Critical Geomechanics Concepts for Hydraulic Fracturing and Well Completions in Shales*

Neal Nagel[1]

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Abstract

While the geomechanics of hydraulic fracture stimulation in shale gas and shale oil reservoirs can be complicated, there are (at least!) two critical issues to remember. First, hydraulic fracturing – particularly in naturally fractured formations like shale – is a fully coupled, hydrothermo-mechanical process. In essence, this means that we cannot solve for the mechanical effects of opening a mode 1 hydraulic fracture and/or natural fractures and then separately evaluate for flow effects, like leakoff, without the potential for significant errors. Secondly, and not divorced from the first issue, is that generated microseismicity during hydraulic fracturing is a manifestation of rock failure – itself a coupled hydrothermo-mechanical process.

During this presentation, the focus will be on a discussion of the critical geomechanical concepts and 'accepted' knowledge about hydraulic fracturing in shales as related to:

- natural fracture behavior,
- stress shadows and the geomechanical effects from multi-stage horizontal well stimulations,
- stress shadow effects from multi-well completions,
- relationship between geomechanics and microseismicity in shale stimulations.

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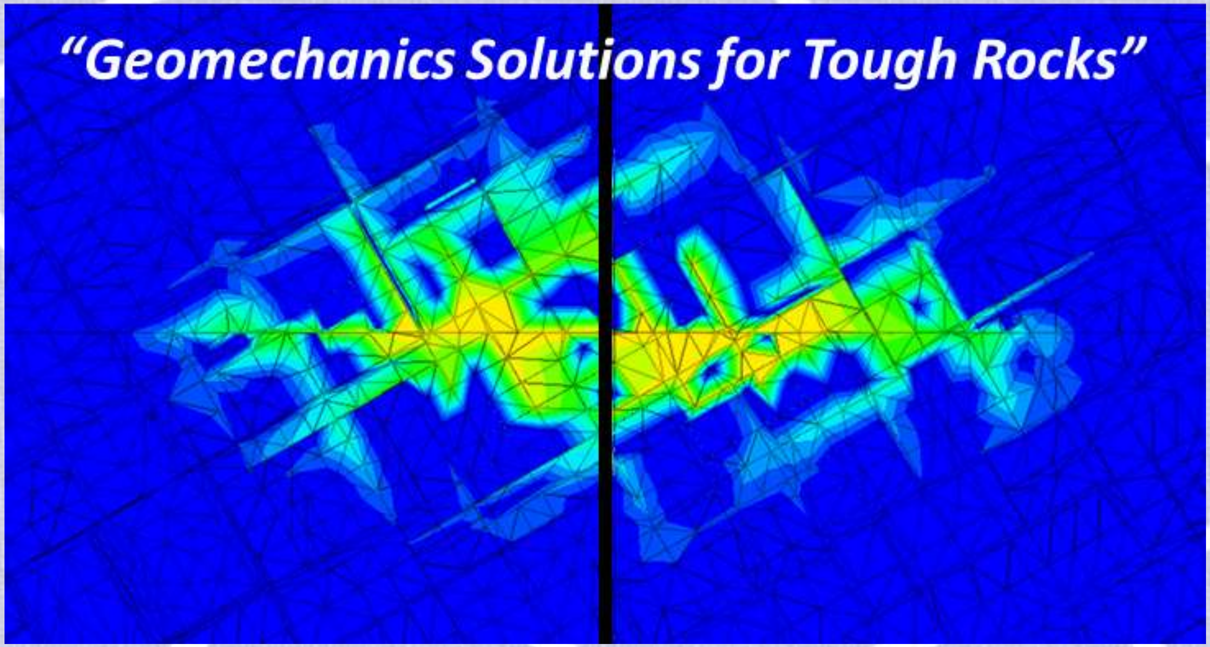

Critical Geomechanics Concepts for Hydraulic Fracturing and Well Completions in Shales

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Itasca Houston

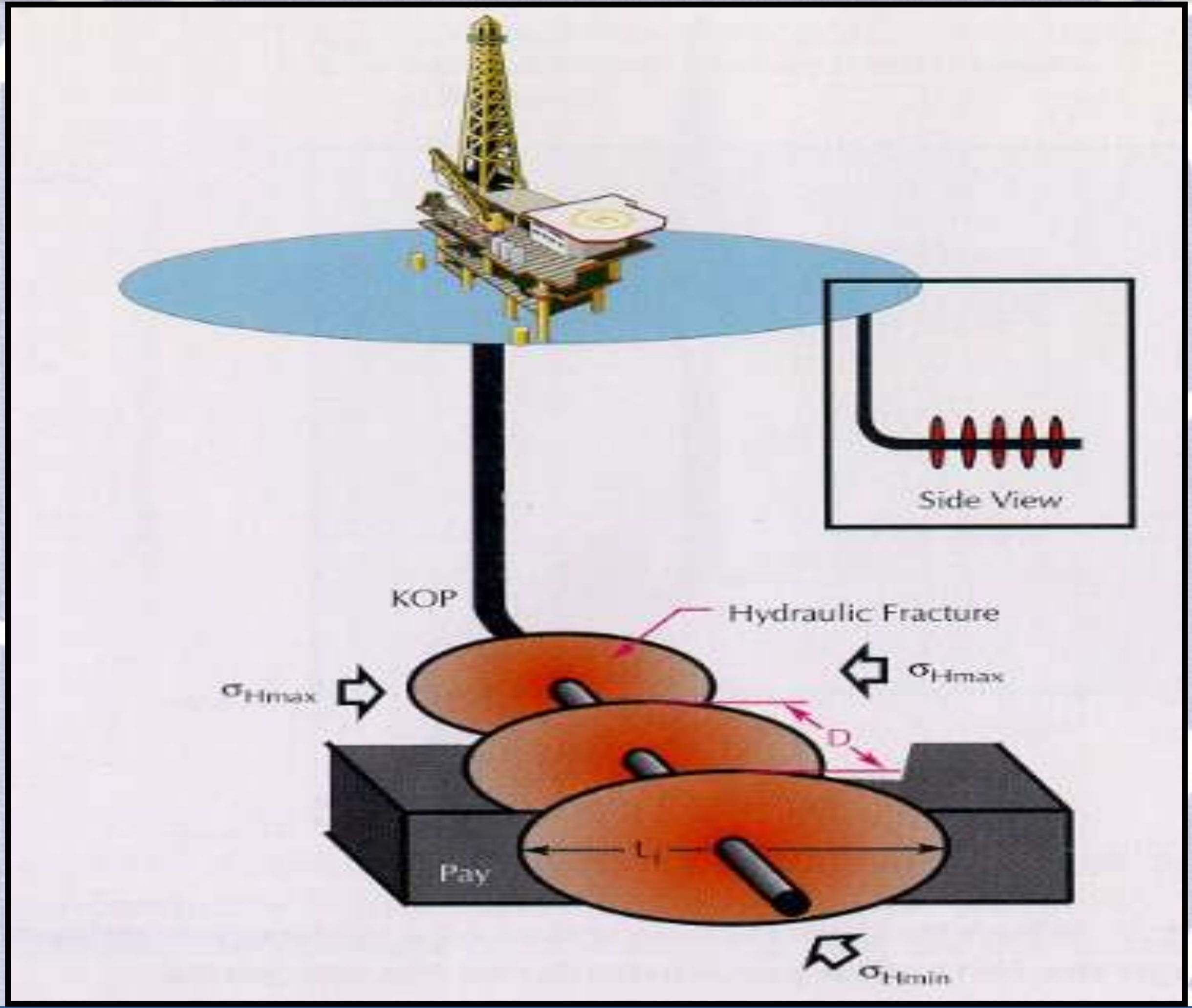
ITASCA™ Houston, Inc.

Hydraulic Fracturing (HF) Basics

$$V_{in} = V_{frac} + V$$

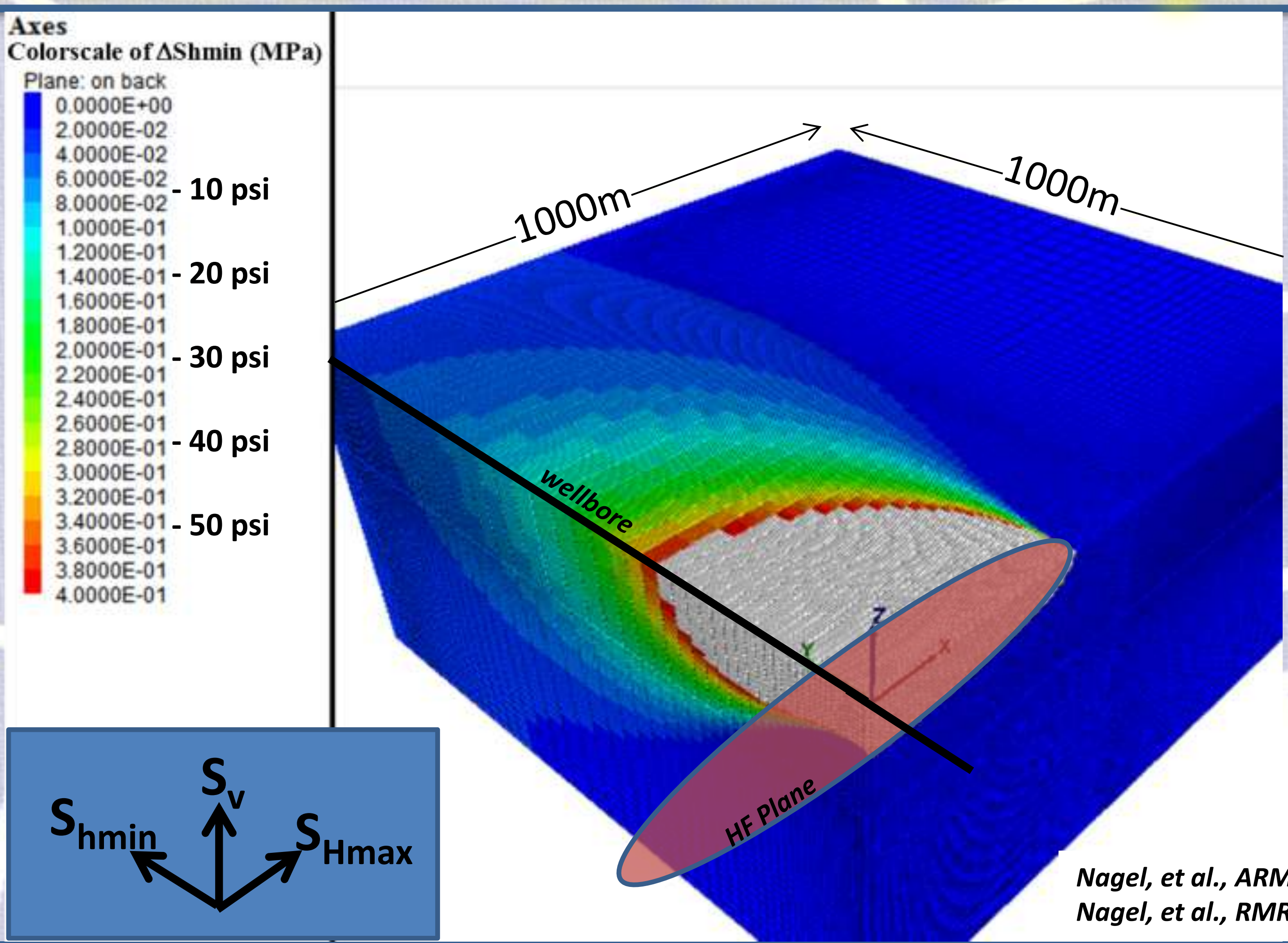
The Goal: Create A Conductive Pathway From The Pore Space To The Wellbore

Multi-Fracture Completions



If one HF is good…then multiple HFs must be even better. Right?!?

Geomechanical Effect of Hydraulic Fractures - In-situ Stress Changes



Nagel, et al., ARMA 12-287
Nagel, et al., RMRE V46N3

What is Microseismicity??

Microseismicity is the <u>acoustic</u> representation of the <u>energy</u> release from rock <u>failure</u>

Generating Mechanism (Transduction)	→	Acoustic Wave Propagation	→	Reception (Transduction)
Geomechanics		*Velocity Model* *Ray Paths*		*Geophones* *Array Setup* *Signal/Noise*

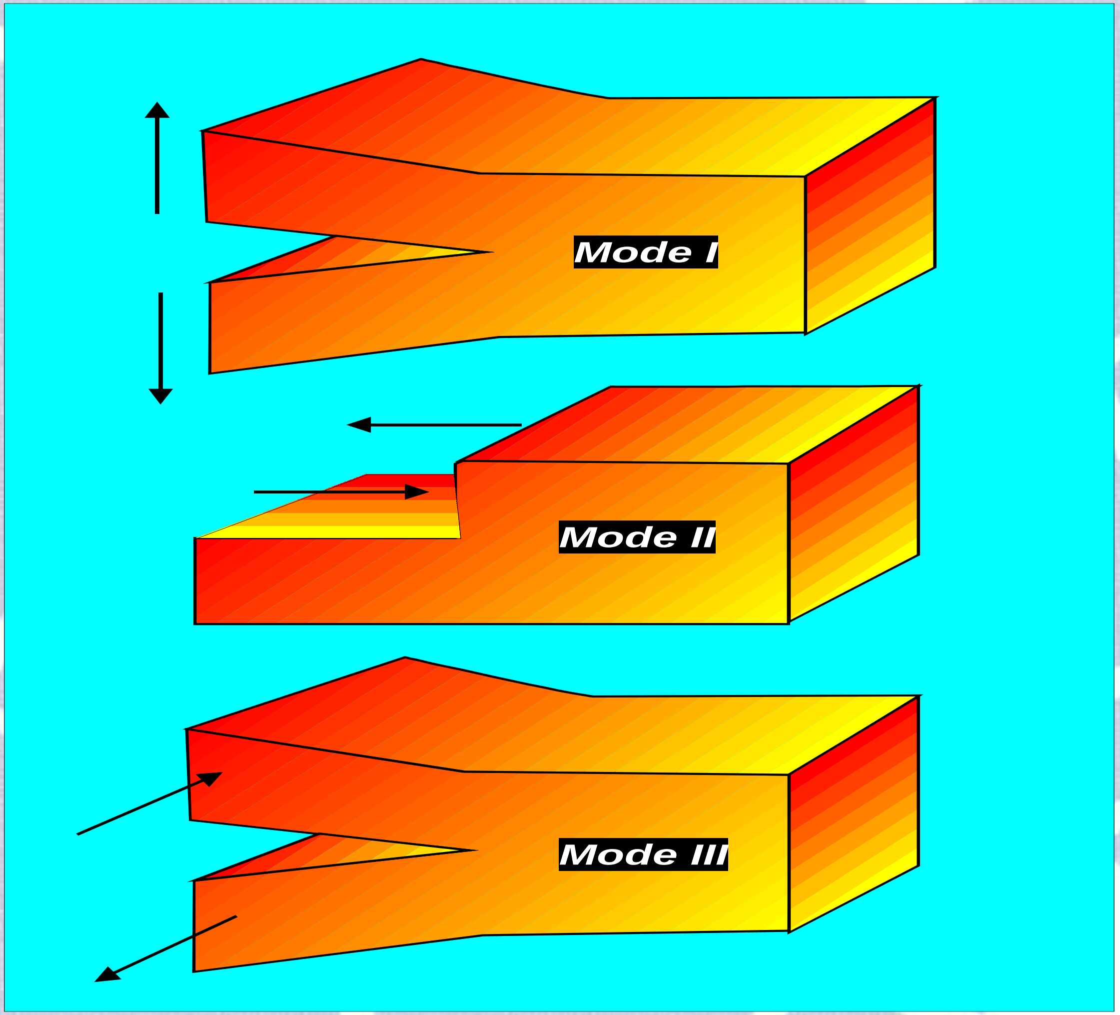
Fault/Fracture Slip Failure

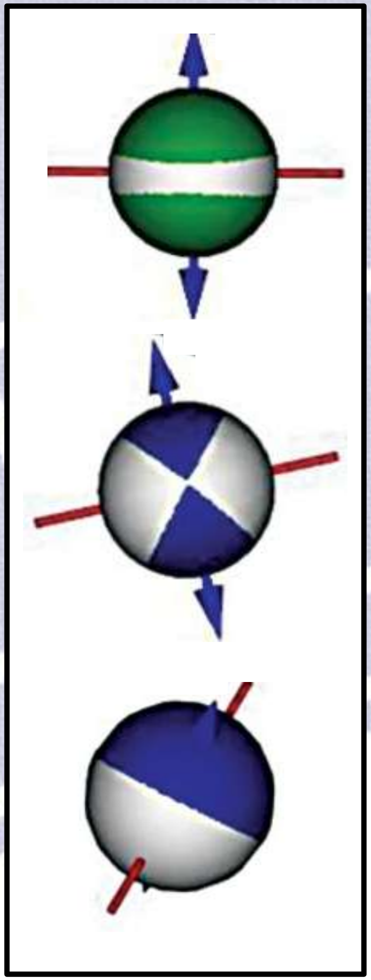
ENERGY

Low

High

High



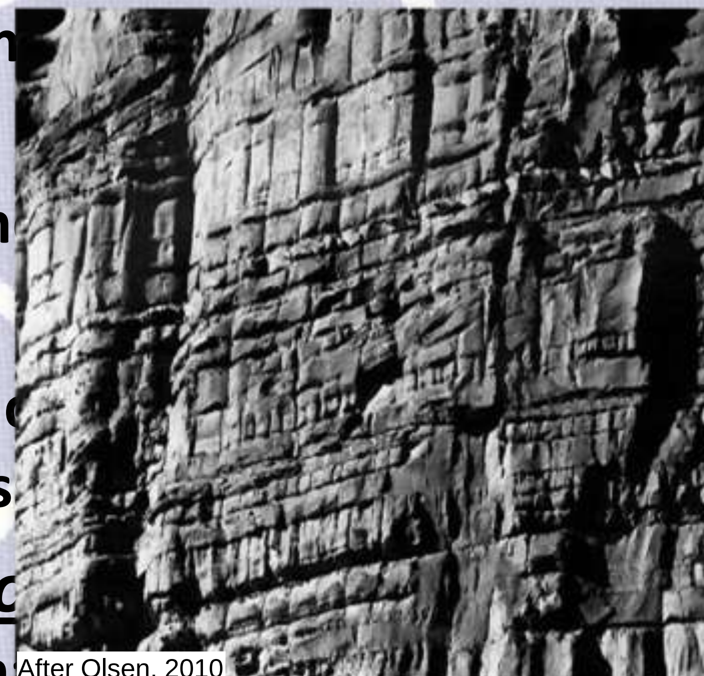


Understanding Natural Fractures

1. ***Variable Size*** **- Natural fractures can range from isolated microscopic fissures to kilometer-wide collections (fracture corridors).**
2. ***Complex Flow Paths*** **- These fractures create complex paths for fluid movement.**
3. ***Deformability*** **- These fractures deform (may close, open, shear) as pressure and stresses change.**
4. ***Variable Mechanical Properties*** **- These fractures have highly heterogeneous mechanical behavior (stiffness, cohesion, friction angle, etc.).**

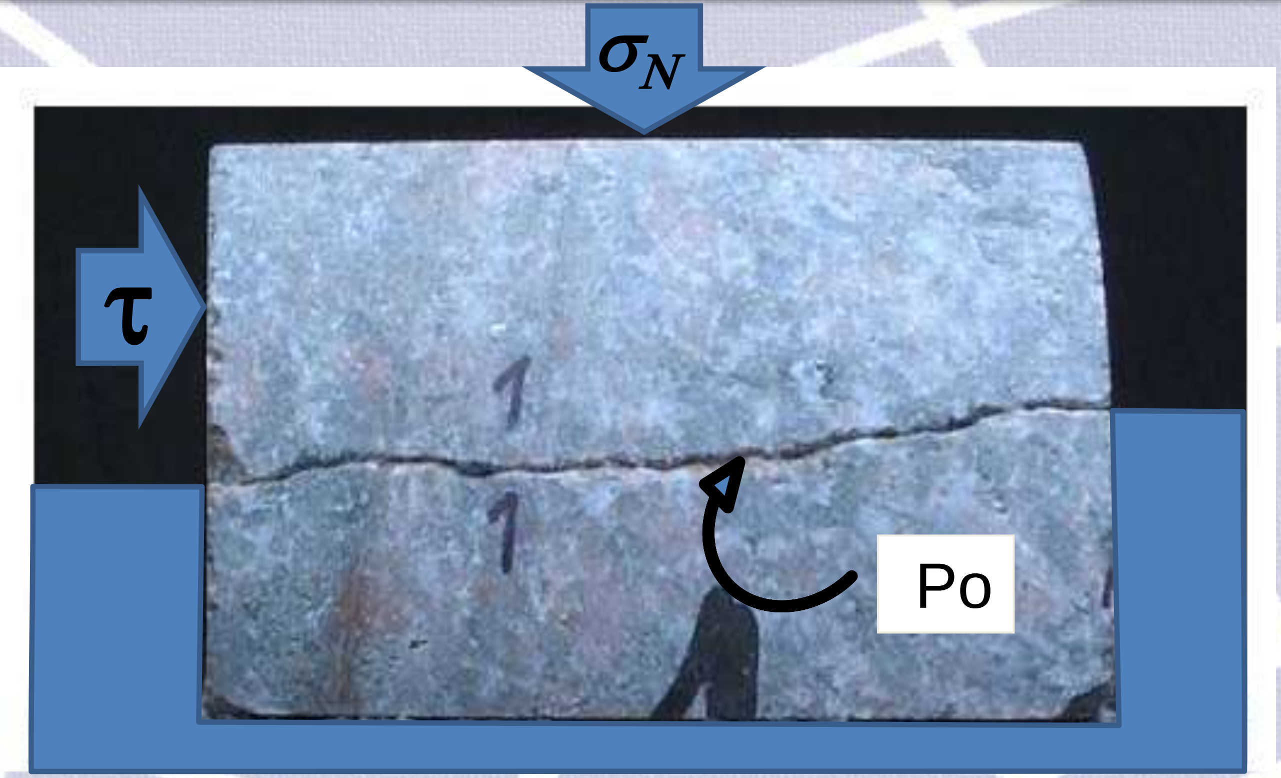
Understanding Natural Fractures

1. ***Variable Size*** **- Natural fractures can range from isolated n… cture c…**
2. ***C…*** **h… ex p…**
3. ***D…*** **a… open, s… es…**
4. ***W…*** ***r…*** **have h… cohesion, friction angle, etc.).**



After Olsen, 2010

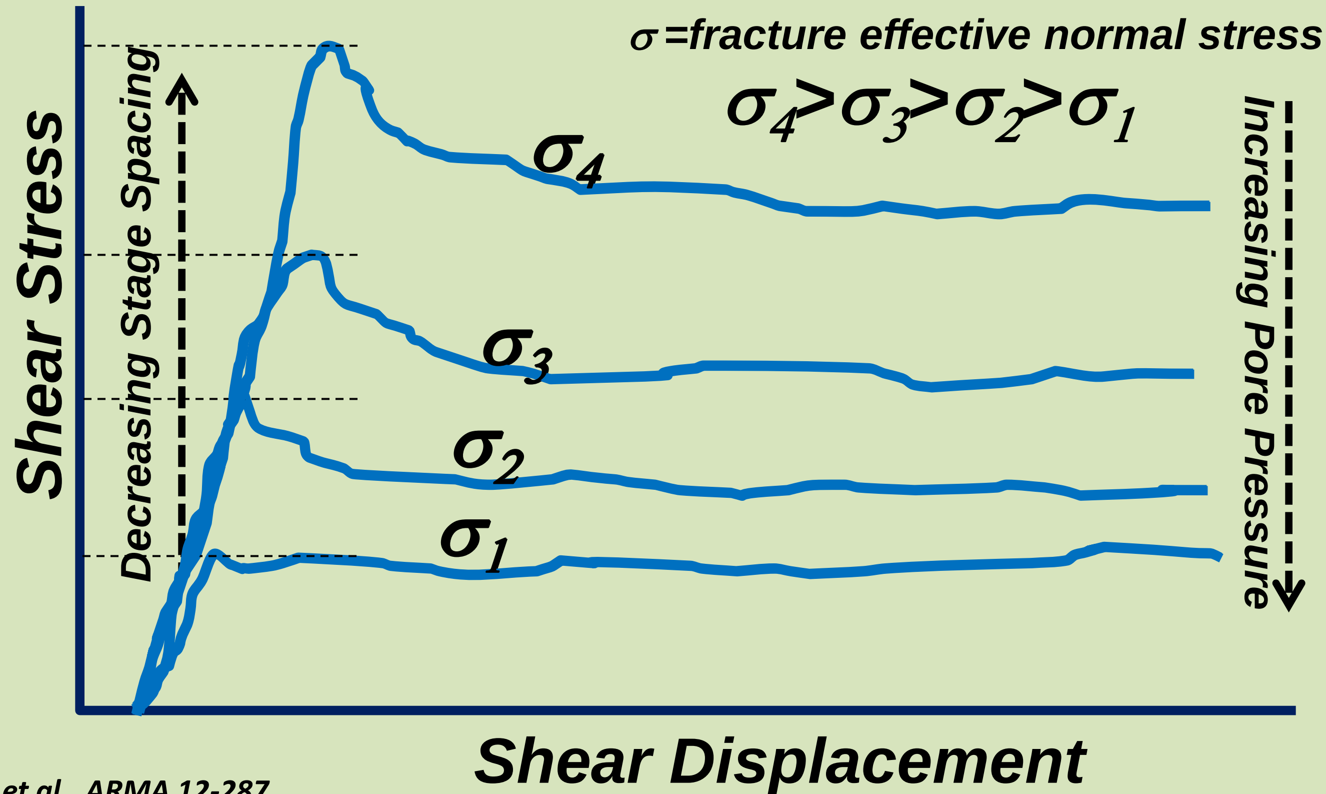
Natural Fracture Mechanical Behavior



Effective stress=σ'
Total stress=σ_N
Pore pressure=Po

$$\sigma' = \sigma_N - P_o$$

Natural Fracture Mechanical Behavior



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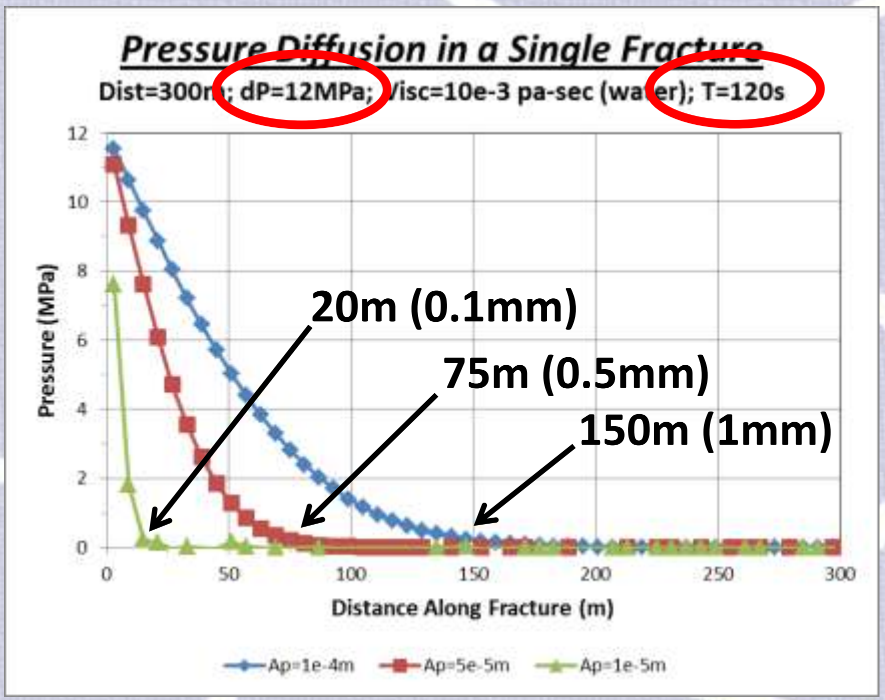
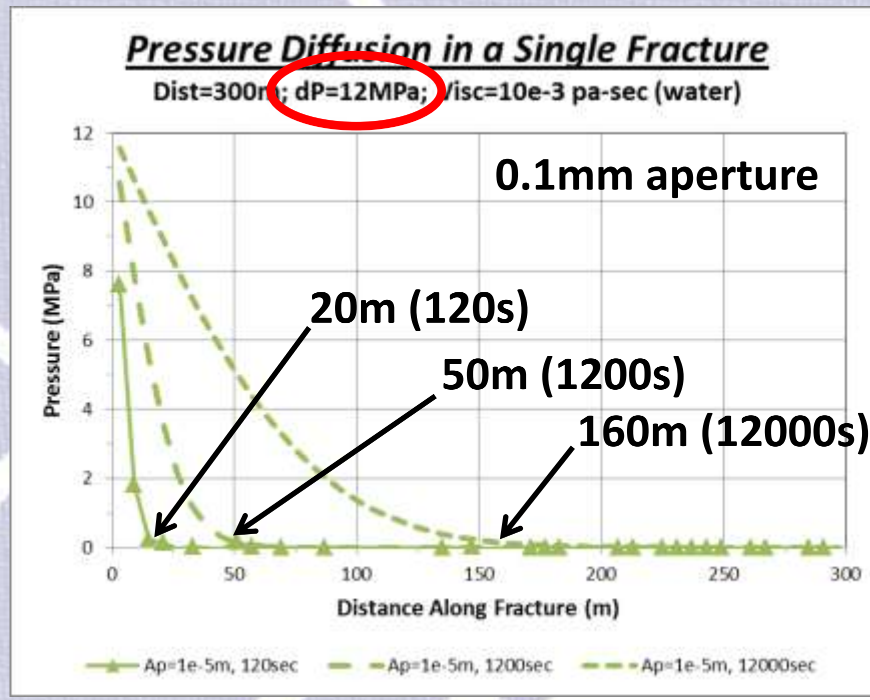
Nagel, et al., RMRE V46N3

Flow and Deformation of Natural Fractures





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Flow and Deformation of Natural Fractures

Relationship between fluid flow and fracture aperture

The cubic law:

$$Q = \frac{\gamma_w}{12\mu} C a^3 \Delta h$$

Aperture cubed

20%⬇ a = 50%⬇ Q

40%⬇ a = 75%⬇ Q

Aperture can be created by:

- Opening (tensile)
- Shear along the natural fracture plane

Completion Engineer For A Day

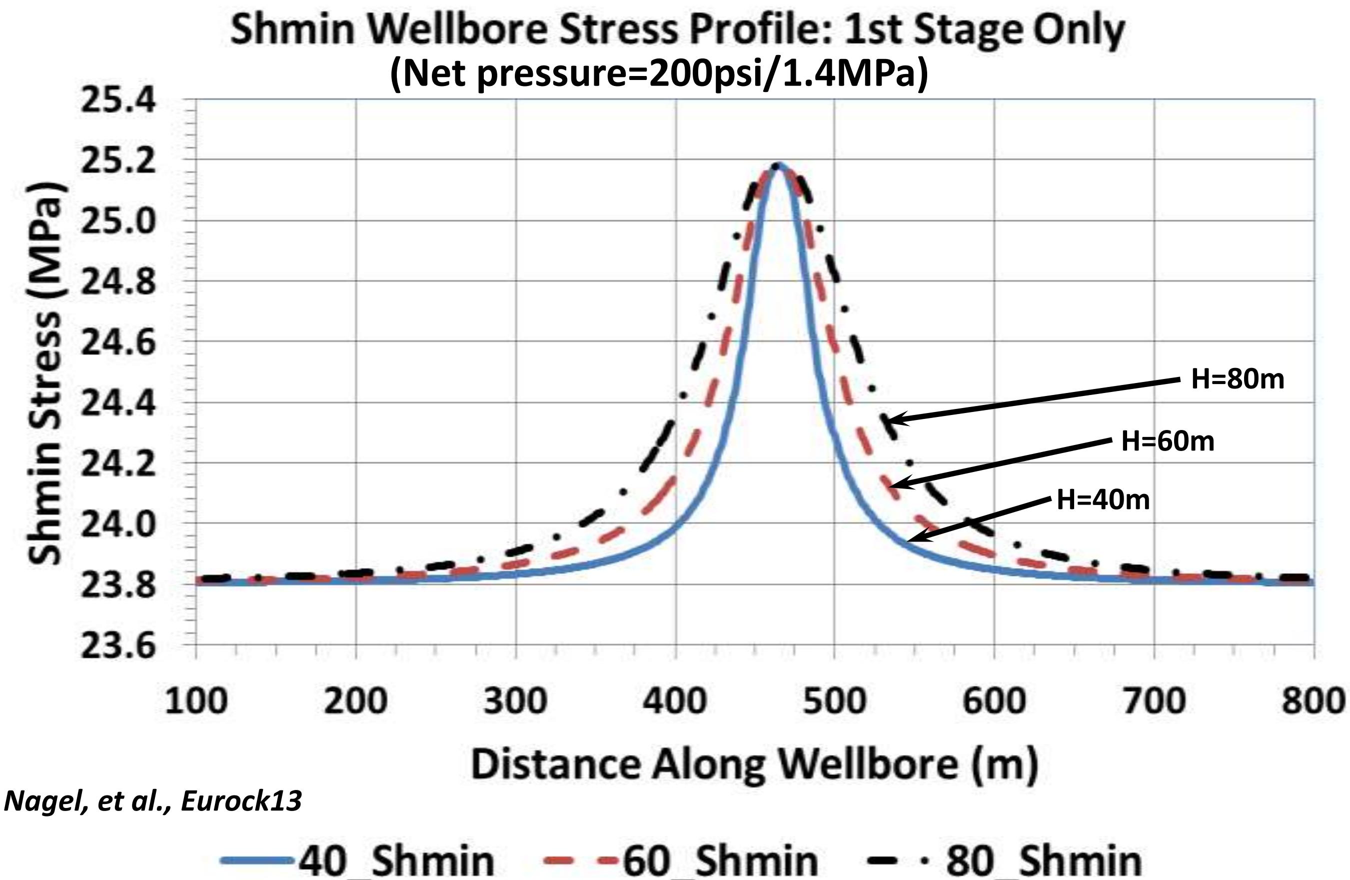
A completion engineer essentially makes four (4) major decisions about his shale well:

- ***Stage spacing (# and distance between fracs)***
- ***Stage volume (fluid and proppant)***
- ***Stage rate***
- ***Fluid viscosity***

Landing location and well spacing are also key!!

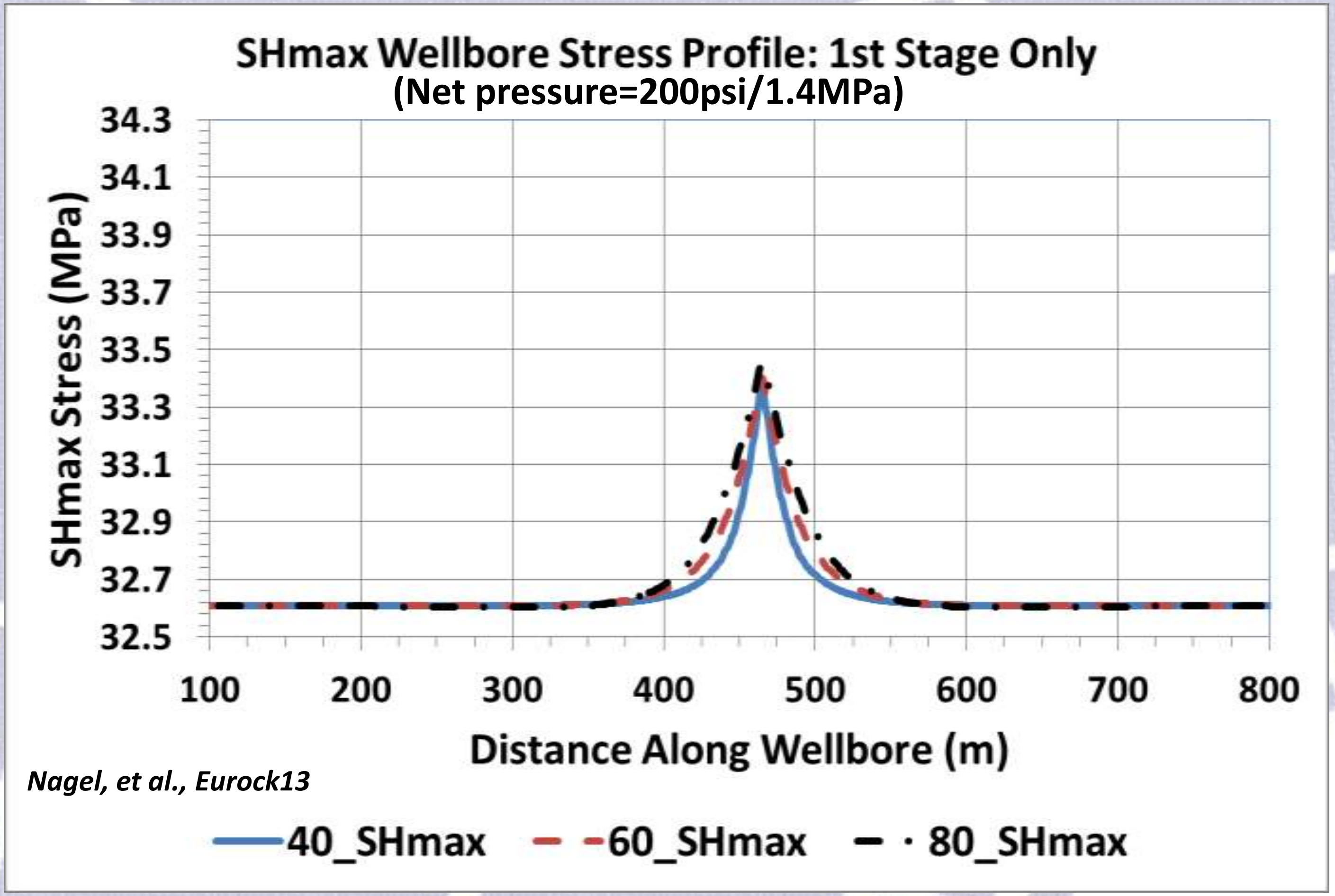
How does MS data help??

Shmin ~f(height) – Single Stage

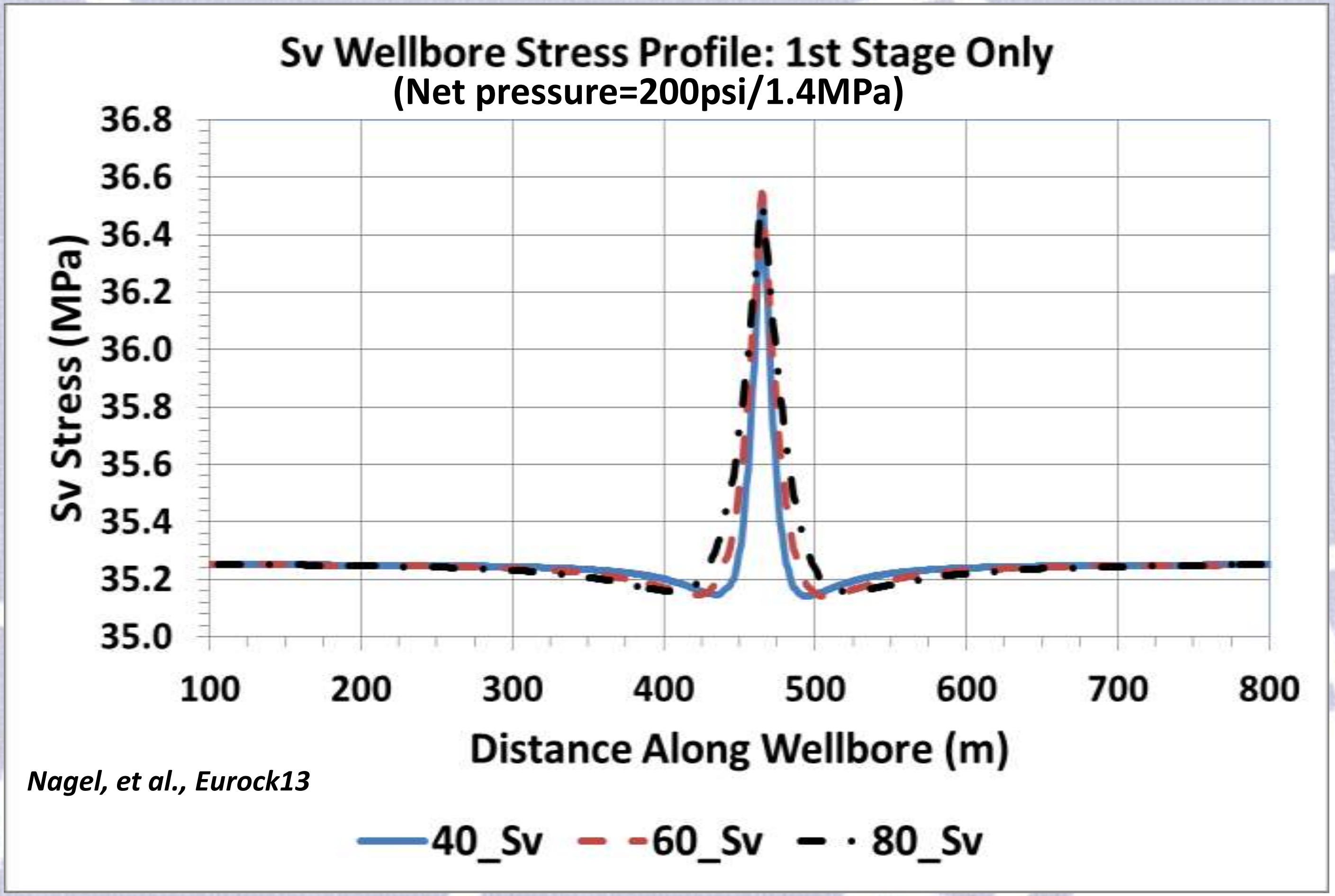


Nagel, et al., Eurock13

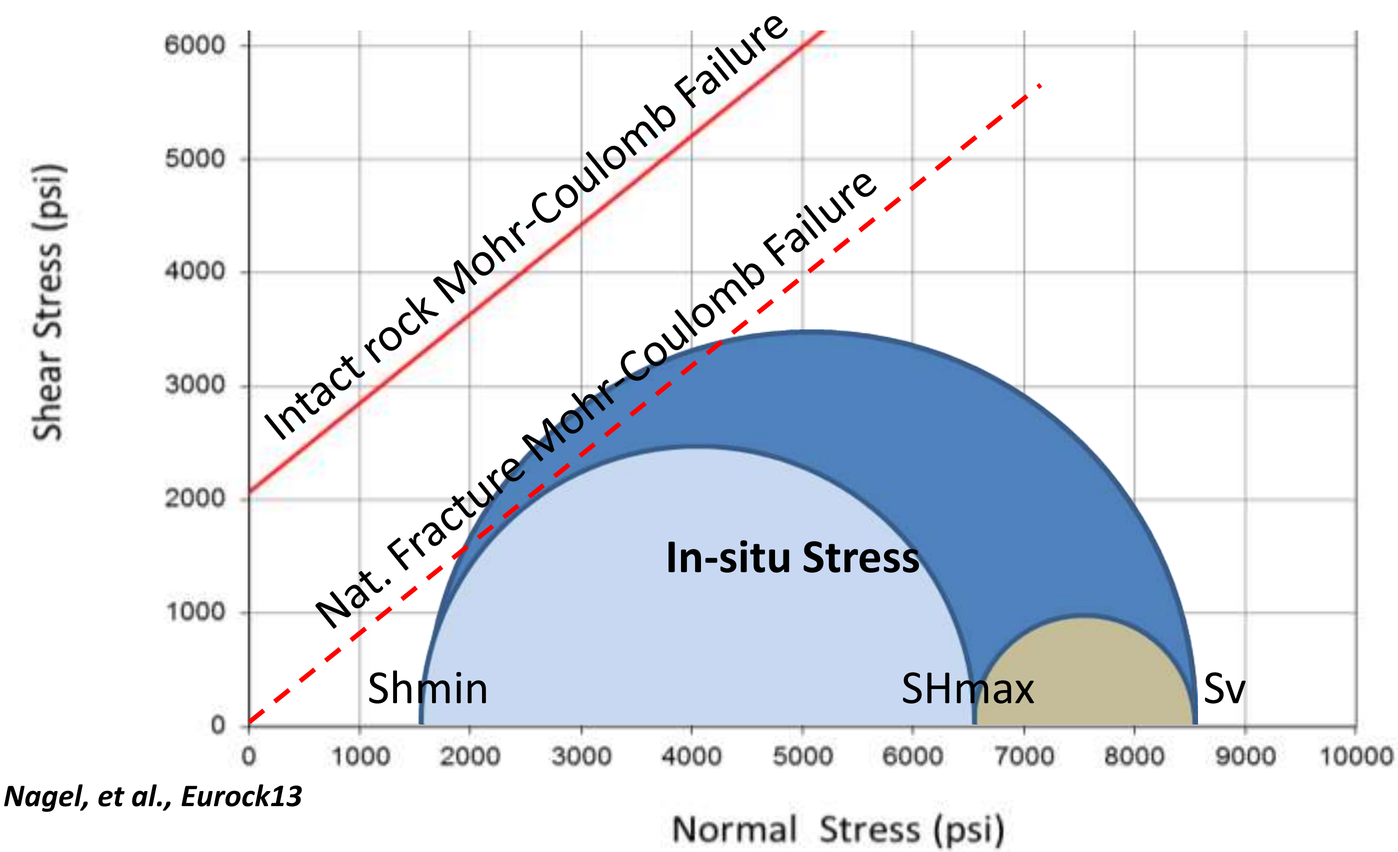
SHmax ~f(height) – Single Stage



Sv ~f(height) – Single Stage



Stress Change Around Hydraulic Fractures



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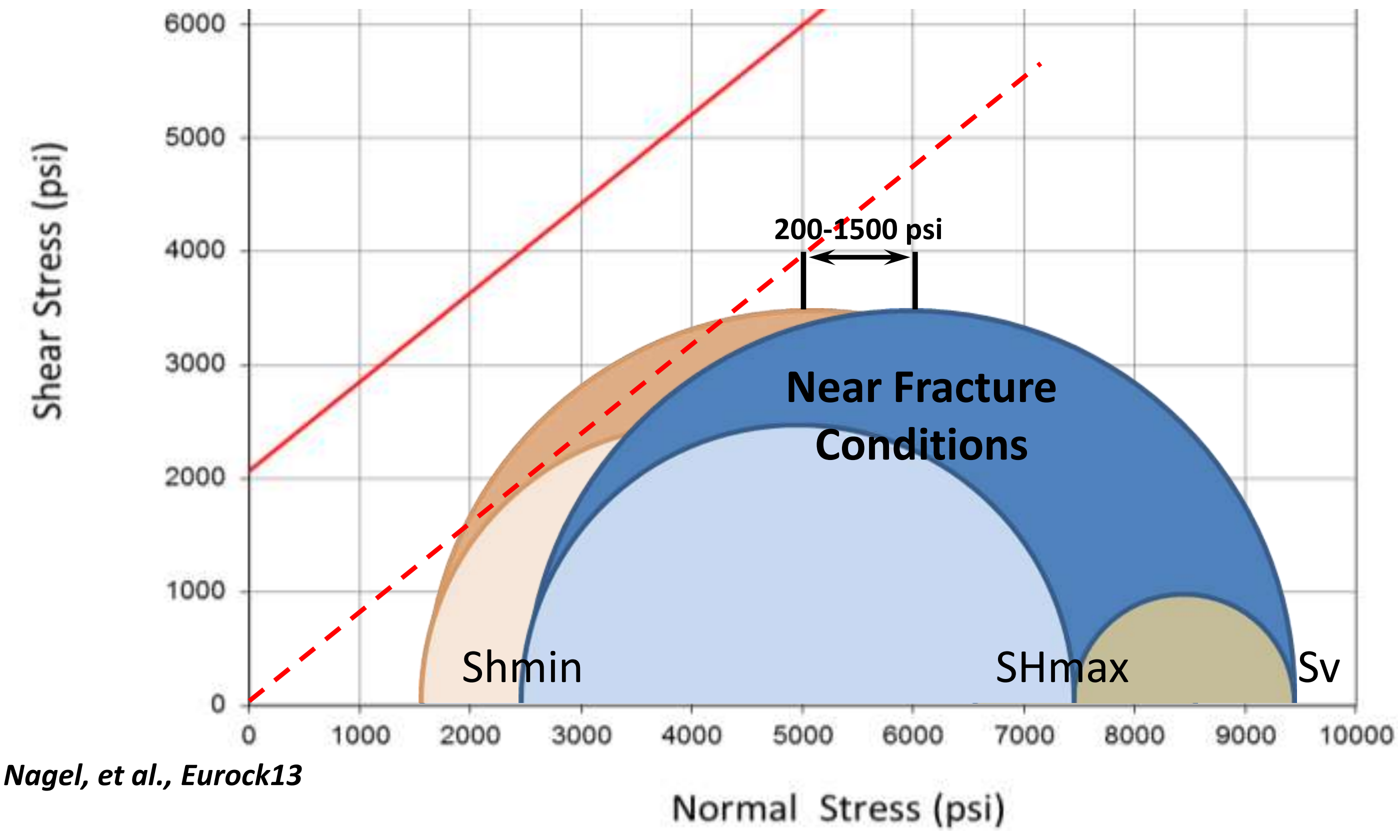

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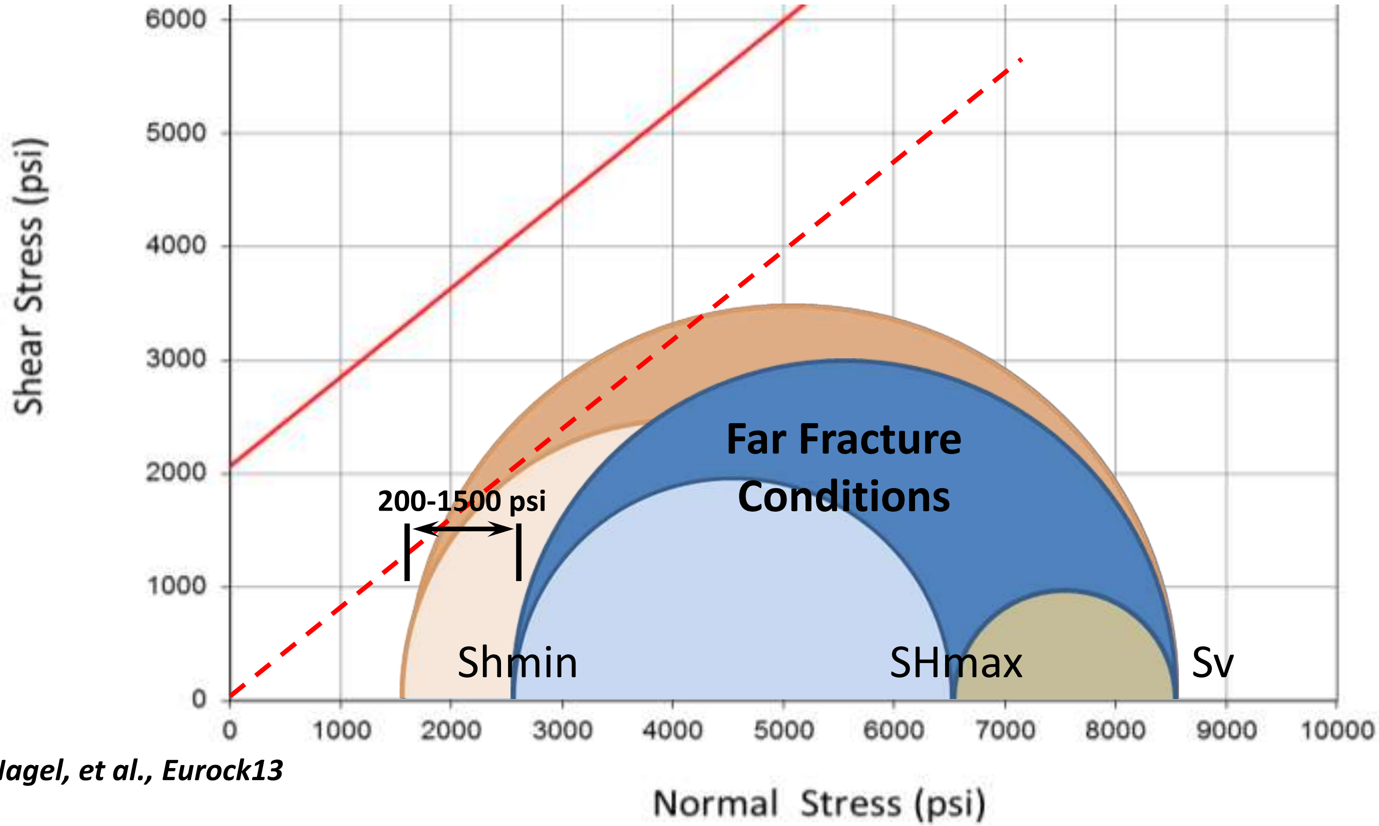
Stress Change Around Hydraulic Fractures



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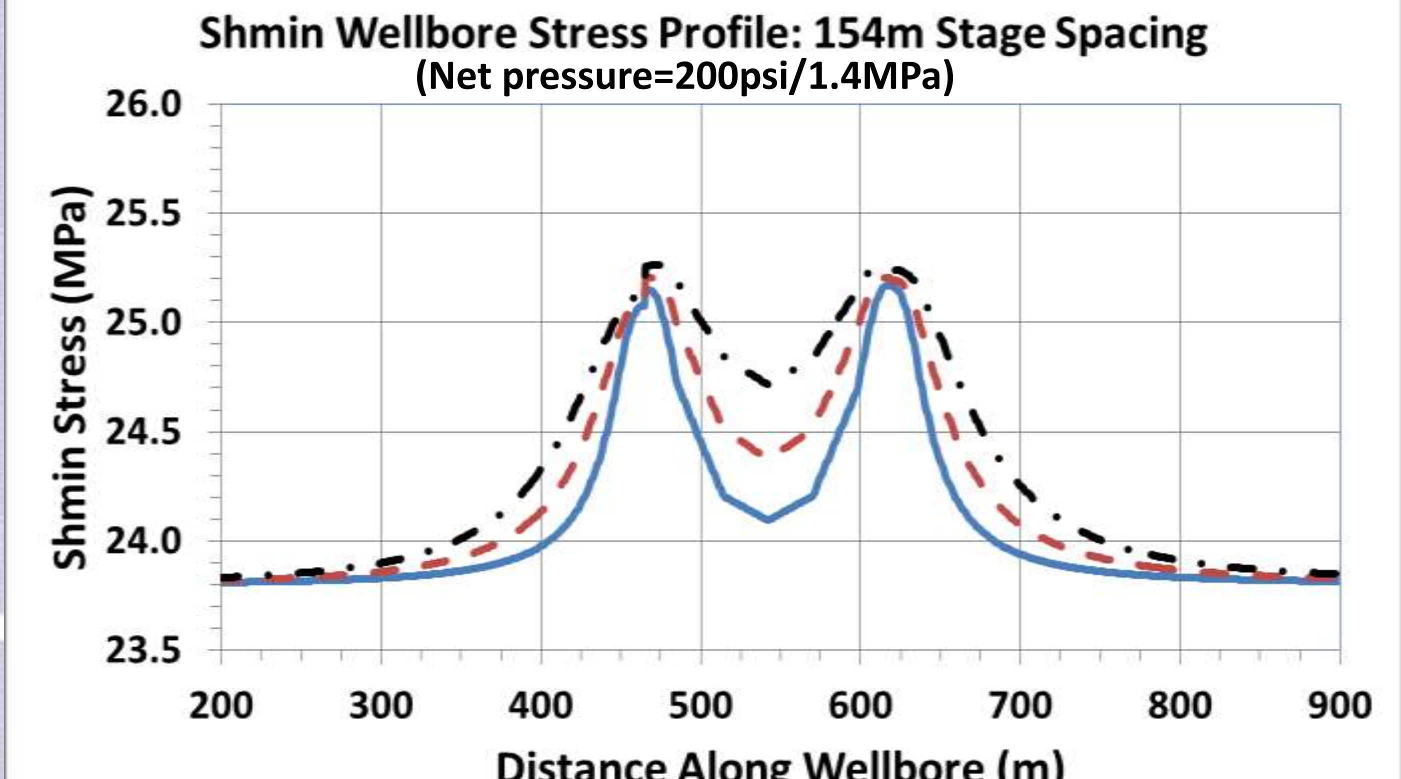
Shmin – Dual Frac, Sp=154m



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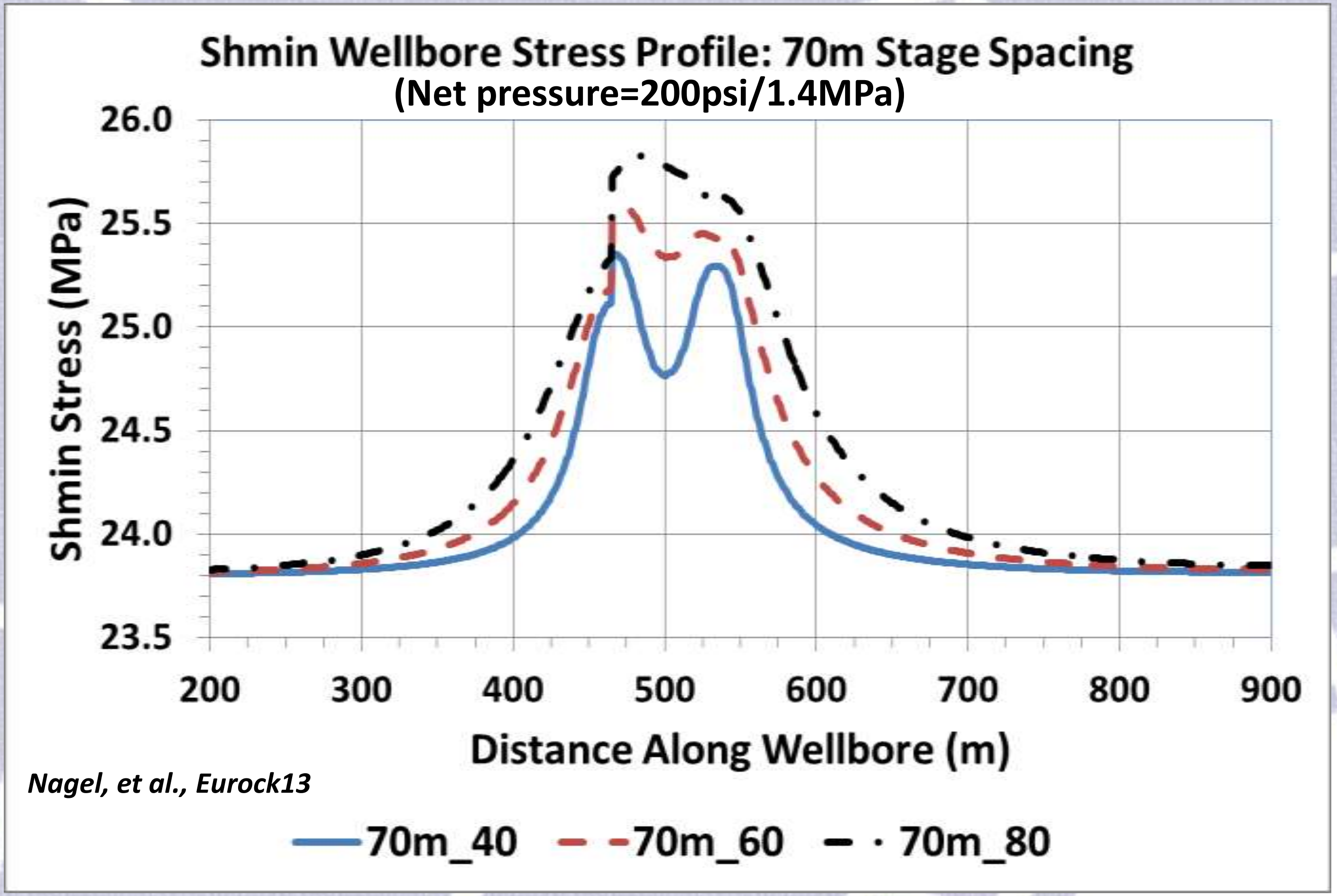
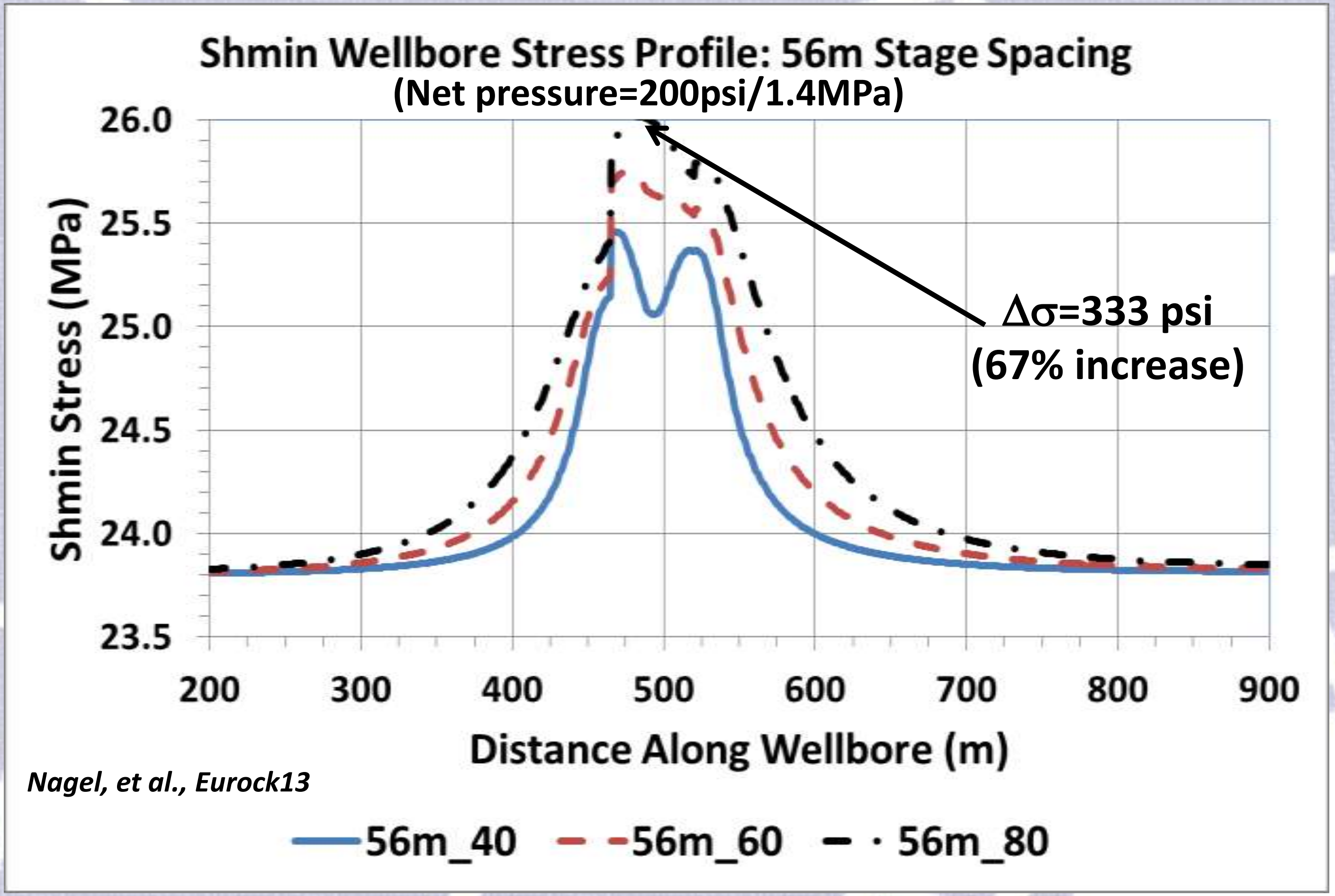
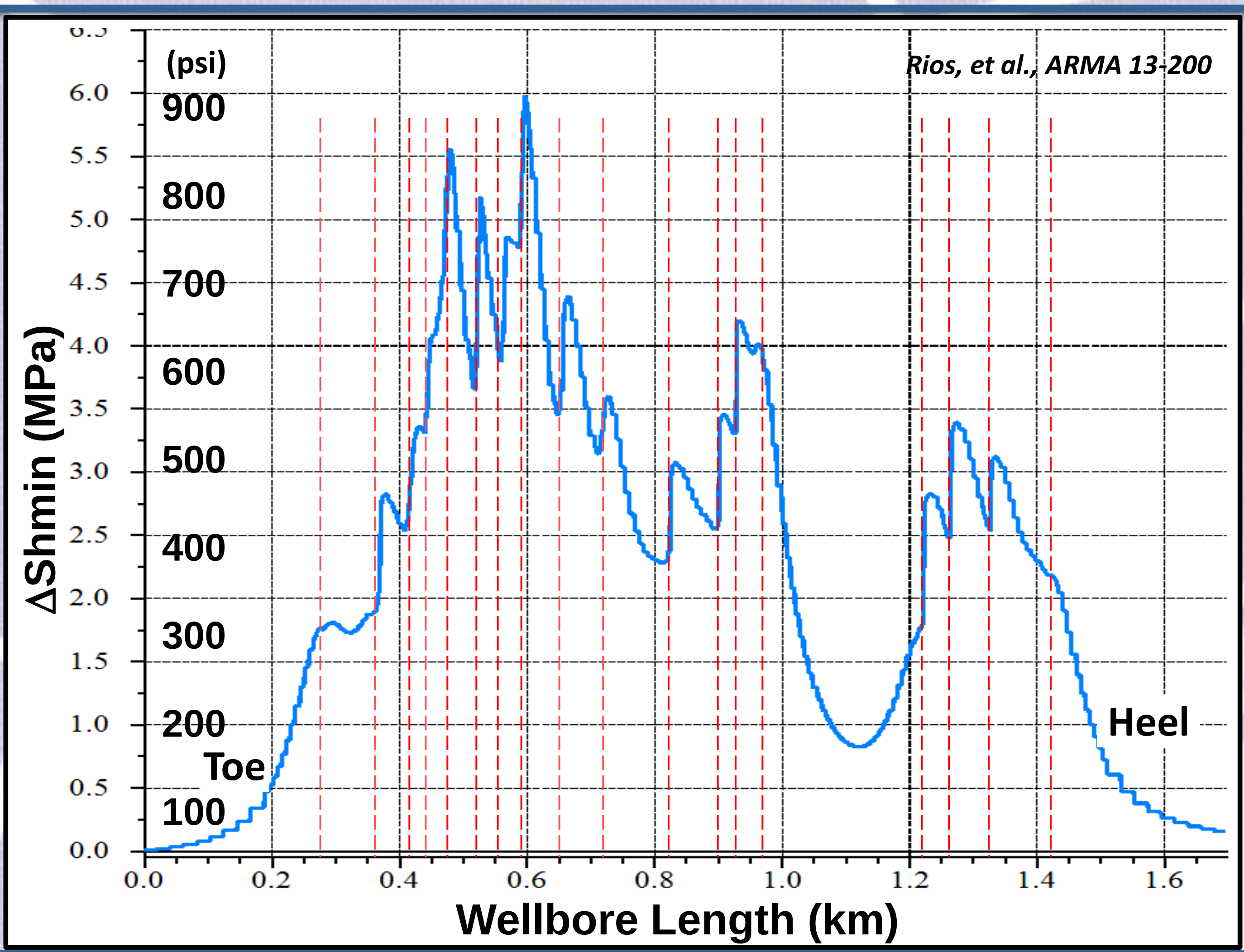
Shmin – Dual Frac, Sp=70m



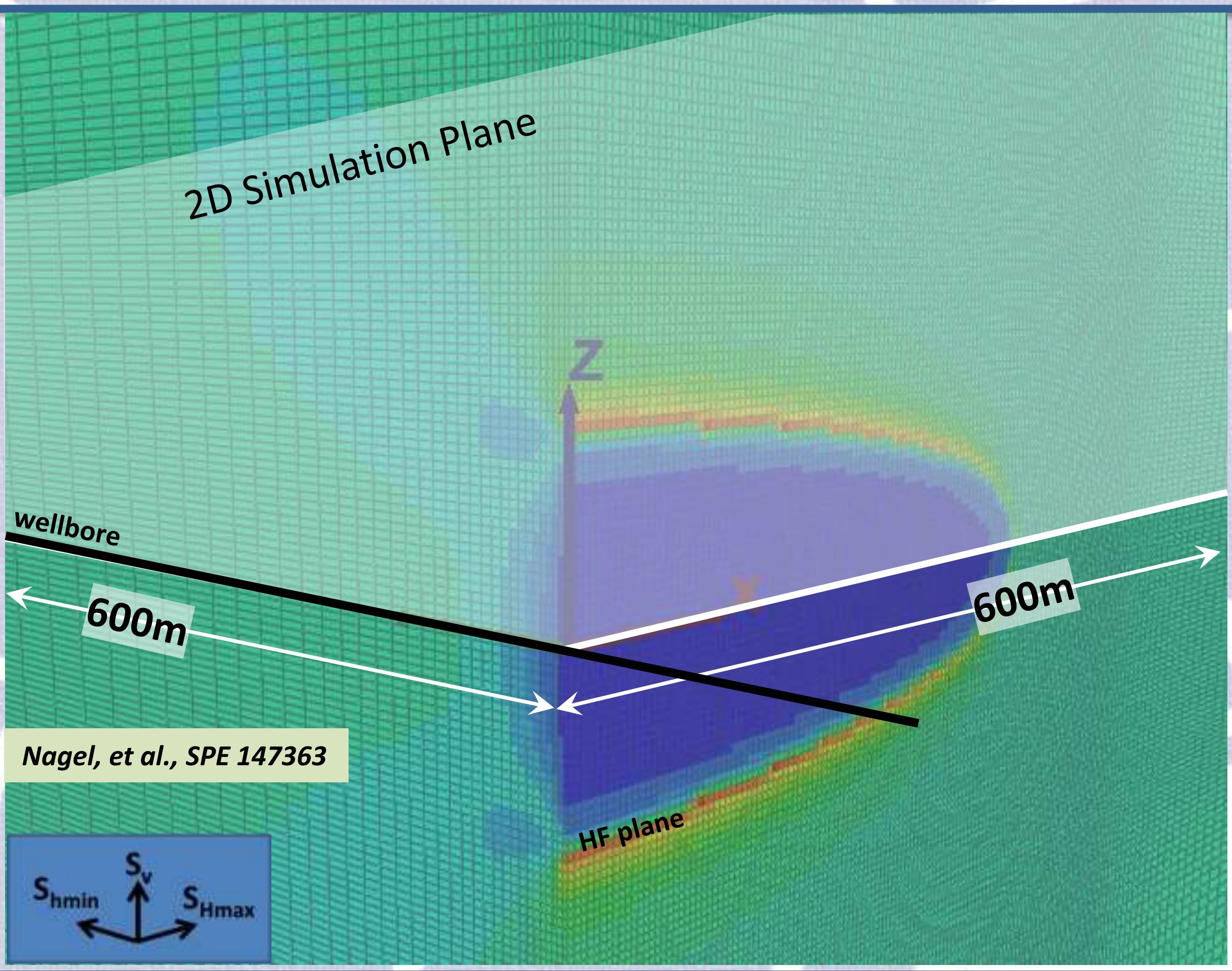
Shmin – Dual Frac, Sp=56m



ΔShmin: 18 Stage Irregular Spacing



2D Hydraulic Fracture Simulations

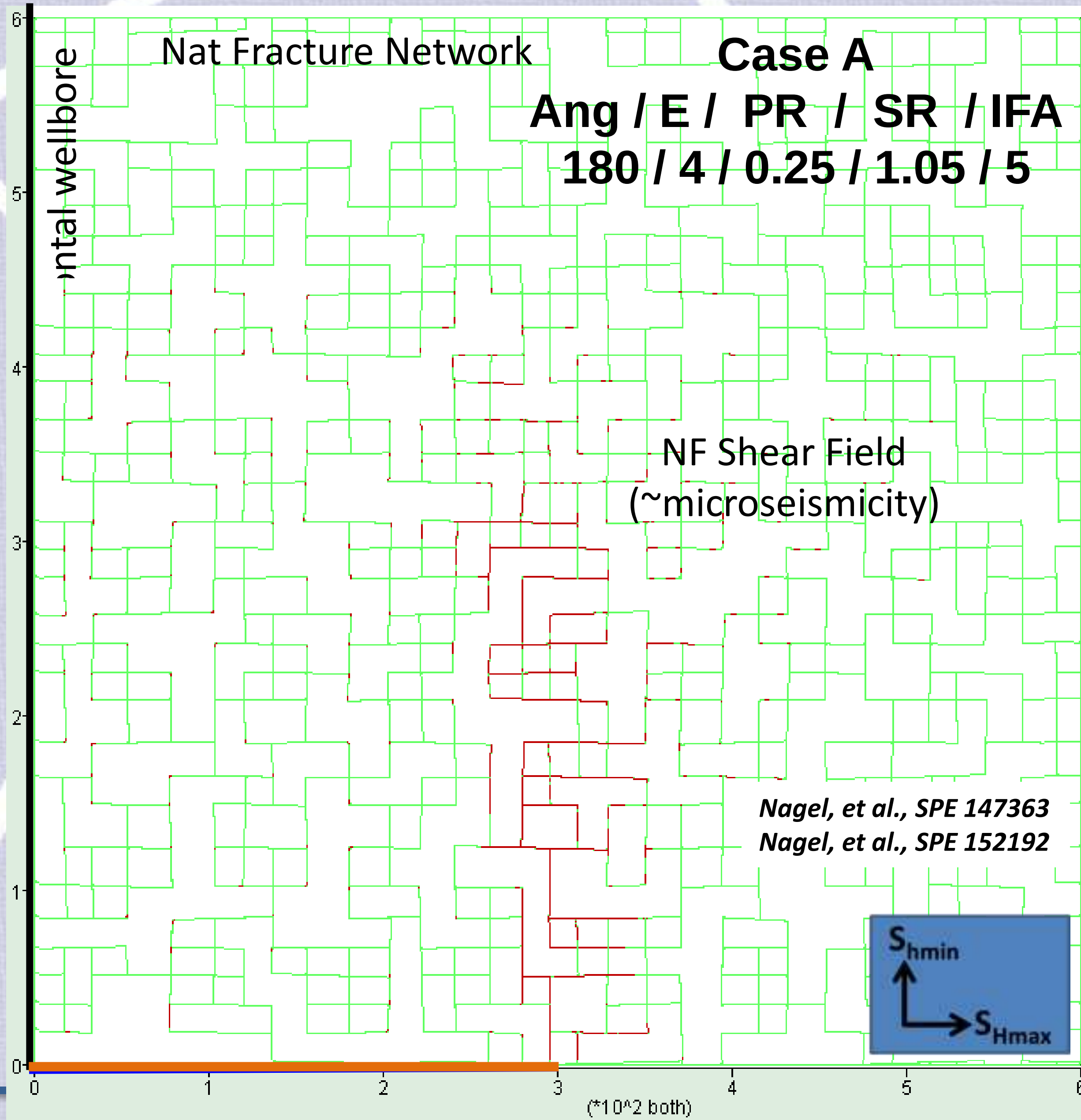


Why DEM?

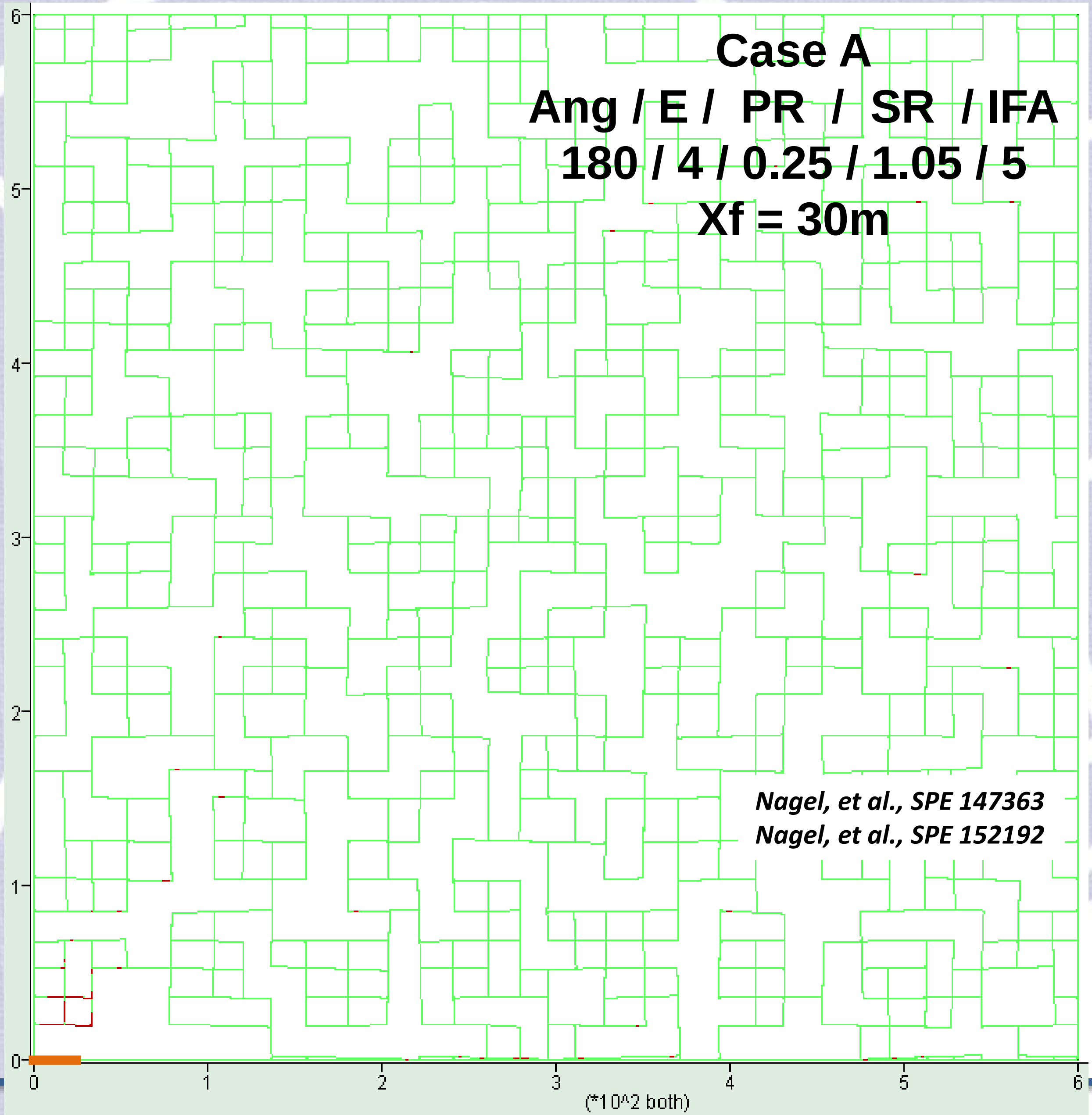
1. DEMs can handle the hydro-mechanical behavior of natural fractures and faults directly including frictional behavior, opening behavior/closing behavior and contacts. No [illegible] simplifications, correlations, or 'rules' f[illegible]
2. DEMs can handle the h[illegible] of the matrix roc[illegible] continuum mechanics w[illegible]
3. DE[illegible] llow for: 1) finite displacements; 2) body rotations; and 3) complete detachment.
4. DEMs also track the loss and generation of new contacts automatically.

Synthetic Microseismicity

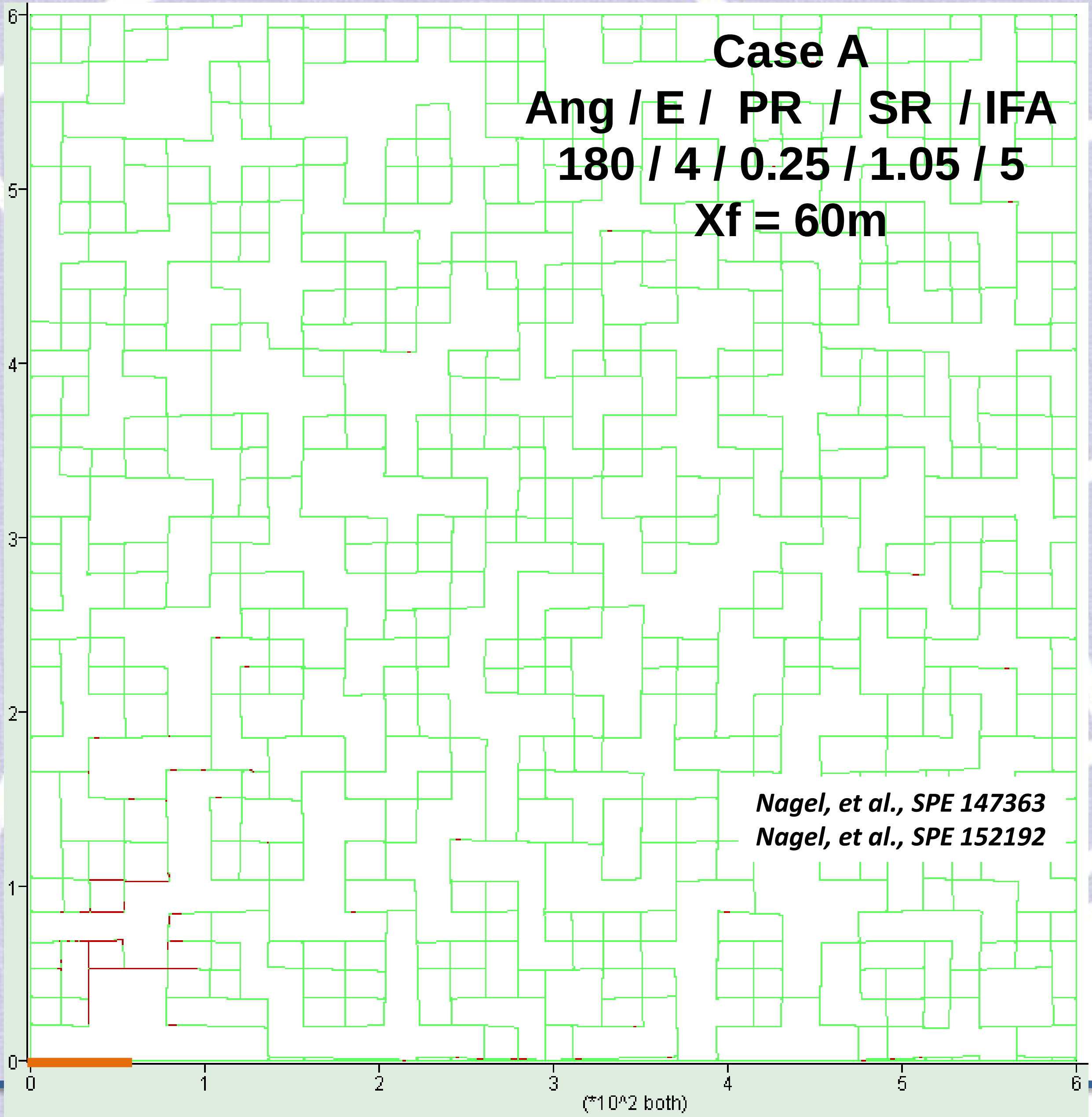
NF Response to Hydraulic Fracture: Mechanical Only



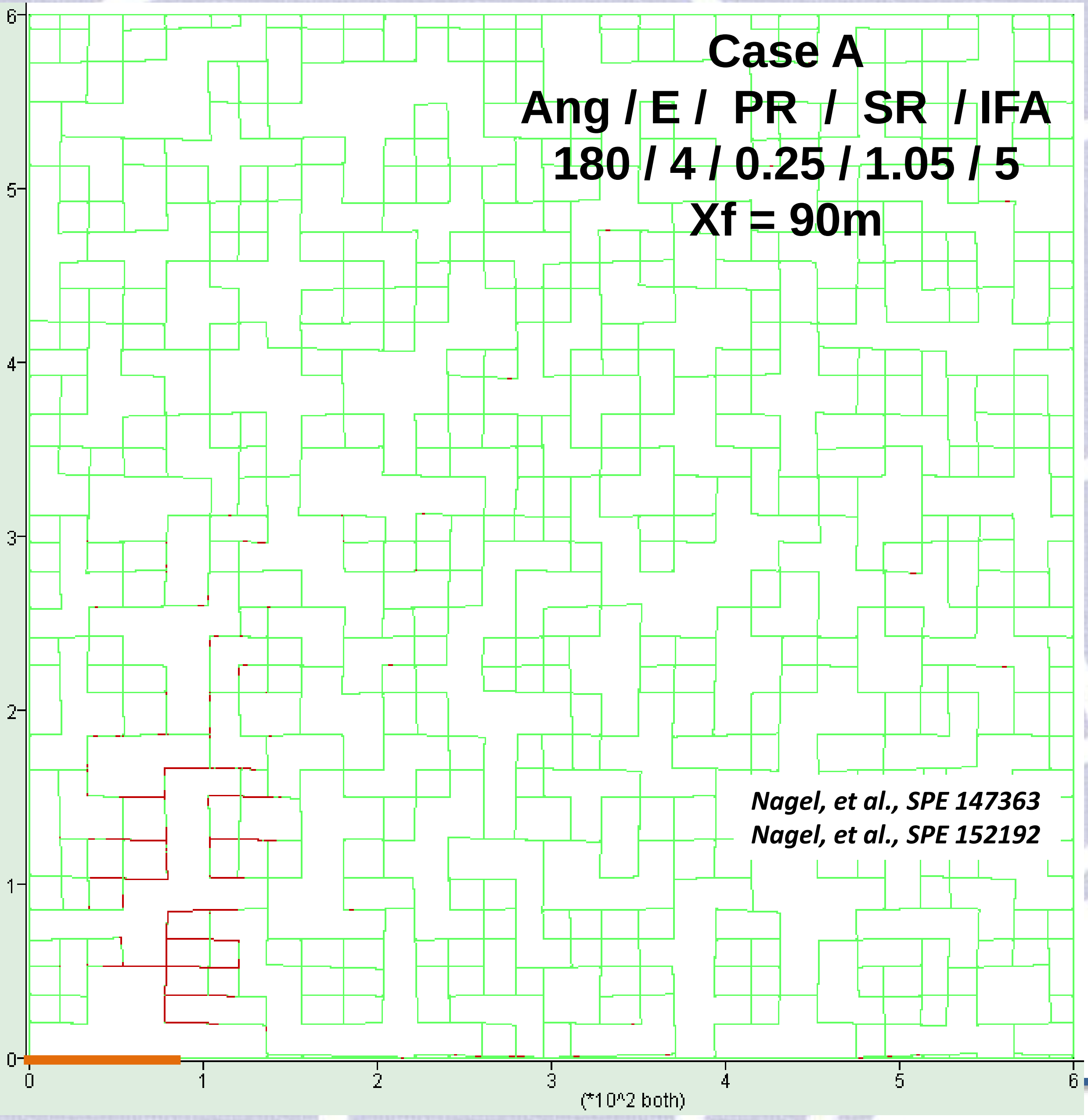
NF Response to Hydraulic Fracture: Mechanical Only



NF Response to Hydraulic Fracture: Mechanical Only



NF Response to Hydraulic Fracture: Mechanical Only



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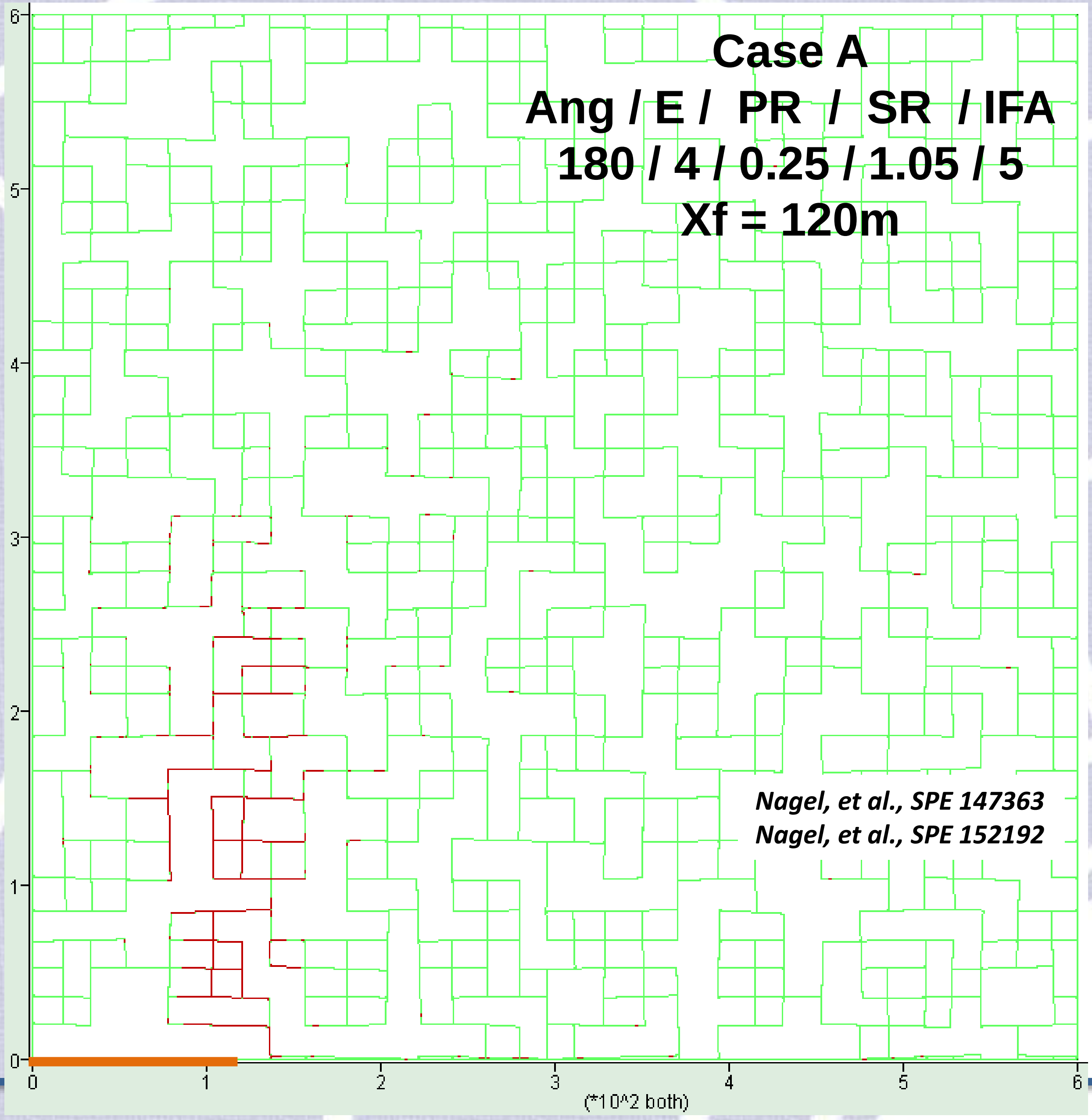
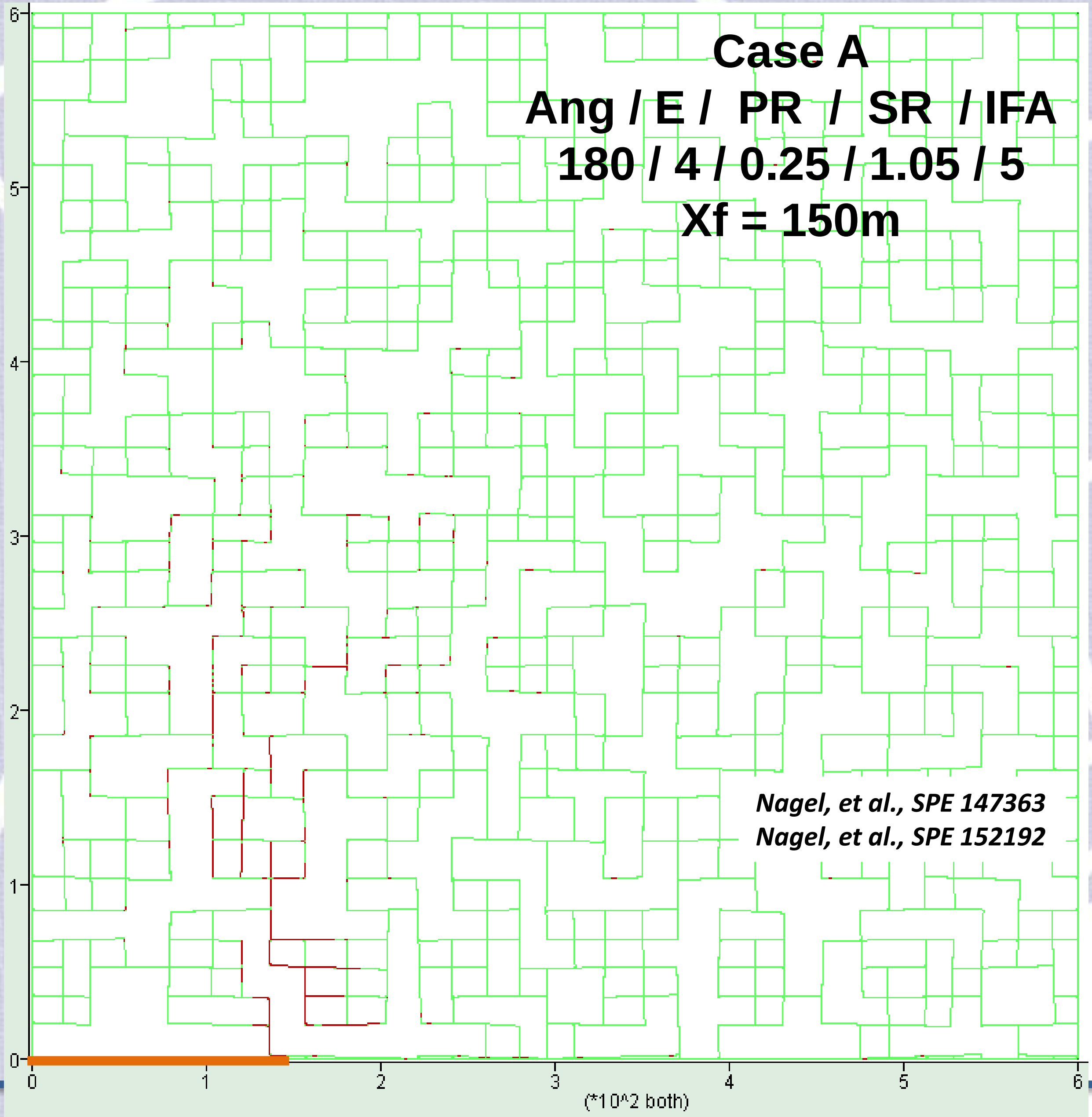


NF Response to Hydraulic Fracture: Mechanical Only



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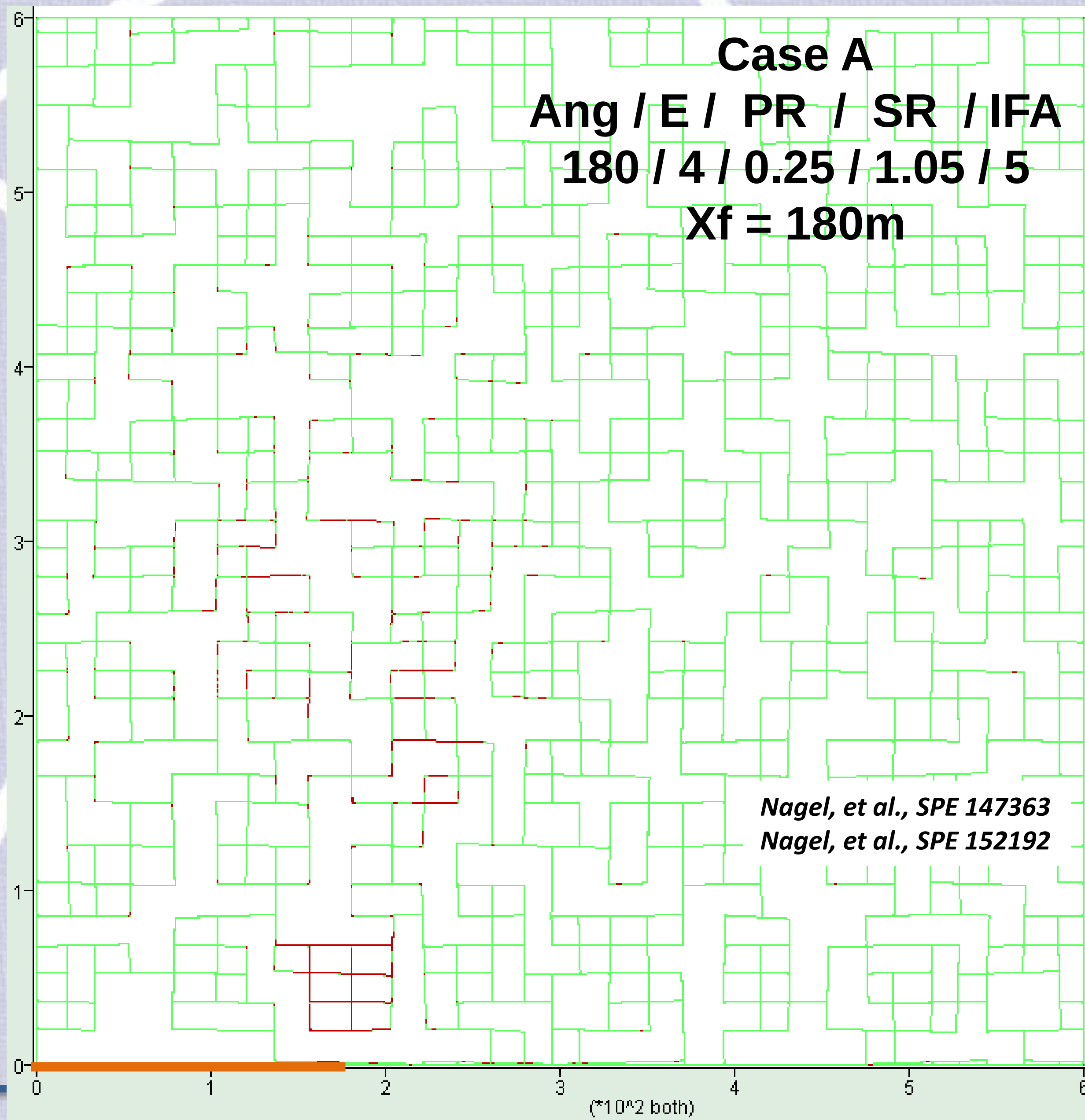

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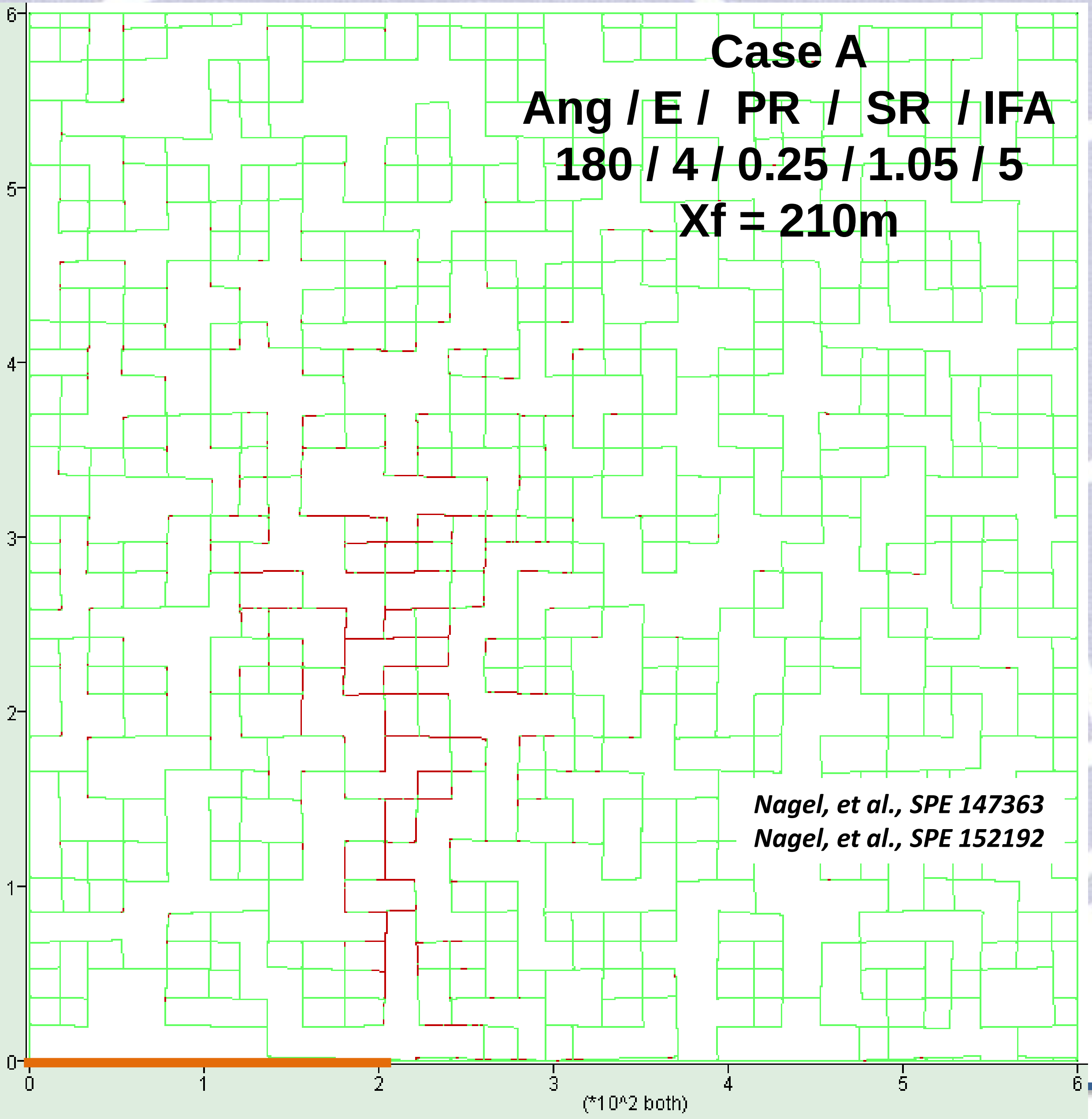
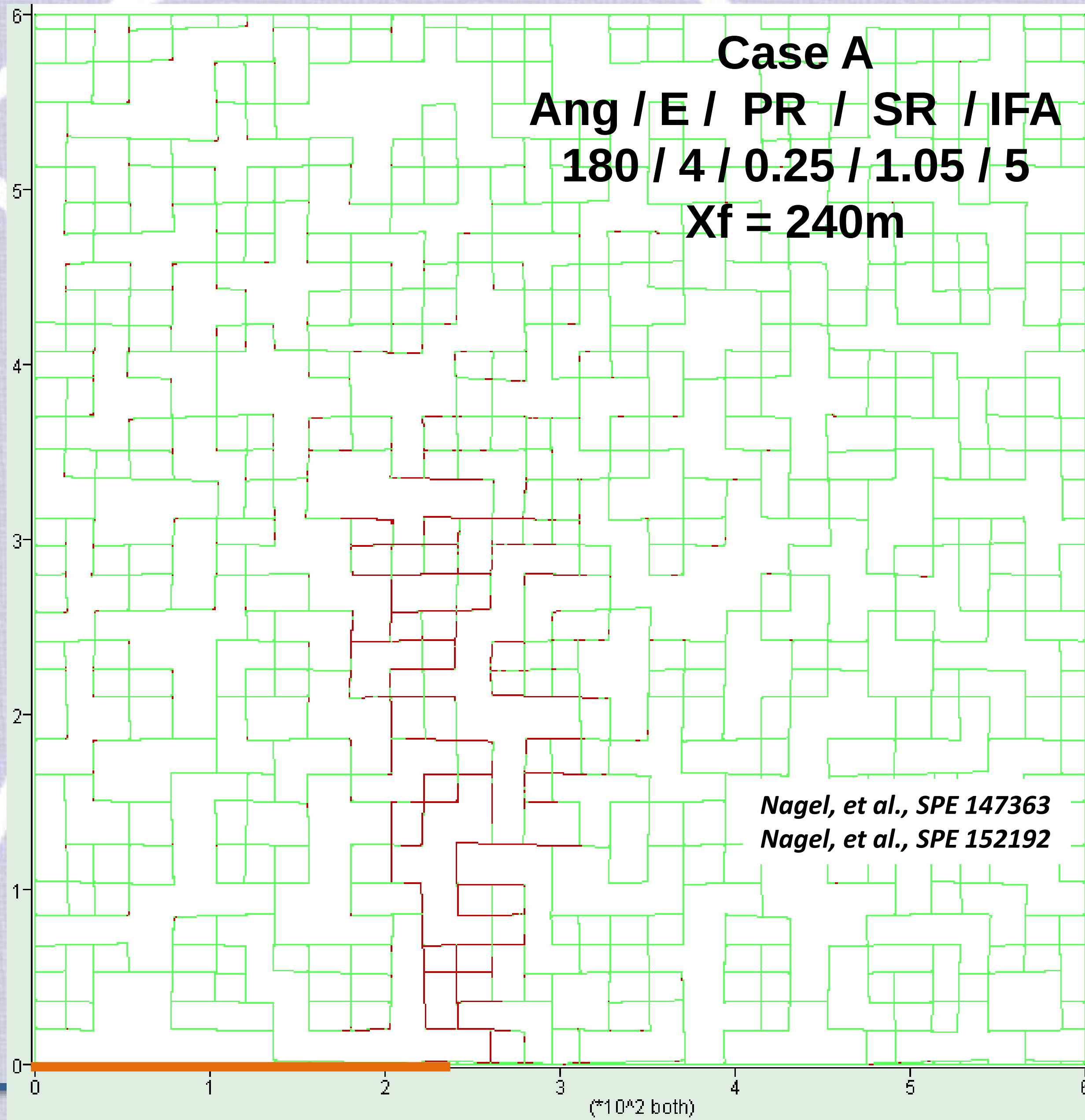


NF Response to Hydraulic Fracture: Mechanical Only



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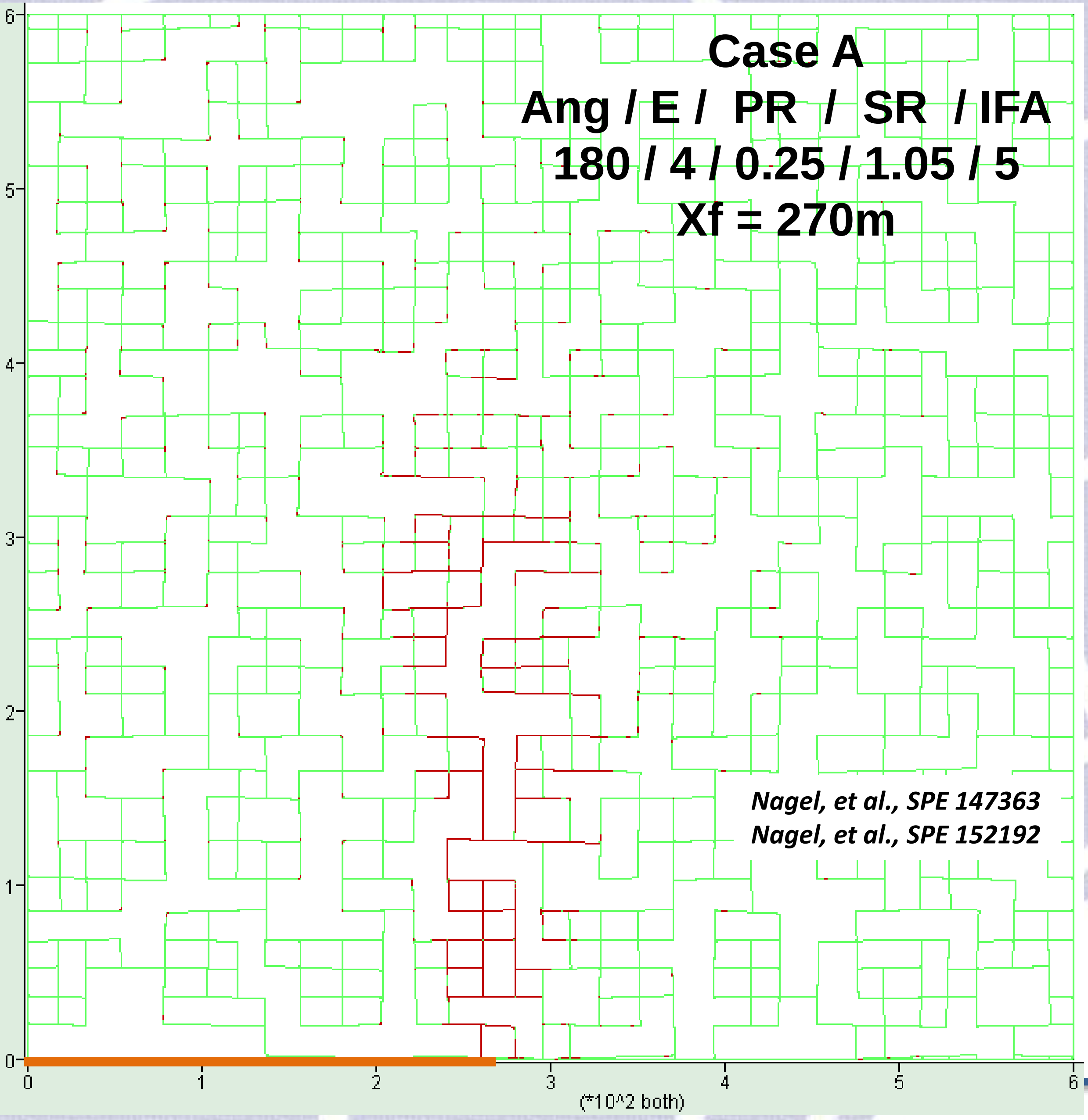
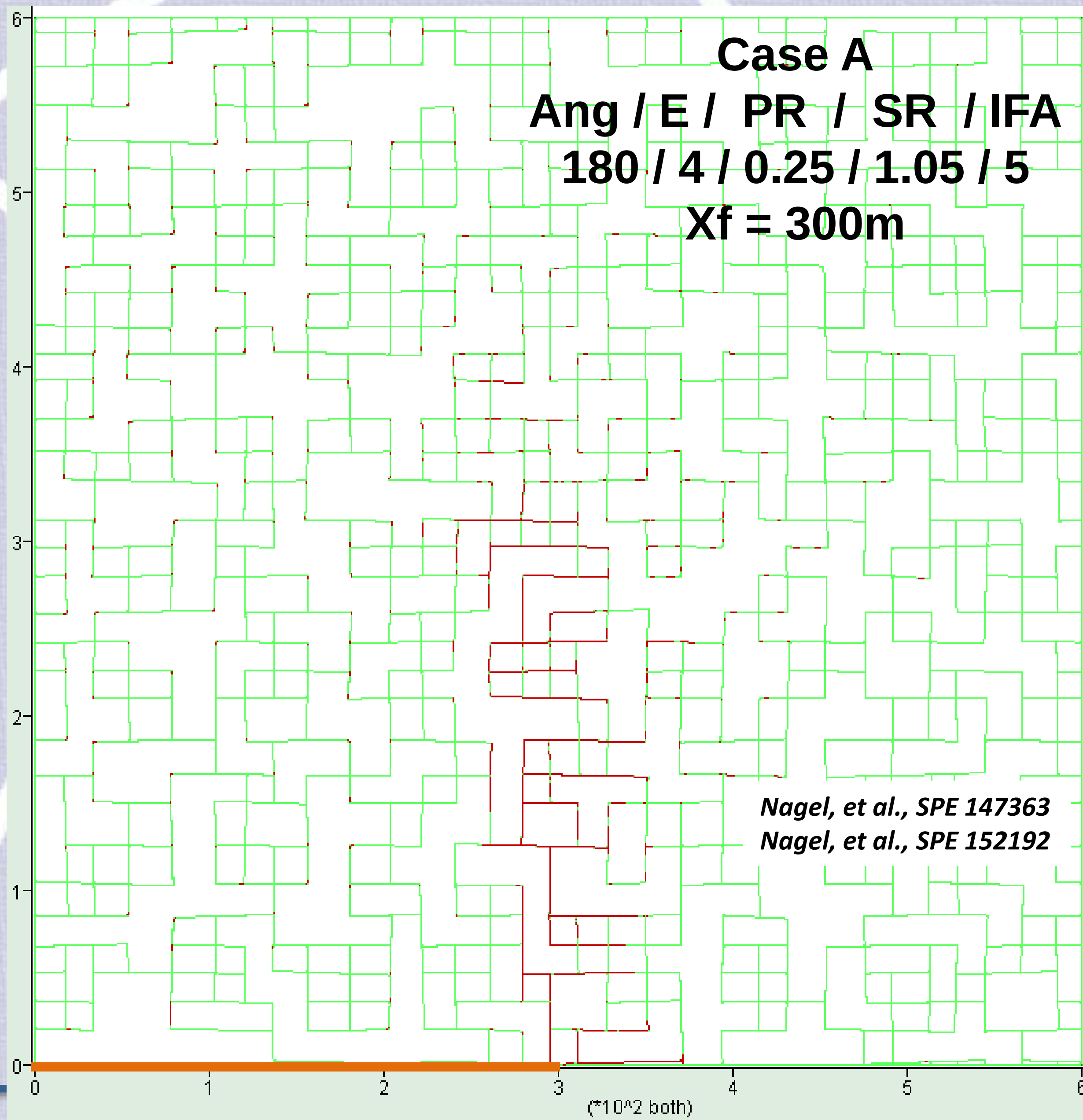
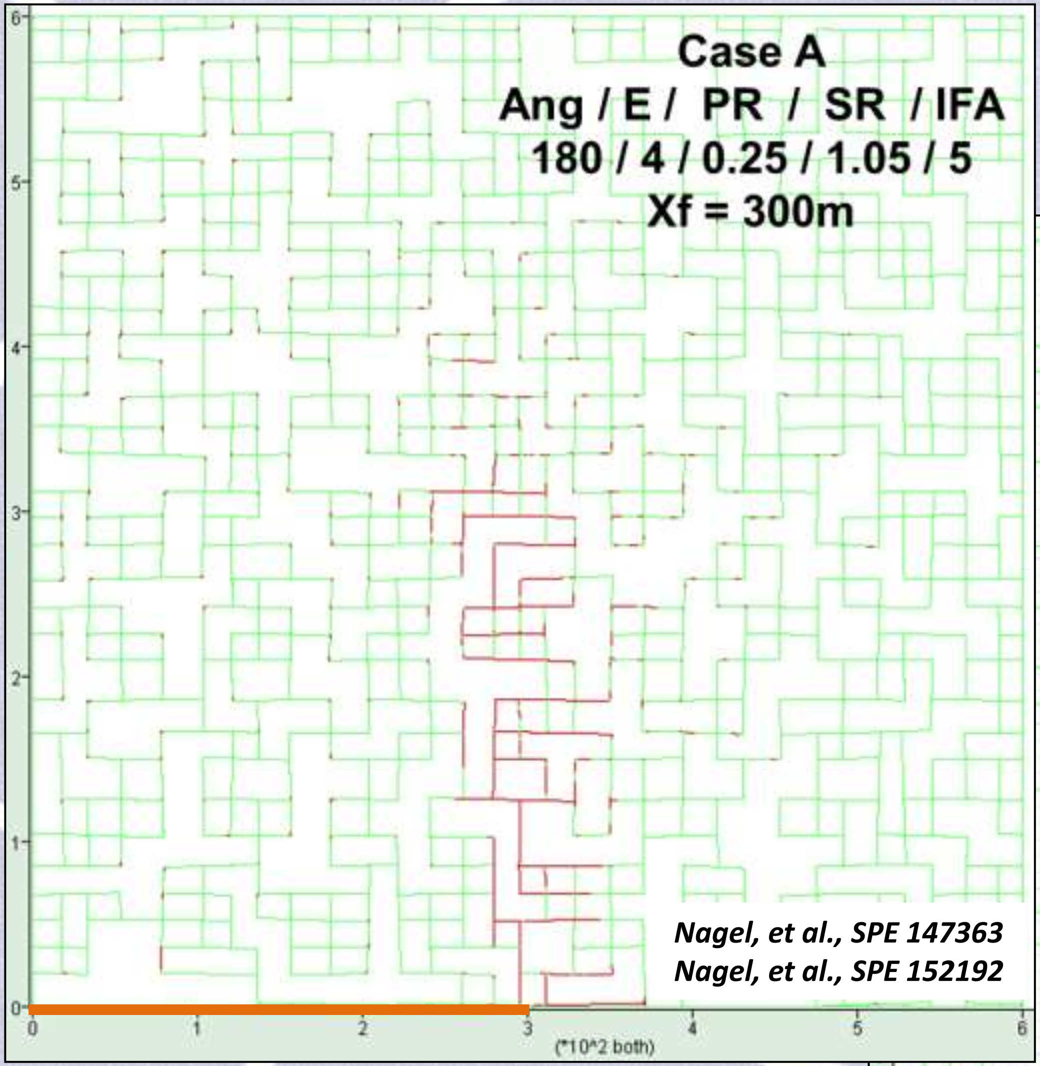


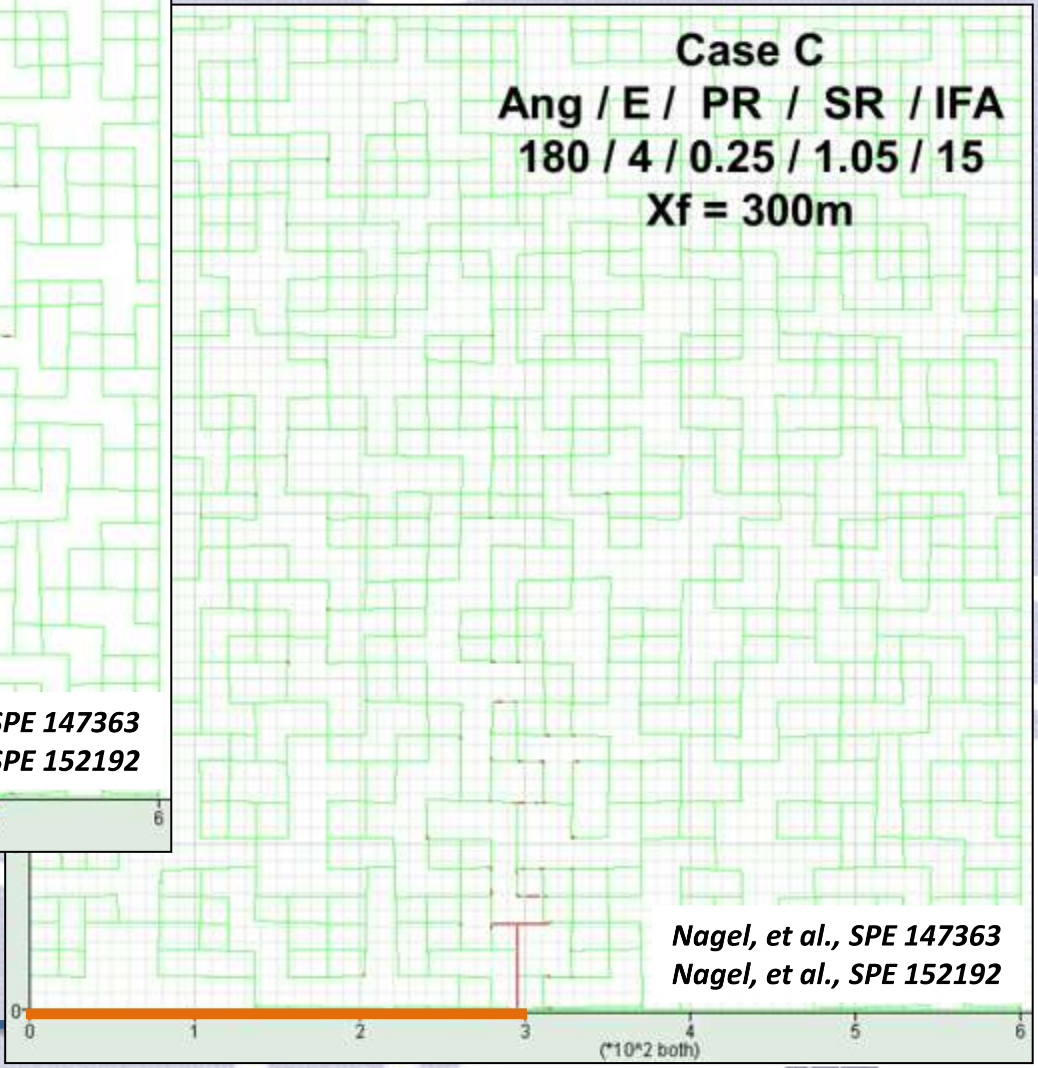
NF Response to Hydraulic Fracture: Mechanical Only



NF Friction Angle Effect



Nagel, et al., SPE 147363
Nagel, et al., SPE 152192



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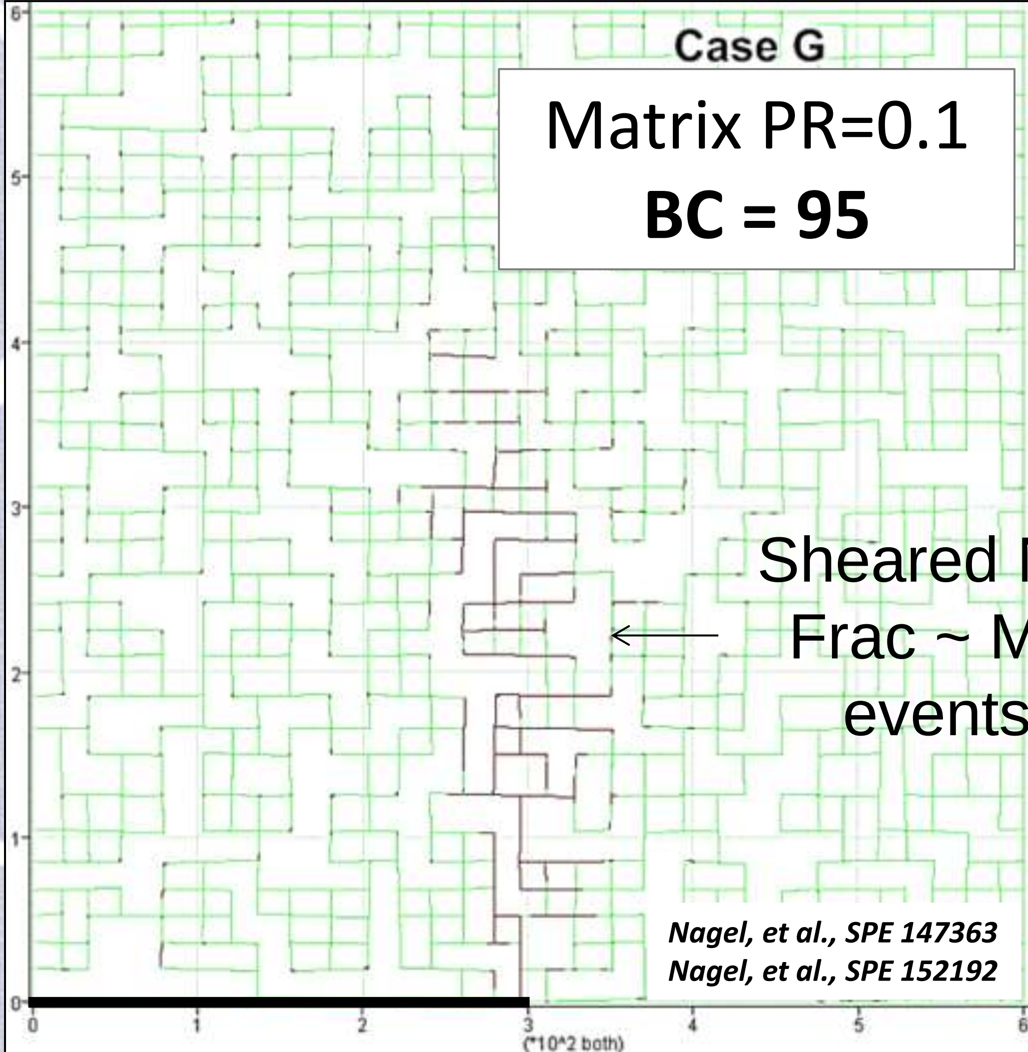
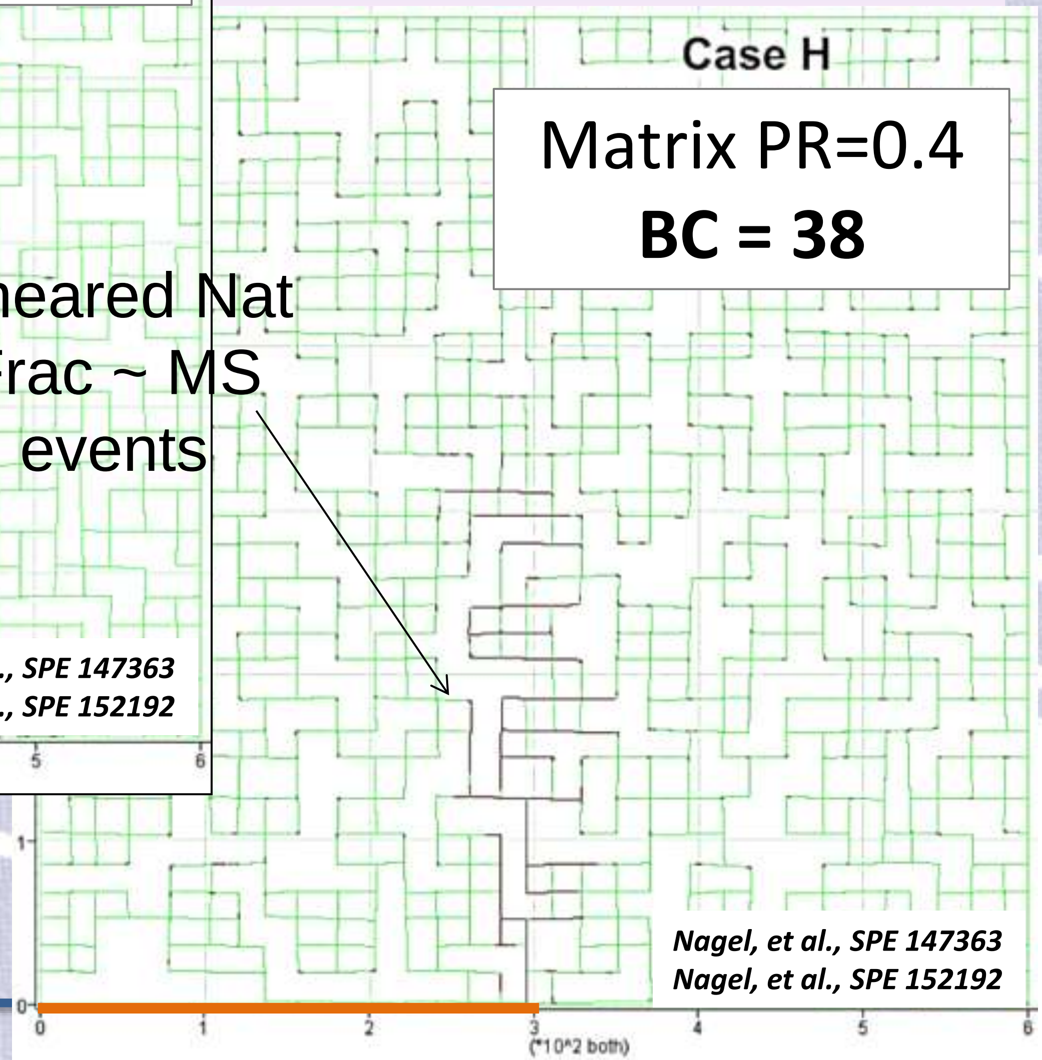
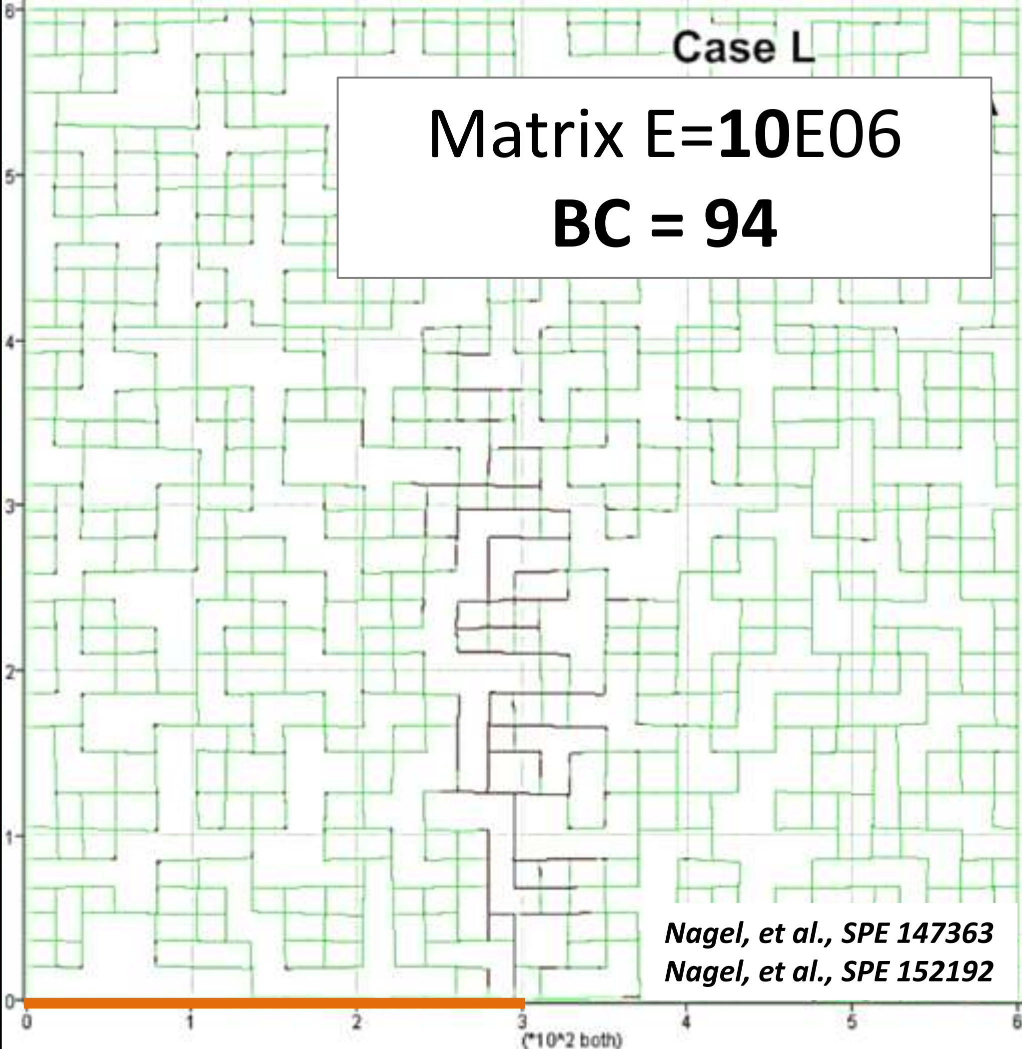
Poisson's Ratio Effect

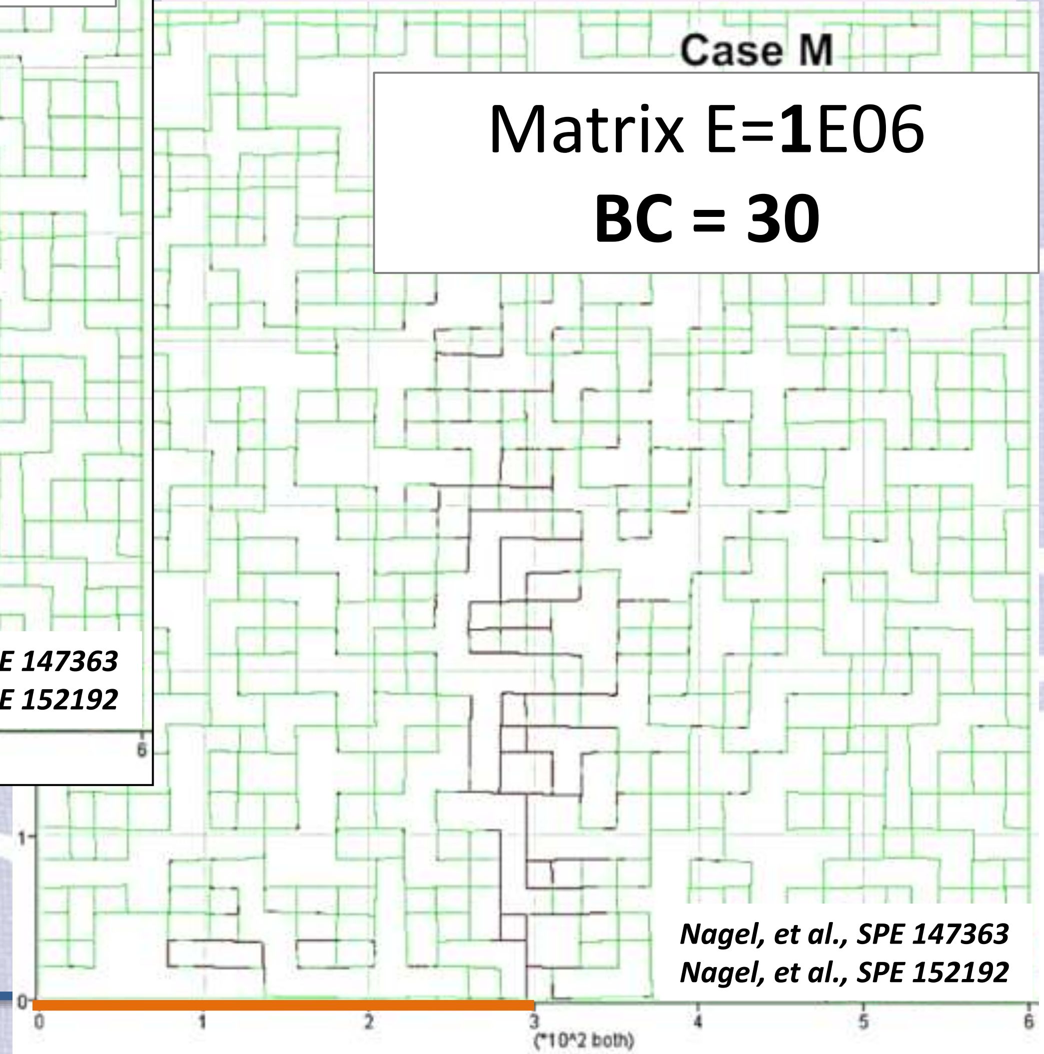


Sheared Nat Frac ~ MS events

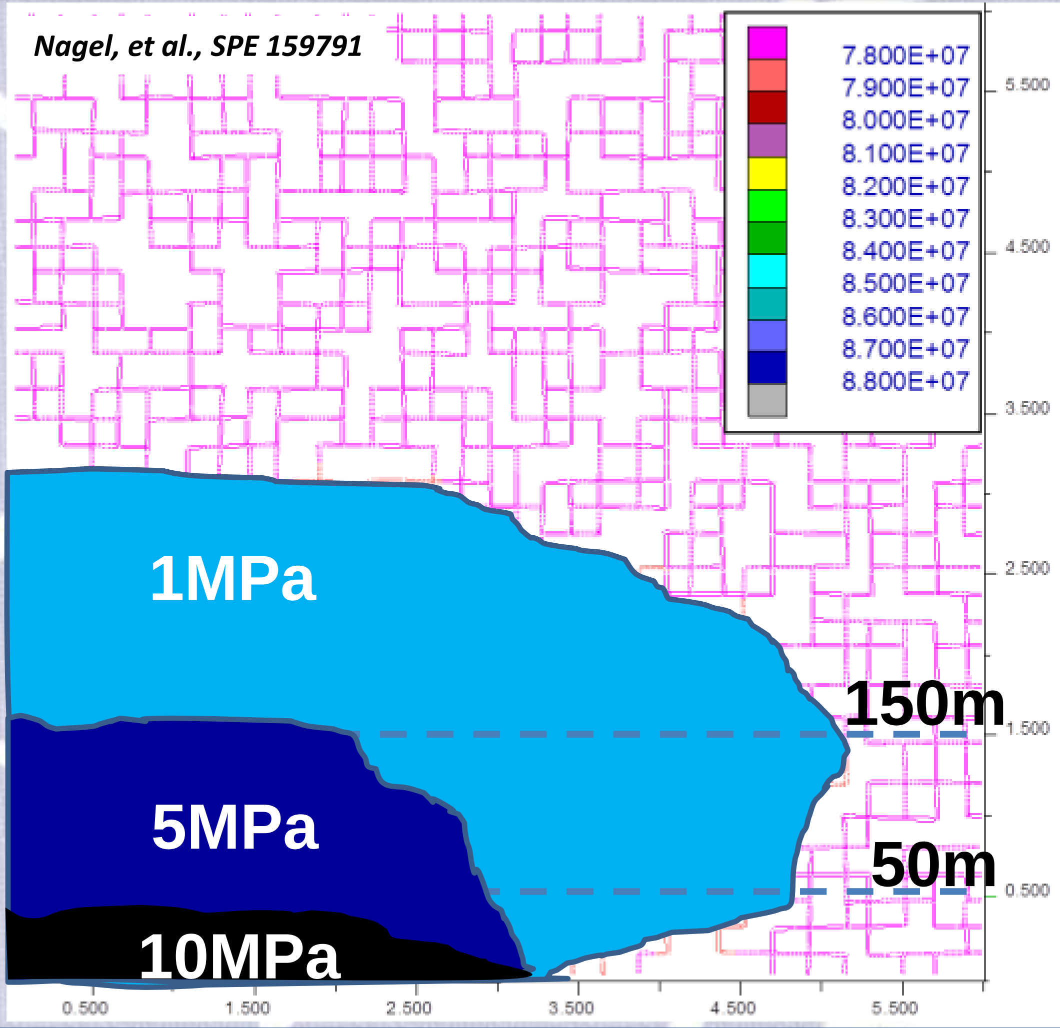


Young's Mod. Effect

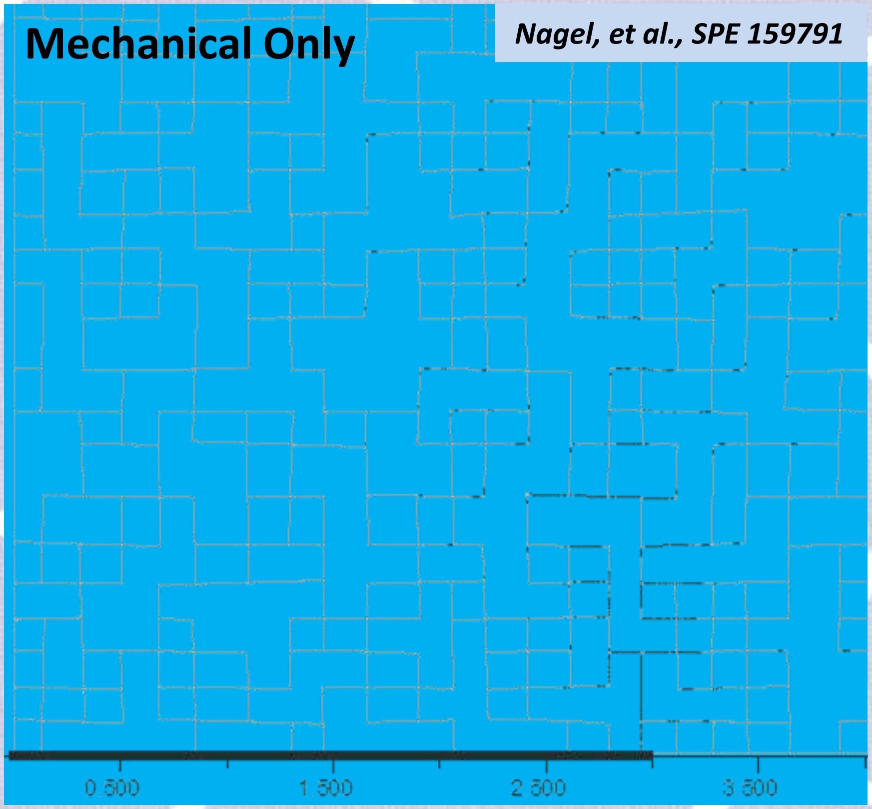


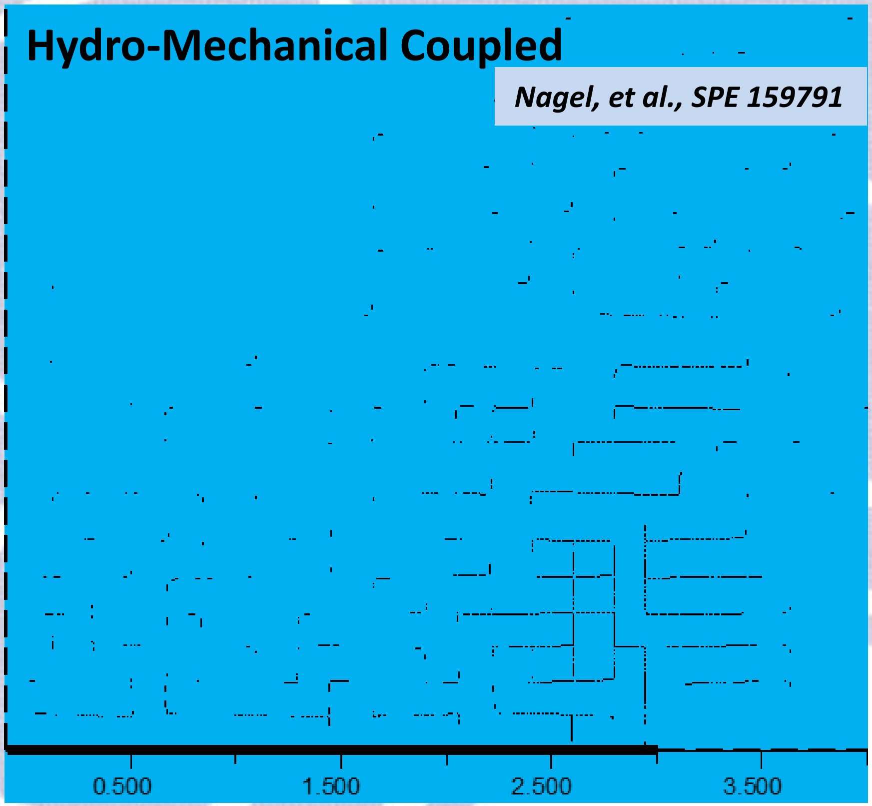


Coupled DEM – Pressure Change

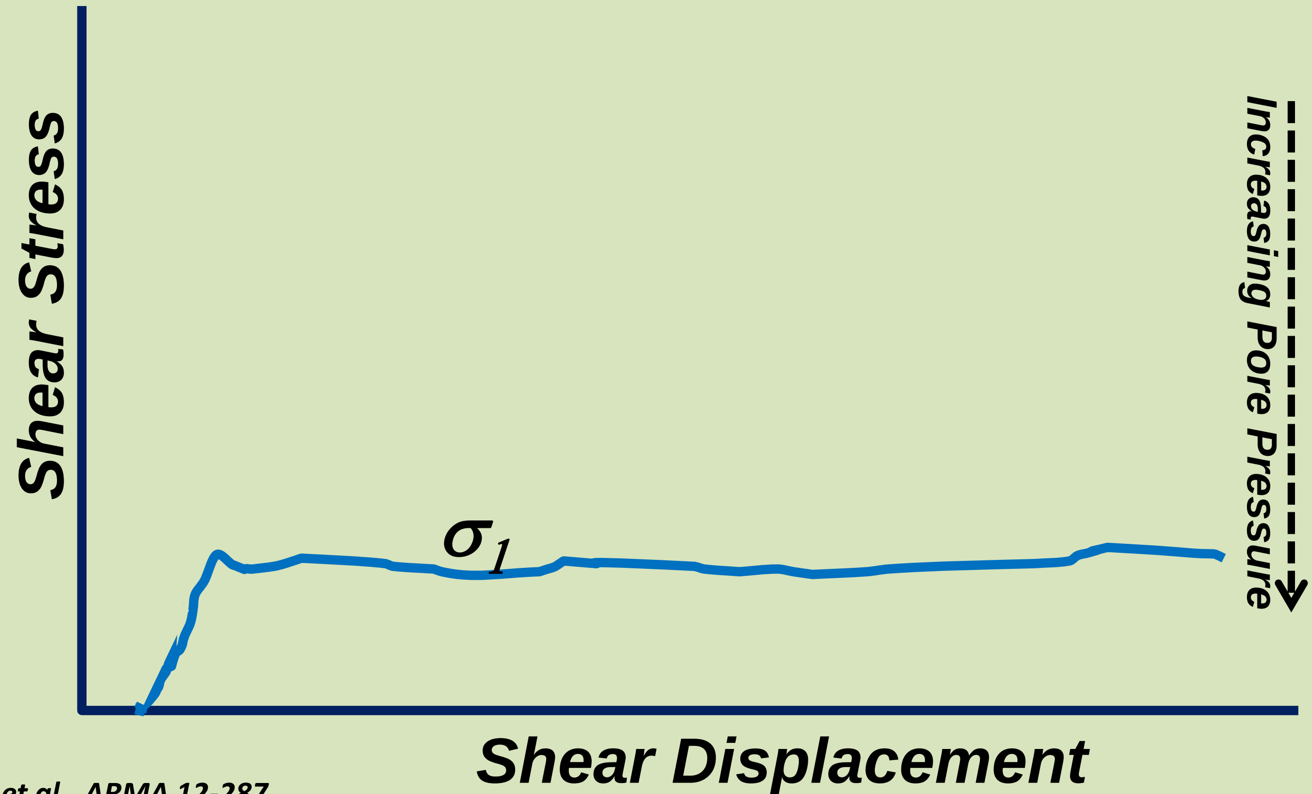


Coupled DEM – Mech. Only vs. Coupled



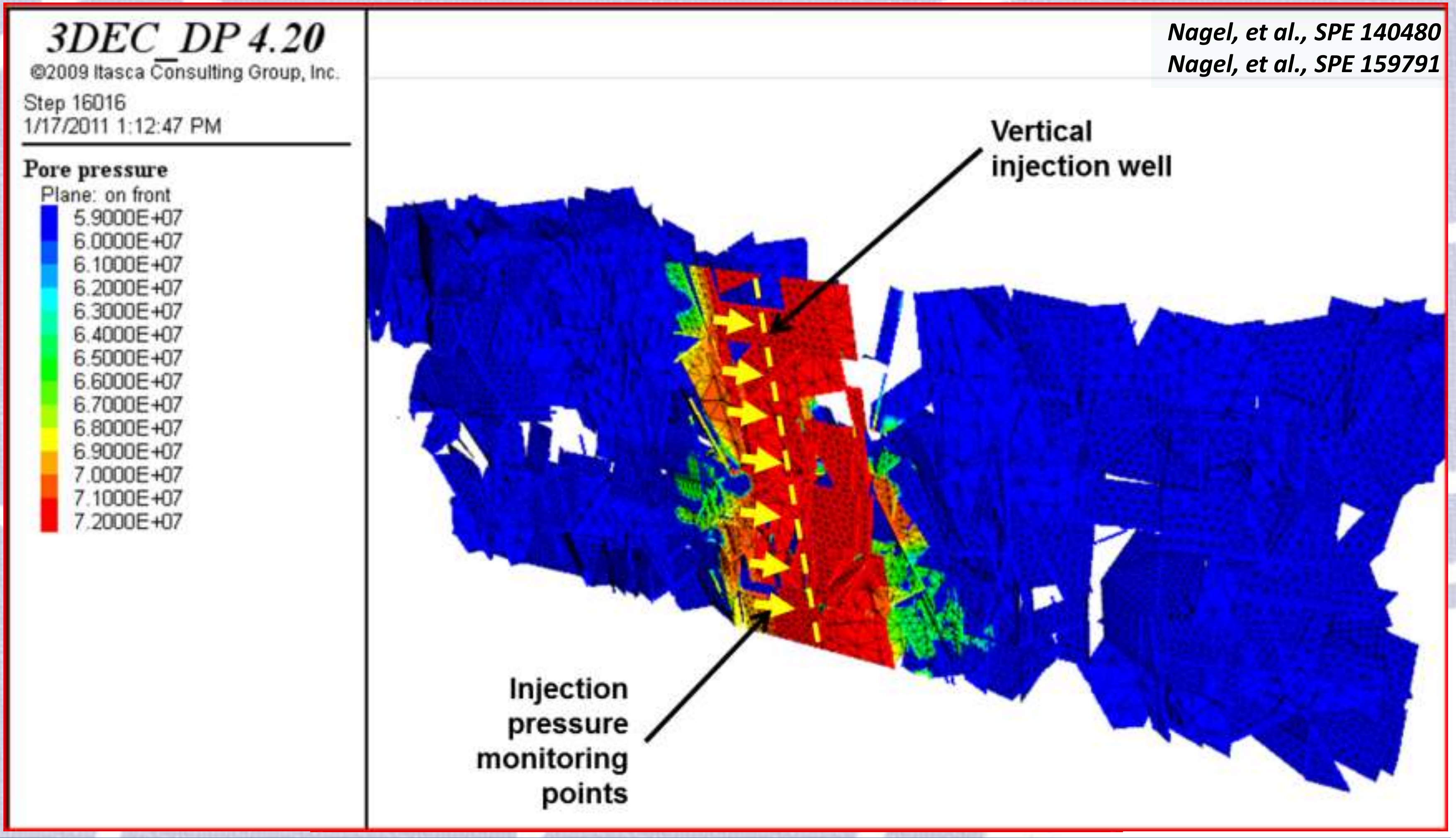


NF Behavior: Coupled Effects

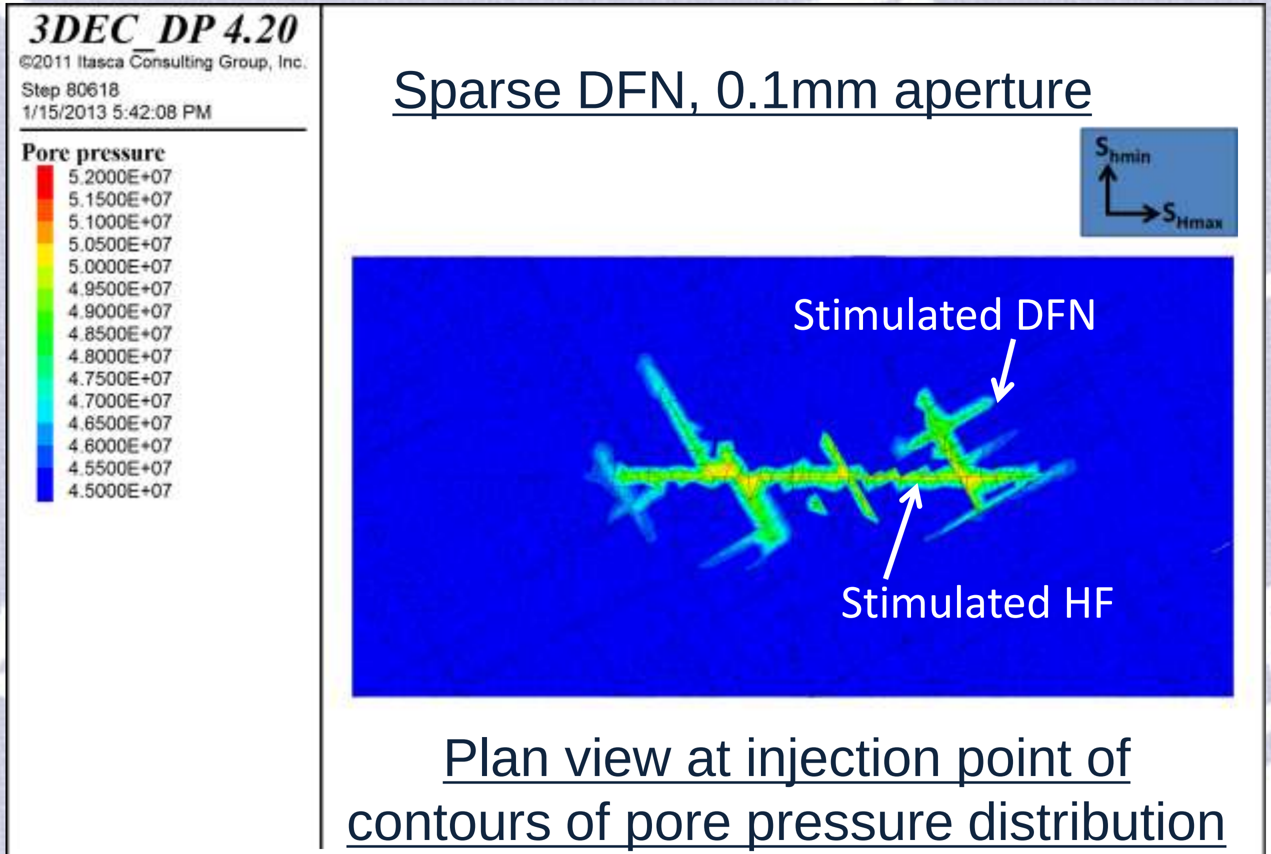


Nagel, et al., ARMA 12-287
Nagel, et al., RMRE V46N3

3D Modeling of HF in a Fractured Reservoir



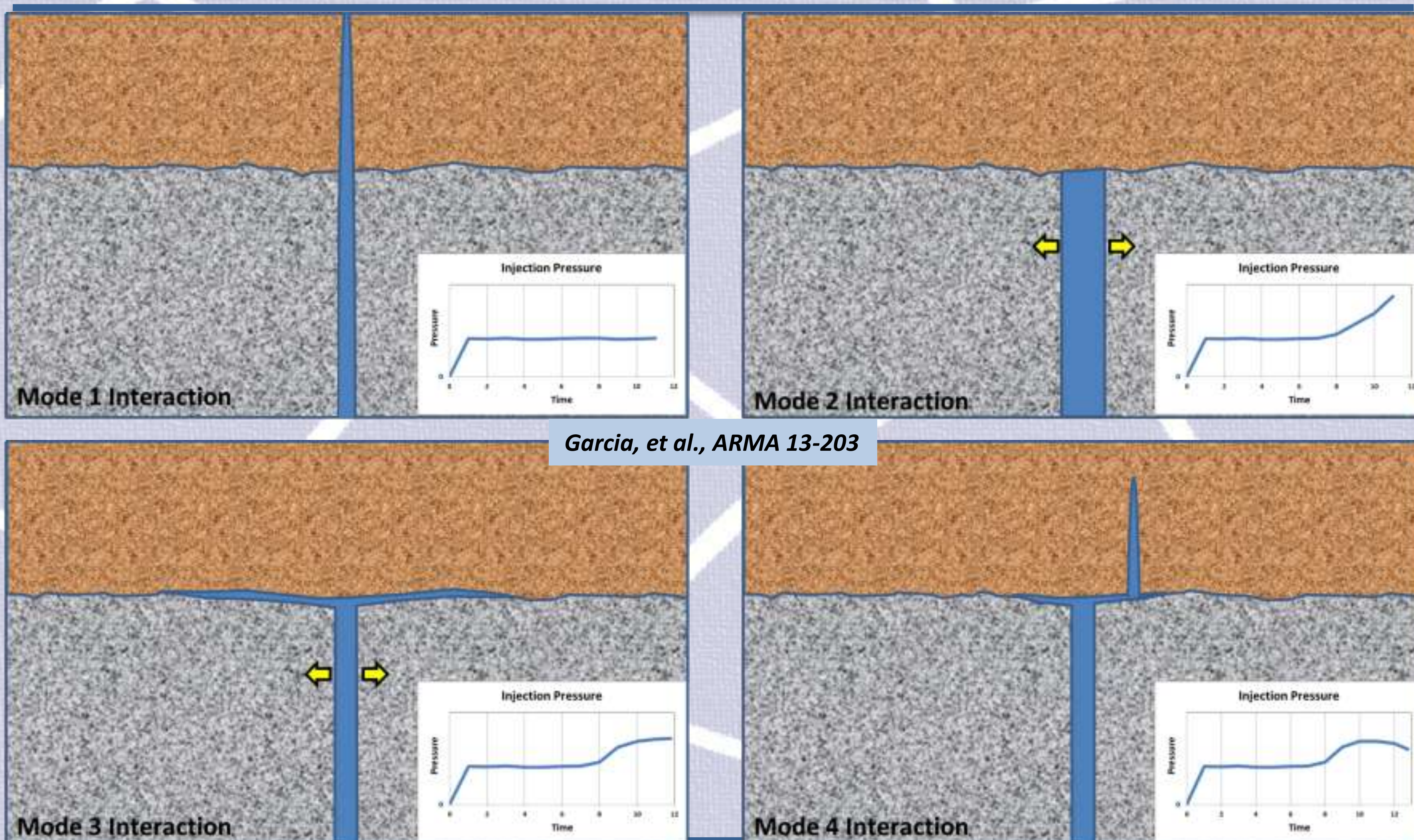
Influence of Fracture Network



Plan view at injection point of contours of pore pressure distribution

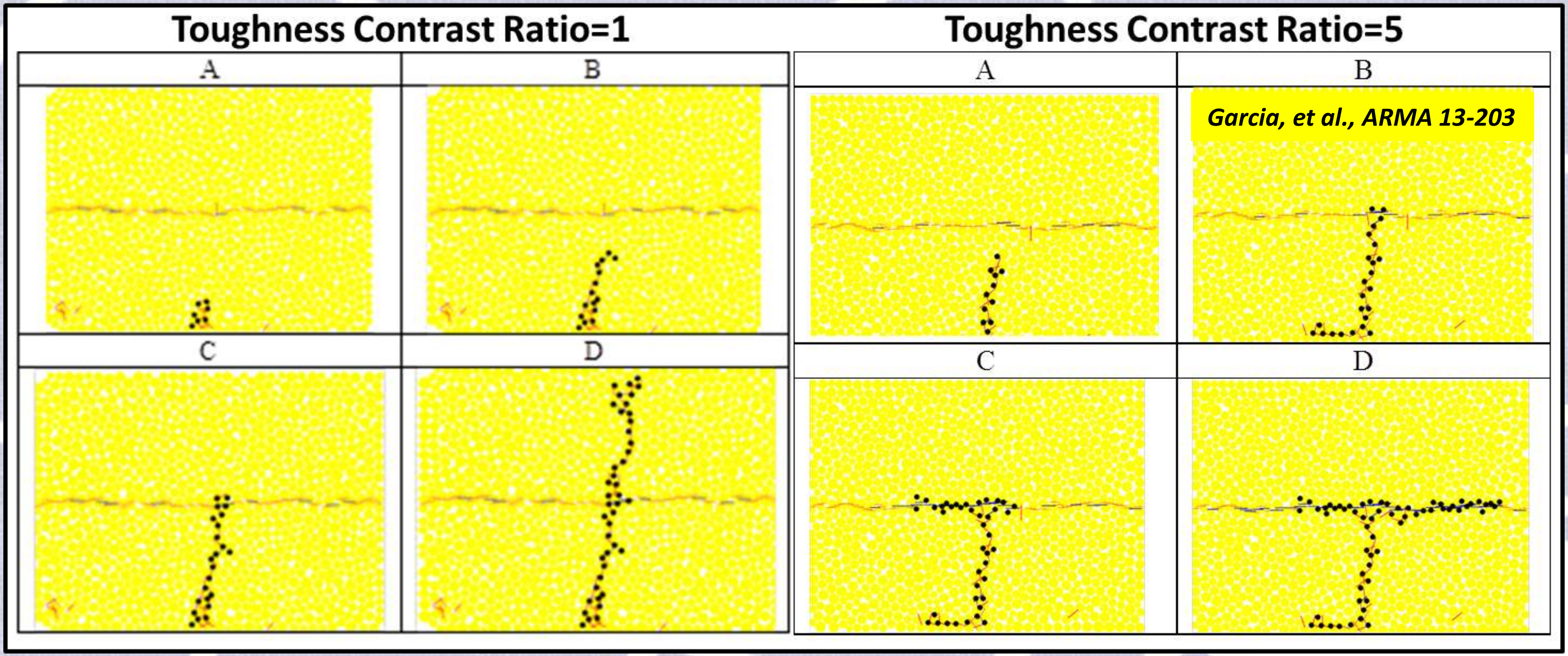
Zhang, et al., ISRM Australia HF2013
Zhang, et al., ARMA 13-199

"Interface" Crossing Types (2D)



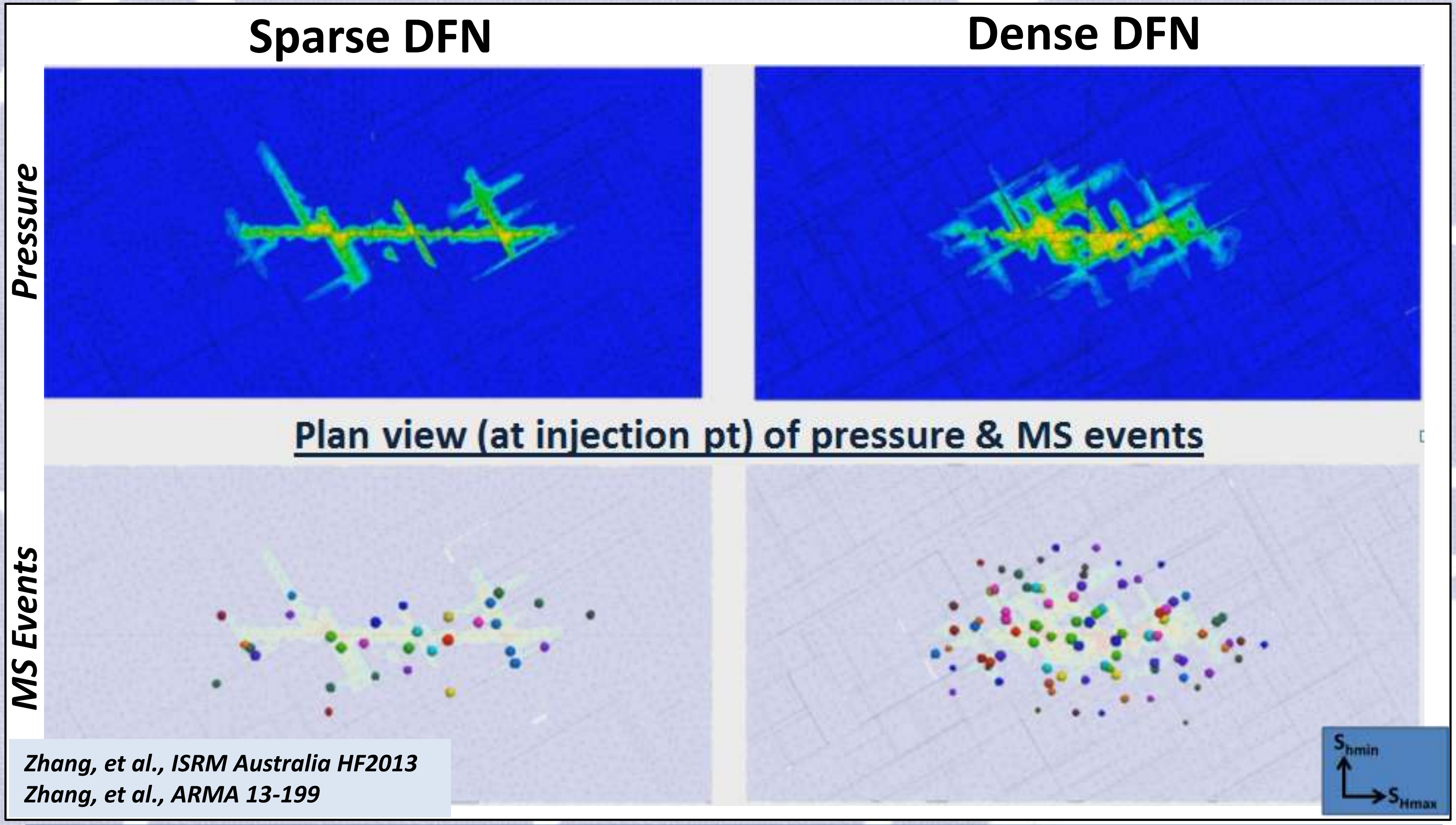
Garcia, et al., ARMA 13-203

Crossing Simulations



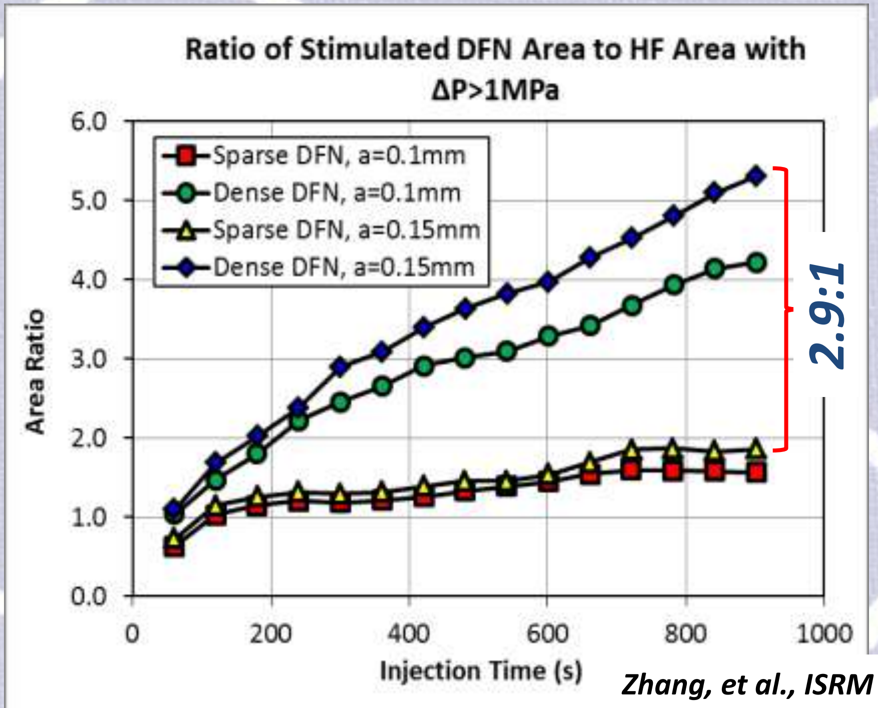
Simulation of the influence of rock fracture toughness…

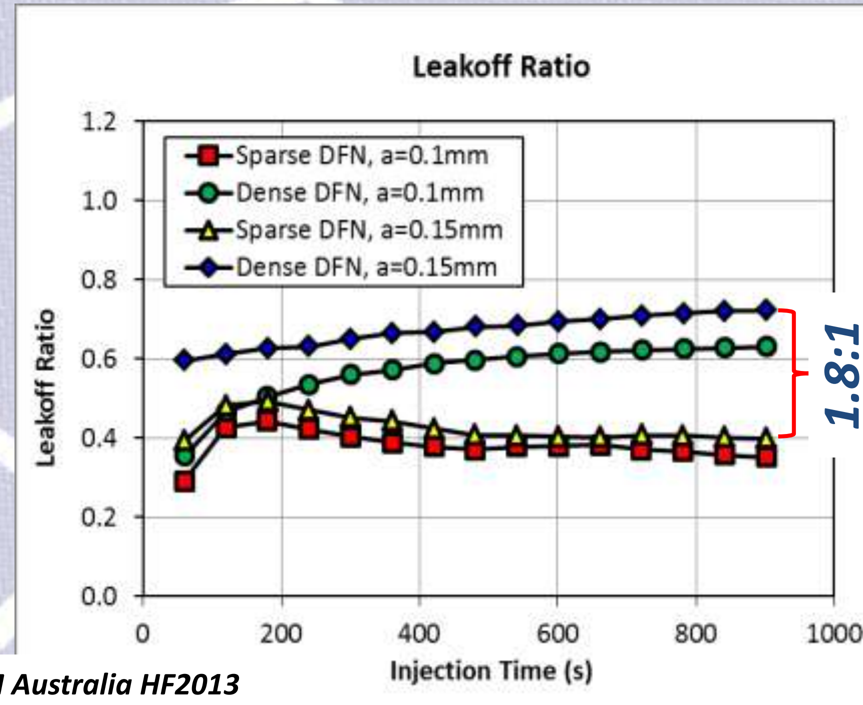
Influence of Fracture Network



Zhang, et al., ISRM Australia HF2013
Zhang, et al., ARMA 13-199

Influence of Fracture Network





Zhang, et al., ISRM Australia HF2013
Zhang, et al., ARMA 13-199

- The Dense DFN had as much as a 5.2 x DFN stimulated area to HF area....
- The Dense DFN had as much as 70% of the fluid go to stimulate the DFN....

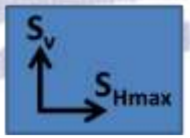
Sparse vs. Dense – HF Plane Aperture

Sparse DFN

Dense DFN

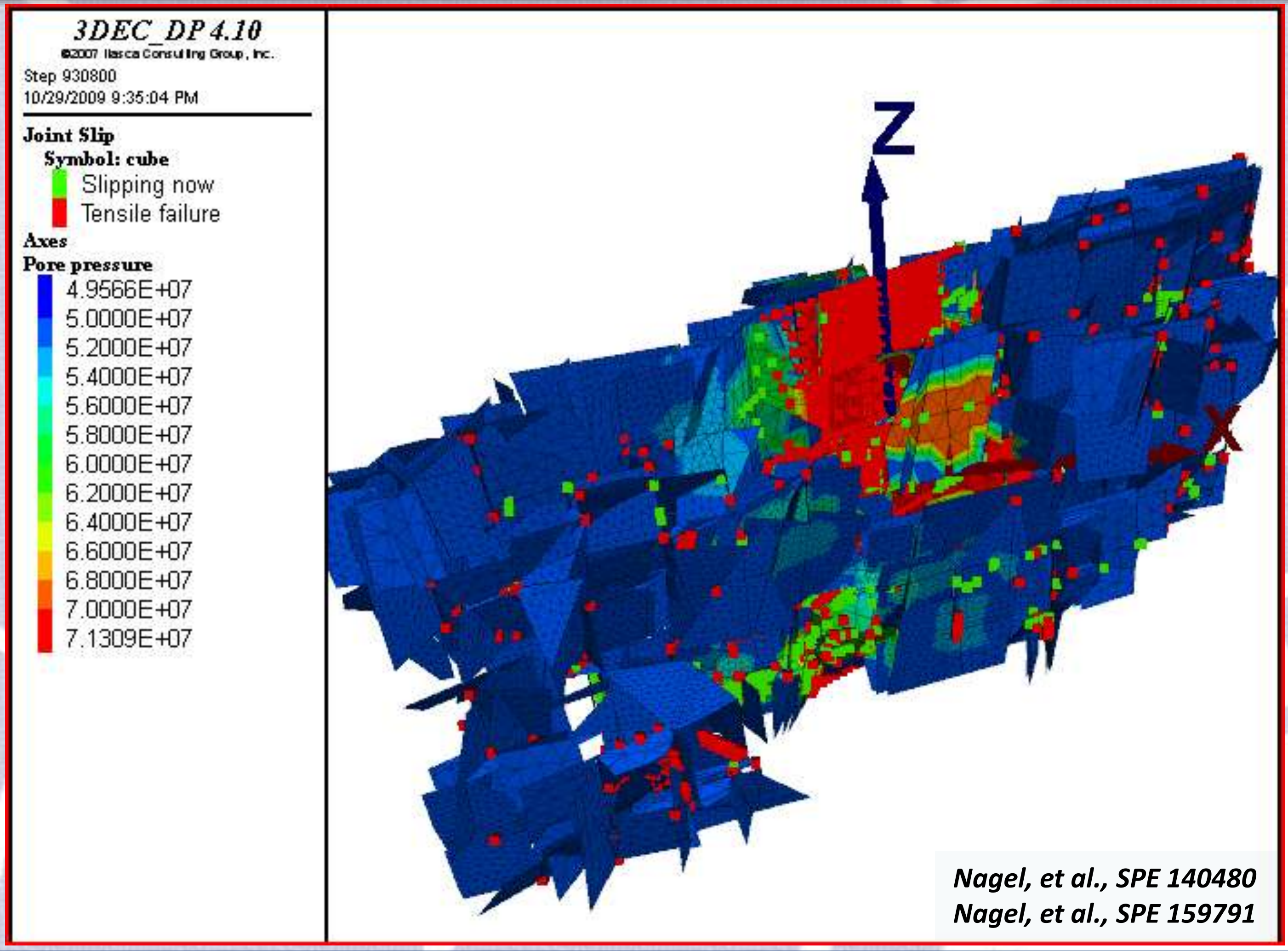
Zhang, et al., ISRM Australia HF2013
Zhang, et al., ARMA 13-199

X-section view (at injection pt) of HF aperture

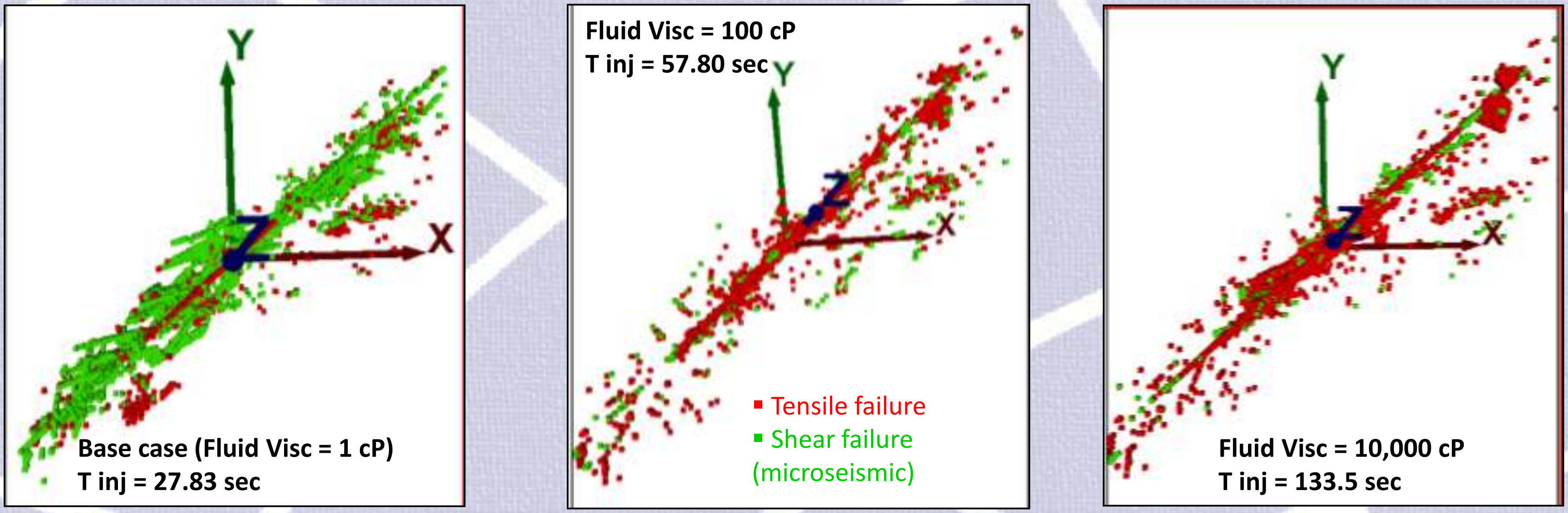


Proppant Transport?????

Rock Failure – aka Microseismicity



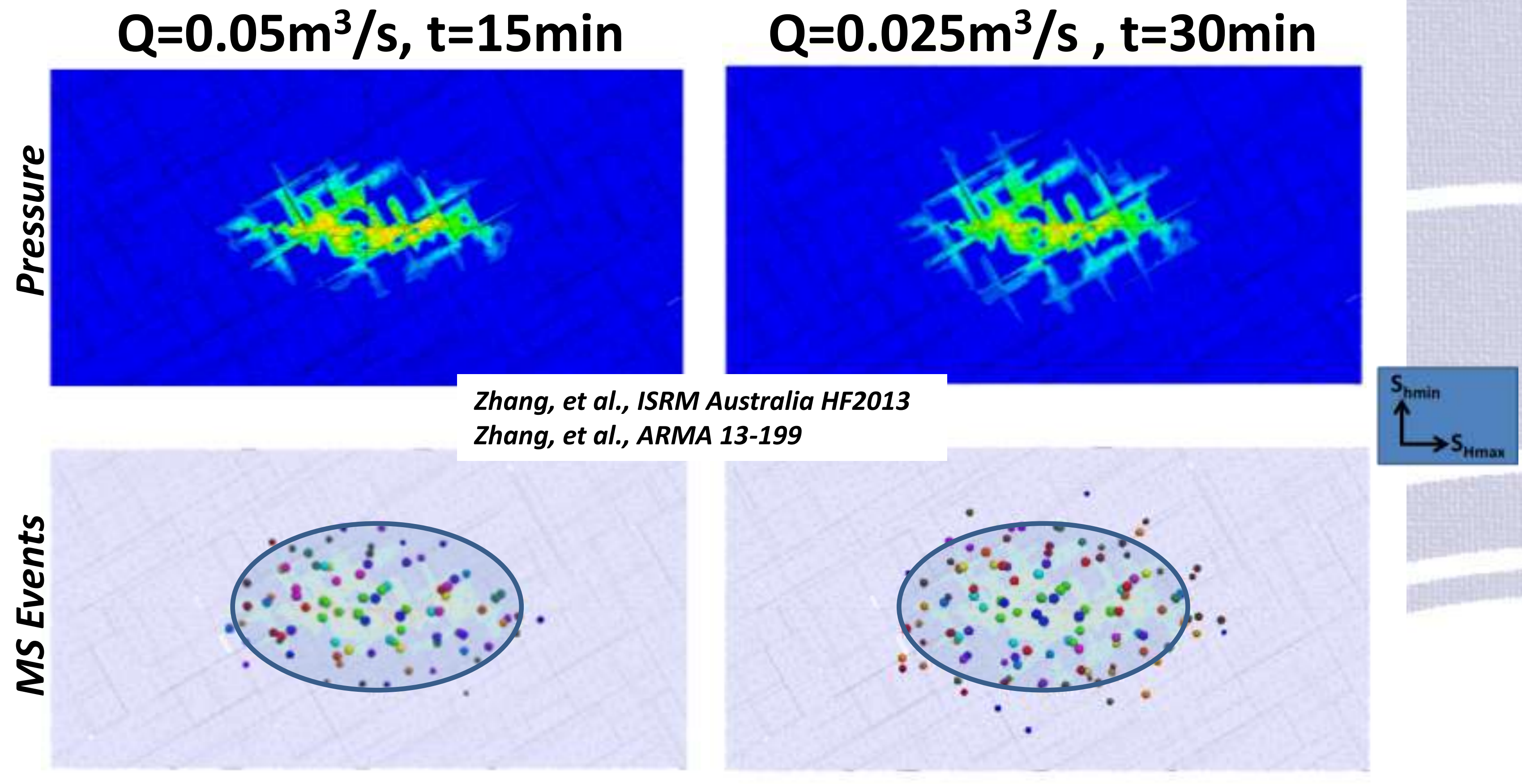
Influence of Viscosity



Nagel, et al., SPE 140480 & Nagel, et al., SPE 159791

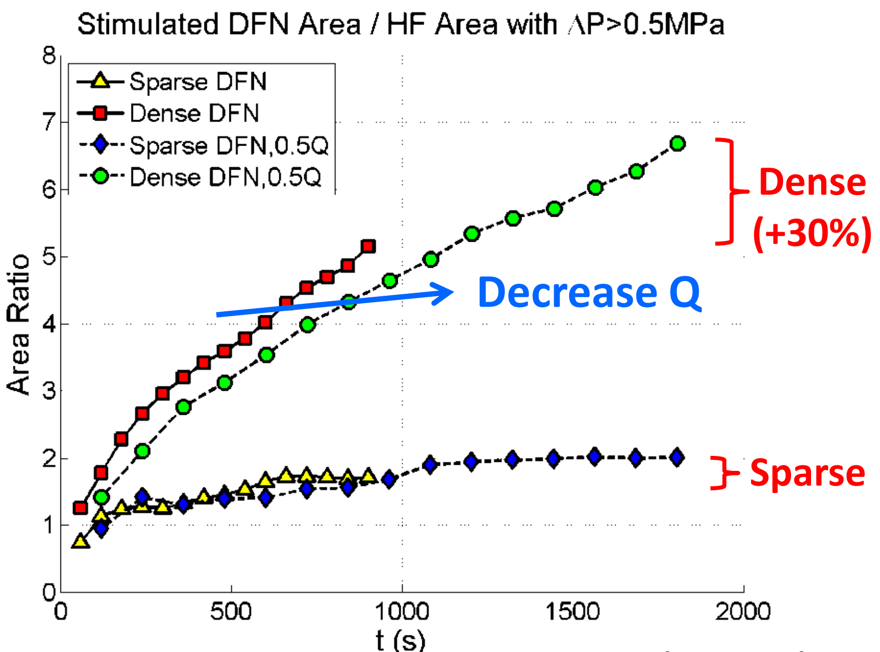
Low viscosity fluids promote more shear failure. Is this good or bad? Does this confirm the Barnett results?

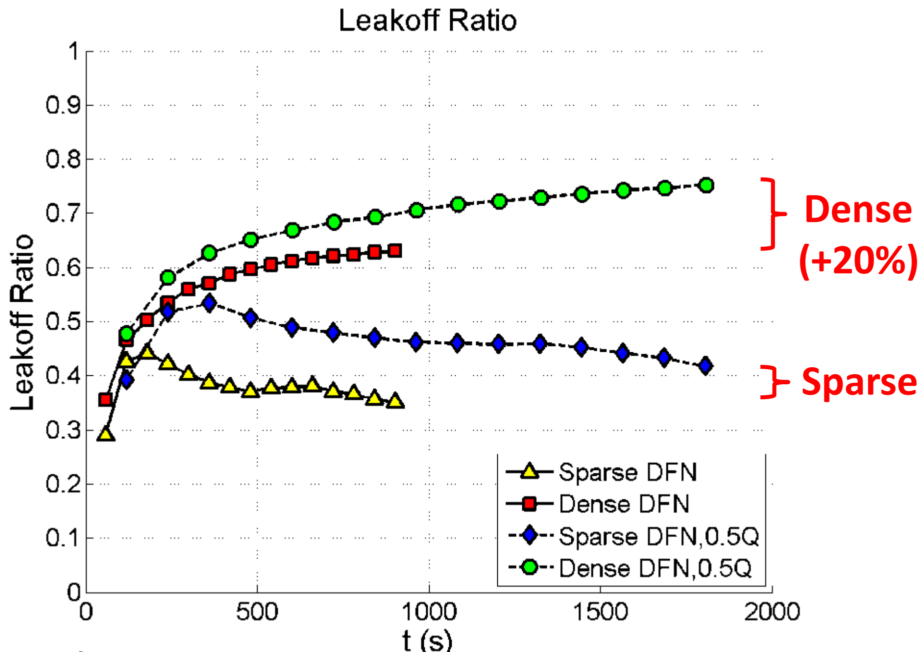
Effect of Injection Rate



Plan view (at injection pt) of pressure & MS events

Effect of Injection Rate

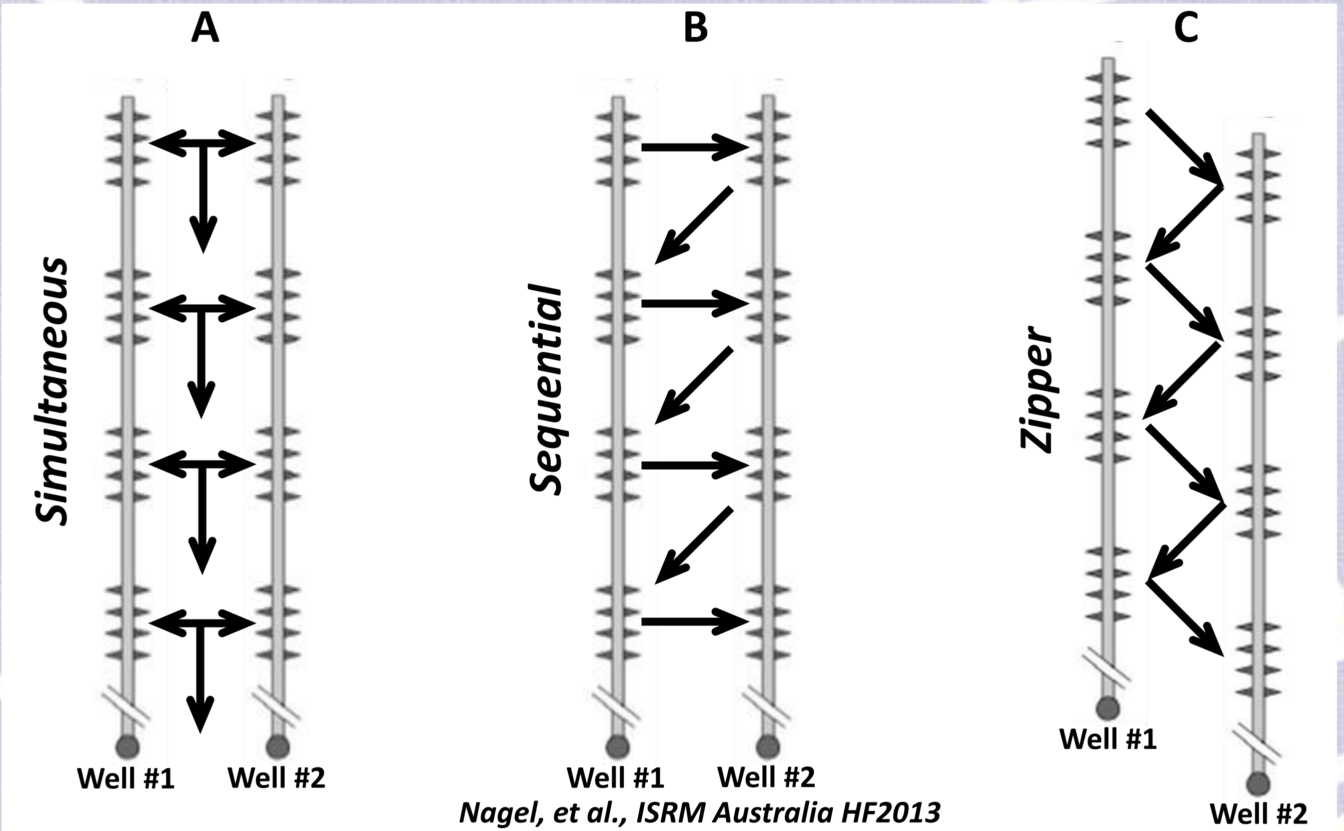




Zhang, et al., ISRM Australia HF2013
Zhang, et al., ARMA 13-199

- ***Injection rate ↓; ratio of stimulated DFN area to HF area ↑.***
- ***Injection rate ↓; leakoff ratio ↑.***
- ***Dense DFN was more sensitive to the change of injection rate.***

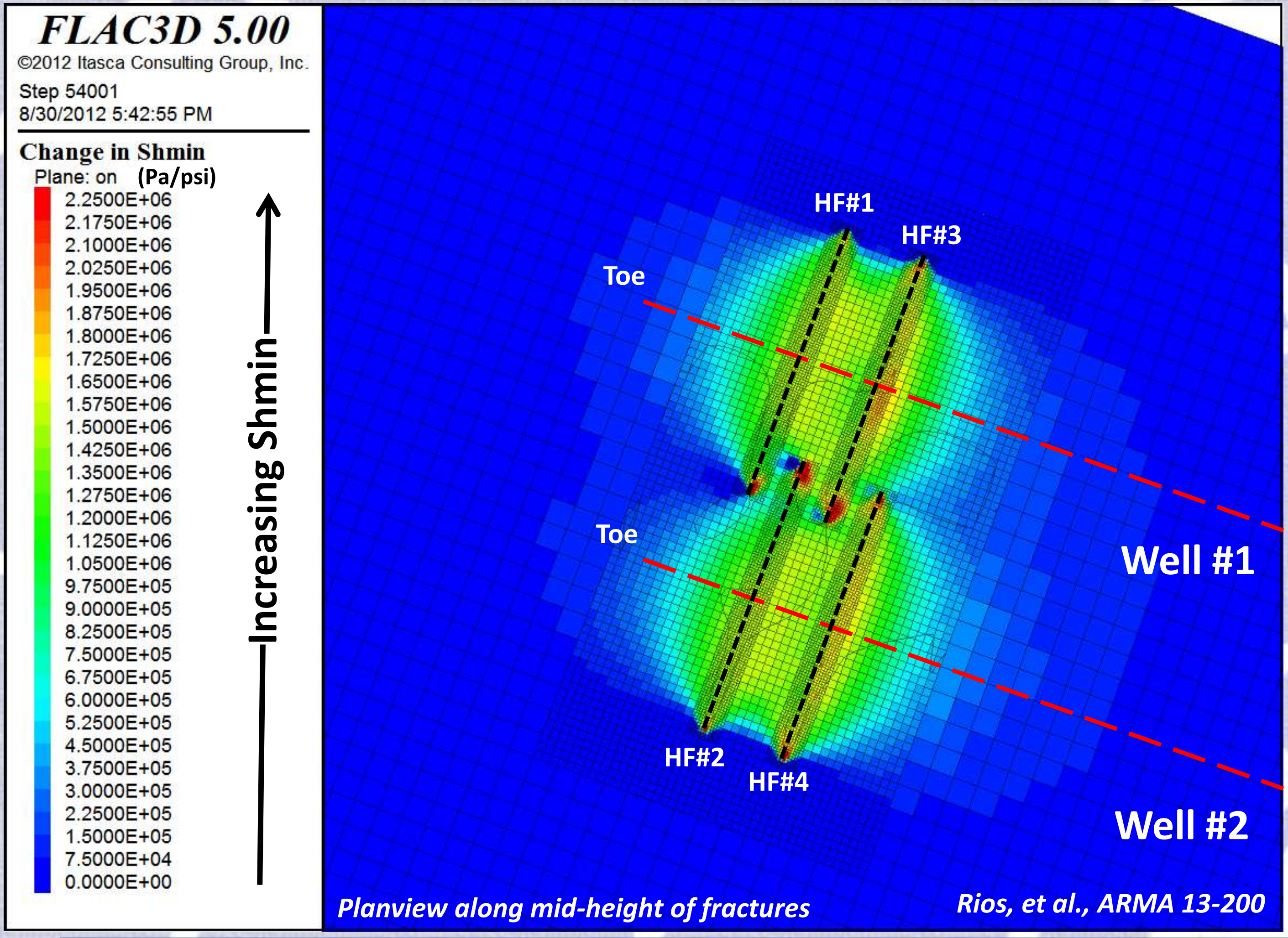
Multi-Well Completion Evaluations



Nagel, et al., ISRM Australia HF2013

Multi-well completions are now being used to increase complexity. Numerical simulations can provide a means to evaluate well and stage spacing in order to optimize complexity.

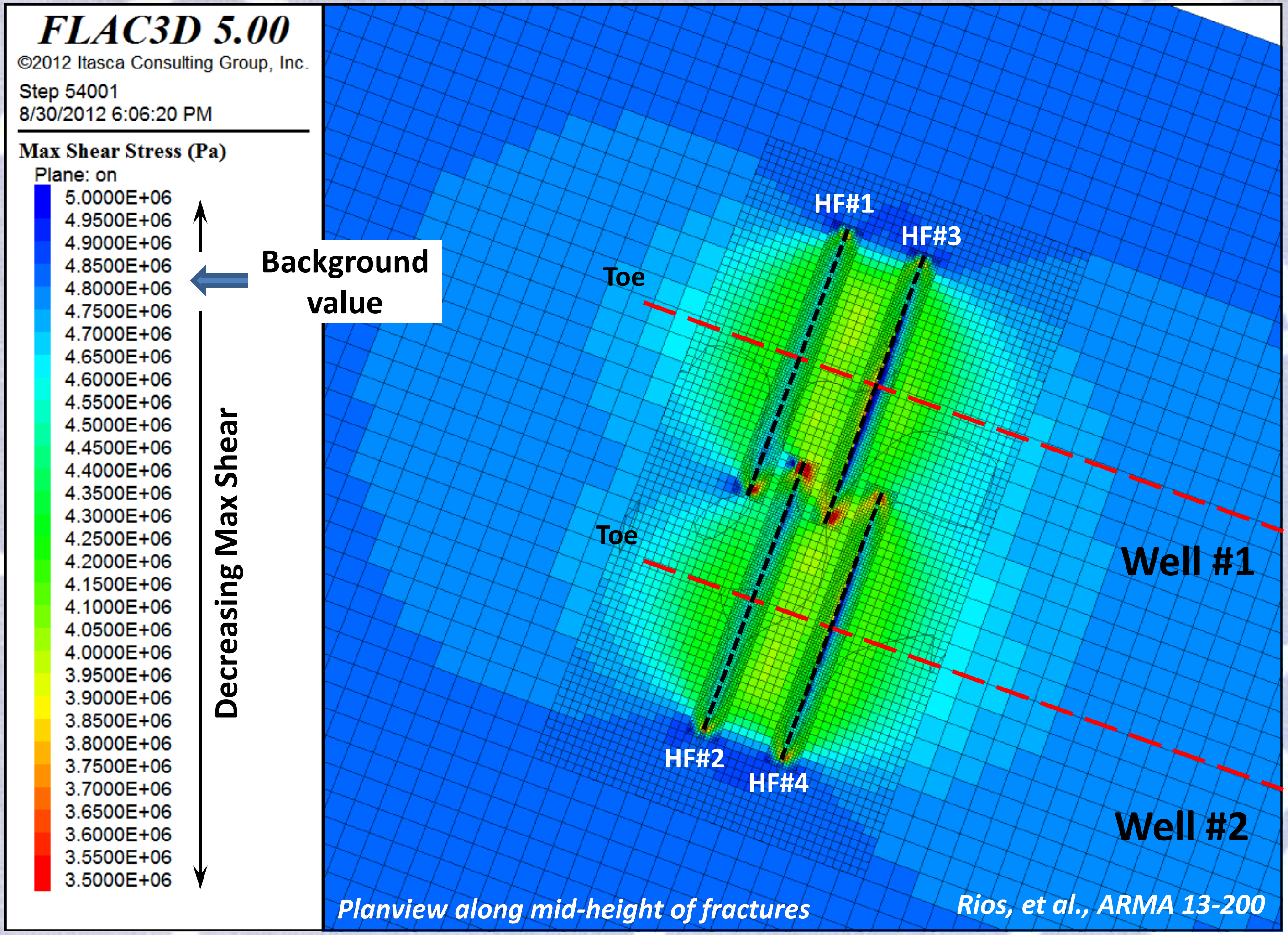
Zipper Frac: Stg#4-ΔShmin



A four stage Zipper frac is shown. The fourth frac has been pumped.

dShmin has increased both towards the Toe (left) and the Heel (right) of both wells. dShmin is higher in the overlap region of the fractures, but there is little effect of the combined wells.

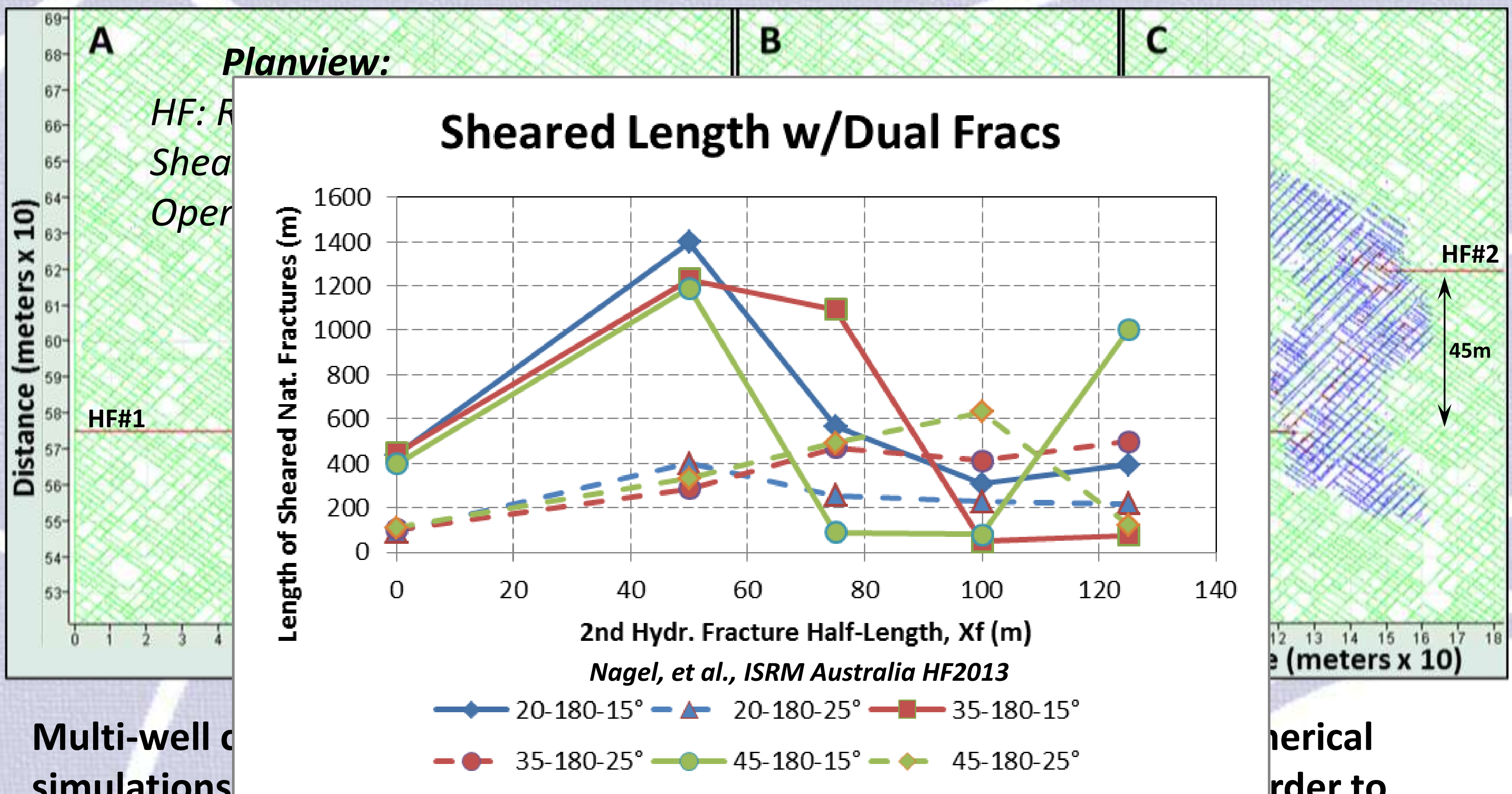
Zipper Frac: Stg#4-ΔMax Shear



A four stage, multi-well completion is shown. The fourth frac has been pumped.

With the exception of minor, very near fracture effects, the Max Shear stress is significantly reduced throughout the region of the two wells.

Complexity: Multi-Well Completion Design



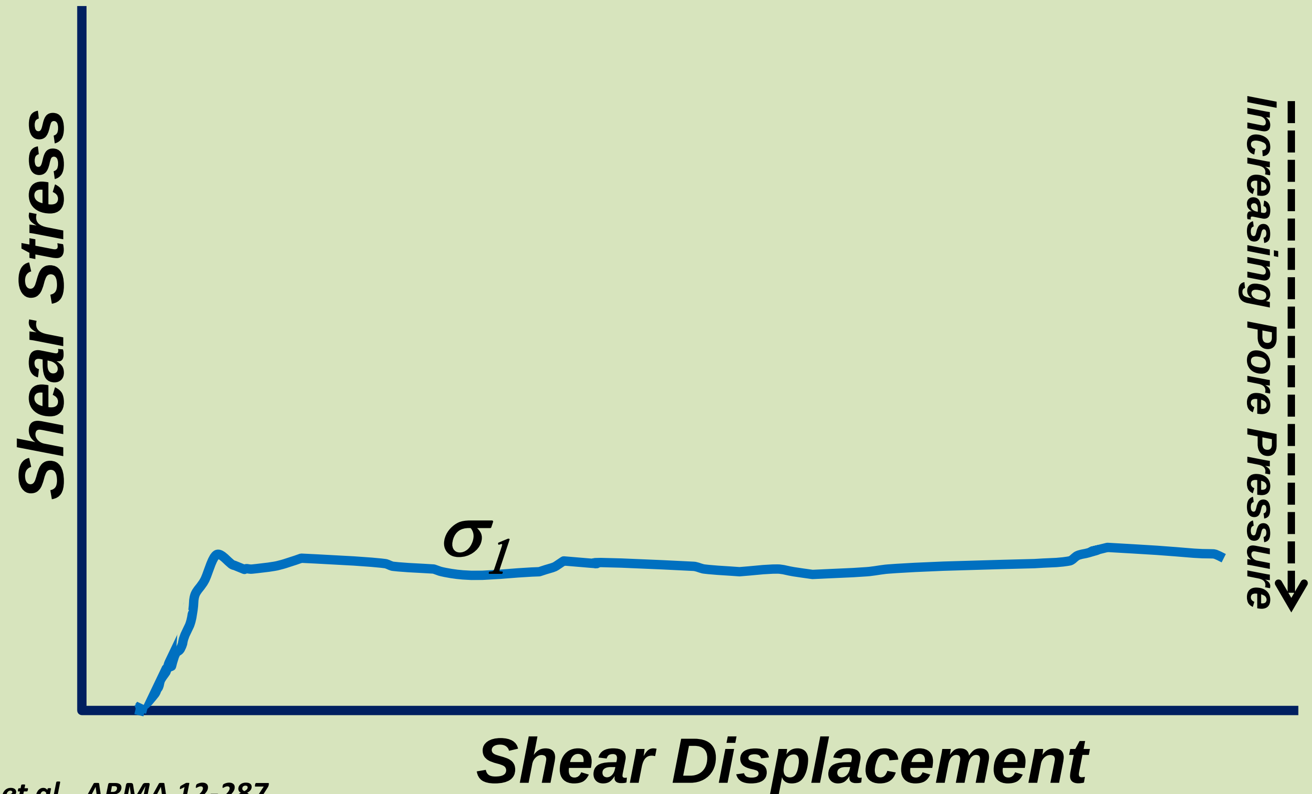
Multi-well c… …nerical simulations … …rder to optimize complexity.

What is Microseismicity??

Microseismicity is the acoustic representation of the energy release from rock failure

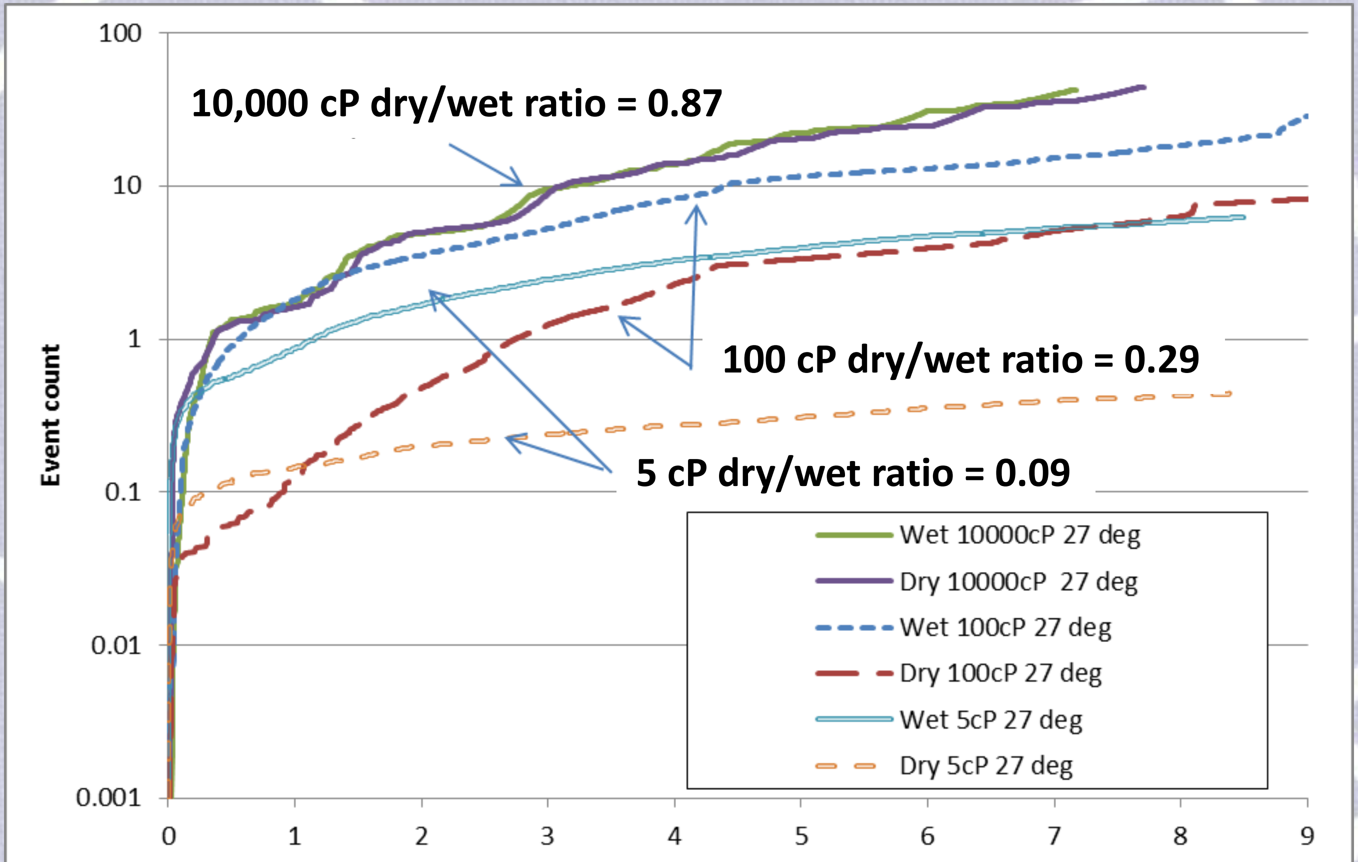
Generating Mechanism (Transduction)	→	Acoustic Wave Propagation	→	Reception (Transduction)
Geomechanics		*Velocity Model* *Ray Paths*		*Geophones* *Array Setup* *Signal/Noise*

NF Behavior: Coupled Effects



Nagel, et al., ARMA 12-287
Nagel, et al., RMRE V46N3

Understanding SRV: 'Dry'/'Wet' Event Ratio as a Function of Fluid Viscosity

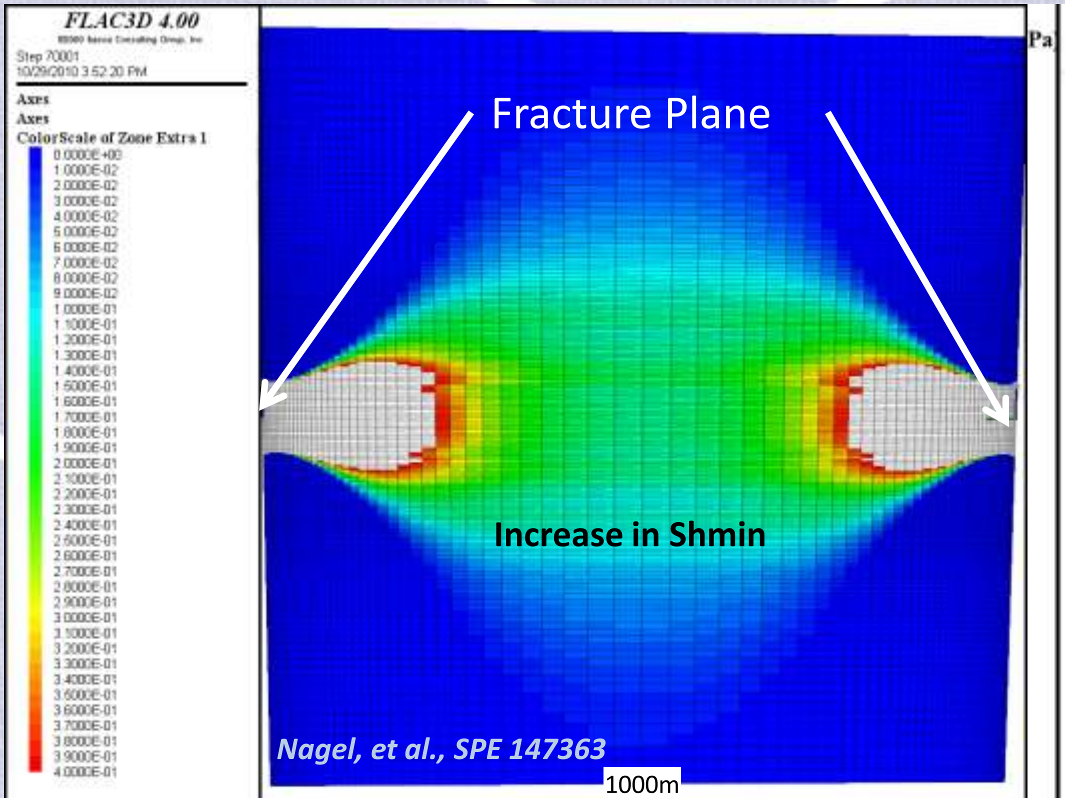


Nagel, et al., SPE 159791

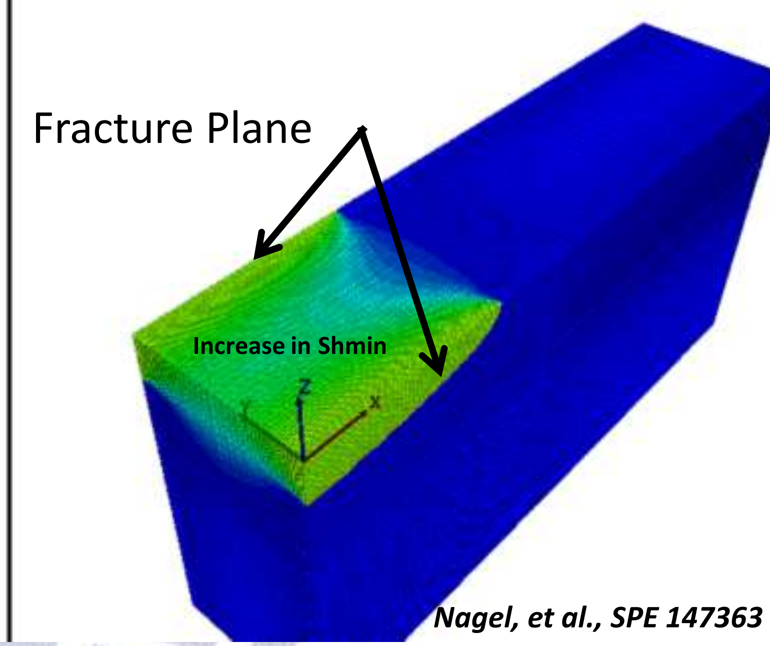
Increasing fluid viscosity significantly increases the ratio of 'dry' to 'wet' microseismic events during the numerical simulation of hydraulic fracturing in fractured shale. 'Dry' events are likely not in hydraulic communication with the wellbore.

Microseismicity & Stress Shadows

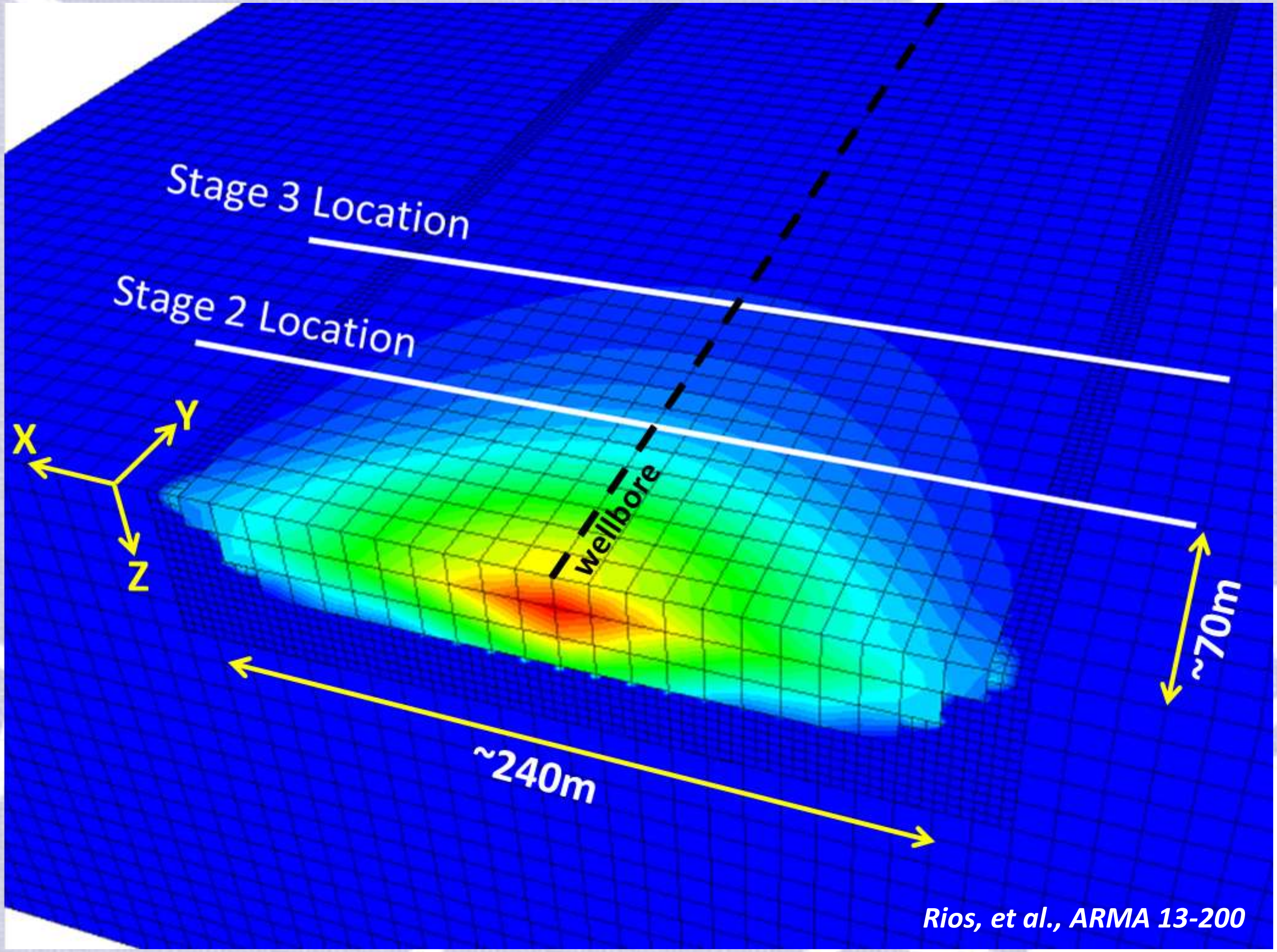
The displacement of the hydraulic fracture alters the stress field – creating the stress shadow effect.



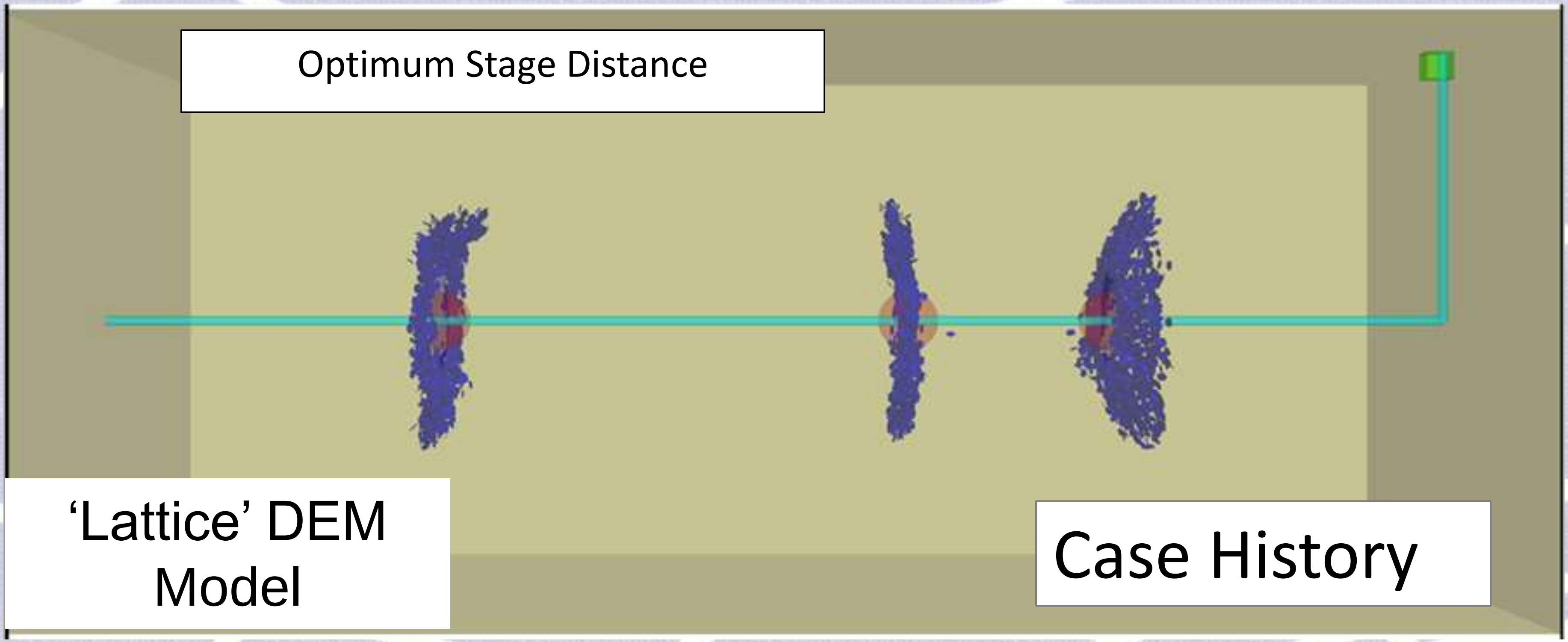
Inter-fracture stress increase due to multiple hydraulic fractures.



Single Stage Stress Effect

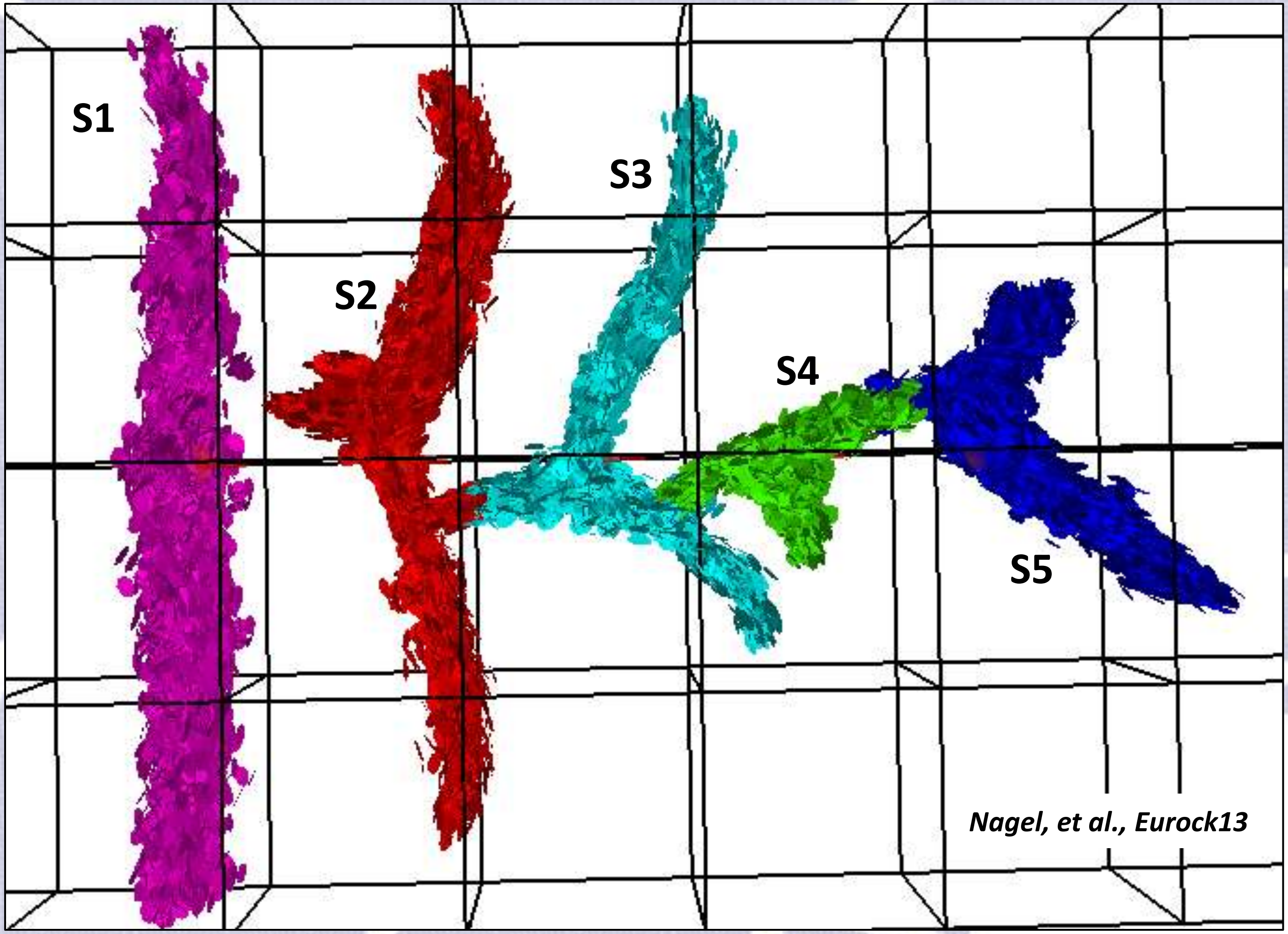


Stress Shadows: Influence on Stimulation Design – HF Rotation



When the stage spacing is large enough, there is little stress shadow effect from stage to stage; however, when stages are small enough, successive HFs will grow away (towards lower stress) and take on curved or conical shapes. In the extreme, they may rotate 90˚

Stress Shadows – Extreme Rotations



Itasca Houston Relevant Publications

1. Nagel, N.B., F. Zhang, M. Sanchez-Nagel and B. Lee, 2013, "***Evaluation of Stress Changes Due to Multi-Stage Hydraulic Fracturing - Consideration of Field Results***", presented at Rock Mechanics for Resources, Energy and Environment, Eurock13, the ISRM International Symposium, Wroclaw, Poland, 21-26 September.
2. Garcia, X., N.B. Nagel, F. Zhang, M. Sanchez-Nagel and B. Lee, 2013, "***Revisiting Vertical Hydraulic Fracture Propagation Through Layered Formations - A Numerical Evaluation***", Paper ARMA 13-203 presented at 47th US Rock Mechanics/Geomechanics Symposium, San Francisco, CA, USA, 23-26 June.
3. Rios, A.M., G. Gutierrez, N.B. Nagel, F. Zhang, M. Sanchez-Nagel and B. Lee, 2013, "***Stress Shadow Evaluations for Chicontepec - Evaluating New Completion Options***", Paper ARMA 13-200 presented at 47th US Rock Mechanics/Geomechanics Symposium, San Francisco, CA, USA, 23-26 June.
4. Zhang, F., N.B. Nagel, B. Lee and M. Sanchez-Nagel, 2013, "***The Influence of Fracture Network Connectivity on Hydraulic Fracture Effectiveness and Microseismcity Generation***", Paper ARMA 13-199 presented at 47th US Rock Mechanics/Geomechanics Symposium, San Francisco, CA, USA, 23-26 June.
5. Zhang, F., N.B. Nagel, X. Garcia, B. Lee and M. Sanchez-Nagel, 2013, "***Fracture Network Connectivity - A Key To Hydraulic Fracturing Effectiveness and Microseismcity Generation***", presented at ISRM International Conference for Effective and Sustainable Hydraulic Fracturing, Brisbane, Australia, 20-22 May.
6. Nagel, N.B., F. Zhang, M. Sanchez-Nagel, X. Garcia, and B. Lee, 2013, "***Quantitative Evaluation of Completion Techniques on Influencing Shale Fracture Complexity***", presented at ISRM International Conference for Effective and Sustainable Hydraulic Fracturing, Brisbane, Australia, 20-22 May.
7. Savitski, A. A., M. Lin, A. Riahi, B. Damjanac and N.B. Nagel, 2013, "***Explicit Modeling of Hydraulic Fracture Propagation in Fractured Shales***", in International Petroleum Technology Conference, Beijing, China.
8. Nagel, N.B., M. Sanchez-Nagel, F. Zhang, X. Garcia, and B. Lee, 2013, "***Coupled Numerical Evaluations of the Geomechanical Interactions Between a Hydrualic Fracture Stimulation and a Natural Fracture System in Shale Formations***", Rock Mechanics and Rock Engineering, DOI 10.1007/s00603-013-0391-x
9. Pettitt, W.S., M. Pierce, B. Damjanac, J. Hazzard, L. Lorig, C. Fairhurst, M. Sanchez-Nagel, N.B. Nagel, J. Reyes-Montes, J. Andrews and R.P. Young, 2012, "***Combining Microseismic Imaging and Hydrofractur Numerial Simulations***", Paper ARMA 12-554 presented at the 46th U.S. Rock Mechanics Symposium, Chicago, Illinois, USA.
10. Pettitt, W.S., B. Damjanac, J. Hazzard, Y. Han, M. Sanchez-Nagel, N.B. Nagel, J. Reyes-Montes and R.P. Young, 2012, "***Engineering Hydraulic Treatment of Existing Fracture Networks***", Paper SPE 160019 presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Texas, USA.

Itasca Houston Relevant Publications

11. Nagel, N.B., M. Sanchez-Nagel, X. Garcia, and B. Lee, 2012, "***Understanding "SRV": A Numerical Investigation of "Wet" vs. "Dry" Microseismicity During Hydraulic Fracturing***", Paper SPE 159791 presented the SPE Annual Technical Conference and Exhibition held in San Antonio, Texas, USA, 8-10 October.
12. Nagel, N.B., M. Sanchez-Nagel, X. Garcia, and B. Lee, 2012, "***A Numerical Evaluation of the Geomechanical Interactions Between a Hydraulic Fracture Stimulation and a Natural Fracture System***", ARMA 12-287 presented at the 46th Rock Mechanics / Geomechanics Symposium, Chicago, Illinois, 24-27 June.
13. Nagel, N.B., X. Garcia, B. Lee, and M. Sanchez-Nagel, 2012, "***Hydraulic Fracturing Optimization for Unconventional Reservoirs - The Critical Role of the Mechanical Properties of the Natural Fracture Network***", Paper SPE 161934 presented at the SPE Canadian Unconventional Resources Conference, Calgary, Alberta, Canada, 30 October - 1 November.
14. Nagel, N., M. Sanchez-Nagel, and BT Lee, 2012, "***Gas Shale Hydraulic Fracturing: A Numerical Evaluation of the Effect of Geomechanical Parameters***", Paper SPE 152192 presented at the SPE Hydraulic Fracturing Technology Conference and Exhibition, The Woodlands, Texas, USA, 6-8 February.
15. Pettitt, W.S., M. Pierce, B. Damjanac, J. Hazzard, L. Lorig, C. Fairhurst, I. Gil, M. Sanchez-Nagel, N.B. Nagel, J. Reyes-Montes R.P. Young, 2011, "***Fracture Network Engineering for Hydraulic Fracturing***", The Leading Edge, 30(8), pp844-853.
16. Nagel, N., I. Gil, M. Sanchez-Nagel, and B. Damjanac, 2011, "***Simulating Hydraulic Fracturing in Real Fractured Rock – Overcoming the Limits of Pseudo3D Models***", Paper SPE 140480 presented at the SPE Hydraulic Fracturing Technology Conference and Exhibition, The Woodlands, Texas, USA, 24-26 January.
17. Nagel, N., B. Damjanac, X. Garcia, and M. Sanchez-Nagel, 2011, "***Discrete Element Hydraulic Fracture Modeling - Evaluating Changes in Natural Fracture Aperture and Transmissivity***", Paper SPE 148957 presented at the Canadian Unconventional Resources Conference, Calgary, Alberta, Canada, 15-17 November.
18. Nagel, N. and M. Sanchez-Nagel, 2011, "***Stress Shadowing and Microseismic Events: A Numerical Evaluation***", Paper SPE 147363 presented at the SPE Annual Technical Conference and Exhibition, Denver, Colorado, USA, 30 October-2 November.
19. Gil, I., N.B. Nagel, M. Sanchez-Nagel, and B. Damjanac, 2011, "***The Effect of Operational Parameters on Hydraulic Fracture Propagation in Naturally Fractured Reservoirs - Getting Control of the Fracture Optimization Process***", Paper ARMA 11-391 presented at ARMA 45th U.S. Rock Mechanics/Geomechanics Symposium, San Francisco, California, USA.
20. Damjanac, B., I. Gil, M. Pierce, M. Sanchez-Nagel, A. Van As, and J. McLennan, 2010, "***A New Approach to Hydraulic Fracturing Modeling in Naturally Fractured Reservoirs***", Paper ARMA 10-400 presented at ARMA 44th U.S. Rock Mechanics/5th US-Canadian Rock Mechanics Symposium, Salt Lake City, UT, USA, June 27-30.

Thank you!

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