The Relationship between Stimulation Mechanism and Sweet Spot Identification*

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Search and Discovery Article #80426 (2014)**
Posted December 8, 2014

*Adapted from oral presentation given at Geoscience Technology Workshop, Unconventionals Update, Austin, Texas, November 4-5, 2014

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Abstract

Hydraulic stimulation in low permeability formations is successful when it generates a large stimulated fracture surface area. Sweet spots are regions within a play or along a well where production is especially prolific. Sweet spots may be related to matrix quality such as permeability. Sweet spots may also be related to formation properties that encourage fracture network quality - the ability to create high stimulated fracture surface area. In the literature, there does not appear to be agreement on the processes that generate a quality stimulated fracture network. I will review different theories and discuss pros and cons of each. I will also report on results from a sensitivity analysis study that used CFRAC (Complex Fracturing ReseArch Code), a discrete fracture network simulator that couples fluid flow with fracture propagation, conductivity evolution, and the stresses induced by fracture deformation. The results suggest that the tendency for shear stimulation - the tendency of natural fractures to slip and experience irreversible conductivity enhancement in the formation - is one of the most important variables in determining fracture network quality. I will discuss efforts towards addressing how this variable may be predicted and quantified, and how this concept might be applied to formation evaluation and sweet spot identification.

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THE UNIVERSITY OF TEXAS AT AUSTIN
Petroleum and Geosystems Engineering

THE RELATIONSHIP BETWEEN STIMULATION MECHANISM AND SWEET SPOT IDENTIFICATION

AAPG UNCONVENTIONALS UPDATE

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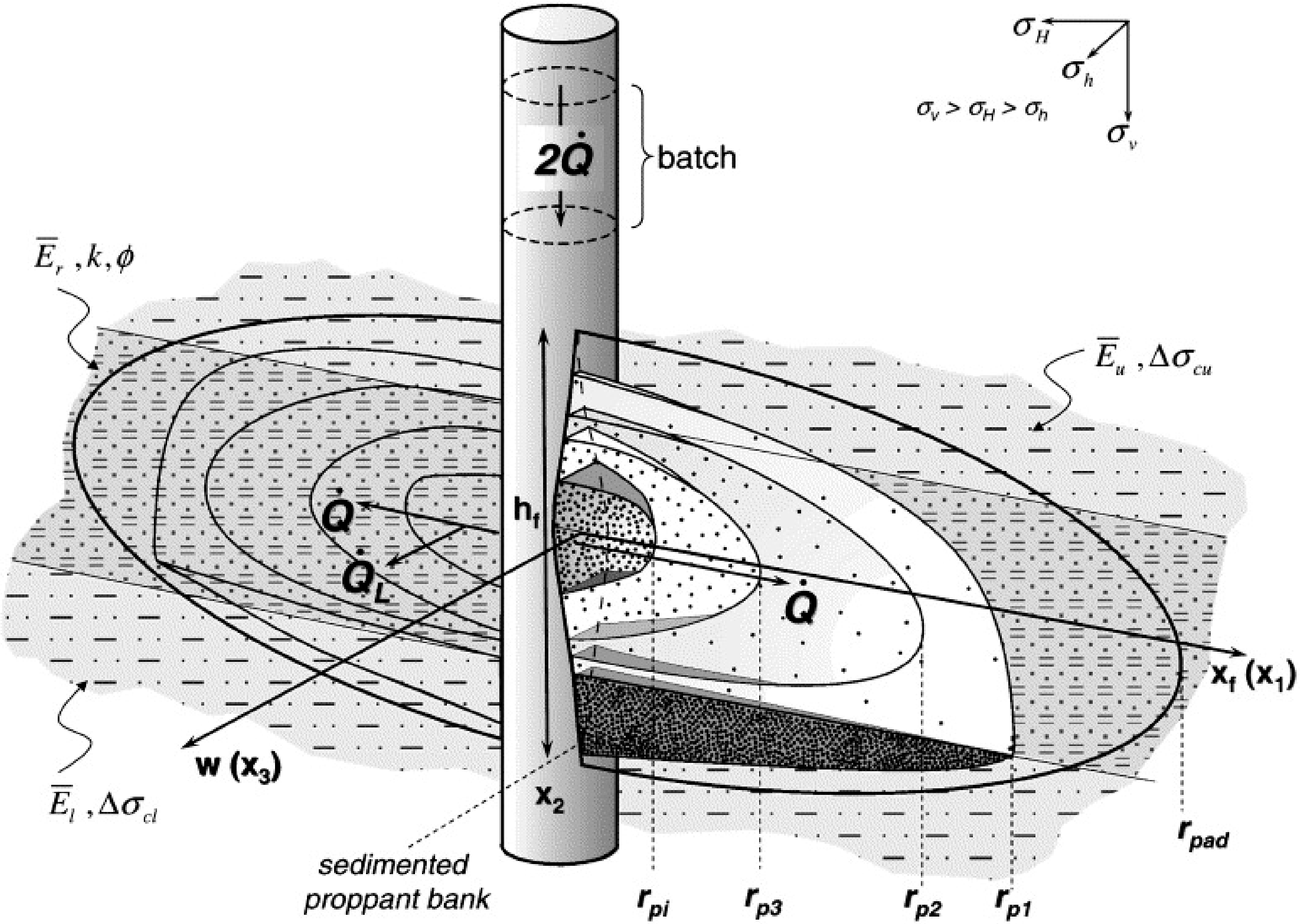
November 5, 2014

Overview

- For identifying "sweet spots," matrix quality is obviously critical. But I am going to discuss fracture network quality.
- I do next generation hydraulic fracture modeling- where I think the industry is going, but isn't really there yet.
- Topics for discussion
  - Complexity – what is it? Good or bad?
  - Hydraulic fracture modeling
  - Role of unpropped fracture conductivity
  - Factors that affect stimulation mechanism
  - Application to sweet spot identification and stimulation design
- What does hydraulic fracturing actually "look like"?

The classical concept of a hydraulic fracture is a planar, ellipsoidal feature



Legarth et al., 2005

Complexity

- The word “complexity“ is used to refer to the presence of a volumetric region of fracturing, rather than a single planar fracture per stage
- Evidence of complexity comes from many sources (microseismic, mine-backs, laboratories, etc.)

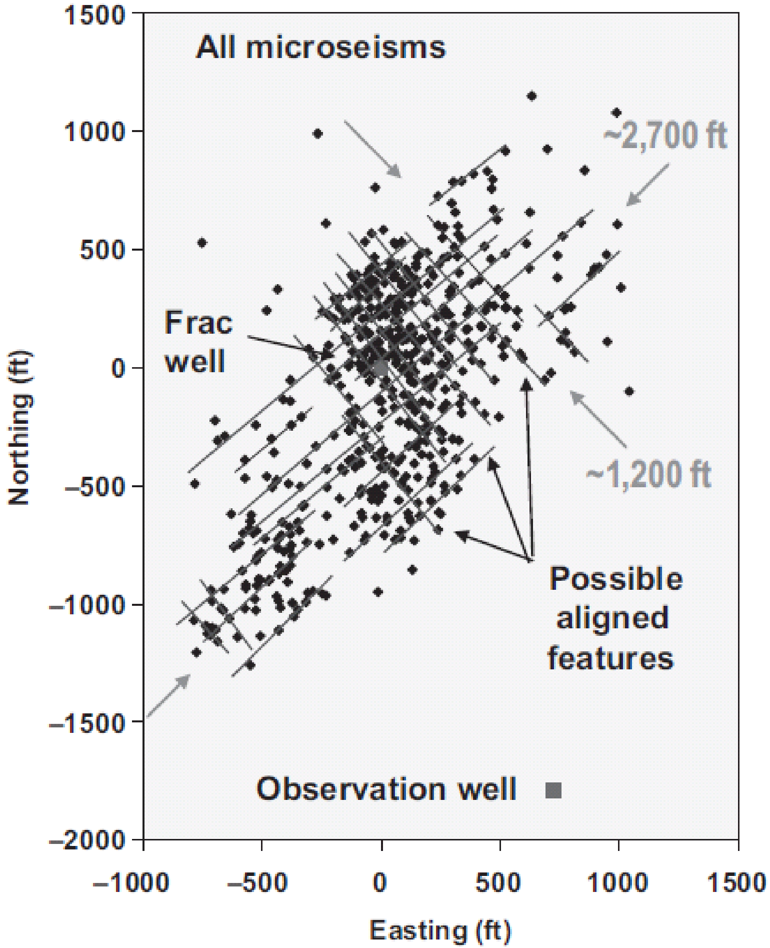
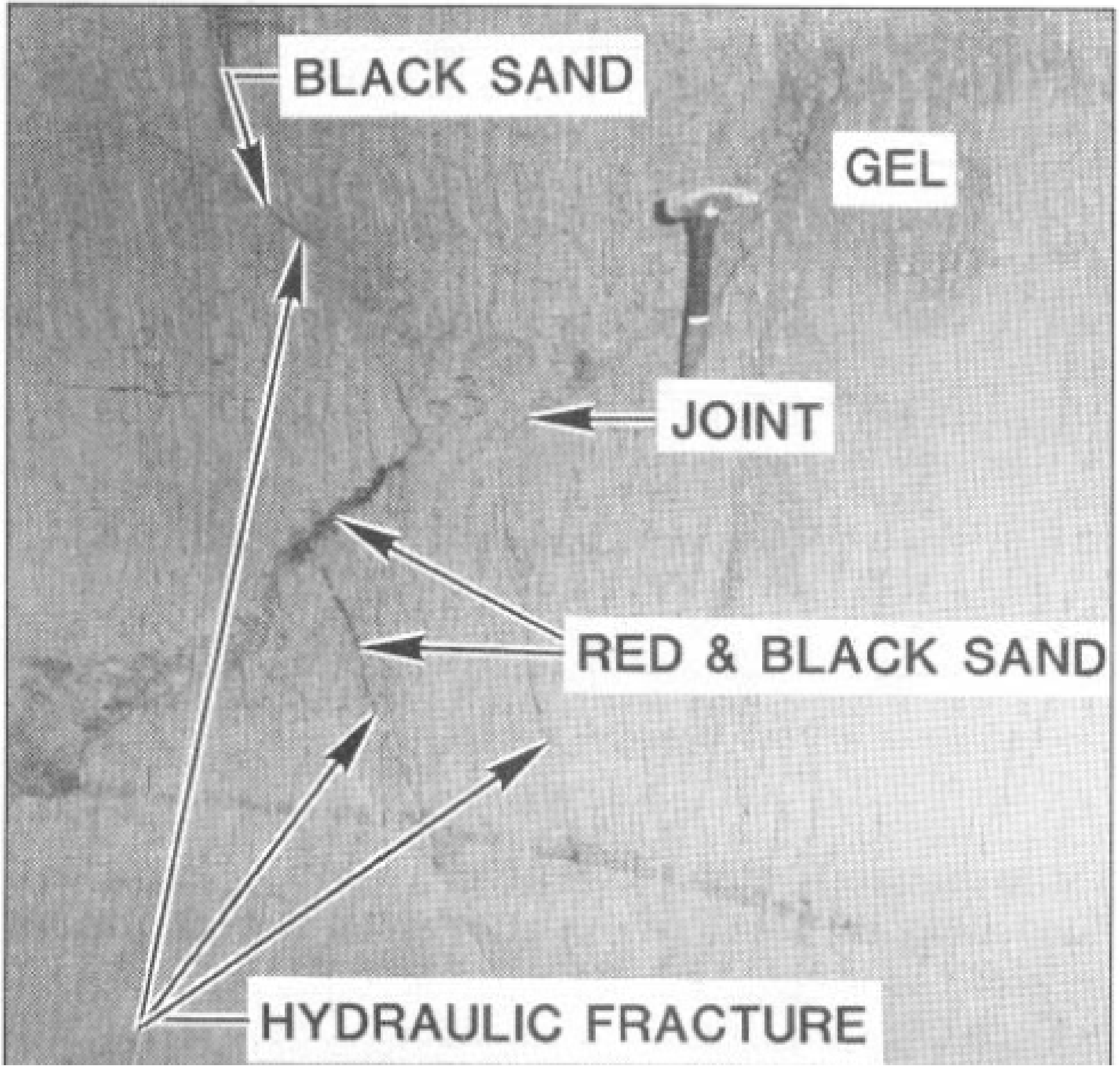


Fig. 3—Microseismic fracture mapping shows complex-network growth in shales (Warpinski et al. 2008).

Mayerhofer et al., 2010



Shallow (1400 ft) mine-back of hydraulic fractures in soft, high porosity, low permeability volcanic tuff

From Warpinski and Teufel (1987)

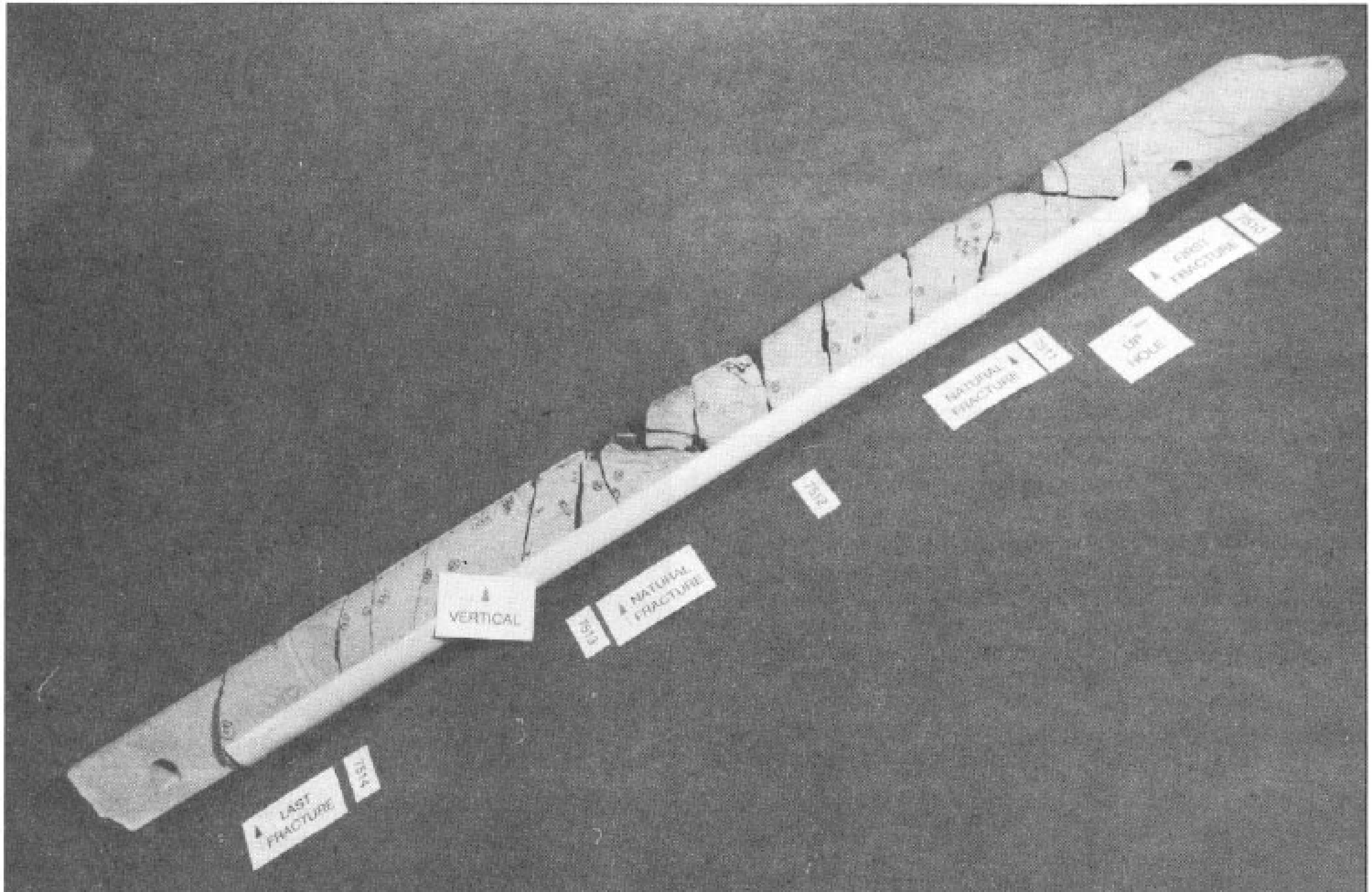


Fig. 5—Photograph of Interval HF-1.

Tight sandstone, 7100 ft. deep

Warpinski et al. (1993)

Unconventional fracture networks are complex

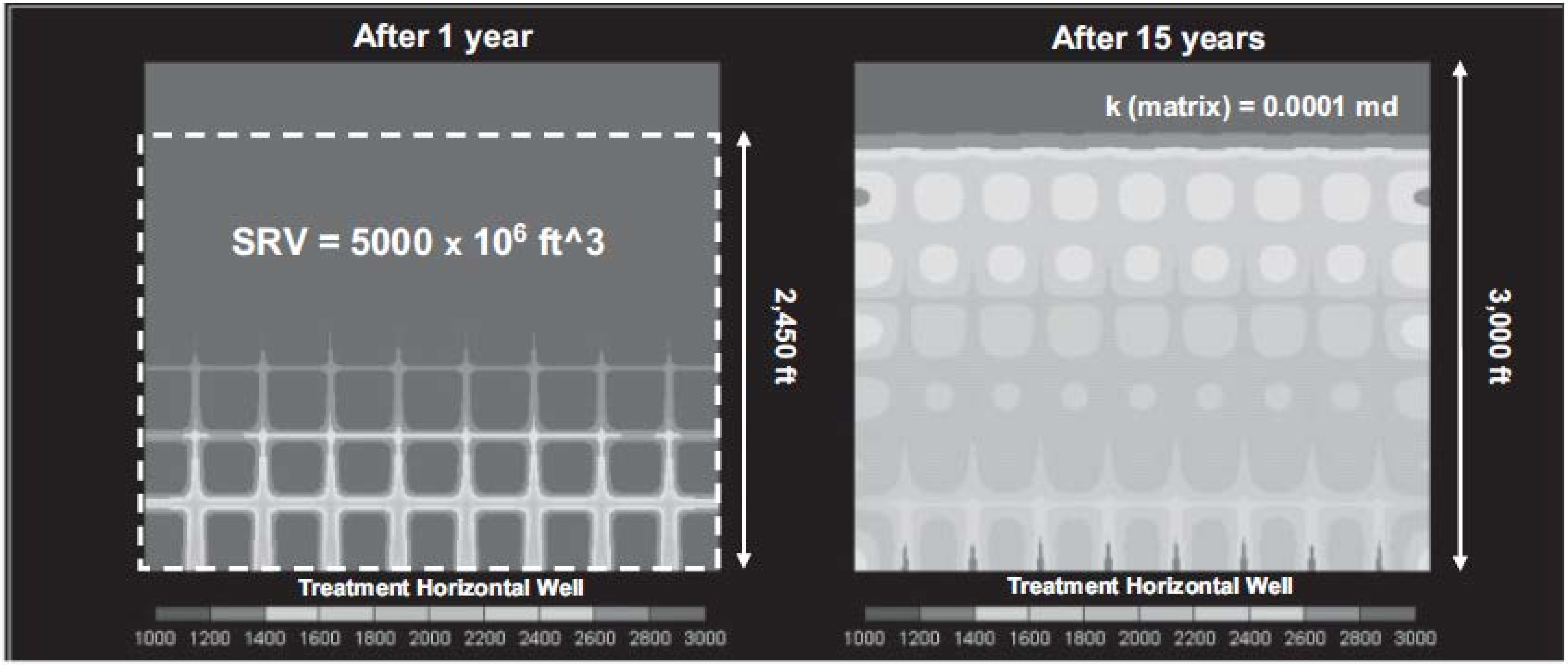


Fig. 11—Simulation of horizontal-well fracture network (SRV = 5,000 × 10^6 ft^3, frac spacing = 400 ft, lateral length approximately 3,000 ft).

Mayerhofer et al., 2010

Unconventional fracture networks are complex

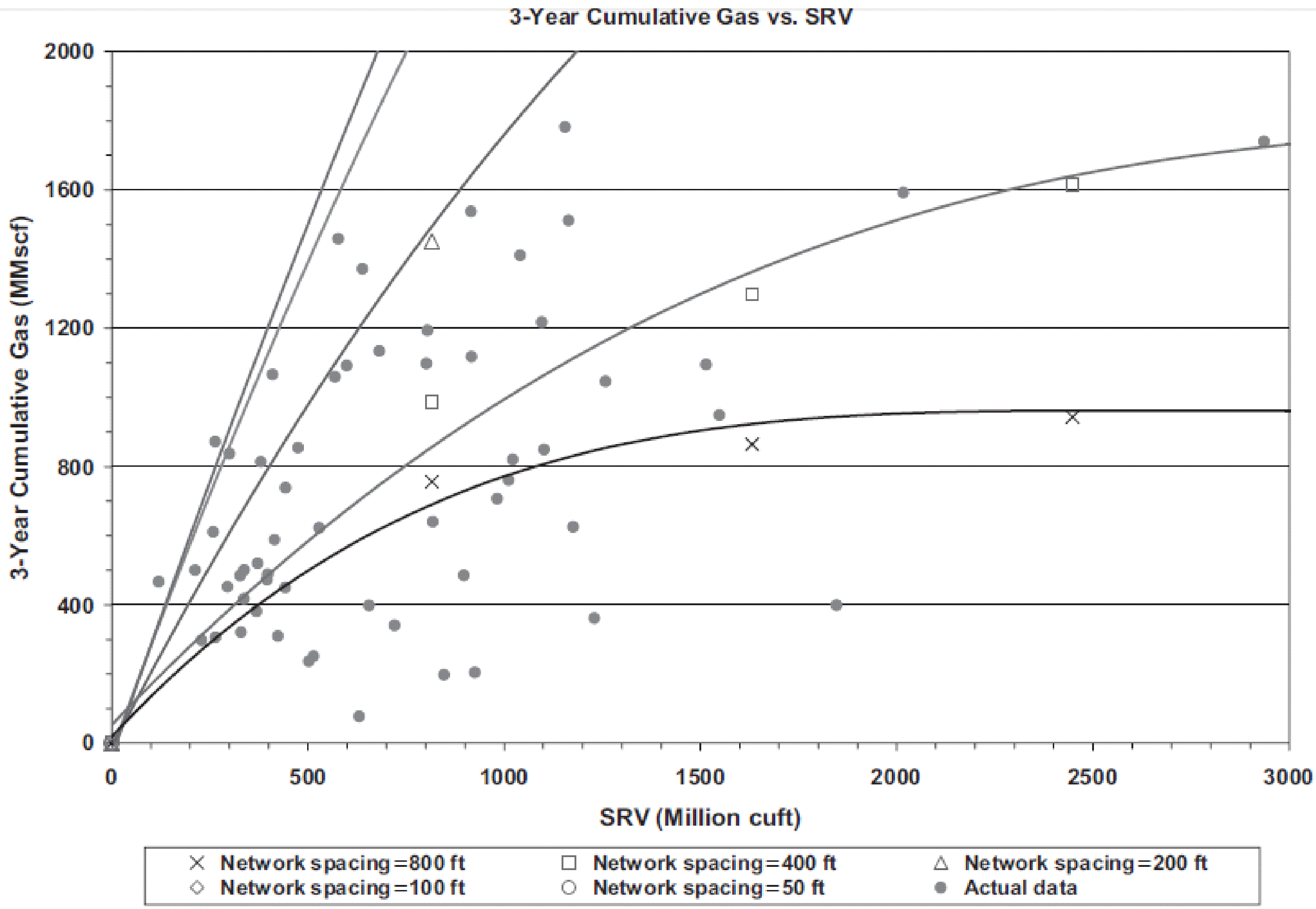


Fig. 14—Simulated SRV and simulated 3-year cumulative production vs. actual Barnett-shale data (entire north Texas area).

Mayerhofer et al., 2010

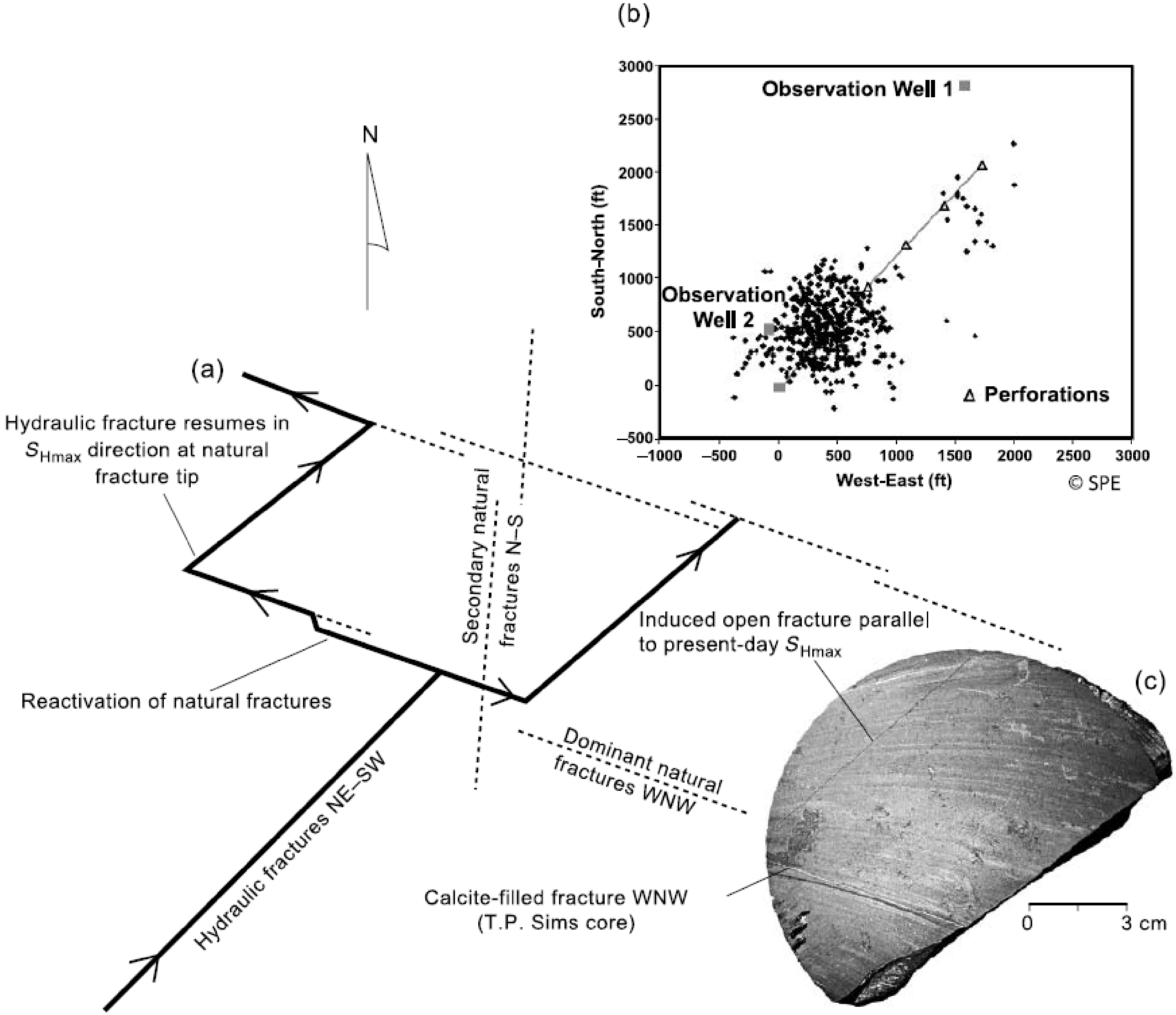


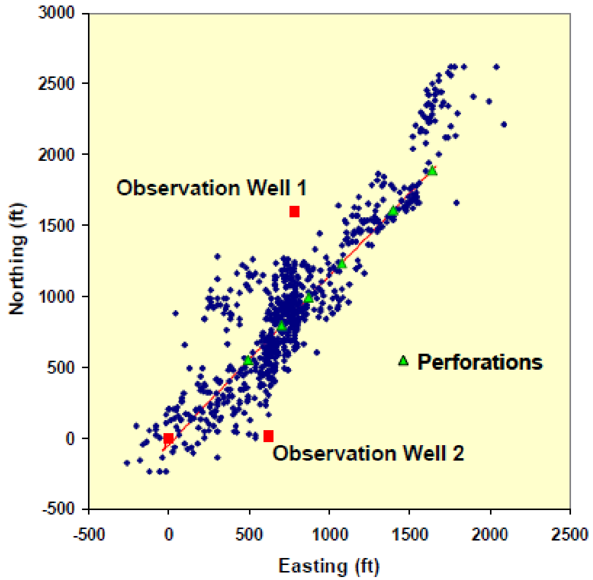
Figure 2. Diagrammatic representation of hydraulic fracture growth showing why natural fracture systems are important for optimal stimulation. (a) Hydraulic fracture growth proceeds northeast-southwest and reactivates natural fractures (dashed lines) trending west-northwest–east-southeast and north-south. Arrows indicate the propagation direction of hydraulic fractures. (b) Map of microseismic data from Warpinski et al. (2005, reprinted with permission from the Society of Petroleum Engineers). (c) A sealed west-northwest–trending fracture and an open, unmineralized, northeast-trending, induced fracture in a disc from the T. P. Sims core.

Gale et al. (2007)

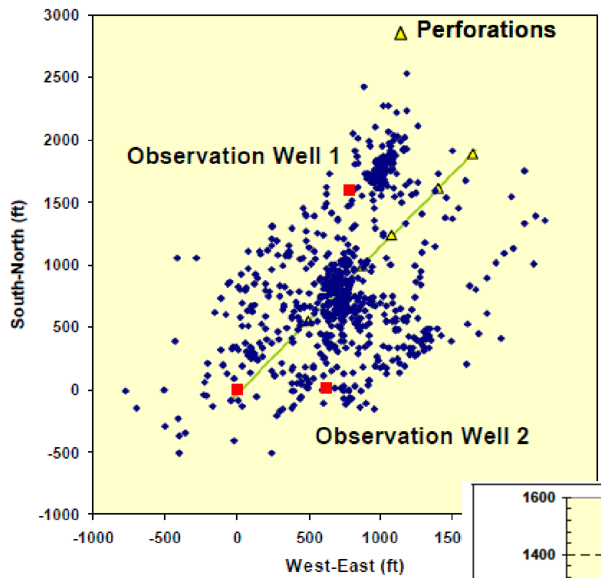
Is complexity good or bad?

- Classically, complexity considered was bad because it caused high net pressure
- Recently we have started to believe that complexity is good in low permeability formation because it helps recovery
- Field evidence suggests either may be true

Barnett Shale case study (Cipolla et al. 2008)



Initial gel frac



Slickwater re-frac

Refrac:

3x increase in SRV (based on microseismic)

Major increase in production

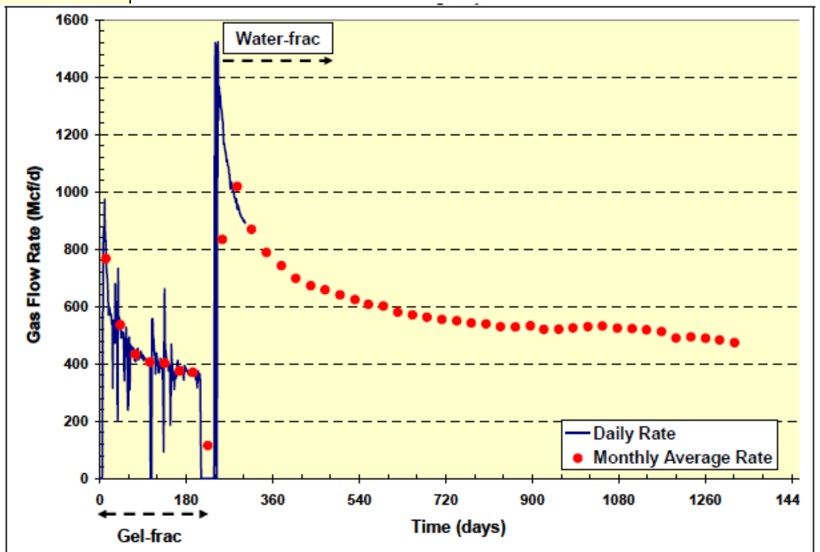


Figure 17 – Production for Barnett Shale case history

Sonora Canyon Sands, Sutton County, TX case study (Cipolla et al. 2008)

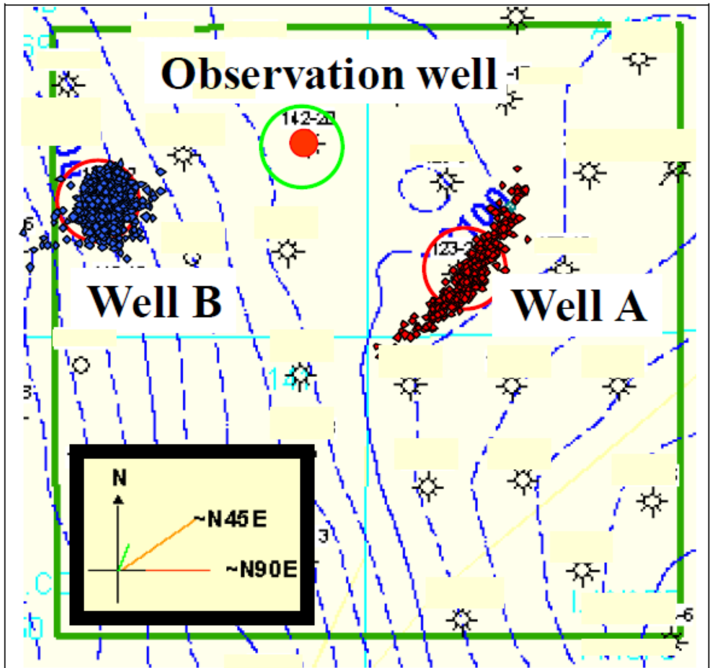


Figure 19 – Summary of microseismic mapping: plan view

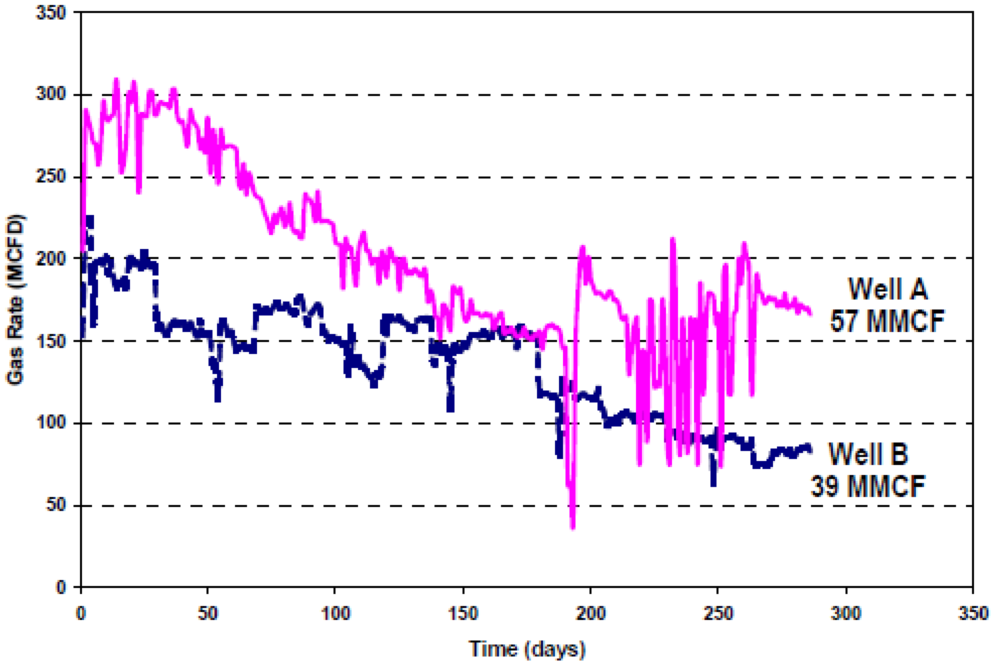


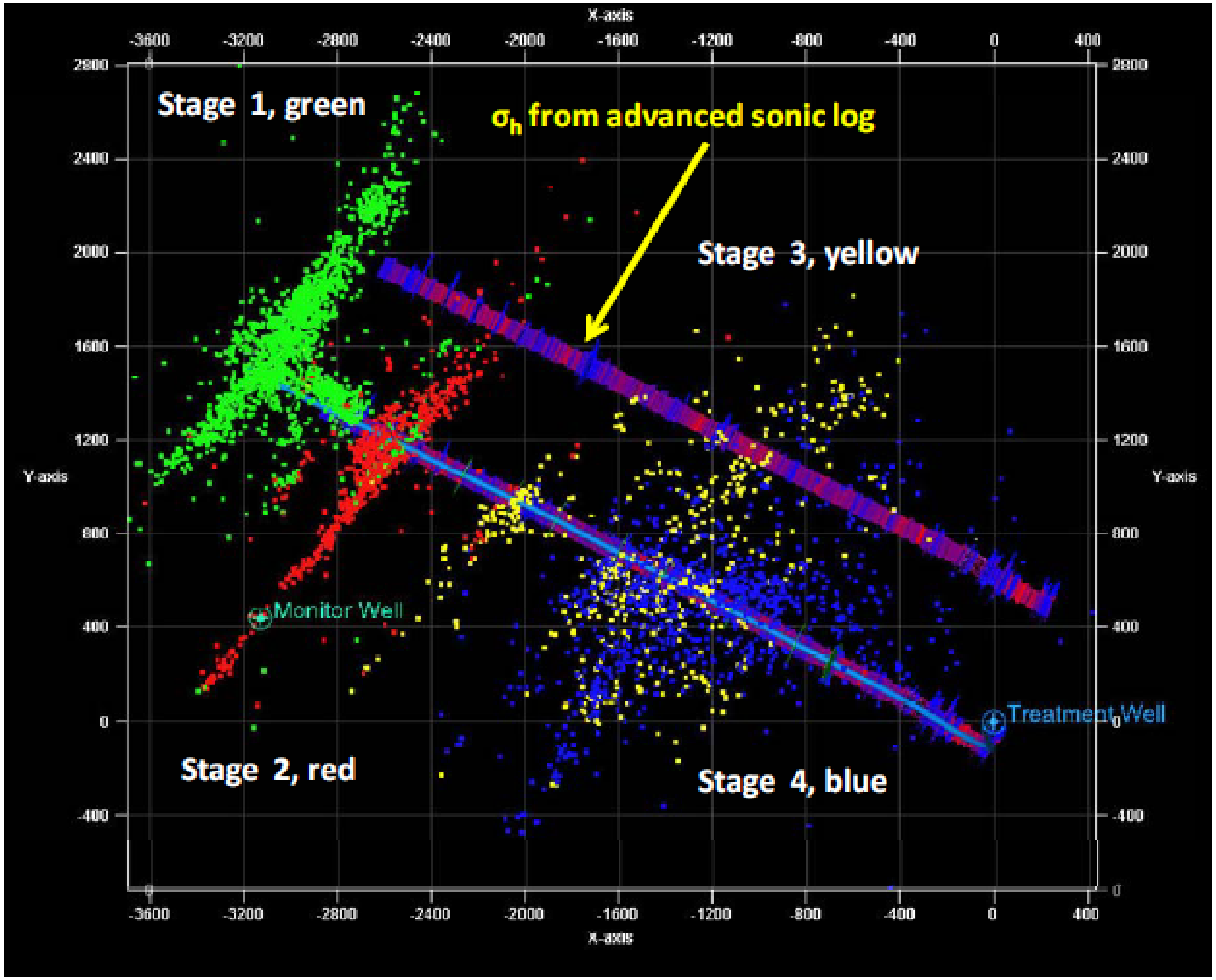
Figure 21 – Wells A and B production comparison

Both wells treated at 40-50 bpm, crosslinked water-based fluid, 30% CO_2, with proppant

ISIP higher for well B

Microseismic is critical here for deciding spacing of future wells!

Stages 1 and 2 are mostly linear. Stage 3 is almost absent. Stage 4 is very wide. What does this mean?



Cipolla et al. (2010)

Comparison of brittleness indices

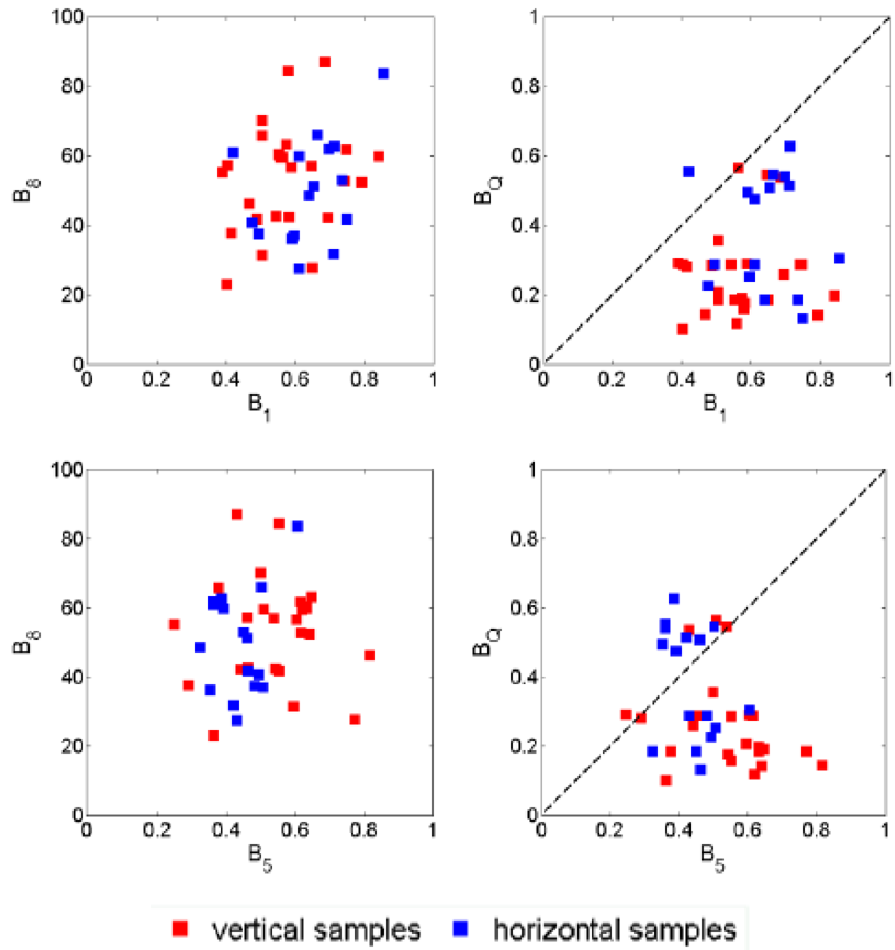


Figure 10: Comparison between various brittleness indices calculated in this study.

From Yang et al. (2013)

This study showed that there is little correlation between different ways of measuring brittleness.

They also found only weak correlation between mechanical test results to quantify brittleness and elastic parameters and composition

Fracture network complexity

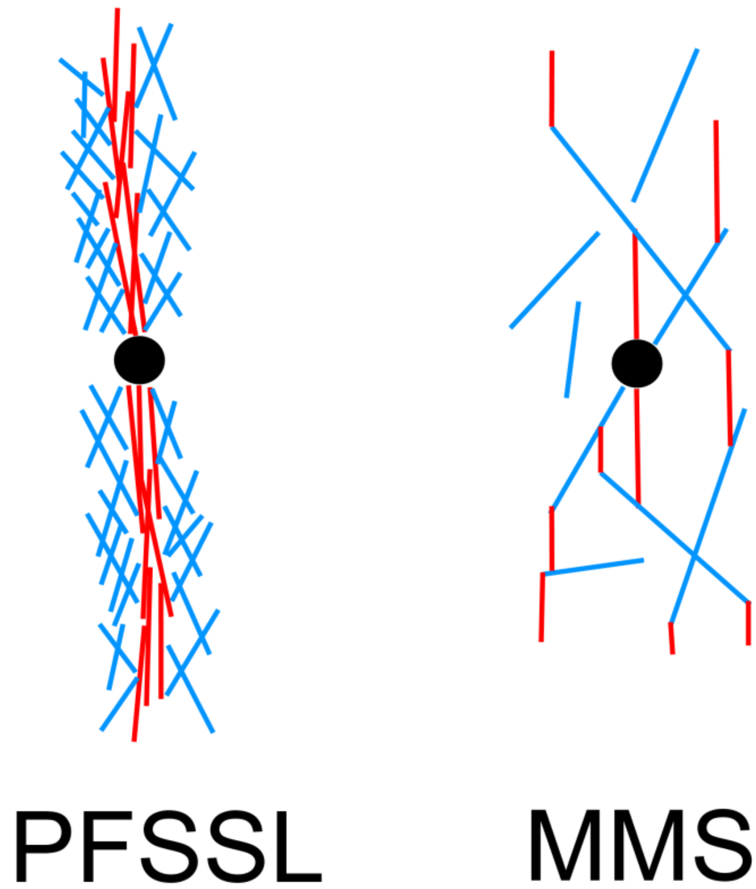
What does fracture network complexity really mean? It depends on what we think complex fracture look like and how they form.

The schematic to the right illustrates two different conceptual ideas about how complexity forms. We don't know to what extent these different processes really occur and impact production.

PFSSL – primary fracturing with shear stimulation leakoff

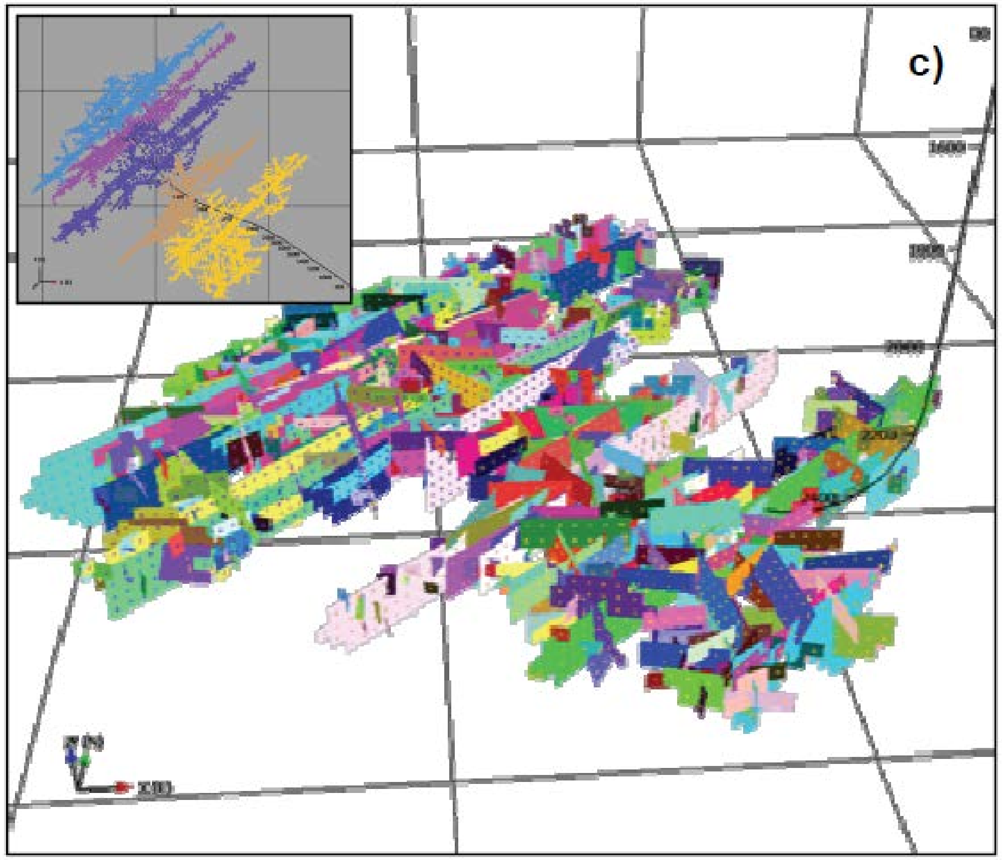
MMS- mixed-mechanism stimulation

Others?



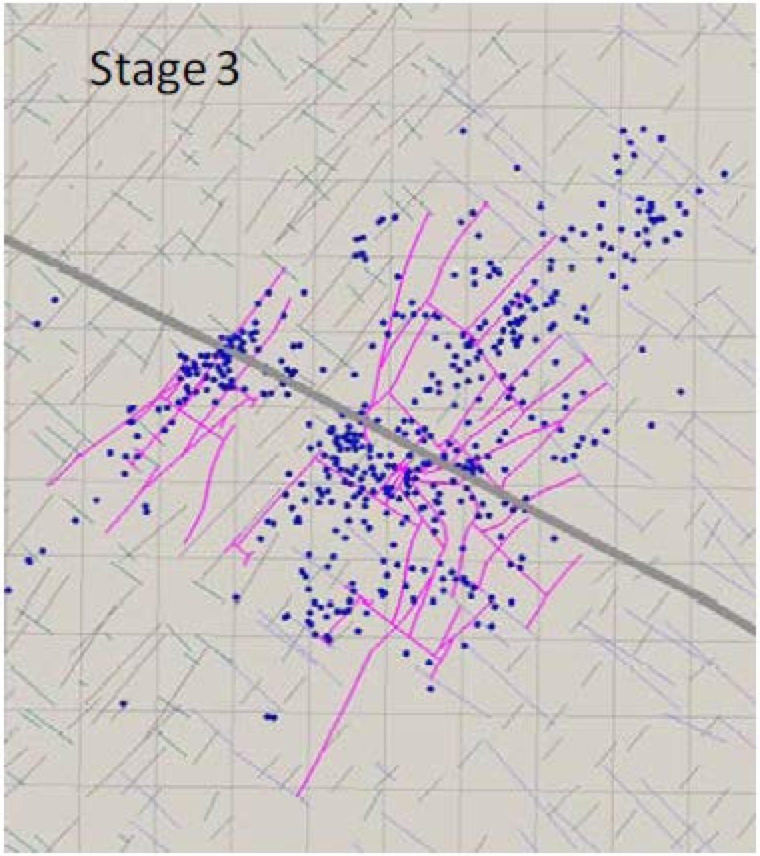
From McClure (2013)

Stimulation mechanism and complexity



Rogers et al. (2010)

Primary fracturing with shear stimulation leakoff

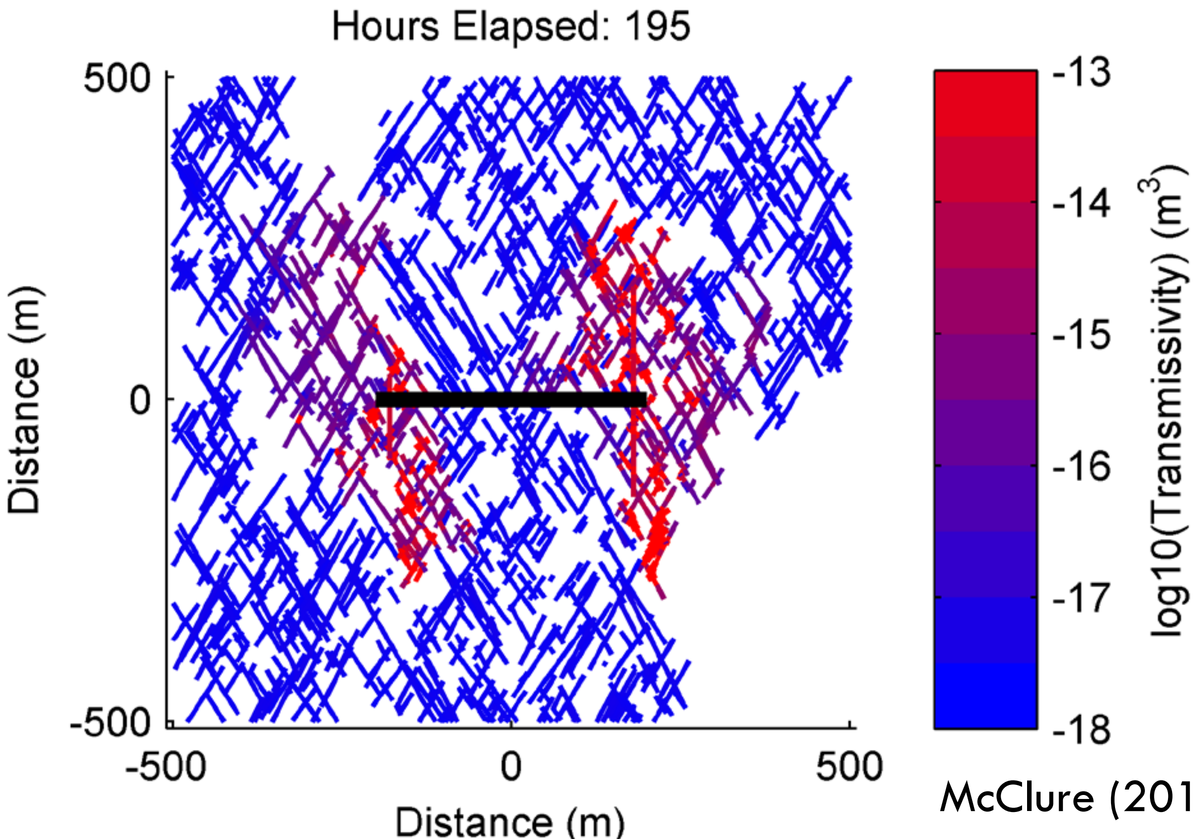


Wu et al. (2012)

Mixed-mechanism stimulation

CFRAC

Full coupling (fully implicit) of fluid flow and stresses induced by fracture deformation (sliding and opening) in large, discrete fracture network models



McClure (2012)

51 hours CPU time

Single processor

~66,000 elements
~80,000 time steps

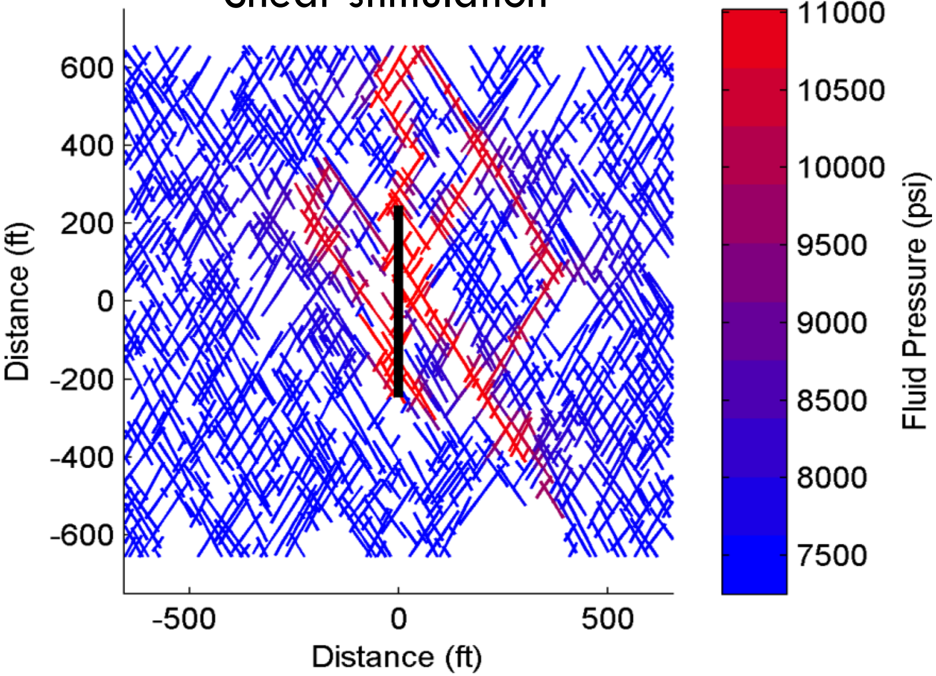
Convergent to refinement in time and space

CFRAC details

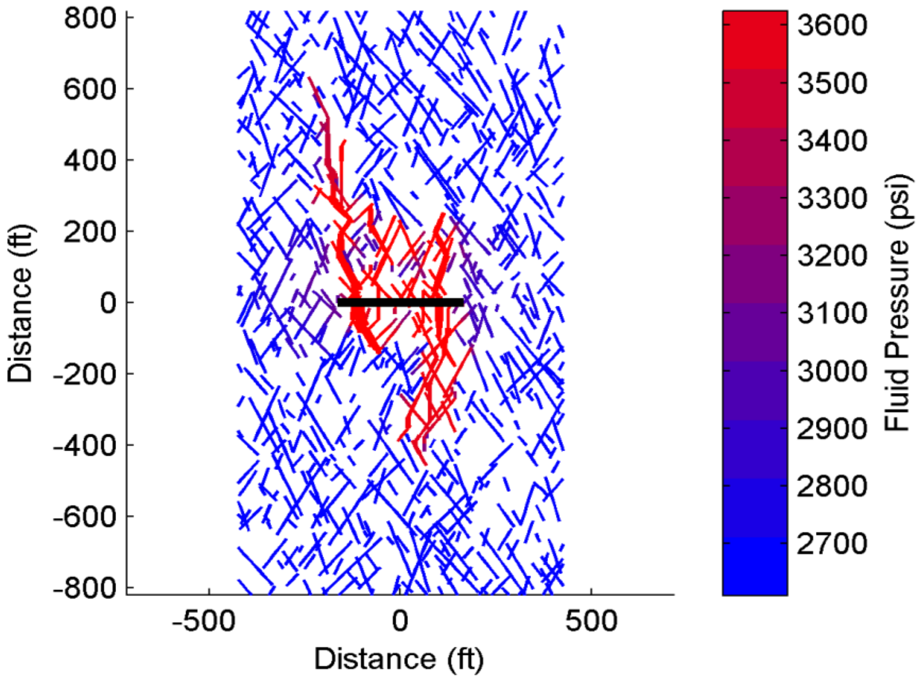
- Stress induced by opening and sliding of both new and preexisting fractures
- Can model microseismicity directly (friction evolution) or with a correlation
- Intended to model the stimulation period, not the subsequent production period
- Assumes single phase liquid water (isothermal)
- Either no flow outside fractures, 1D leakoff model, or full 2D simulation of leakoff with a conforming mesh of the surrounding area
- Uses the boundary element method (isotropic, homogeneous, linear elastic material), can use Olson (2004) to correct for the finite formation height
- Formation and propagation of new fractures treated with linear fracture mechanics and the locations of potentially forming fractures must be specified in advance

CFRAC examples

Shear stimulation

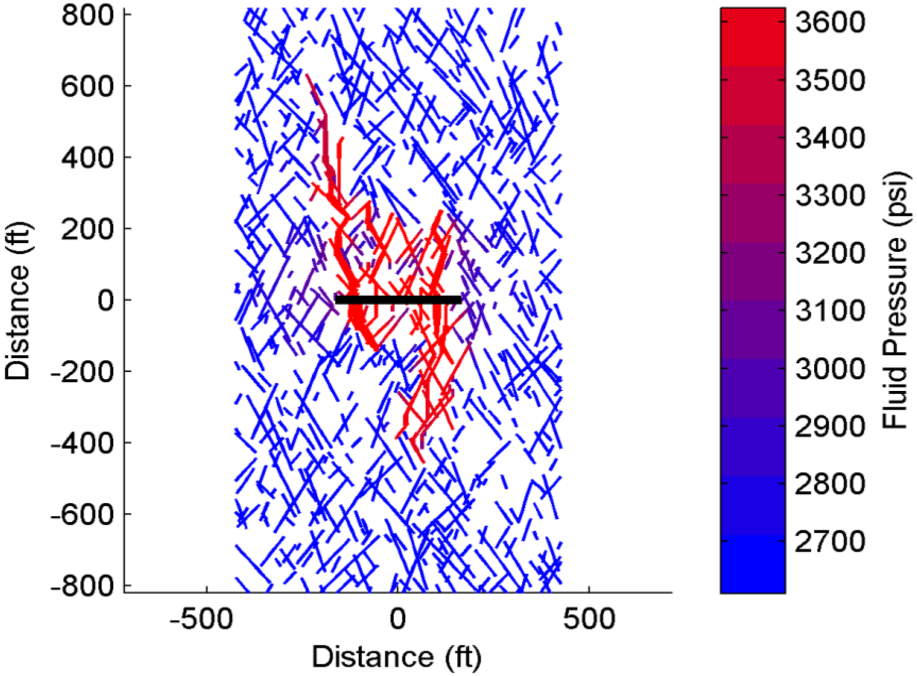


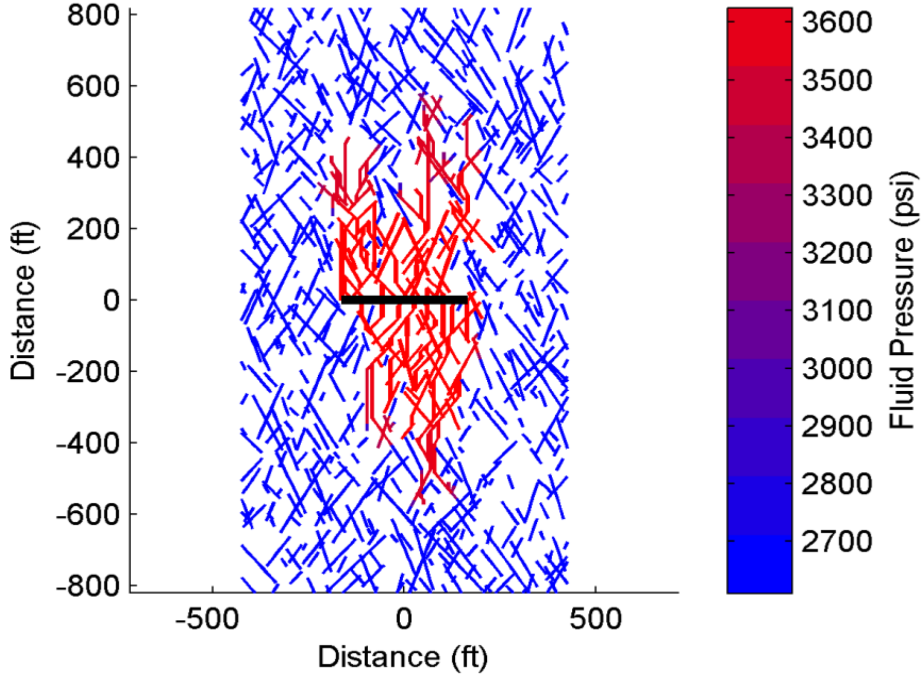
Mixed-mechanism stimulation



McClure (2013)

Effect of induced stresses

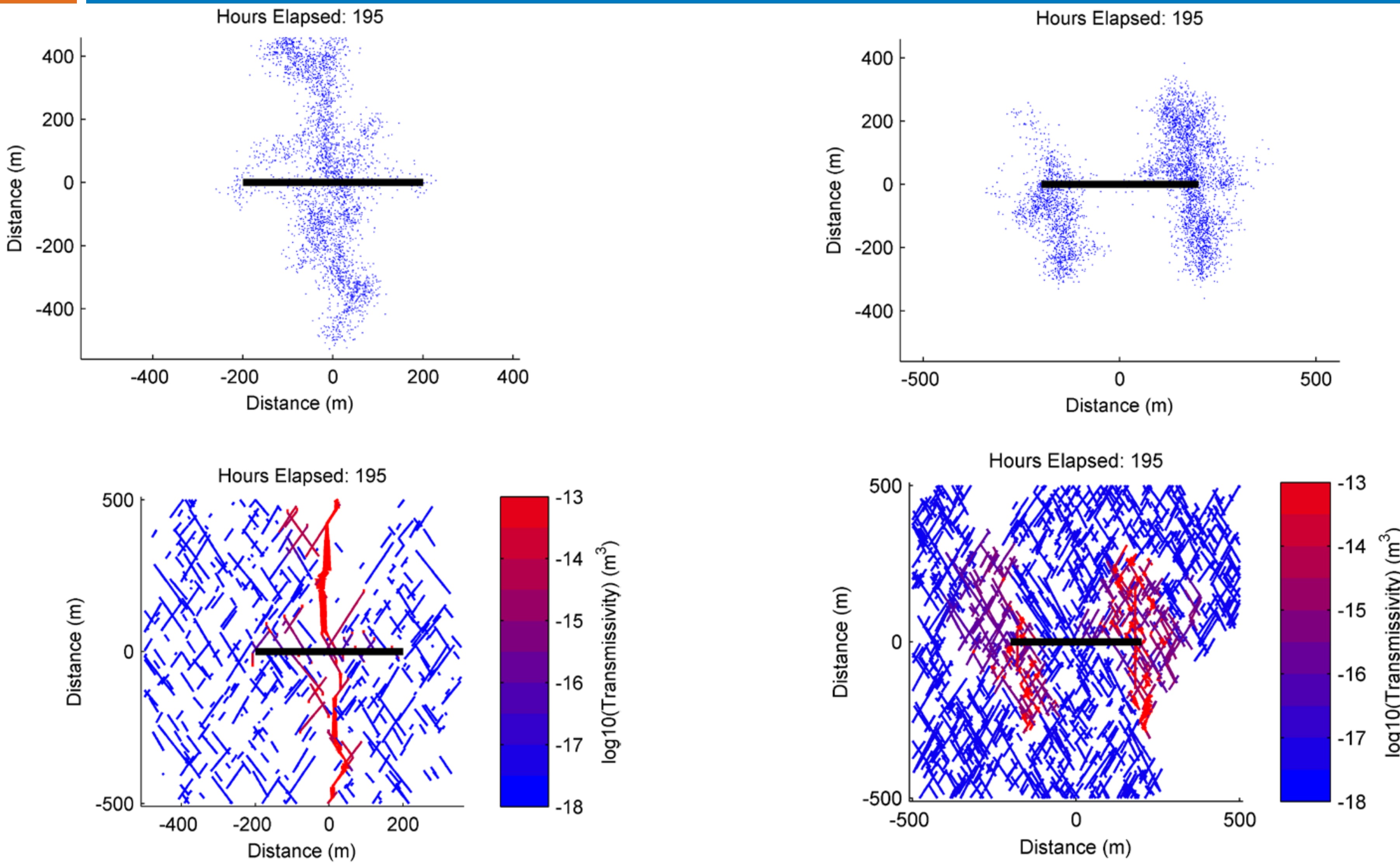




McClure (2013)

Stimulation mechanism and microseismic

From McClure (2012)



Questions to ask

- Does complexity help recovery?
- Is our fracture network complex?
- What causes complexity, how can we predict it?
- What does a complex network even look like?

- These issues touch many of the decision we make --
  - Well spacing, formation evaluation, hf design, etc.
- And much of the analysis we do –
  - Microseismic interpretation, fracture modeling, etc.

Unpropped fracture conductivity

- In my opinion, this is probably the most important variable that determines whether complexity helps or hinders production
- Proppant is unlikely to reach far out into a volumetric, complex network of fractures
- So for complexity to be useful, the unpropped fractures need to retain conductivity after fluid pressure has drawn back down

Unpropped fracture conductivity

Figures from Fredd et al. (2001)

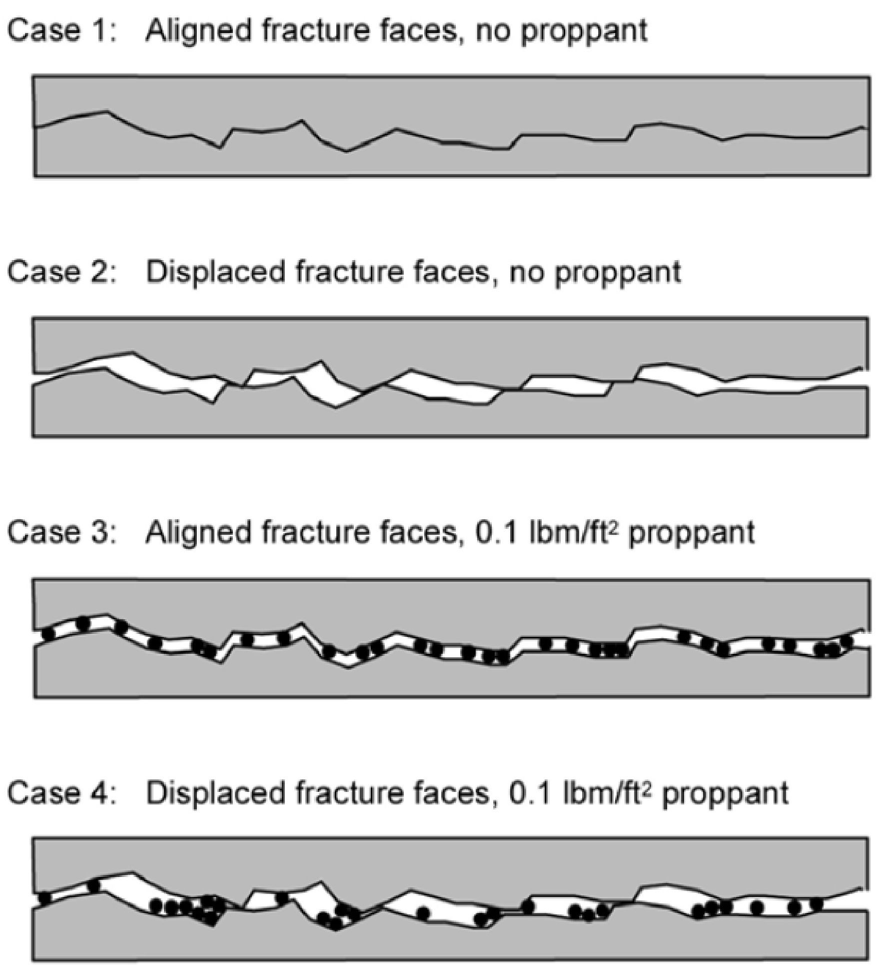


Fig. 9—Water-fracturing cases investigated in this study.

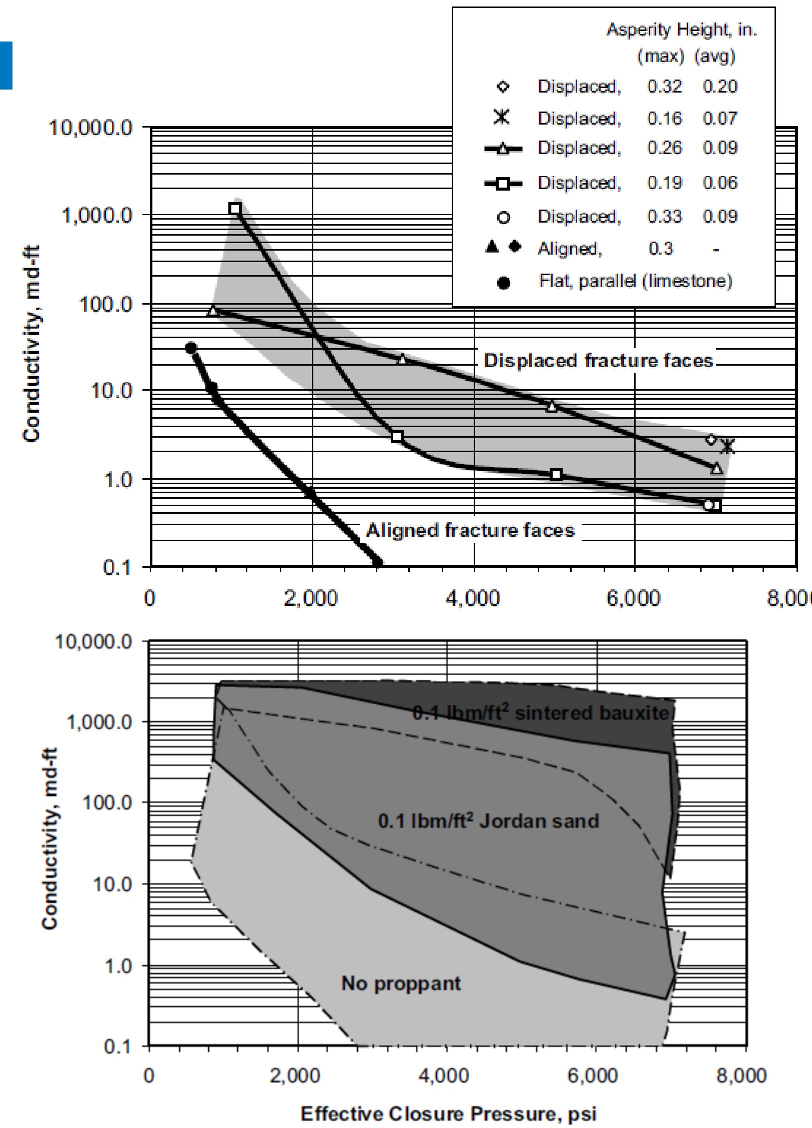
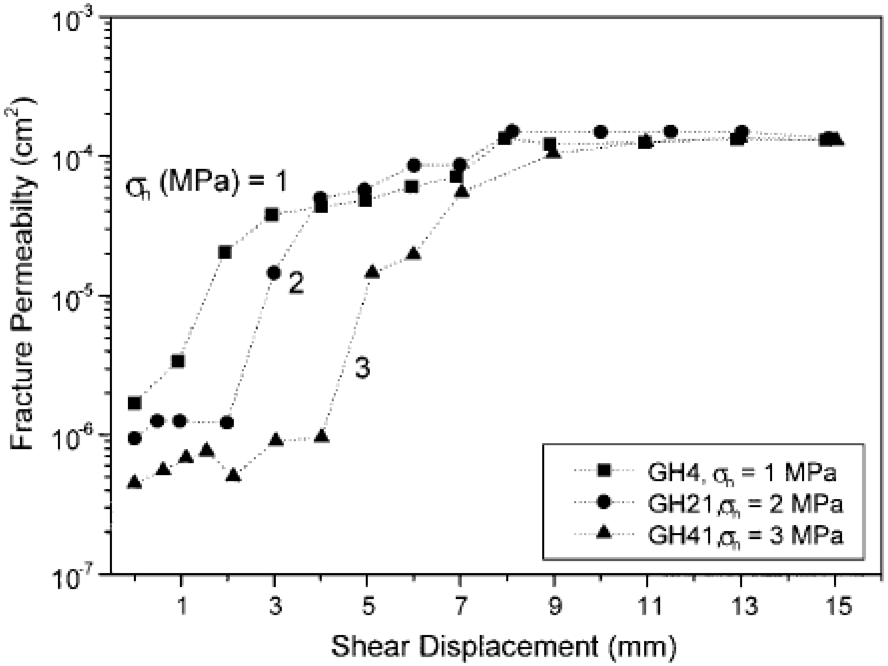


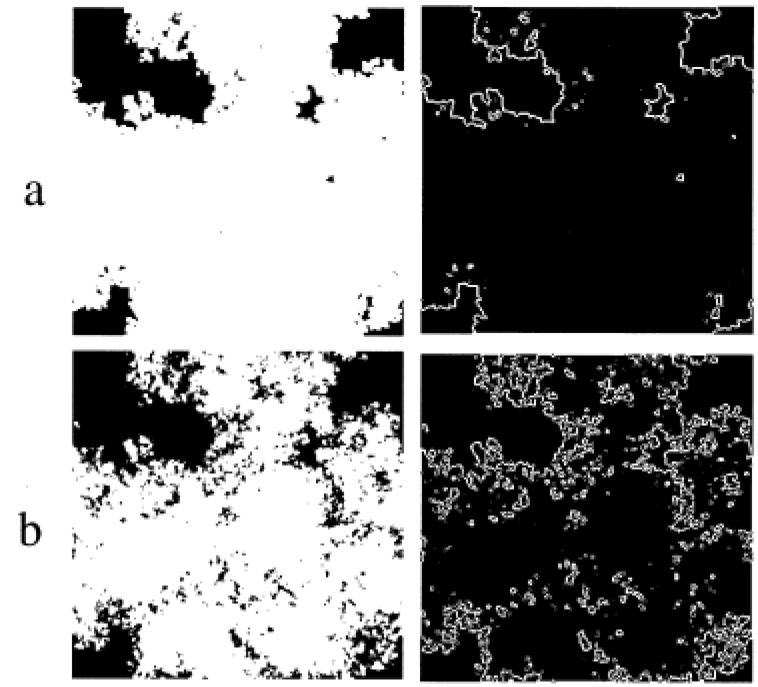
Fig. 26—Wide variation in conductivity for water-fracturing cases.

Unpropped fracture conductivity

- The ability for fractures to experience shear stimulation and to retain conductivity at elevated normal load is a property of the rock and the fracture geometry. I think more work is needed on how we might be able to predict this.



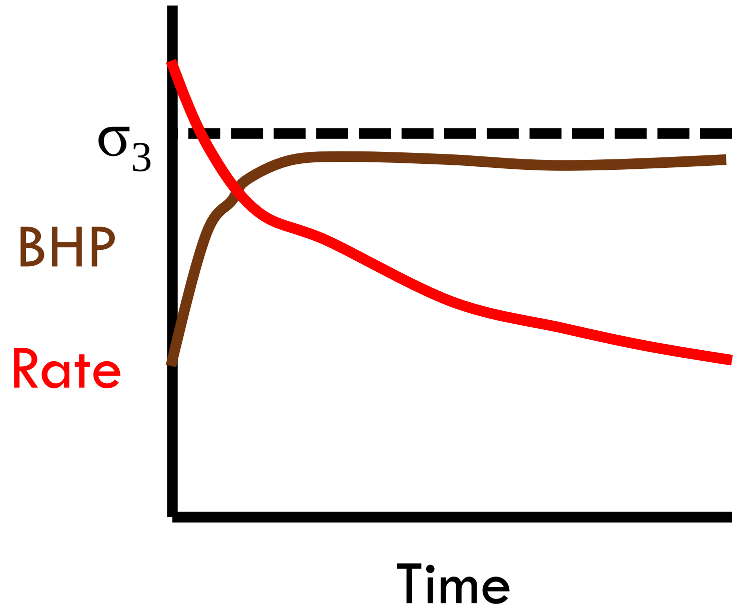
From Lee and Cho (2002)



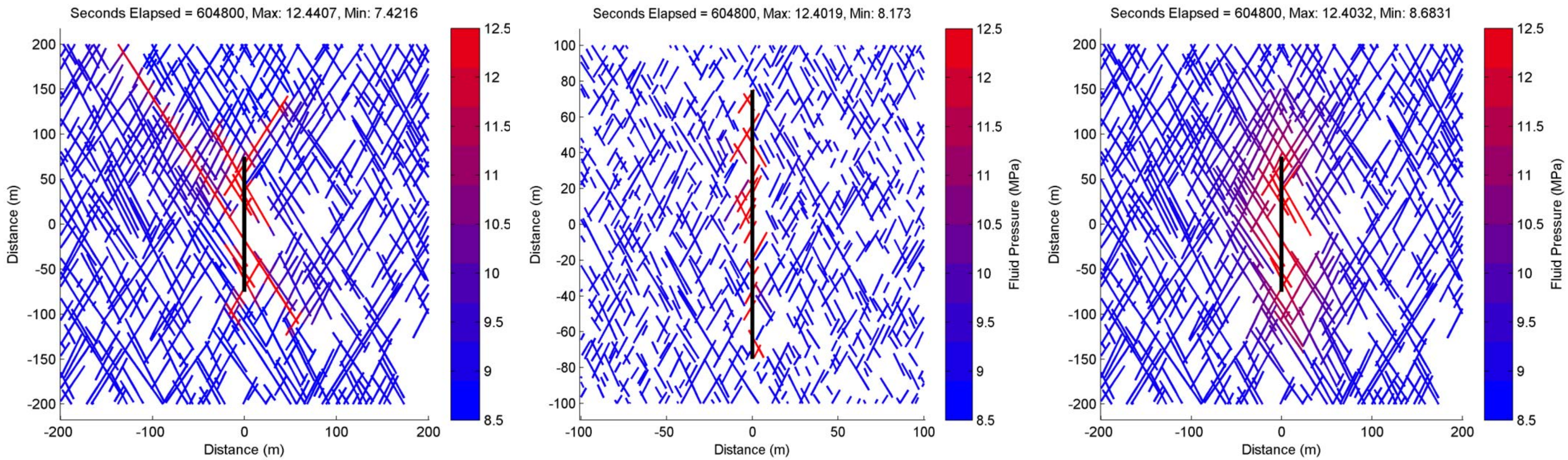
From Pyrak-Nolte (1999)

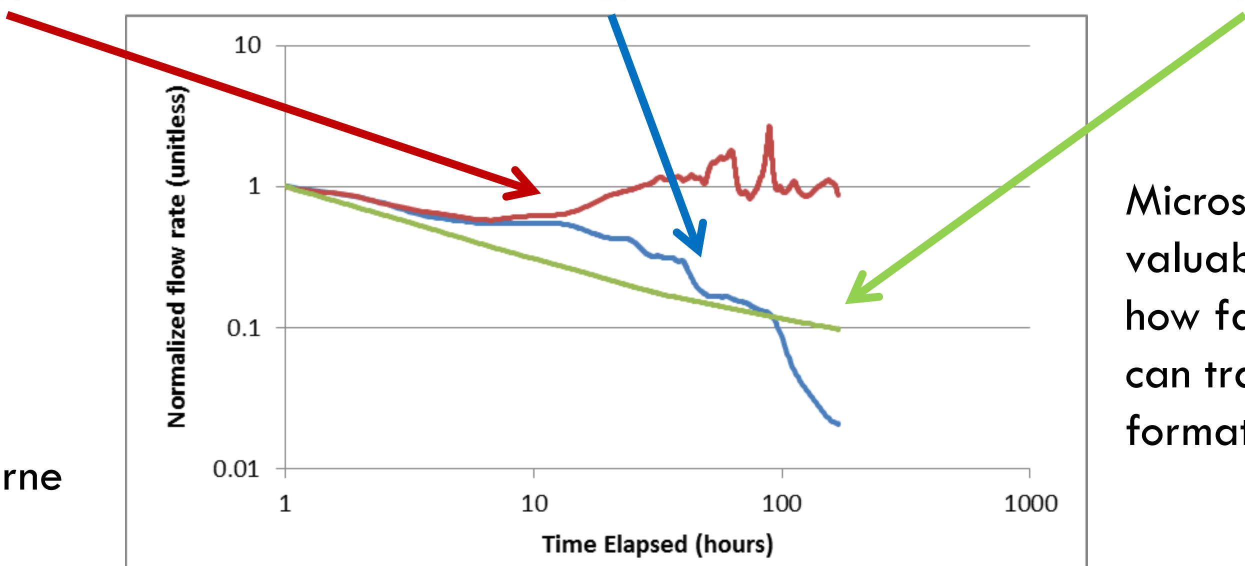
Tendency for shear stimulation test

- Injection into an open hole section in a well that has not yet been stimulated
- Intentionally maintain the BHP below the minimum principal stress
- Shear stimulation is the only possible mechanism of stimulation
- Does stimulation occur?
- The objective is to evaluate the ability of natural fractures to shear stimulate and retain conductivity



Results





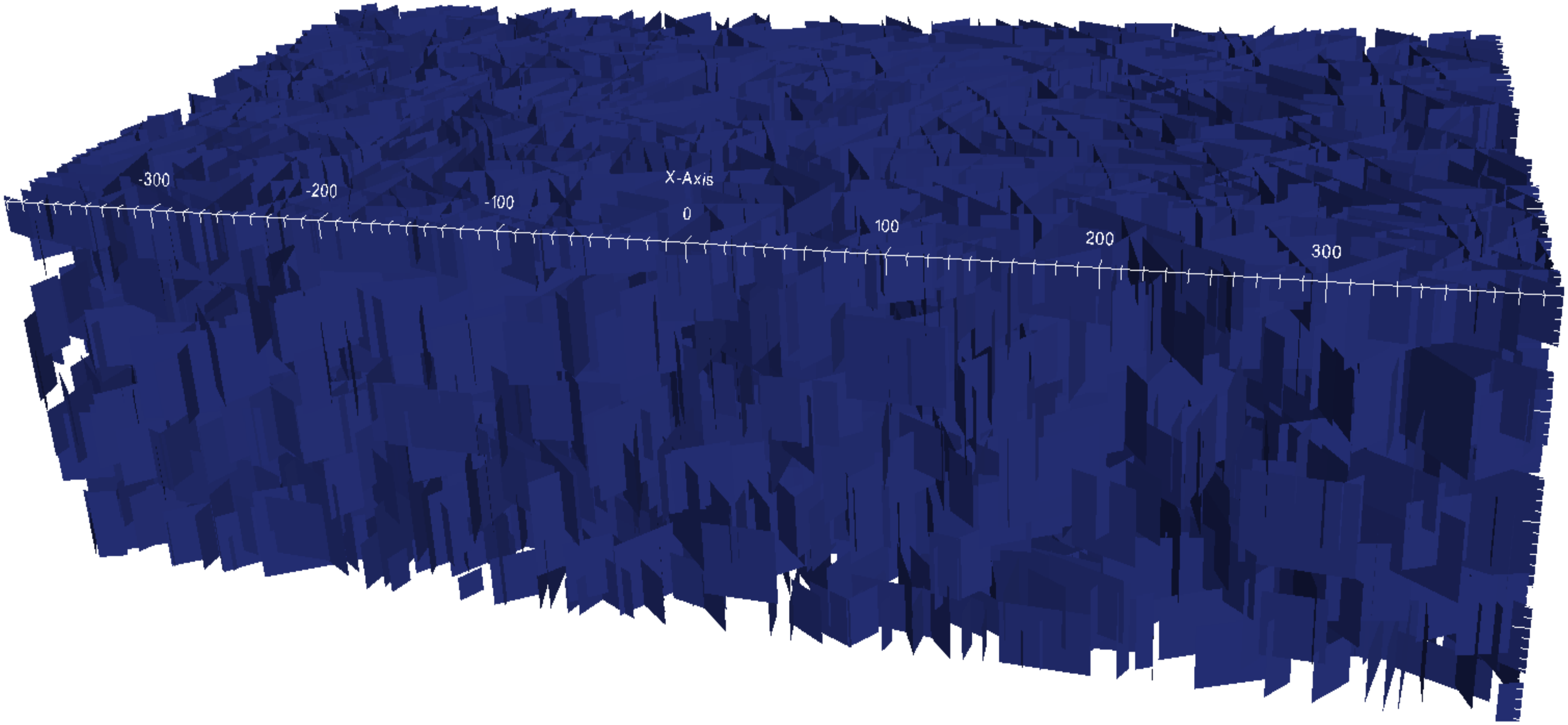
Microseismic would be valuable here, to see how far stimulation can travel through the formation.

McClure and Horne (2014)

What affects stimulation mechanism?

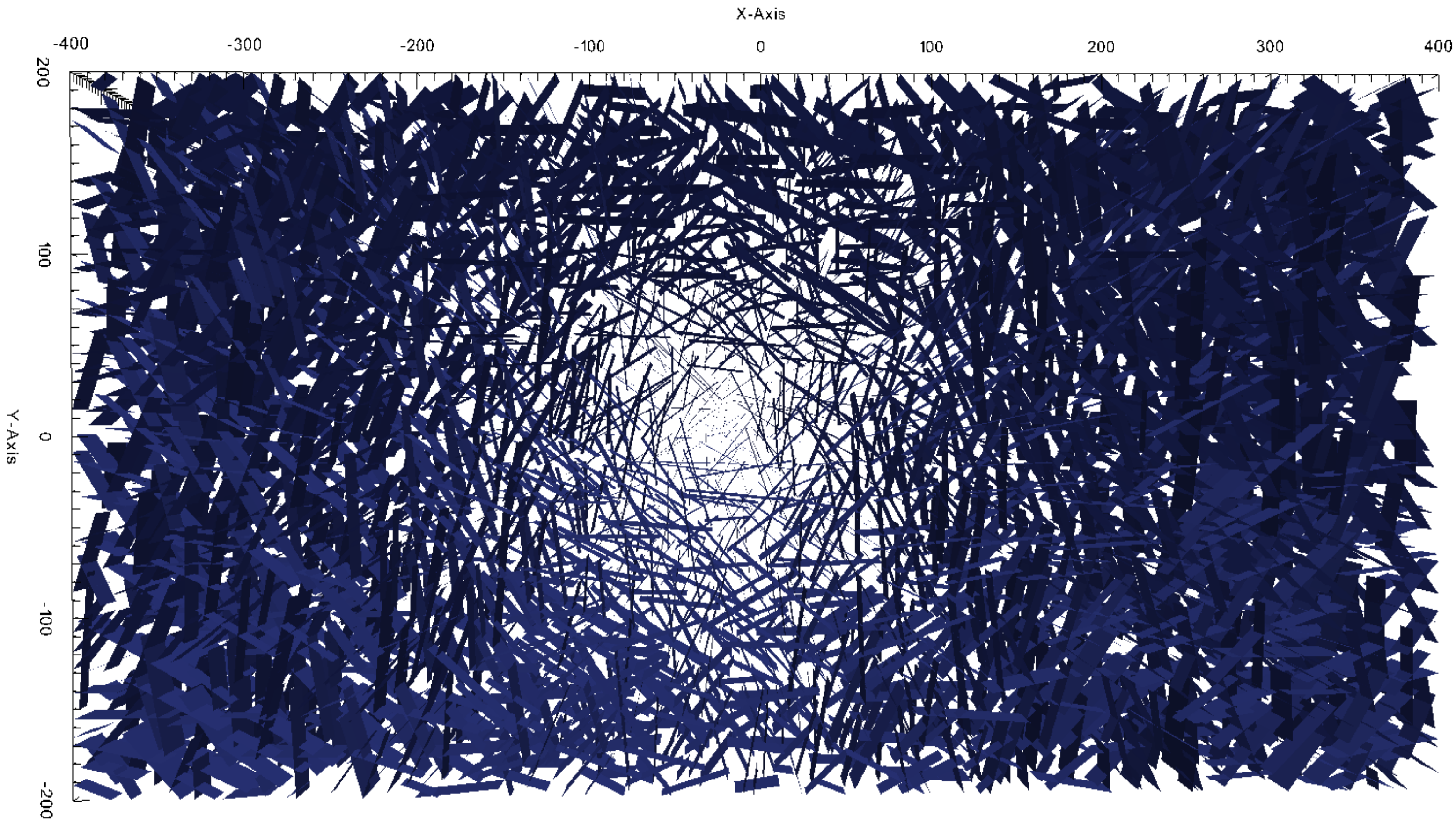
- Four 3D simulations from my upcoming paper at the SPE Hydraulic Fracturing Technology Conference in February
  - McClure, Mark W., Mohsen Babazadeh, Sogo Shiozawa et al. 2015. Fully coupled hydromechanical simulation of hydraulic fracturing in three-dimensional discrete fracture networks. Paper SPE 170956 presented at the SPE Hydraulic Fracturing Technology Conference, The Woodlands, TX.

What affects stimulation mechanism?



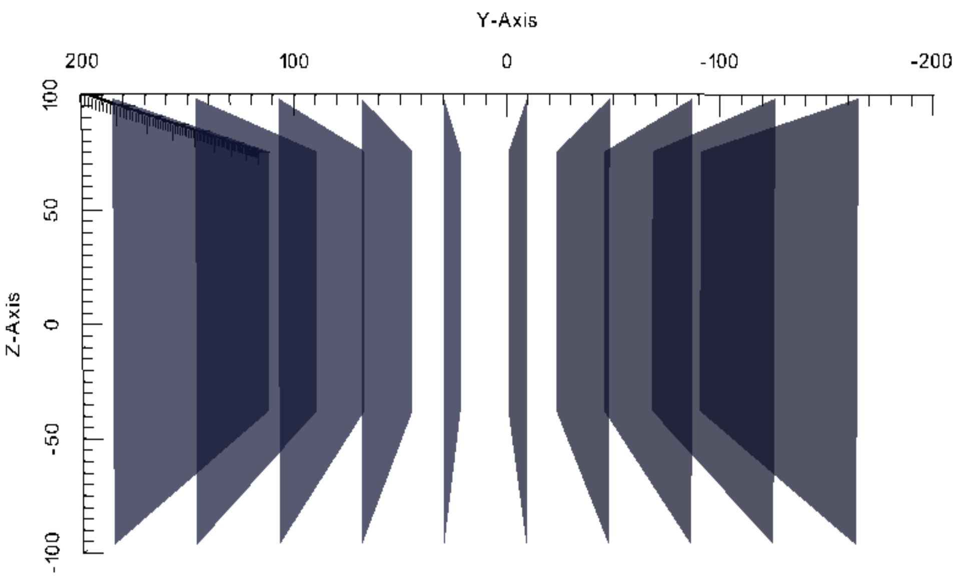
Initial natural fracture network

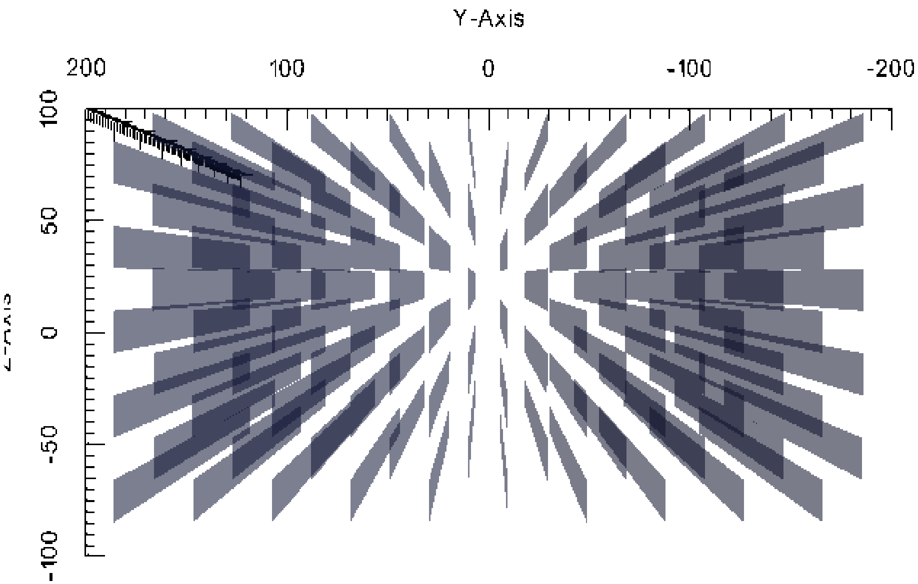
What affects stimulation mechanism?



Initial natural fracture network

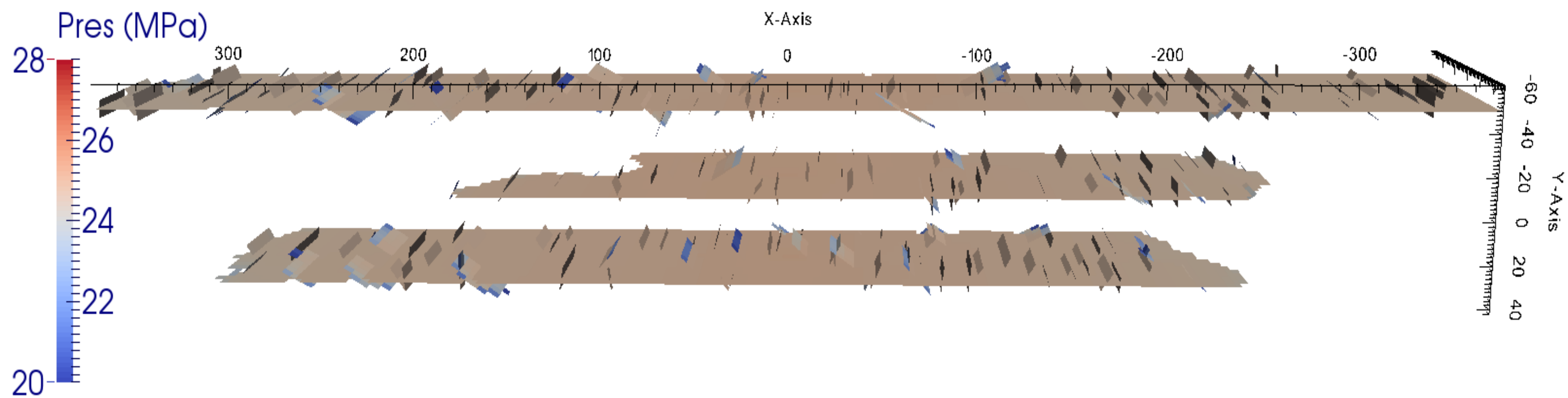
What affects stimulation mechanism?

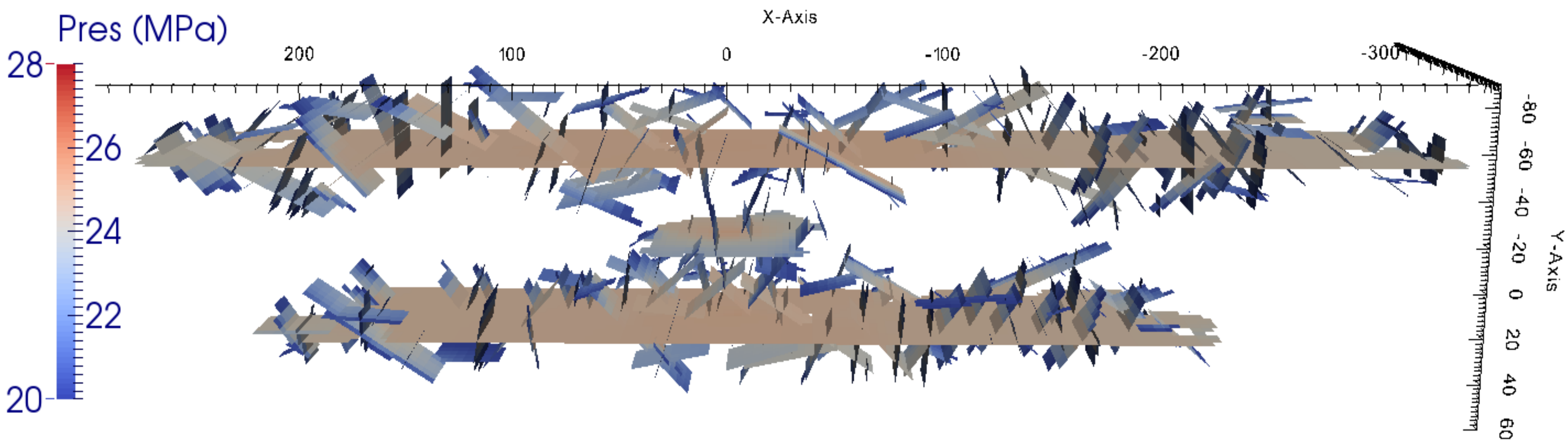




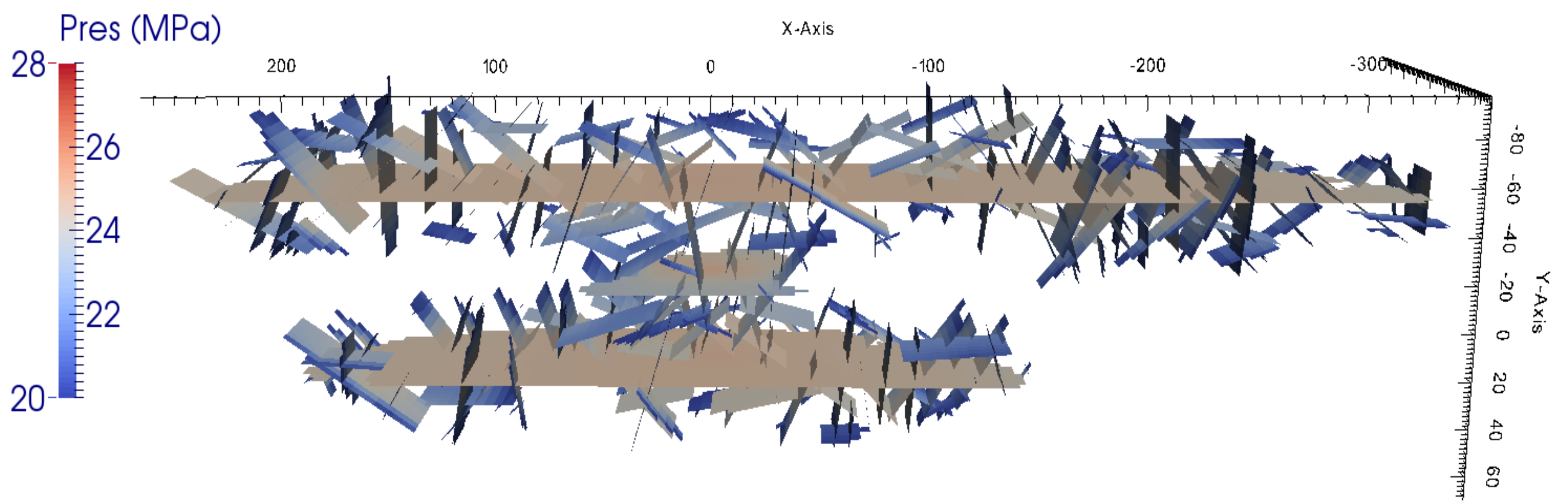
Locations of potentially forming hydraulic fractures

What affects stimulation mechanism?

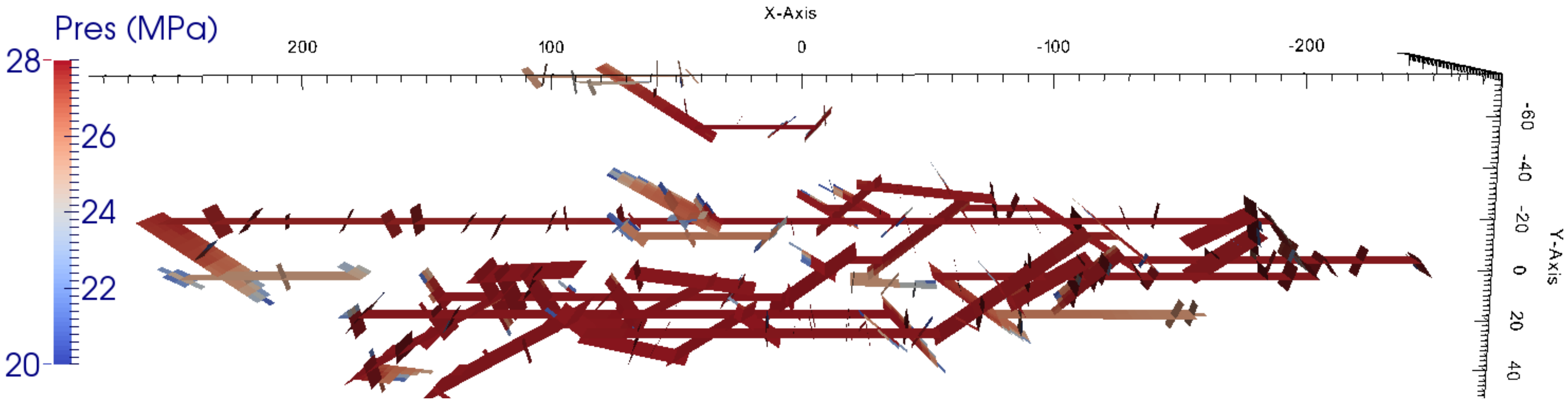


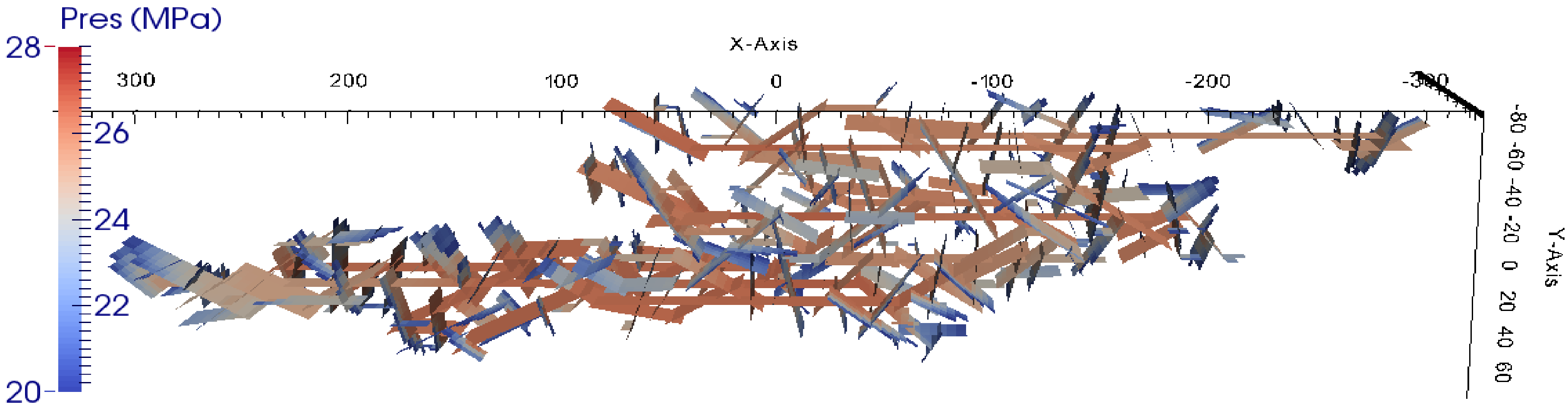


What affects stimulation mechanism?

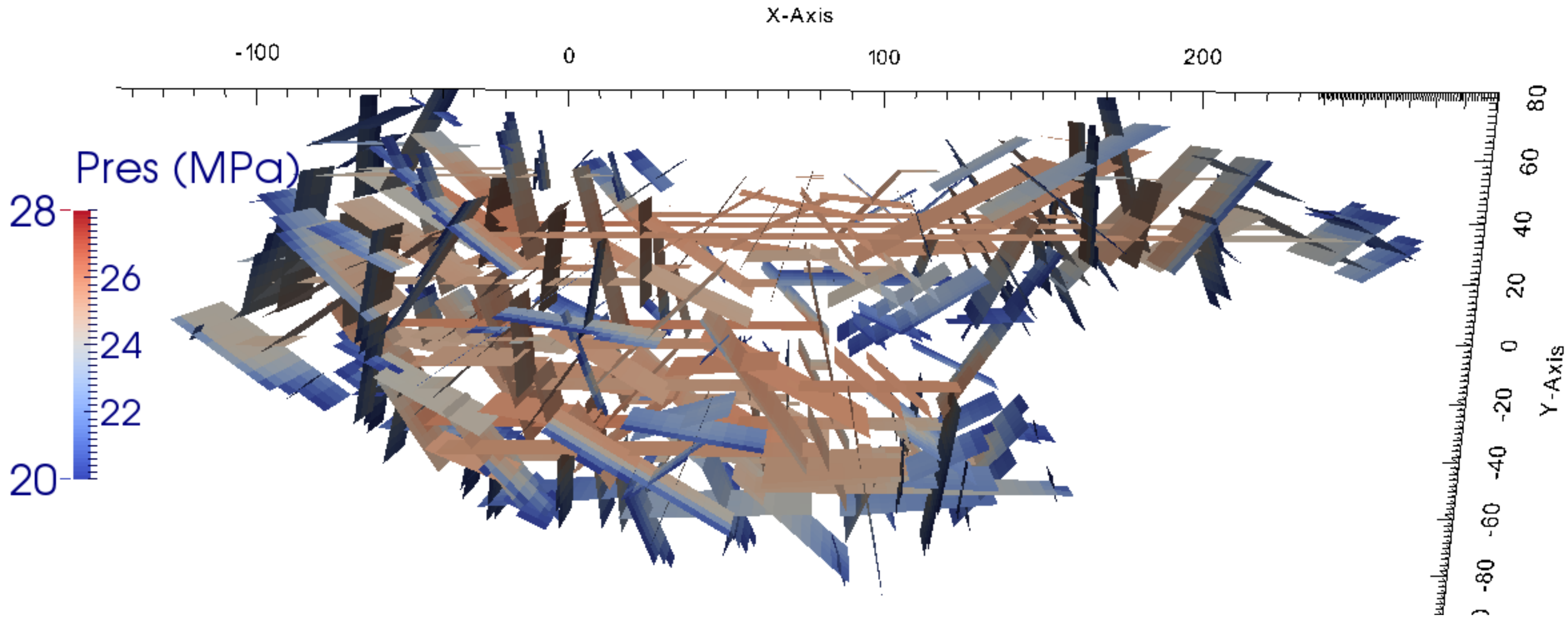


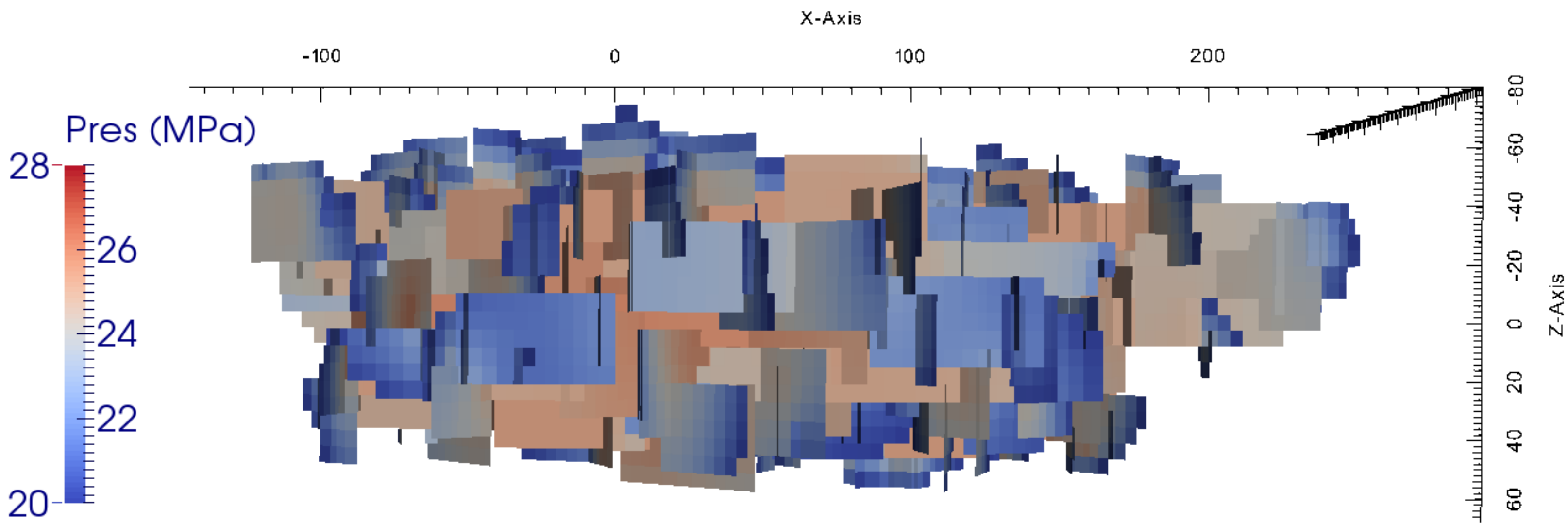
What affects stimulation mechanism?



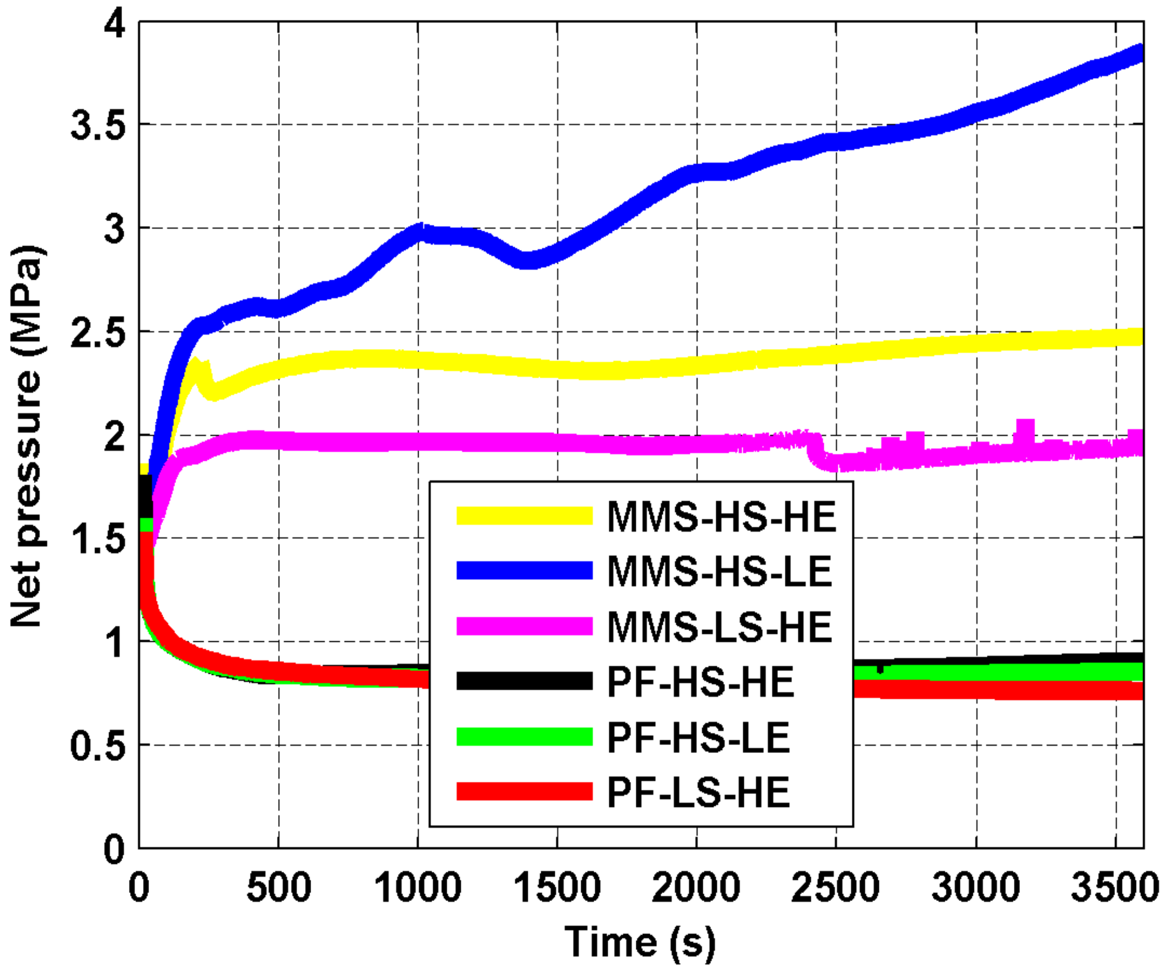


What affects stimulation mechanism?





What affects stimulation mechanism?



Mixed-mechanism stimulation

- The branching mixed-mechanism simulations are naturally higher net pressure and shorter overall fracture length – which is more realistic

Fracture properties that relate to fracture conductivity are key

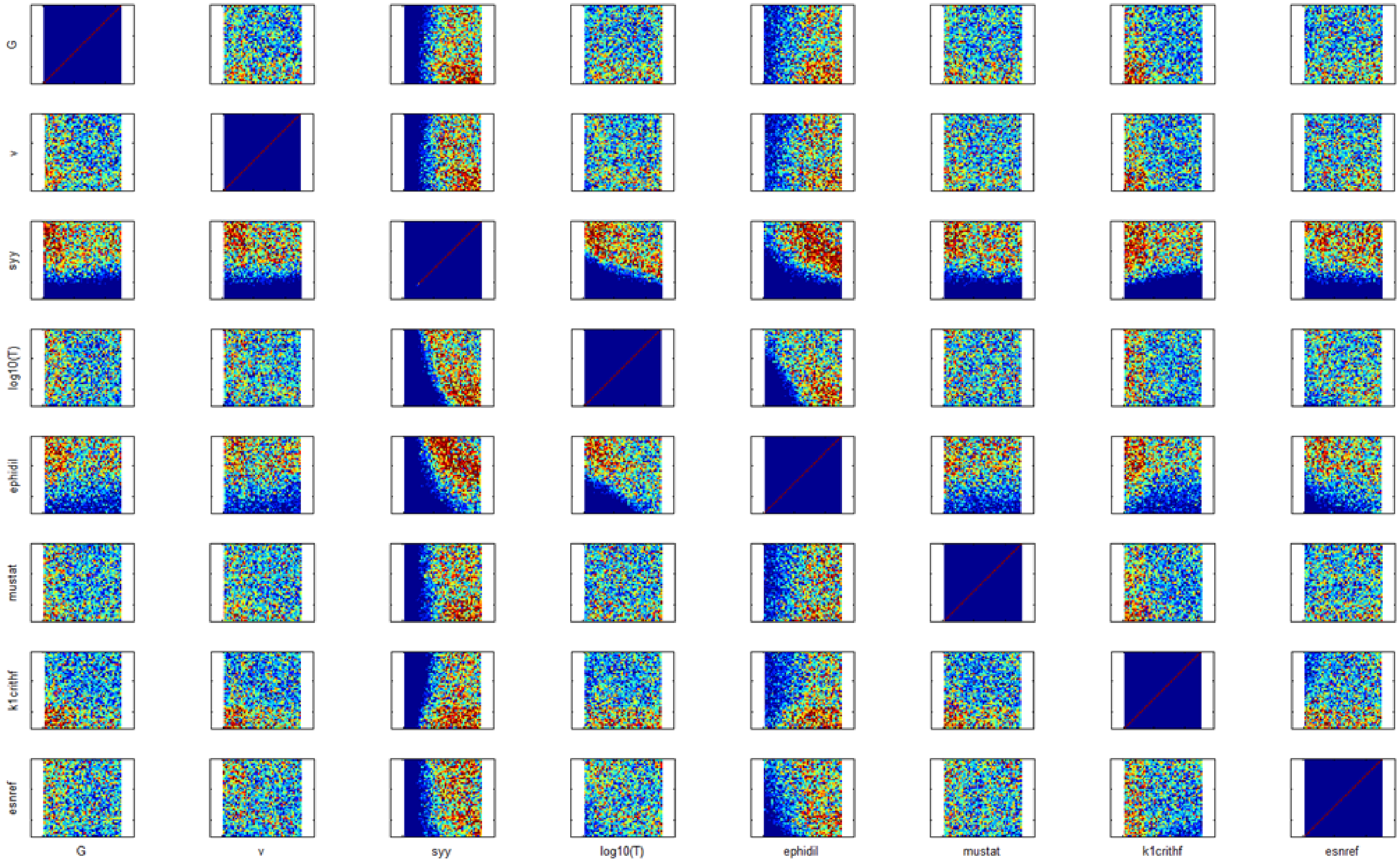
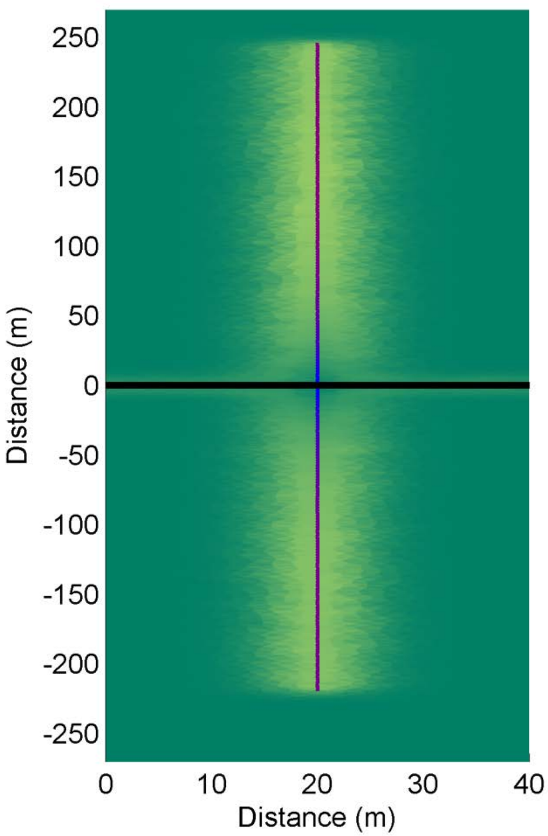


Image courtesy of Mingyuan Yang

Differences in fluid recovery?

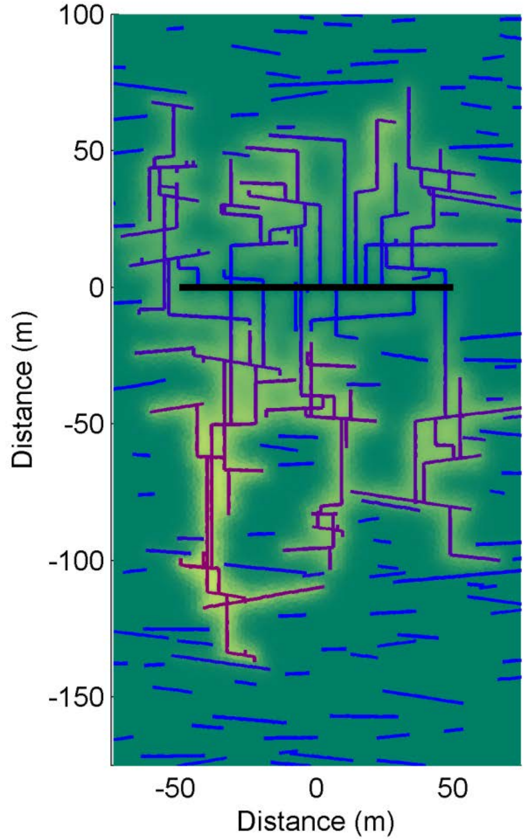
From McClure (2014)

Single, continuous fracture



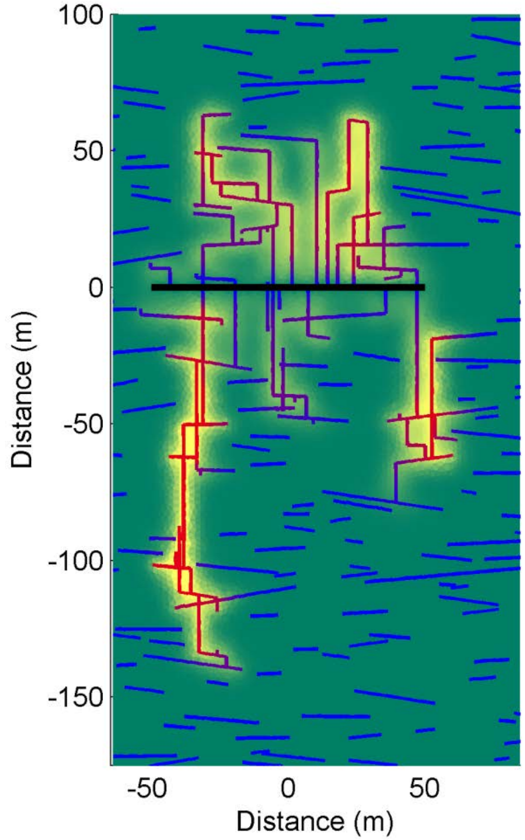
75% fluid recovery

Network with termination
Intermediate fracture conductivity



41% fluid recovery

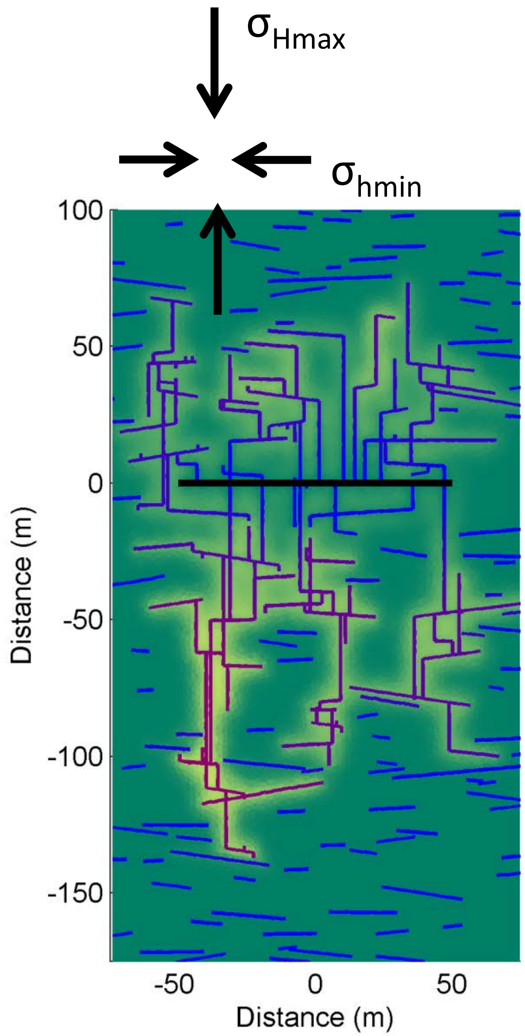
Network with termination
Low fracture conductivity



30% fluid recovery

Differences in fluid recovery?

From McClure (2014)



Branching creates bottlenecks because flow must go through fractures that are not oriented perpendicular to the minimum principal stress.

They close at a higher pressure and bear greater normal stress after closure.

Branching may be vertical (bedding planes) or horizontal (natural fractures).

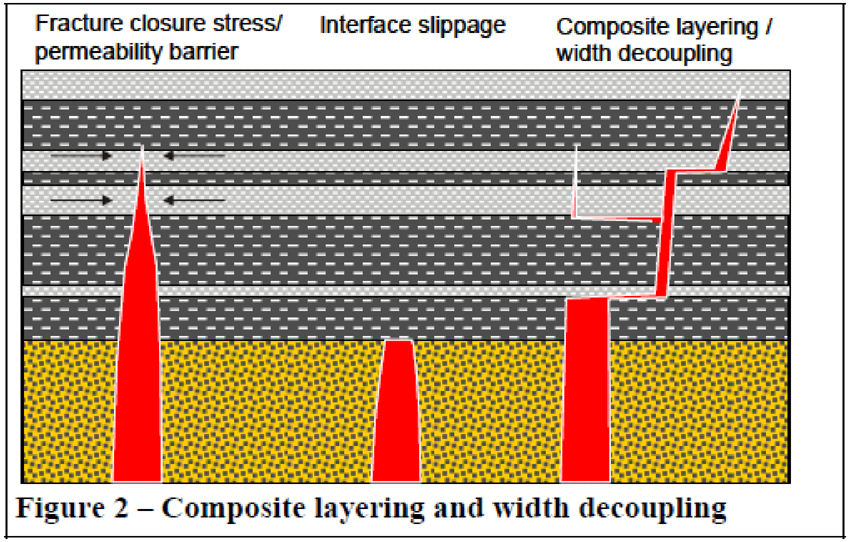


Figure 2 – Composite layering and width decoupling

From Cipolla et al. (2008)

Practical applications

- In settings with high unpropped fracture conductivity, frac jobs can be designed with greater fluid volume, less proppant, further spacing
- With low unpropped fracture conductivity, proppant placement is key, wells should have lower volume, more proppant, and closer spacing of both stages and wells. Higher viscosity may be beneficial- simplify the fracture.
- The "microseismic" SRV may not be the depleted SRV

Conclusions

- Fracture "complexity" is often assumed to be good- but let's keep in mind that's not always true
- The processes that create complexity are not well-known
- The unpropped fracture conductivity is a critical parameter, and only hydraulic testing can measure directly
- Formations will tend to create branching networks if there is more tendency to for termination and height containment
- Stress anisotropy plays a complicated role
- Dense, conductive natural fractures obviously help
- Concepts about "stimulation mechanism" and hydraulic fracturing modeling haven't yet reached full potential

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