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Stimulating Shale Reservoirs – What Have We Learned From Fracture Mapping

Norm Warpinski

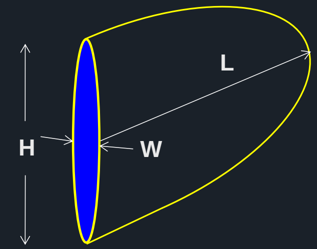
Hydraulic fracturing in shales

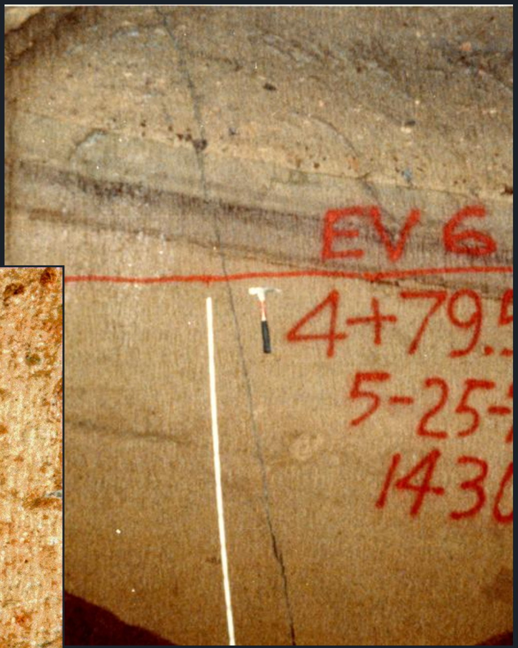
- Fracturing in shales provides significant information on the shale reservoir
  - Natural fractures
  - Stress conditions
  - Rock properties
- Fracturing in shales has also provided significant information about fracturing mechanisms in complex (naturally fractured) reservoirs
- Achieved largely through mapping and tracers

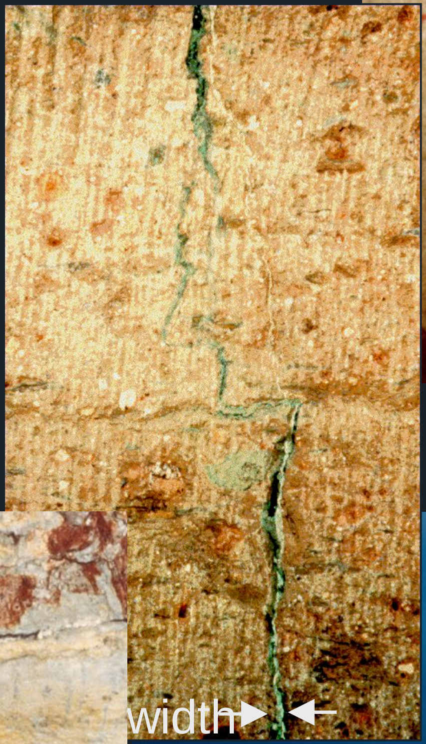
Hydraulic Fracturing

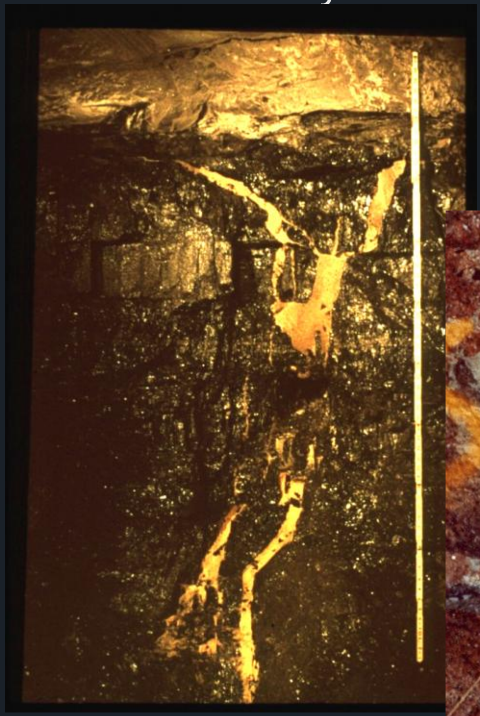
- Planar fractures for relatively simple reservoir conditions
  - May still have local complexity
- Complex fracture networks in naturally fractured reservoirs
  - Particularly with low stress bias

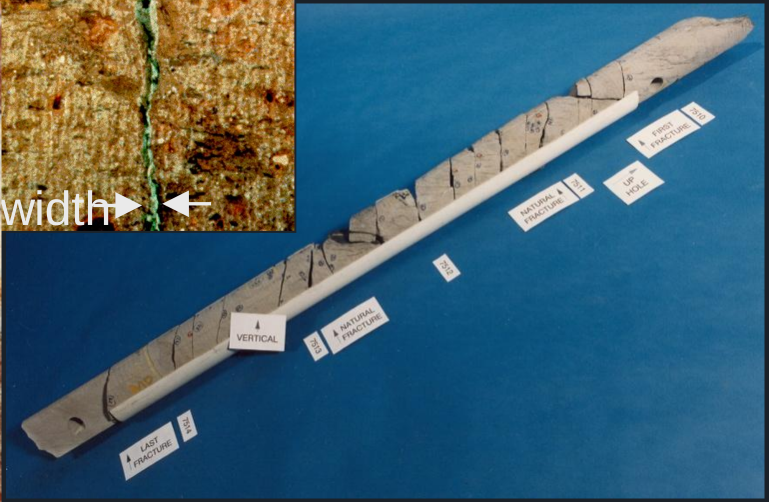
Planar Fracture











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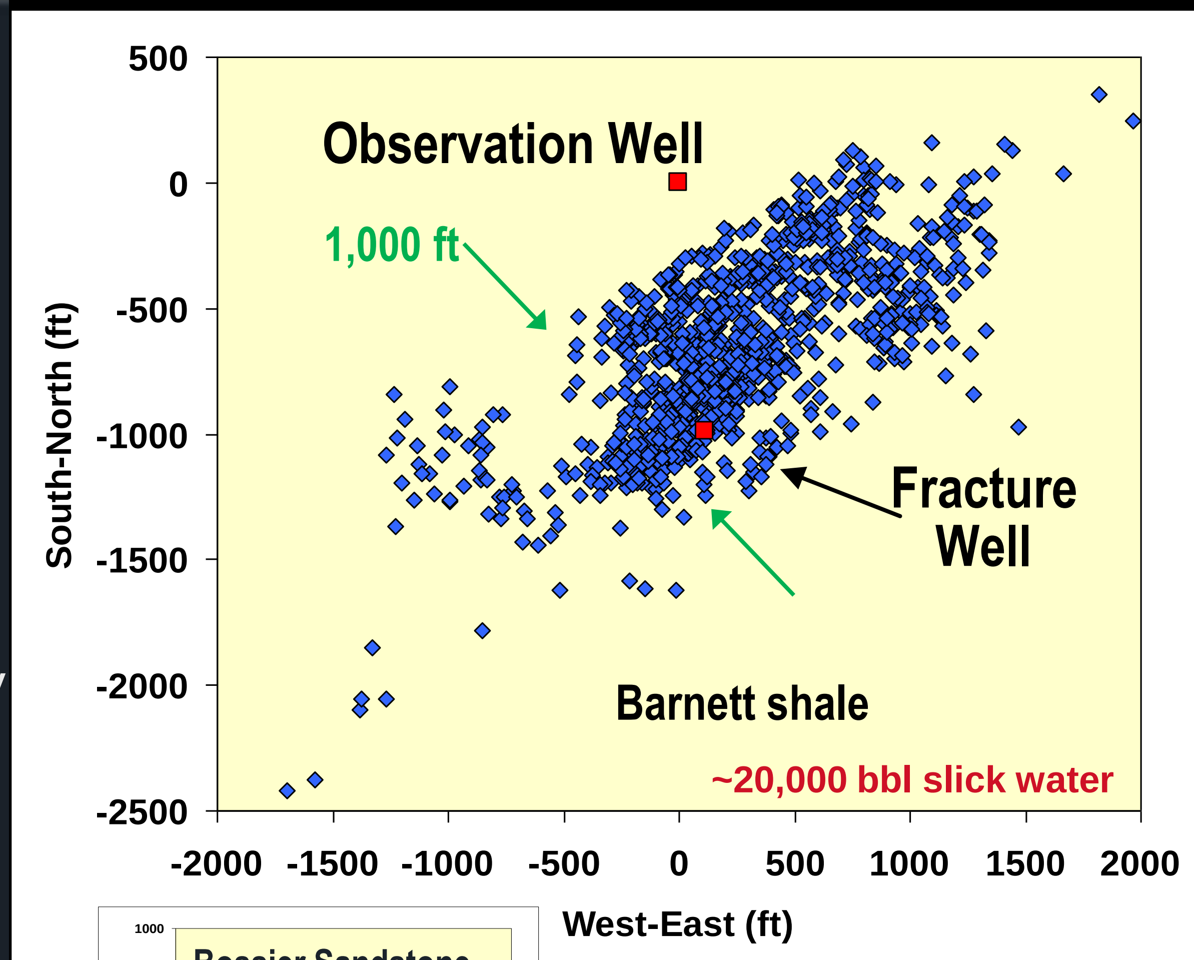
Background – Gas Shale Resources

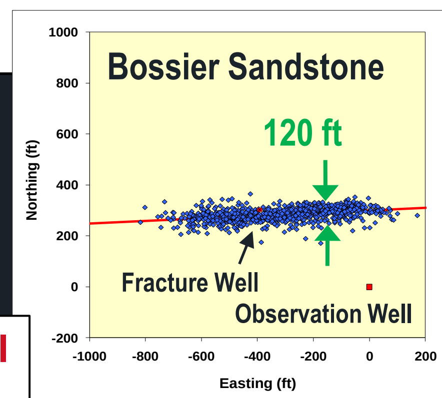
- Shale reservoirs likely have average matrix permeabilities of 100 – 800 nanodarcys
- Gas will likely flow no more than a few tens of feet in the lifetime of a well
- Economic production and significant volume recovery will require:
  - Large number of wells
    - Closely spaced wells
  - Highly fractured reservoir (Intrinsically or Stimulated)
  - Effective completions
    - Cost, operations, adequately stimulated reservoir volume

Hydraulic Fracture Behavior In Gas Shales

- Initial Barnett slick water fractures
  - Widespread complexity
    - Wide microseismic distribution
    - Asymmetric
    - Linear Features
  - Apparently a very different process than observed previously



From Devon, SPE 77441



~8,000 bbl hybrid

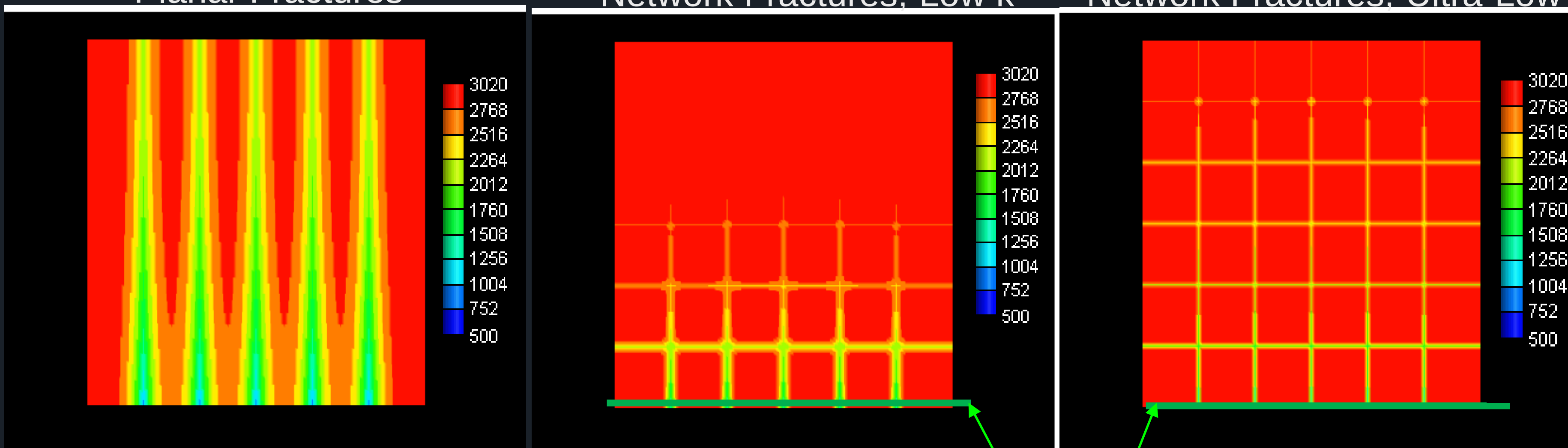
From Anadarko, SPE 89876

Same scale

Example Simulations: Ultra-Low Permeability

- Simplistic Reservoir Model (e.g., Homogeneous, Uniform, etc.)
- Comparison Of Tight Sandstone Case (Low Permeabiity) With Gas Shales Cases (Ultra-Low Permeability)
  - Tight Sandstone: Single Fractures From Closely Spaced Vertical Wells (Or Single Horizontal Well)
  - Gas Shale: Orthogonal Network With Limited Conductivities
- Depletion After 3 Months Production

Planar Fractures | Network Fractures; Low k | Network Fractures; Ultra-Low k



Planar Fractures	Network Fractures; Low k	Network Fractures; Ultra-Low k
k=1.0 μd	k=0.1 μd	k=0.01 μd
Spacing=300 ft	Spacing=300 ft	Spacing=300 ft
k_fw=50 md-ft	k_fw=5 md-ft	k_fw=5 md-ft

Horizontal Well

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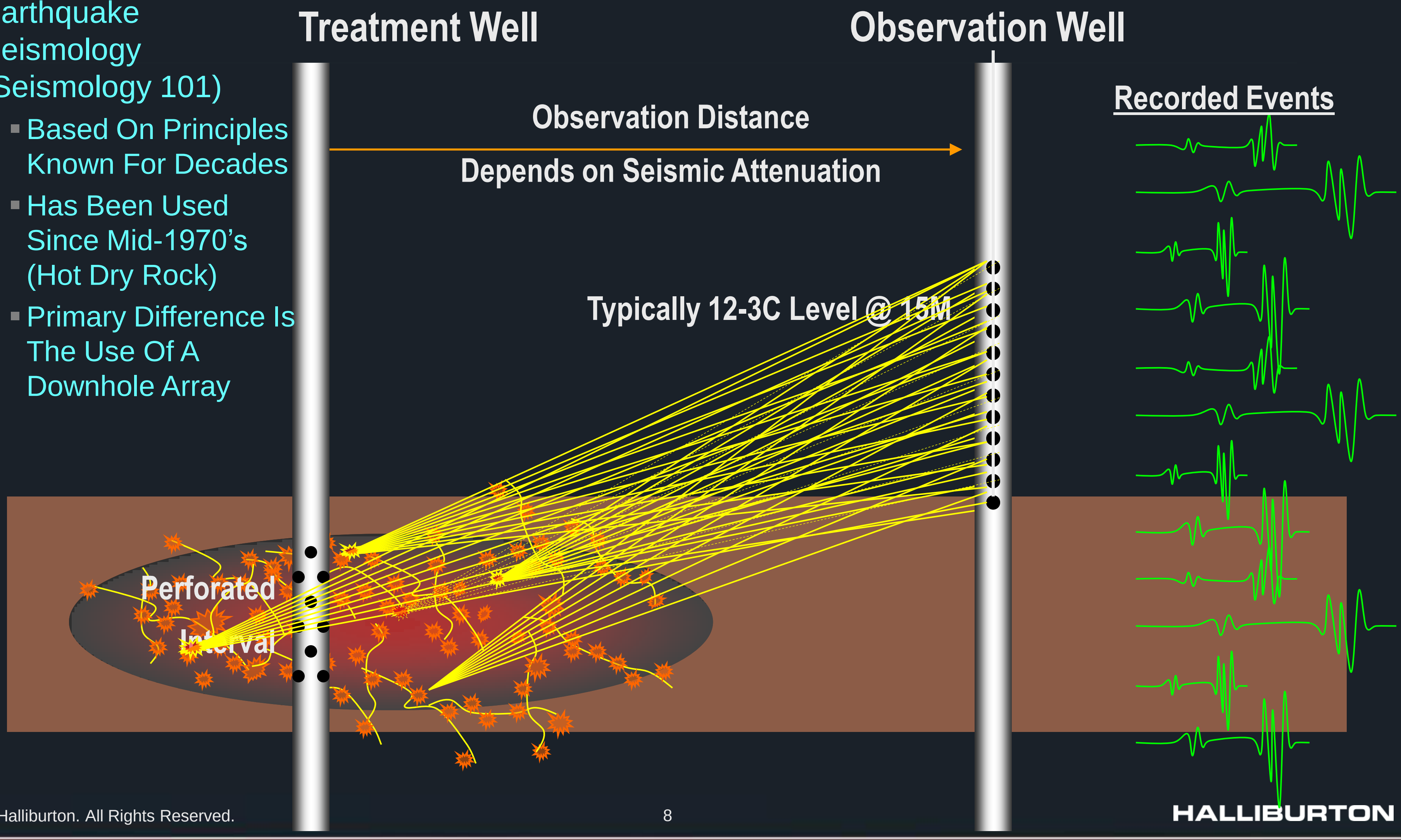
Microseismic Monitoring Background

Offset -Well Microseismic Mapping

- Microseismic Monitoring Is Applied Earthquake Seismology (Seismology 101)
  - Based On Principles Known For Decades
  - Has Been Used Since Mid-1970's (Hot Dry Rock)
  - Primary Difference Is The Use Of A Downhole Array



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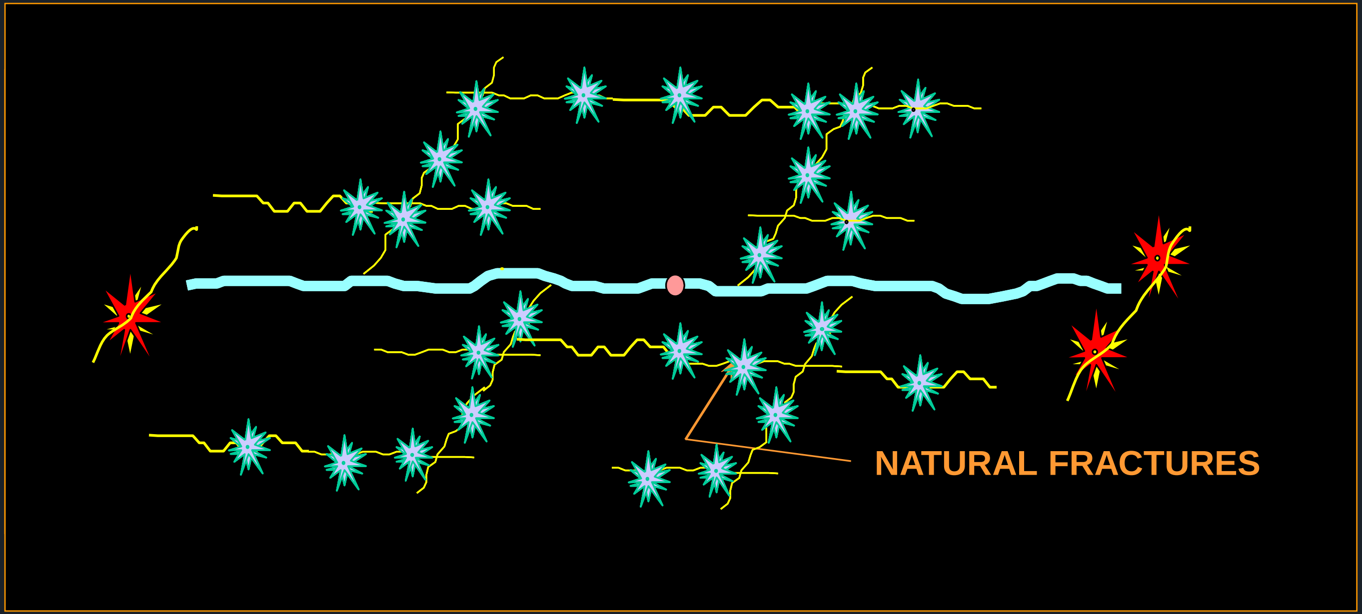
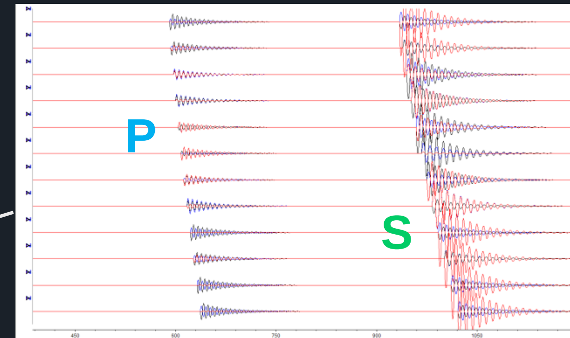
Microseisms

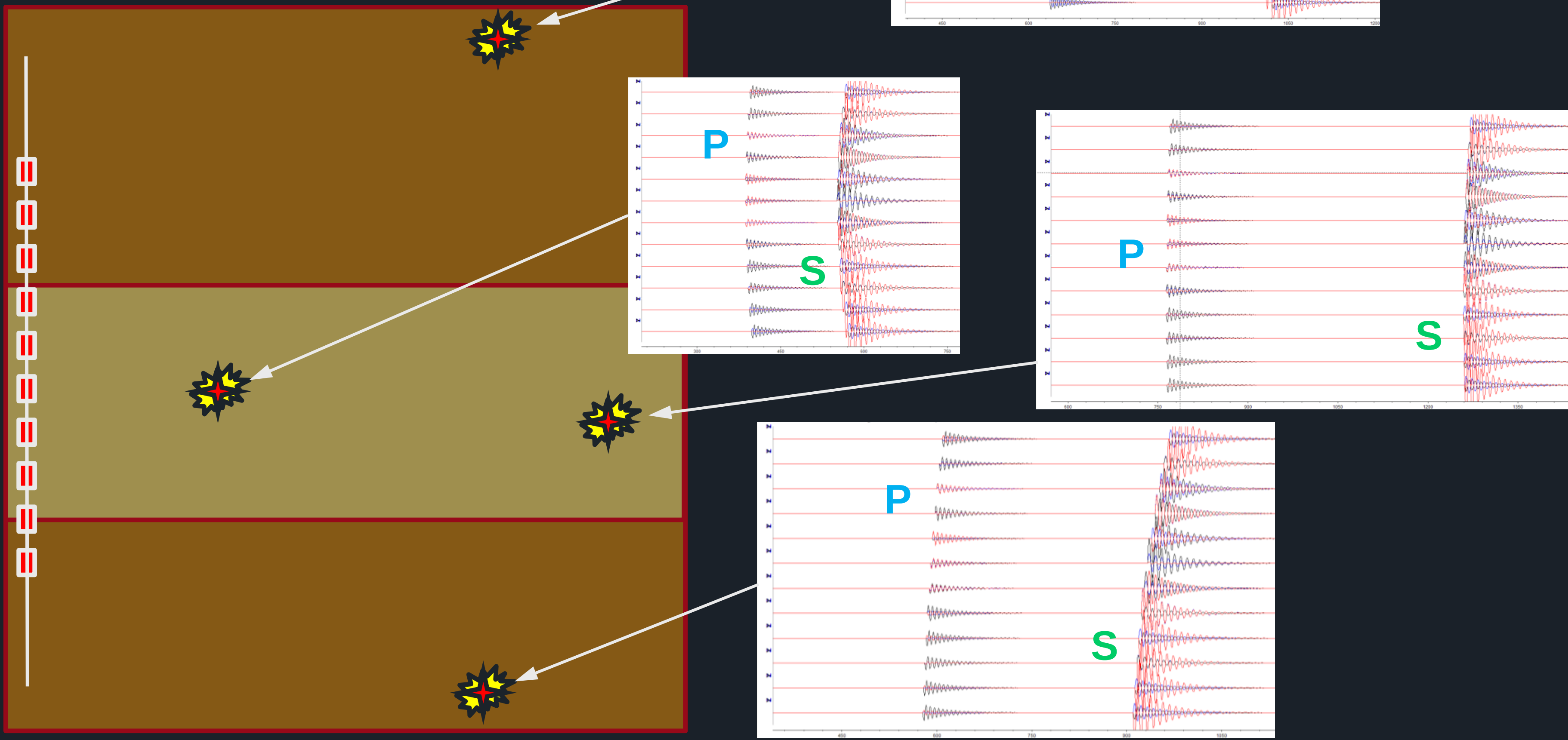
- What Is It?
  - A Microseism Is Literally A Micro-Earthquake. It Is A Shear Slippage Along An Existing Plane Of Weakness.
  - Microseisms That Occur During Hydraulic Fracturing Are Caused By:
    - Changes In Stress And Pressure As A Result Of The Treatment
  - Excellent Technology For Monitoring Network Fractures



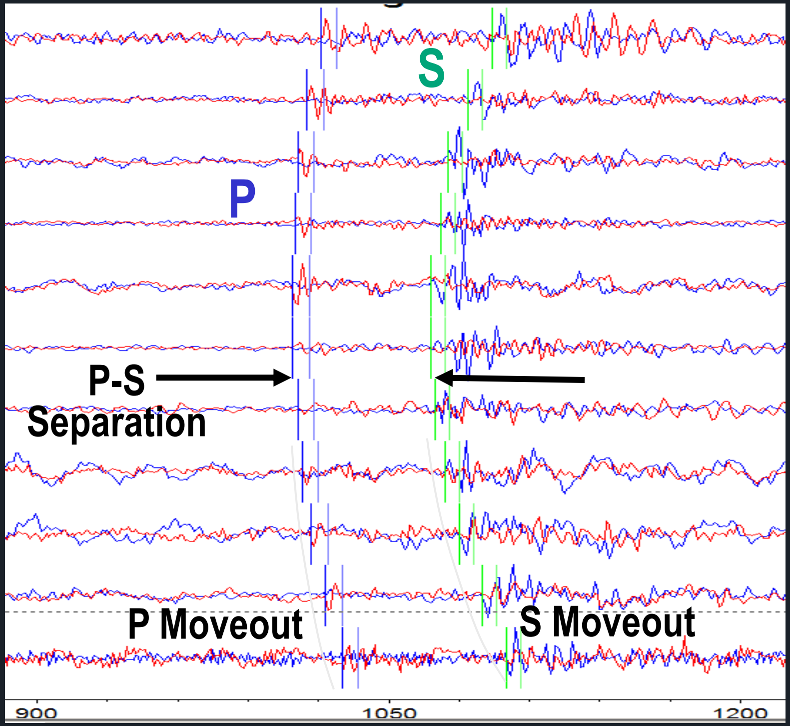
Microseismic locations – waveform back tracing

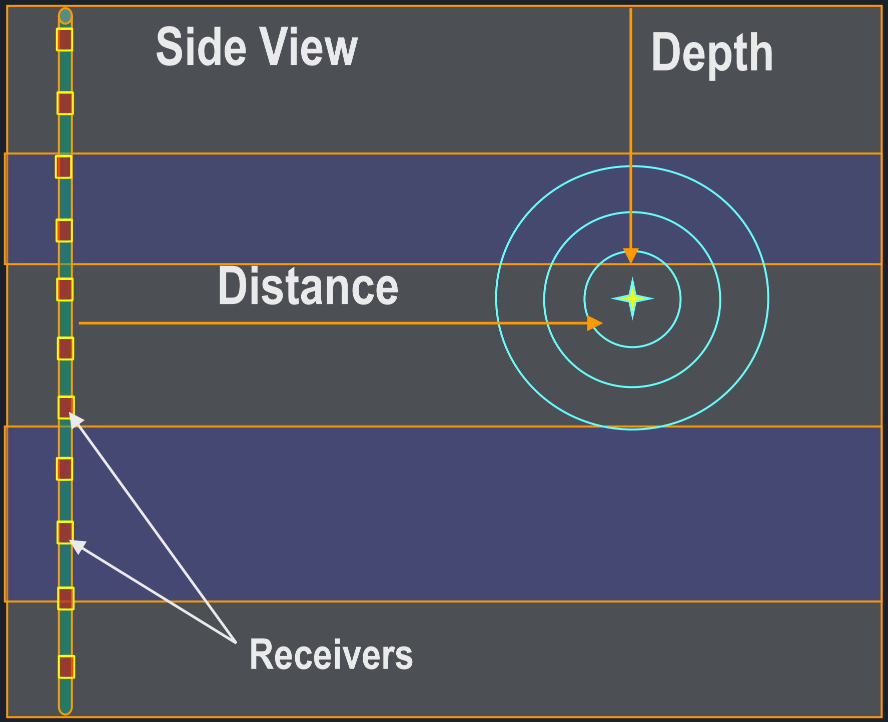
- Moveout and P-S separation define location (along with velocity structure)



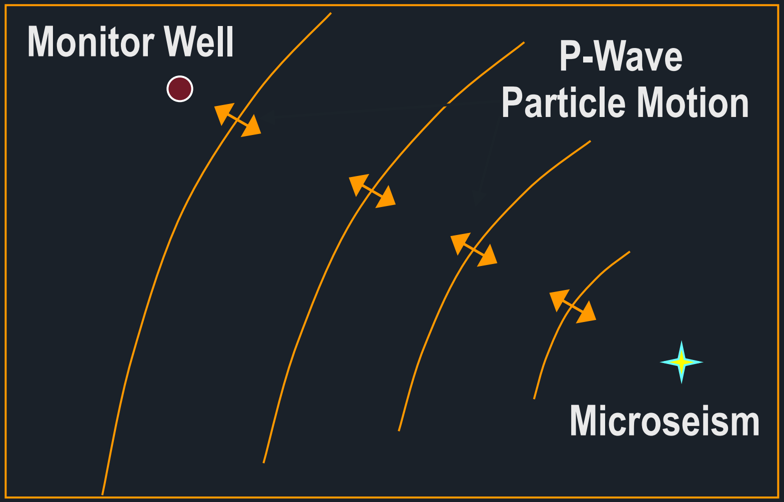


Locating Microseisms





- Distance Obtained Primarily From P-S Separation
- Depth Obtained Primarily From Moveout
- Direction Obtained From Wave Particle Motion (Vibration)
  - P-Wave: Always Pointed In Direction Of Wave Propagation (Back To Source)
  - S-Wave: Orthogonal To P Wave



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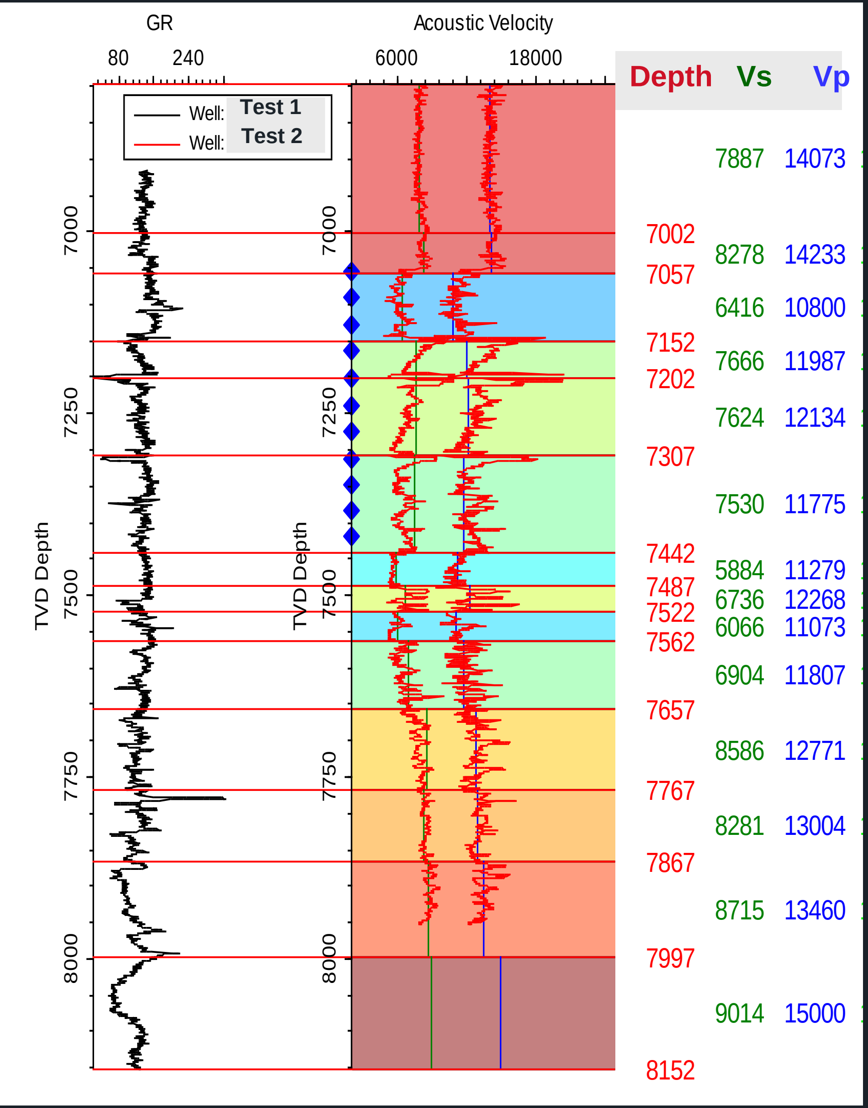
Velocity Model – Microseismic Location

- Determining the velocity structure is the most critical element of microseismic modeling
  - Start with dipole sonic log
    - Good resolution
    - Wrong velocity (vertical)
  - Perforation Timing
    - Obtain shot time
  - Optimization
    - Minimize residuals and location errors
  - Integrate all data



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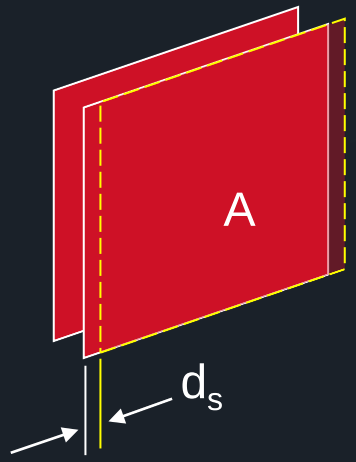
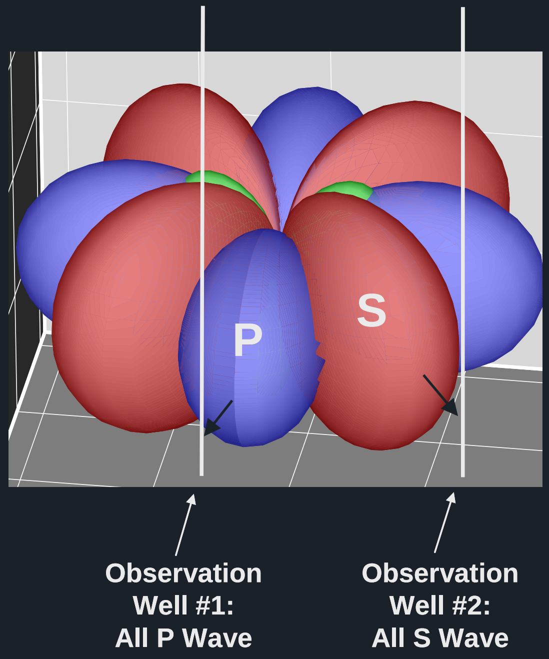
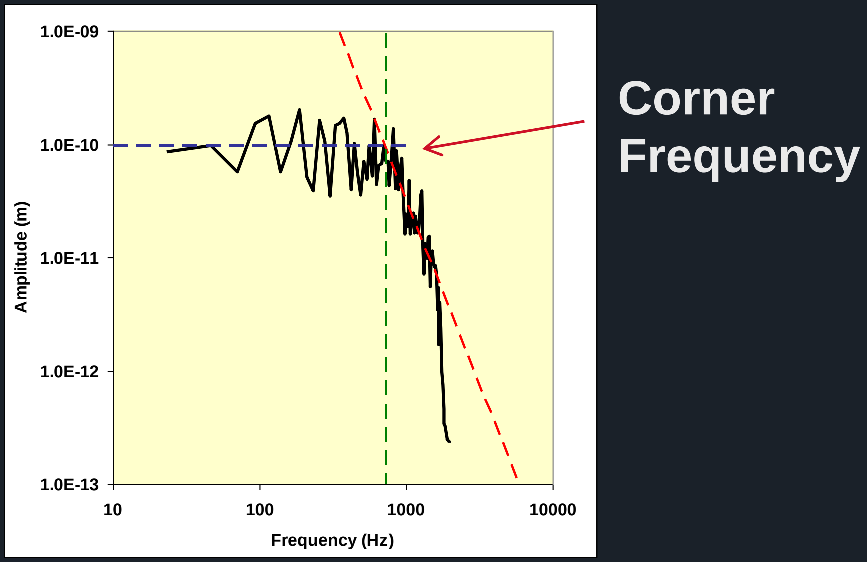
Source Mechanisms

- Information on the microseismic activity
  - Size & strength
    - Seismic moment
      - $M_o = G\ A\ d_s$
    - Magnitude
      - $M_w = 2/3\ \{\log_{10}(M_o) - 16.1\}$
  - Orientation from radiation pattern
- Inversion for source mechanisms
  - Fault plane & slip direction
- Spectral analysis for source size and magnitude



Double Couple Radiation Pattern





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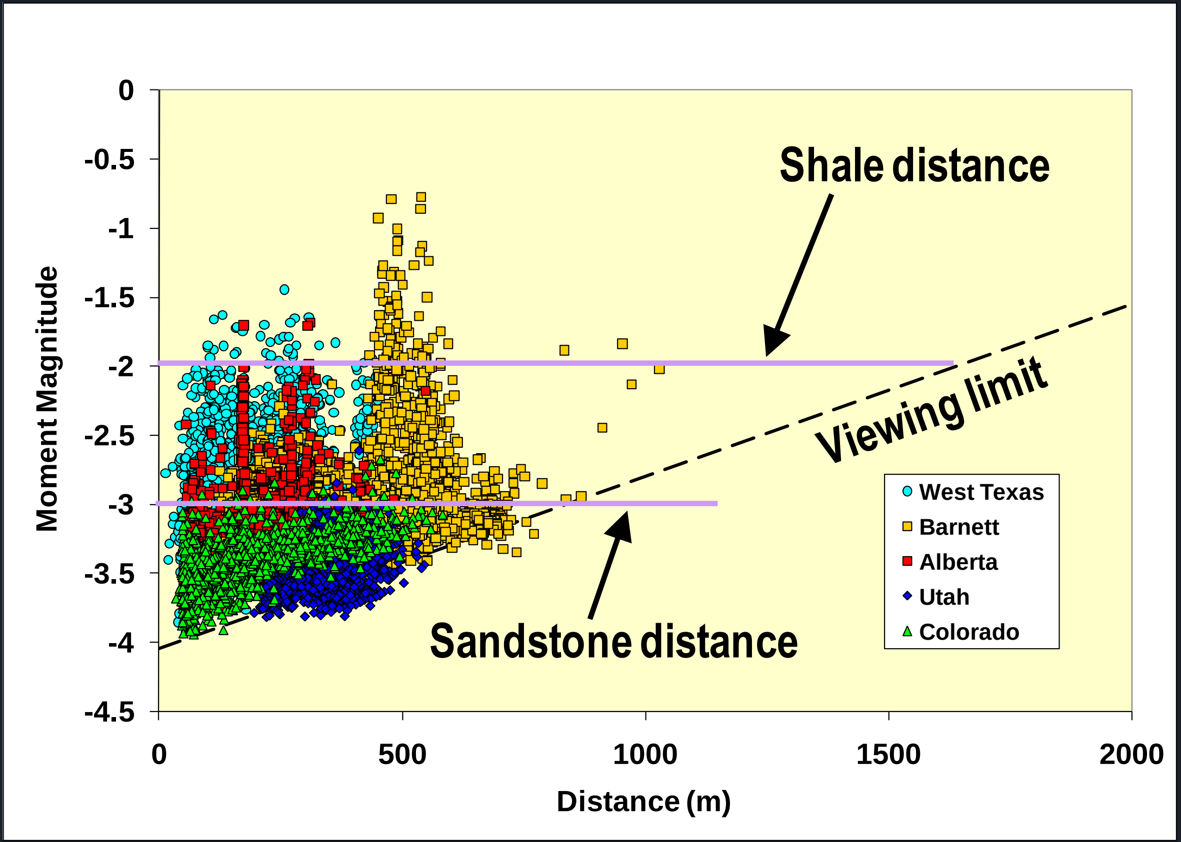
Microseismic Viewing Distance

- Moment Magnitude Versus Distance Plot
  - Viewing Distance
  - Biased Data
  - Fracture Limits
  - Faults
- Clearly shows effect of lithology on viewing distance
- Microseismic Moment
  - Intrinsic strength of the microseism
  - $M = A\, d_s\, G$

    A – area
    d_s – slippage distance
    G – shear modulus
  - Obtained from the shear-wave amplitude and distance



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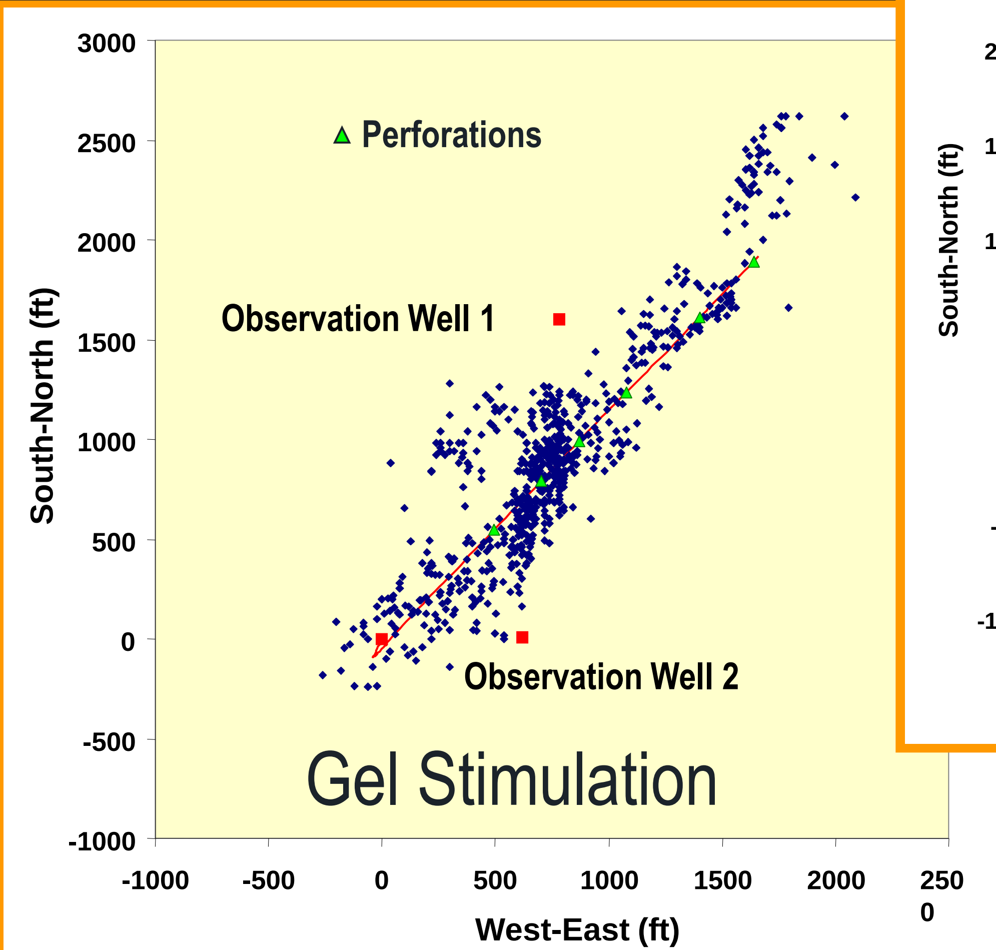
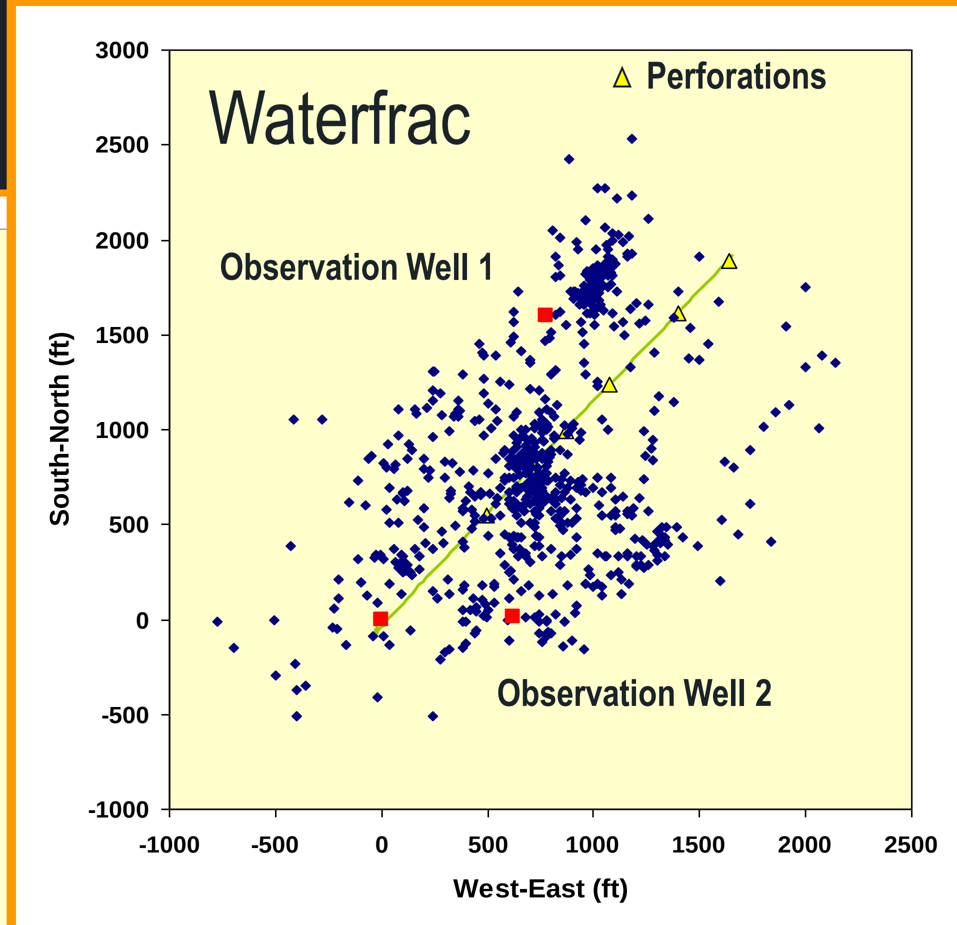
Examples

The Treatment Matters

- Barnett Shale Longitudinal
  - Gel Frac Versus Waterfrac

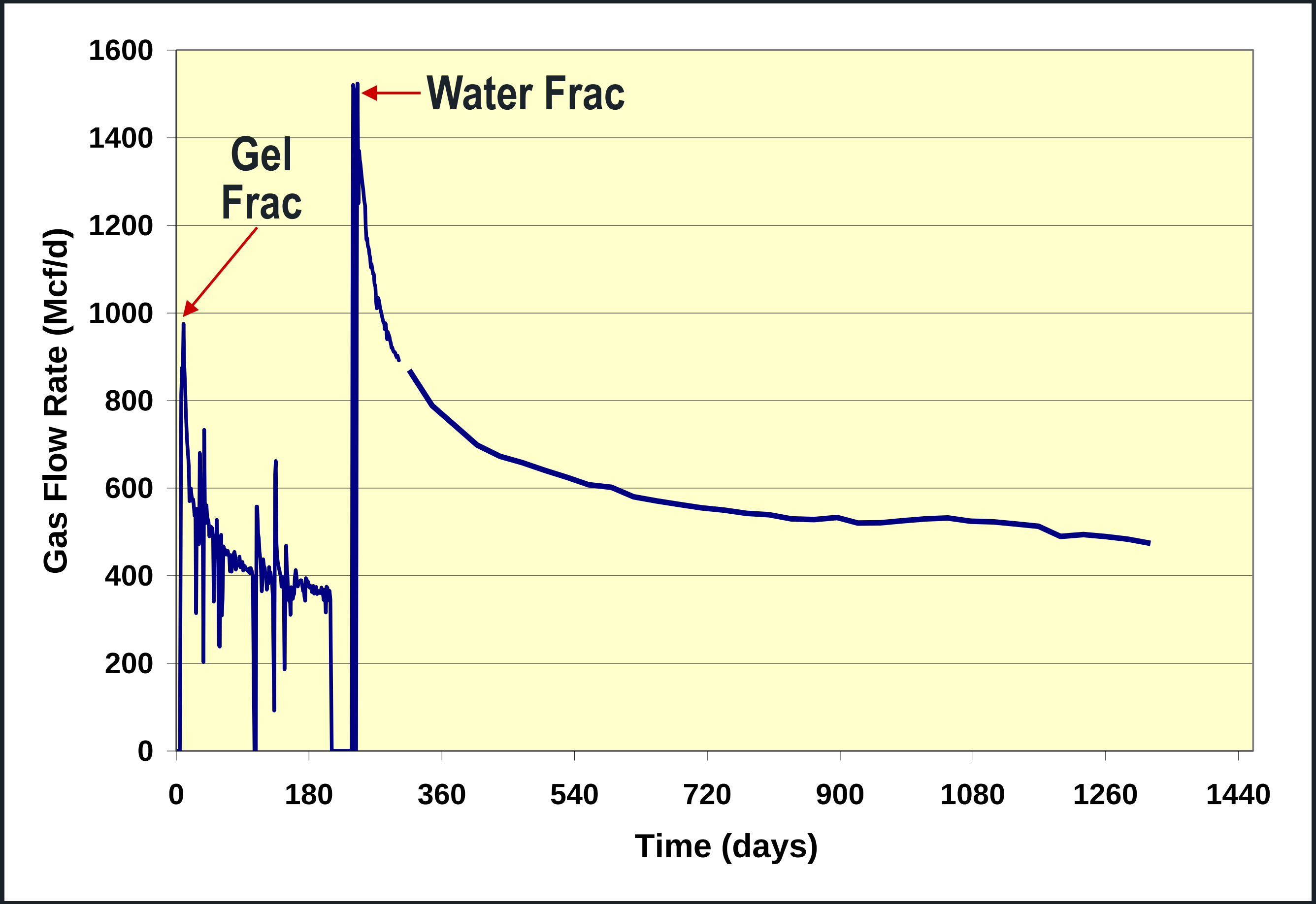




SPE 95568 (Devon)

Gas Production

- Waterfrac Significantly Outperformed Gel Stimulation
  - SRV: 430 vs 1,450 million ft^3
  - Factor Of 2 Production Increase



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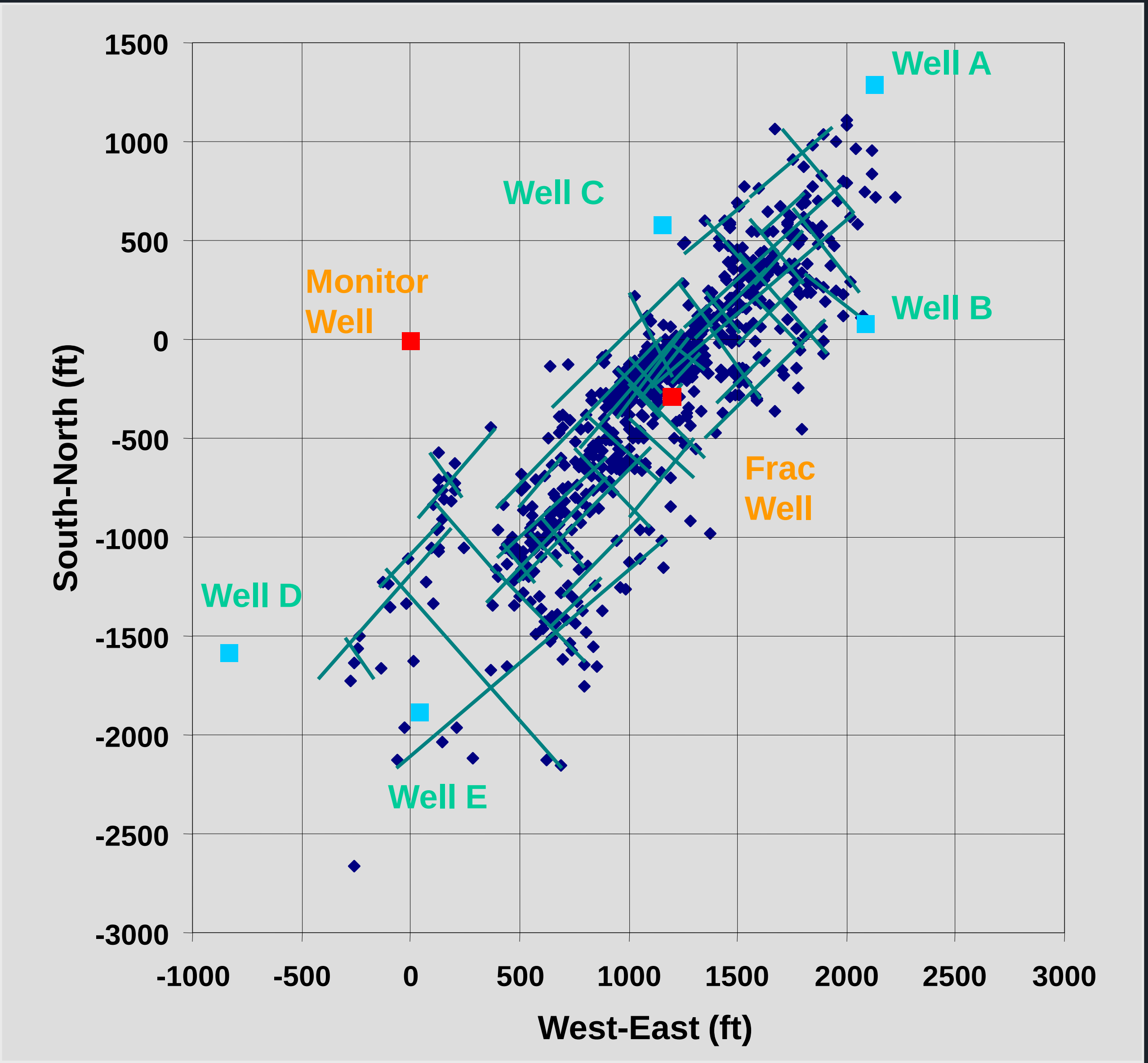
Structures In WaterFracs



- Structures Are A Clear Sign Of Network Behavior
- Killed Wells Illustrate That Fracture Lengths & Networks Can Exceed Microseismic Dimensions

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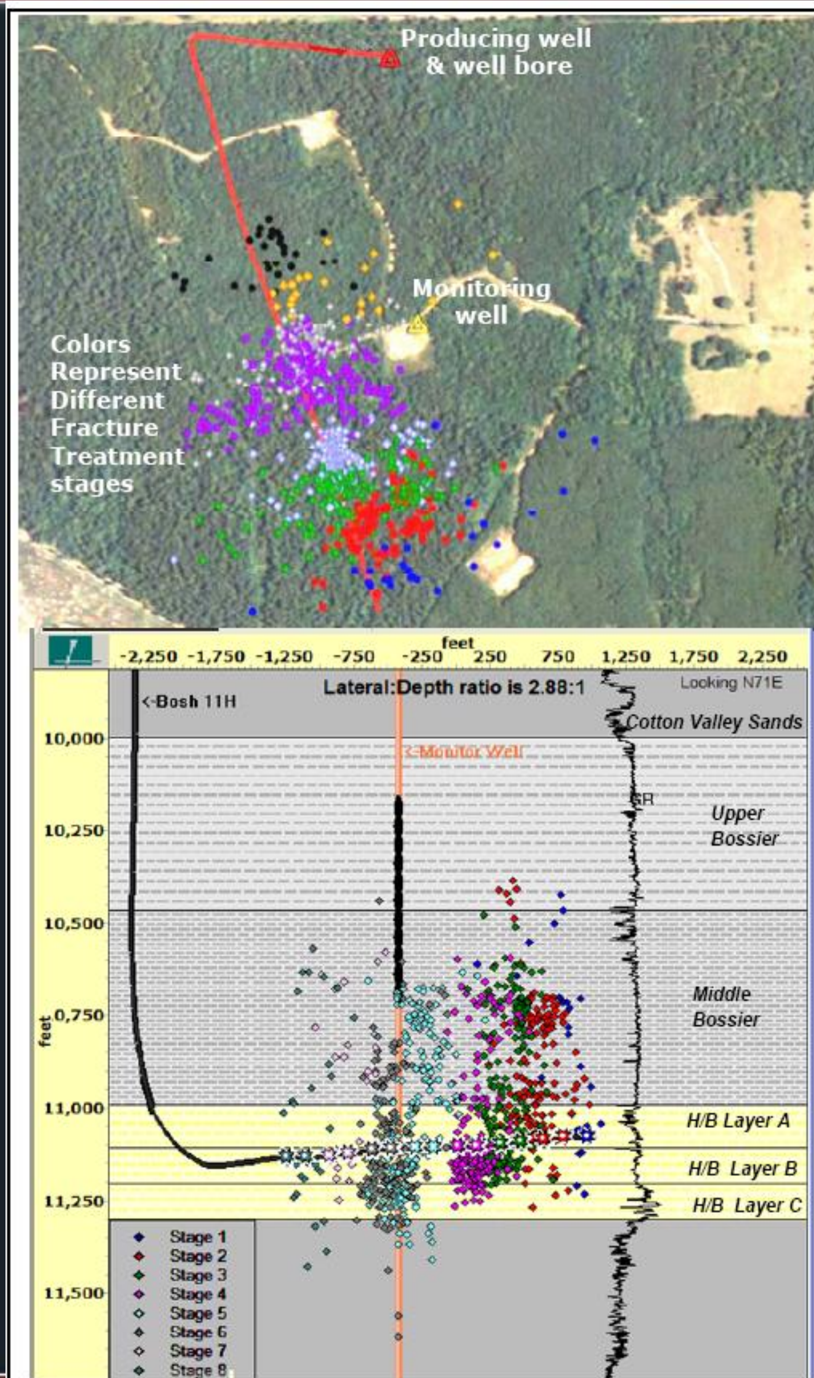
GMX Haynesville Map

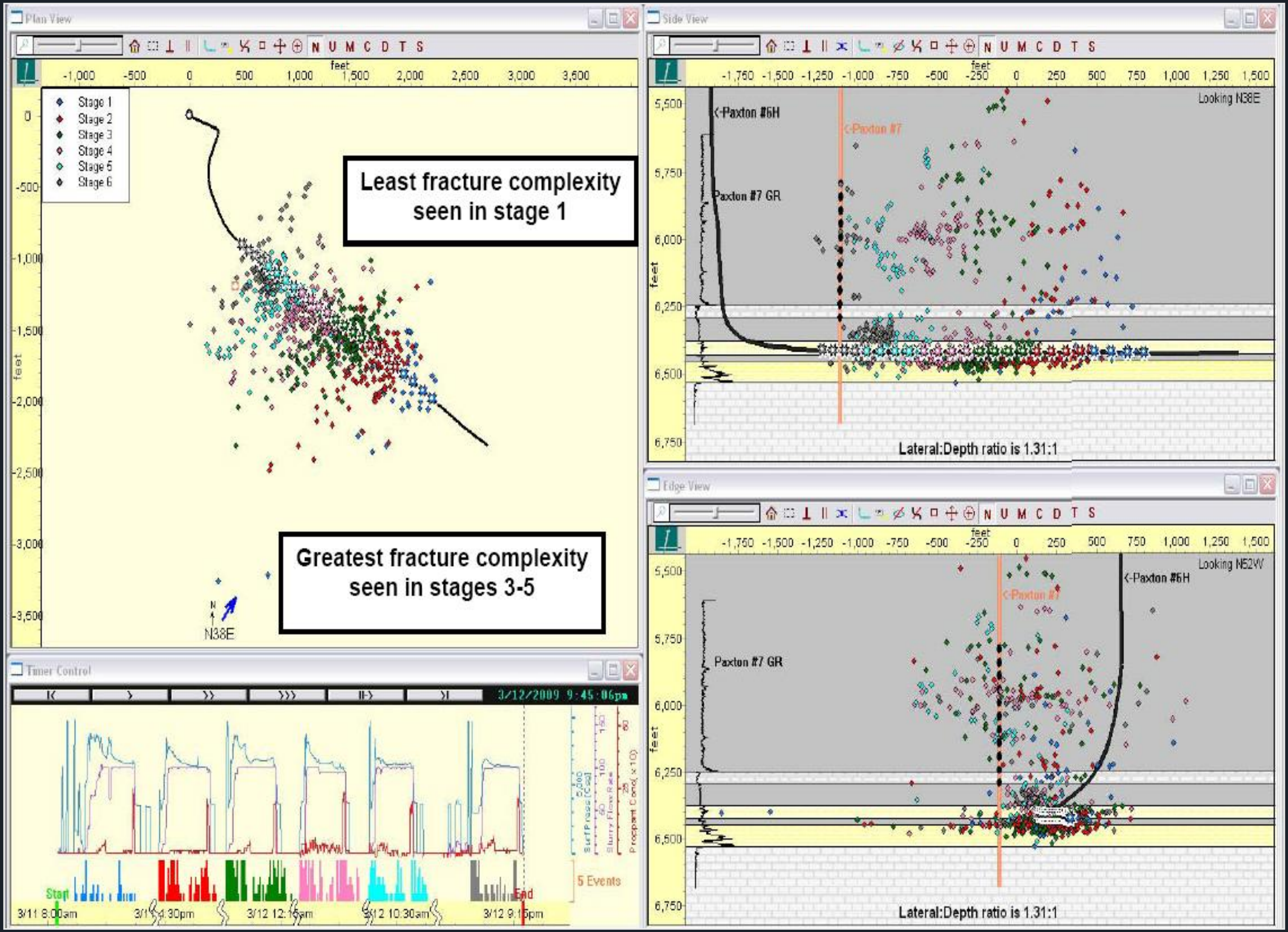
- Haynesville
  - GMX Fracture Treatment
  - 3,000 – 5,000 ft Laterals
  - 7 – 10 Stages
    - 300 ft Spacing
    - 2 Perf Clustes / Stage
  - Stimulation
    - 8,000 – 12,000 bbl / Stage
    - 65 bpm Rate
    - 270,000 lb Proppant / Stage
    - Slickwater, Hybrid, & X Link



SPE 12507 GMX Resources

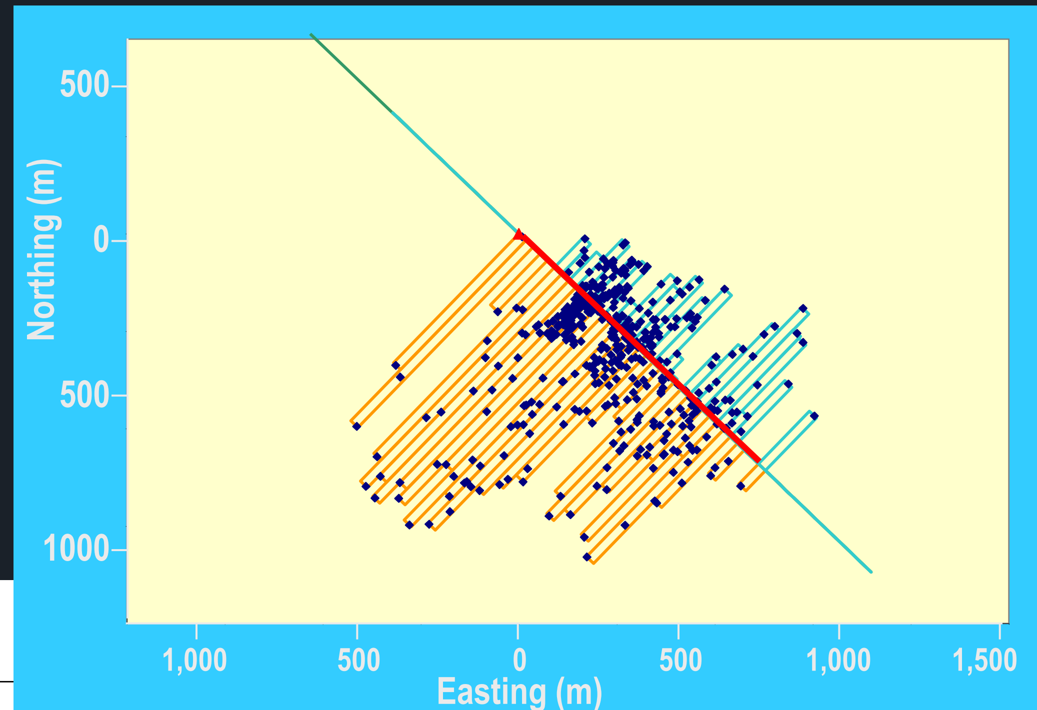
Marcellus Microseismic Map

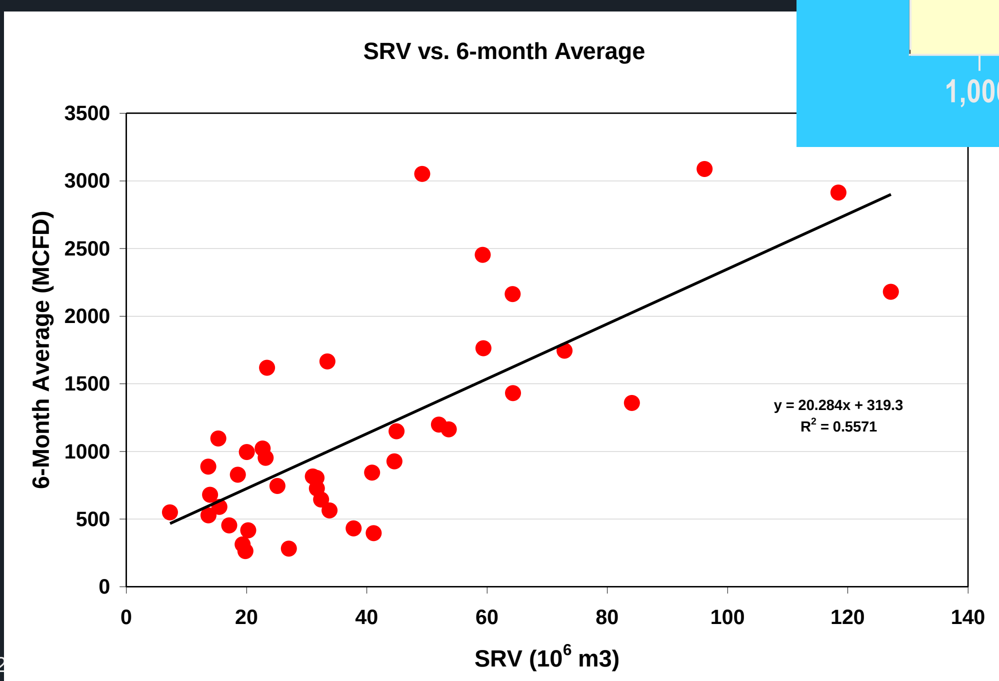
SPE 242783,Curry et al, 2010

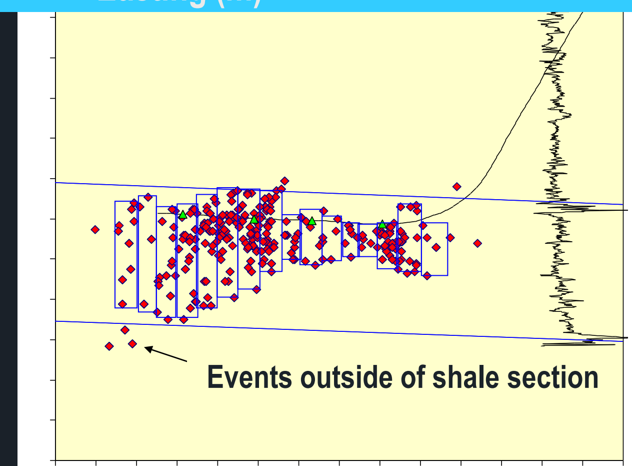


Stimulated Reservoir Volume

- Volume Of Reservoir Rock Stimulated
  - Relationship Between Total Volume Stimulated (Microseismic Activity) And Production







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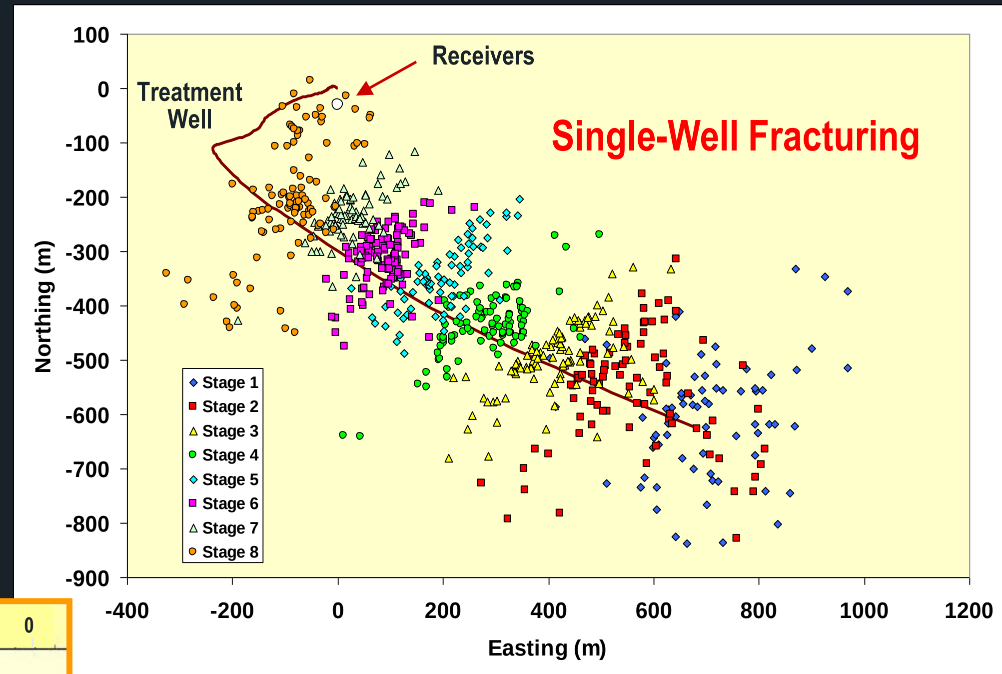
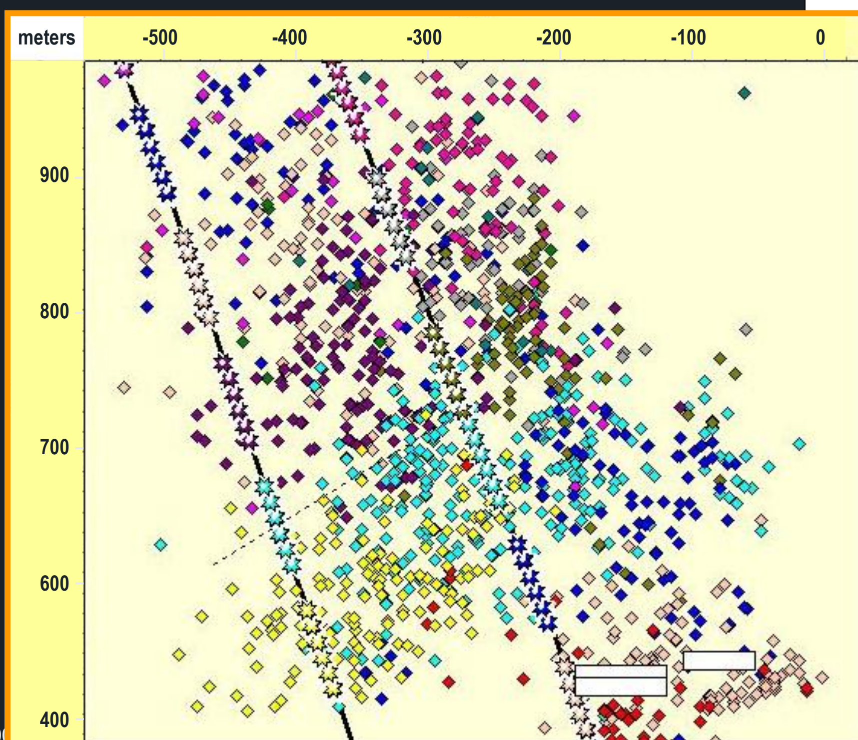
Assessing Fracture Behavior

SPE 119896 (Rimrock)



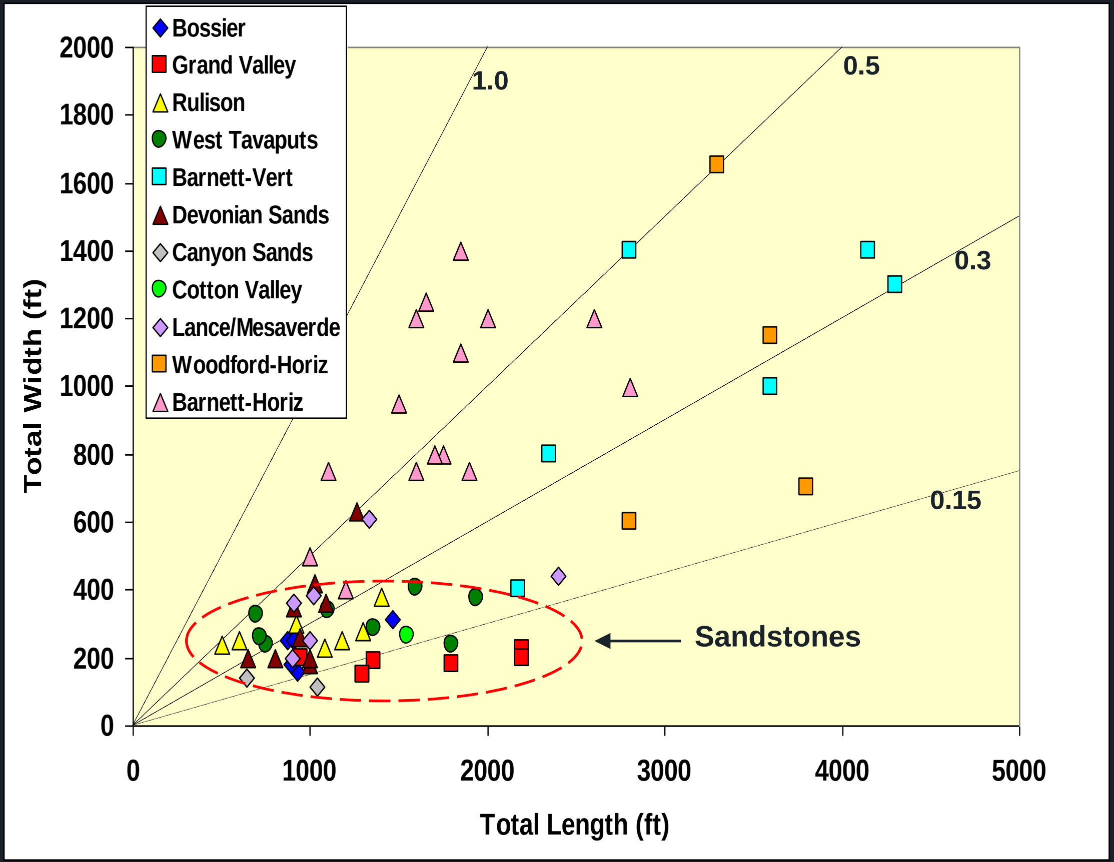


- Simultaneous Fracturing Results
  - Typically More Microseismic Activity
  - Overlapping Microseismic Behavior
  - Still See General Fracturing Behavior

Microseismic Interpretation

- Fracture complexity
  - Due to interest in gas shales, complexity is a key parameter
  - Can we determine when a fracture treatment results in a complex network
  - Factors?
    - In Situ Stress Bias
    - Natural Fractures
    - Brittleness
    - Treatment
    - Completion

Fracture Complexity Index Chart



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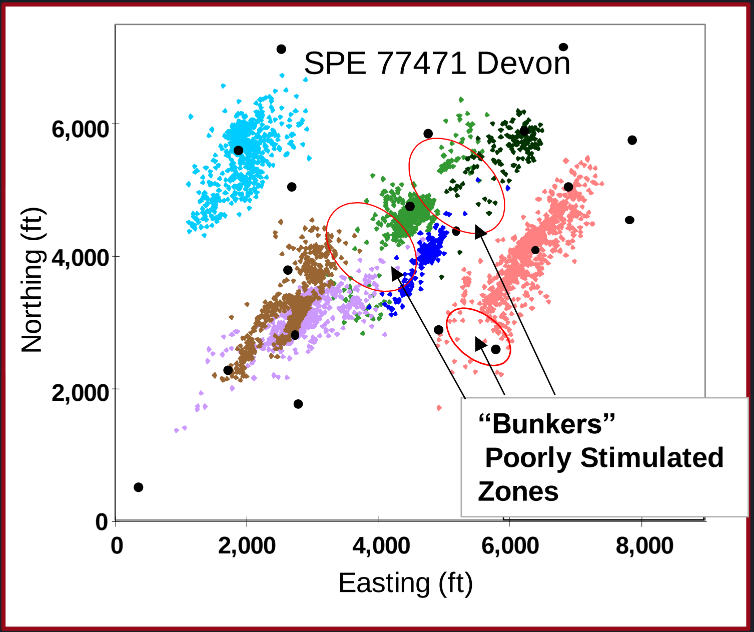
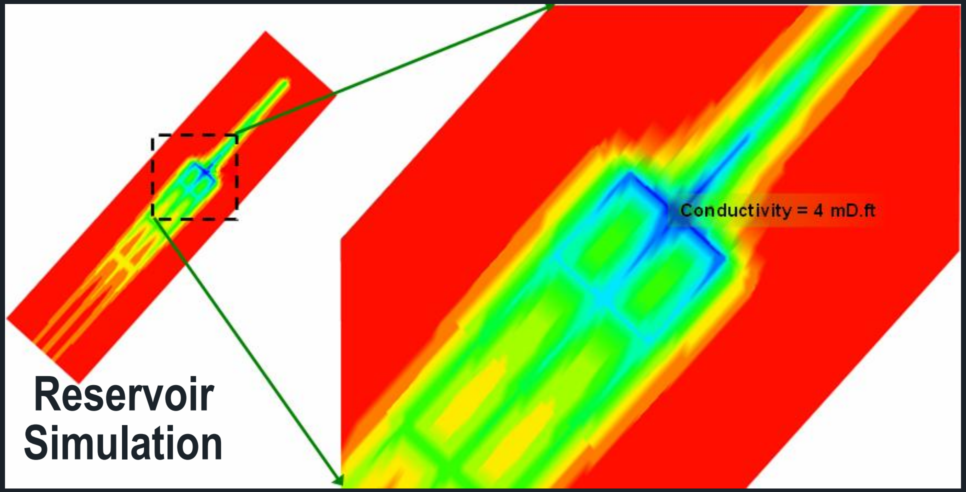
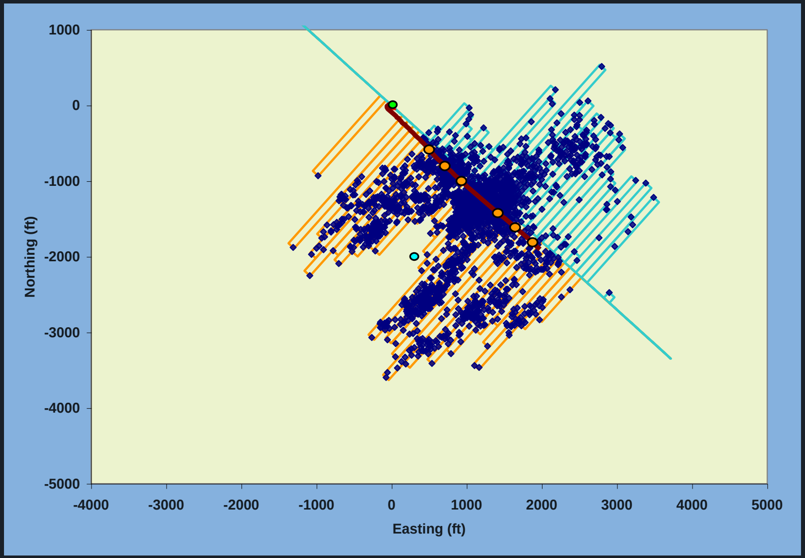
Using Diagnostic Data

- Well Layout
- Well Spacing
- Horizontal Well Staging
- SRV Calculations
- Missed Reserves
- Height Growth
- Reservoir engineering







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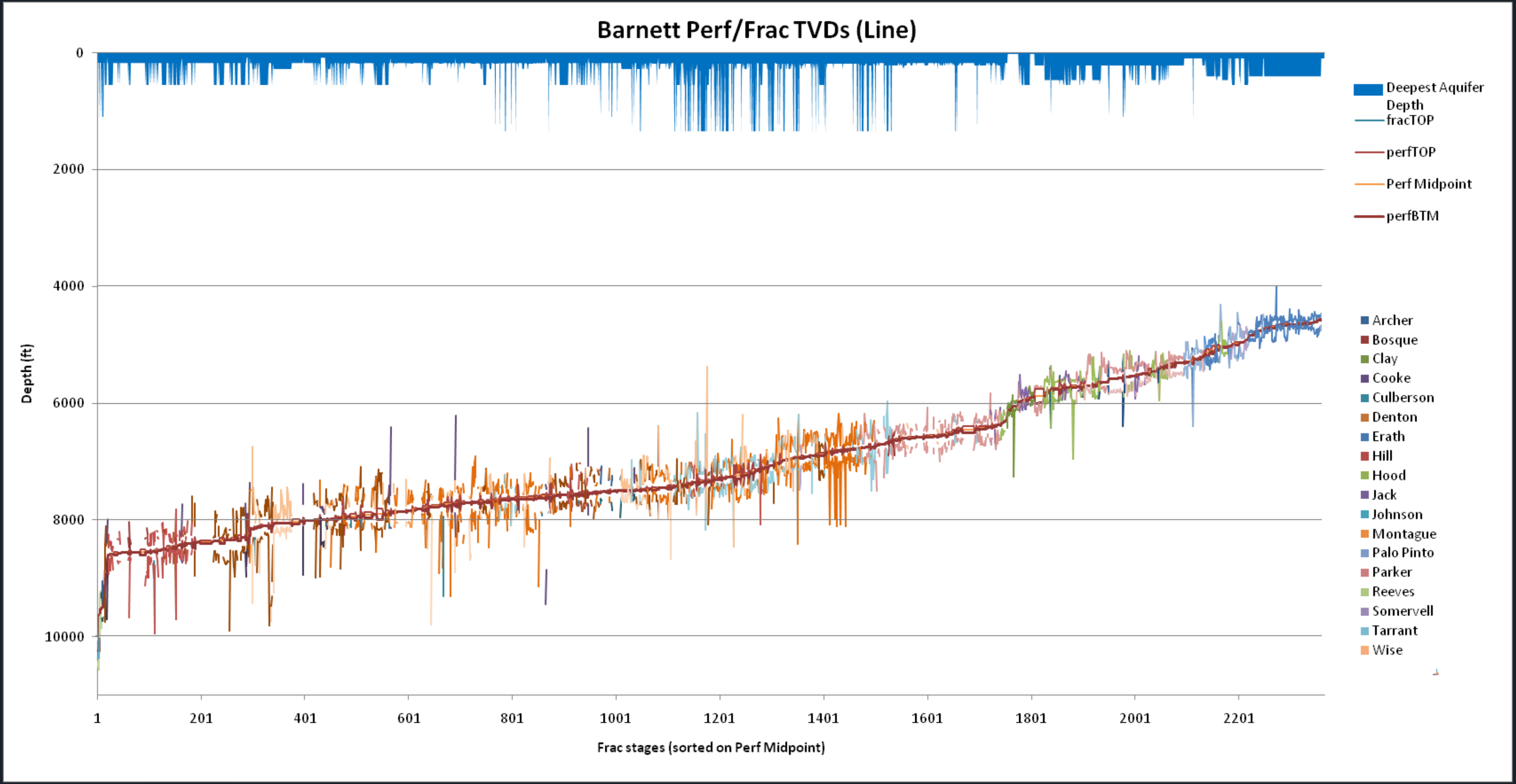
Hydraulic fracturing versus the environment: what do diagnostics say?

- Fractures are far from mapped aquifers



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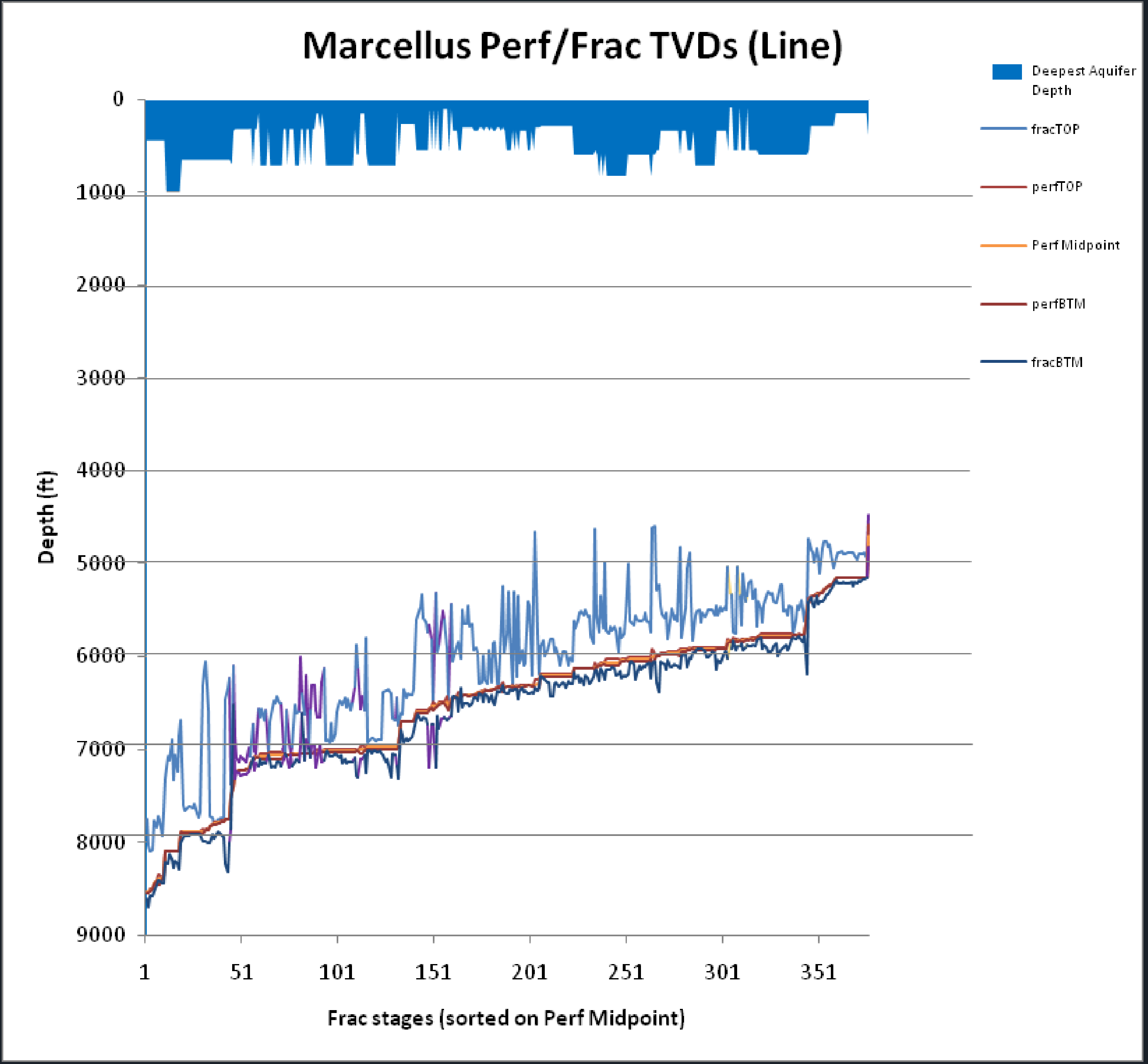
Hydraulic fracturing vs the environment: what do diagnostics say?

- Marcellus issues?
  - More height growth than Barnett
  - Far from mapped aquifers



Conclusions

- Microseismic monitoring is probably the only way to evaluate details of stimulation & completion results in shale reservoirs
  - Height growth
  - Network development & fracturing intensity
  - Stimulated reservoir volume
  - Staging tools
  - Completion & stimulation approaches
    - Perforation clustering
    - Simultaneous fracturing