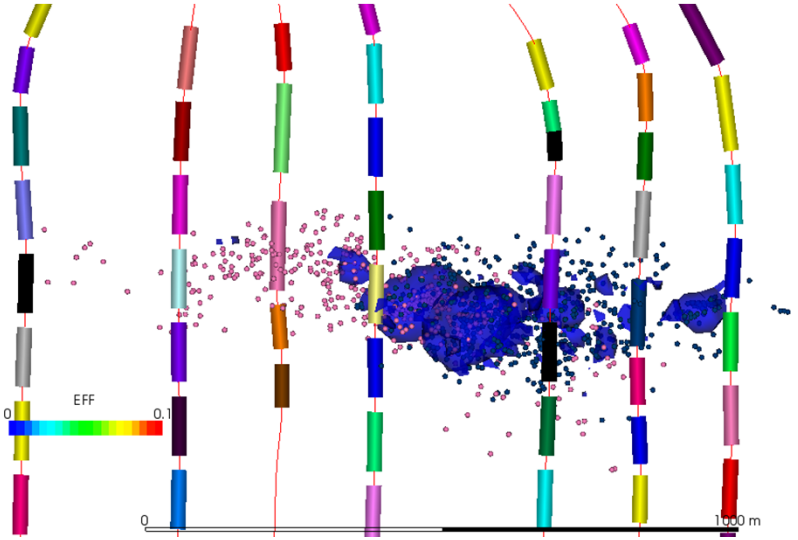
Post Shut-In

Enhanced Fluid Flow - EFF

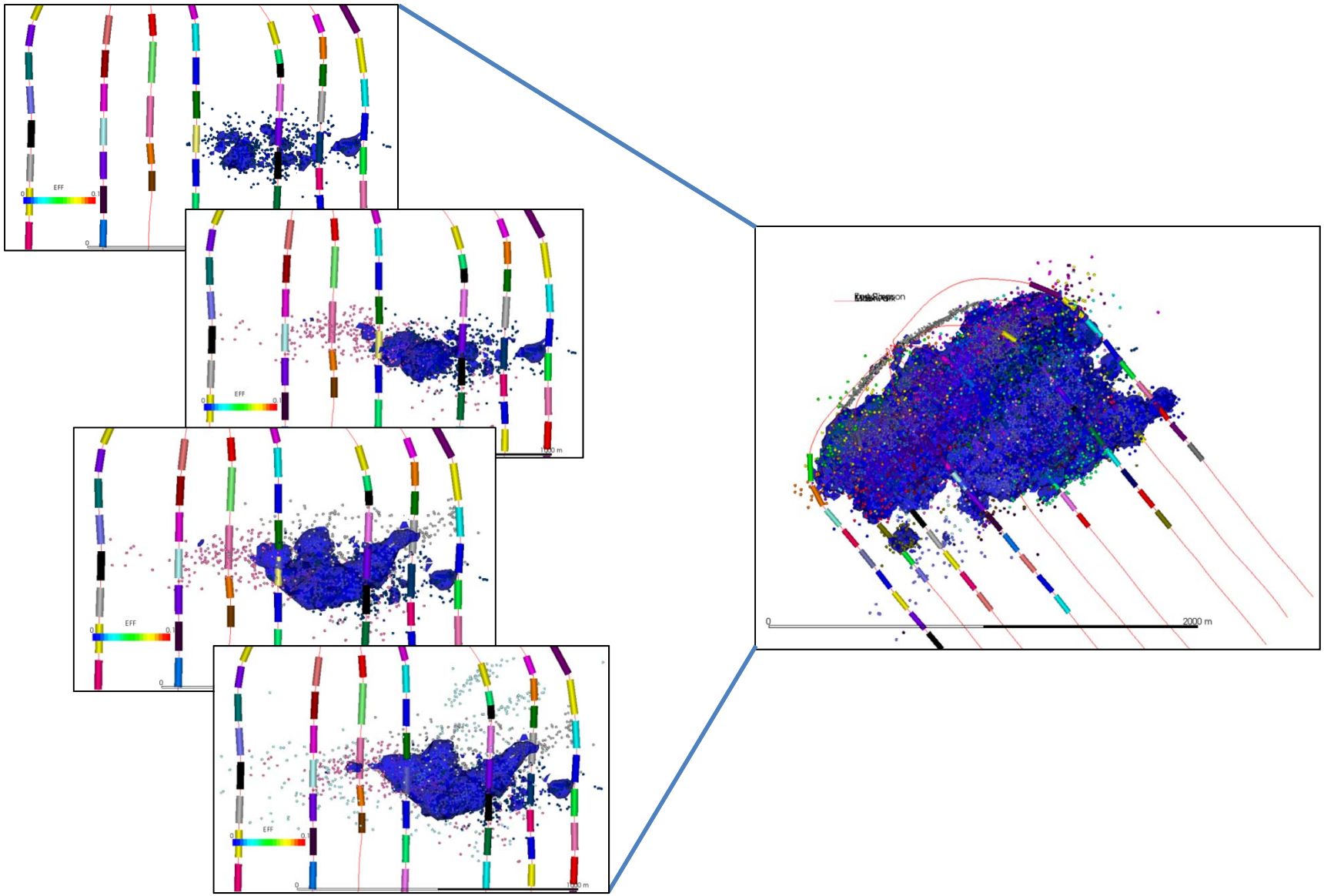


- Opening aperture is calculated based on the strain from the moment tensor factoring in the source dimensions.
- Average individual fracture openings over a neighbourhood (nearest neighbour statistical approach) of fractures with similar orientation





Building Fracture Complexity, EFF



Where Do We Go Next?

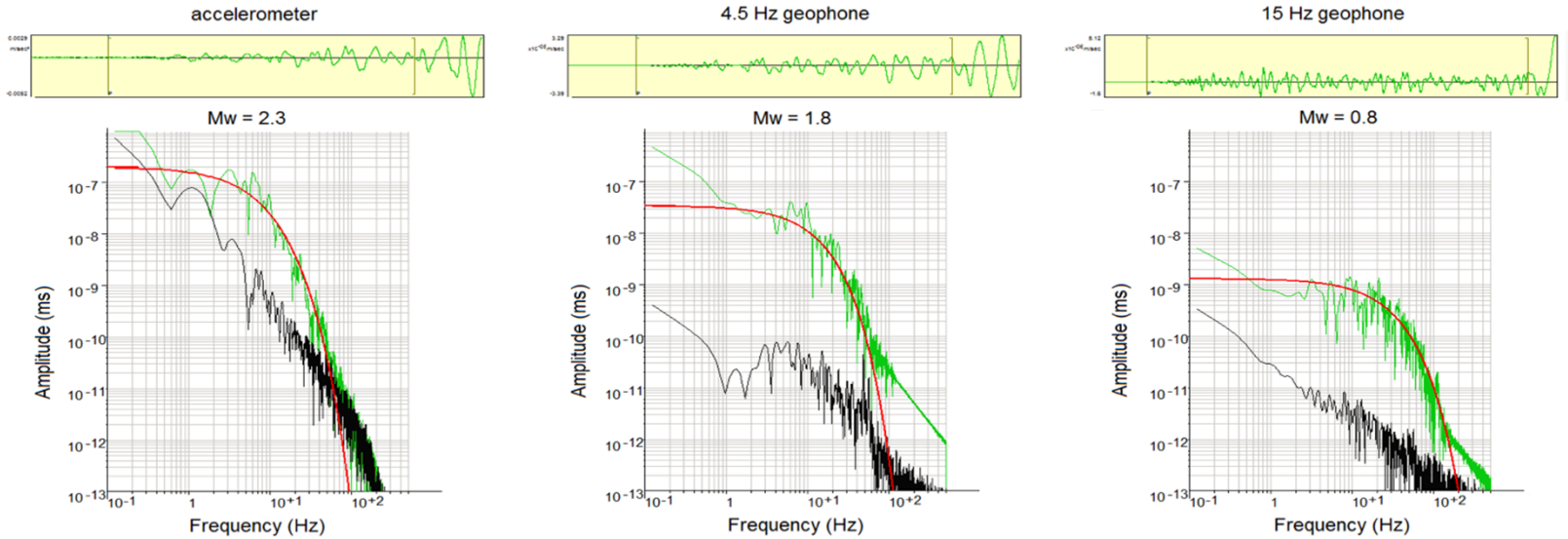
- Are we seeing the whole picture?
- Seismic vs. aseismic and the age old balance of energy question?
- Can we go into deeper and hotter wells?

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
- Combination of downhole sensors with lower frequency geophones on the surface
  - Treatments are producing events with moment magnitudes > 0
  - Traditional downhole geophones mis-calculate the actual size of larger events.

Hybrid Solutions:

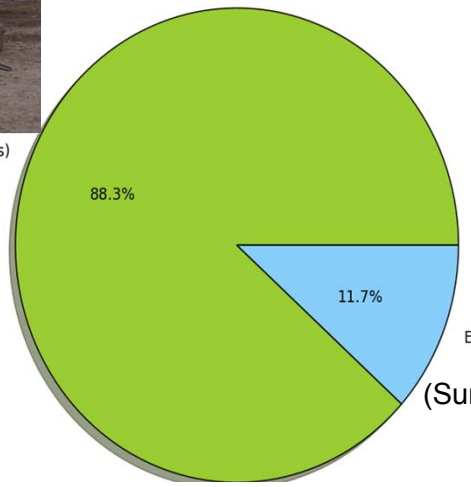
Combining Surface + Downhole + lower Freq. Geophones



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

Energy (14304 events)

(Downhole Array Dataset)



Energy (seven events)

(Surface Array Dataset)

Conclusions

- For the last decade or so, microseismic monitoring has been used to enhance the understanding of hydraulic fracturing.
  - Early observations identified the importance of structure within shale plays, movement away from simple bi-wing fracture models
  - Avoidance of geo-hazards in real time
- Extensive array coverage and advances in understanding of event signals has recently allowed for:
  - The identification of opening vs. closing fractures
  - assessment of the role natural fractures play in stimulations
  - targeted injection programs
  - Determination of refined estimates of enhanced fluid flow (SRV, SSA)
- Moving the microseismic industry forward
  - Gaining accurate source parameters through hybrid monitoring configurations
  - linkage provided through microseismic calculation of FC and FI, and power law behavior of fractures to reservoir models
  - Improvements to geophones allowing for monitoring of hotter reservoirs
- Putting all the pieces together to build more accurate reservoir models