Hydraulic Fracturing: What we have Learnt and What Challenges Remain: A 40-year Perspective

Mukul M. Sharma,
University of Texas at Austin

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3. Dr. Shuang Zheng (ExxonMobil)
4. Dr. Haotian Wang (ExxonMobil)
5. Dr. Emmanouil Karantinos (ExxonMobil)
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21. Dr. Shivam Agarwal (Spark Cognition)
22. Dr. Sophie Yi (ExxonMobil)
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Past and Present Sponsors of JIP on Hydraulic Fracturing and Sand Control at UT Thank You

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- Schlumberger
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- Talisman Energy
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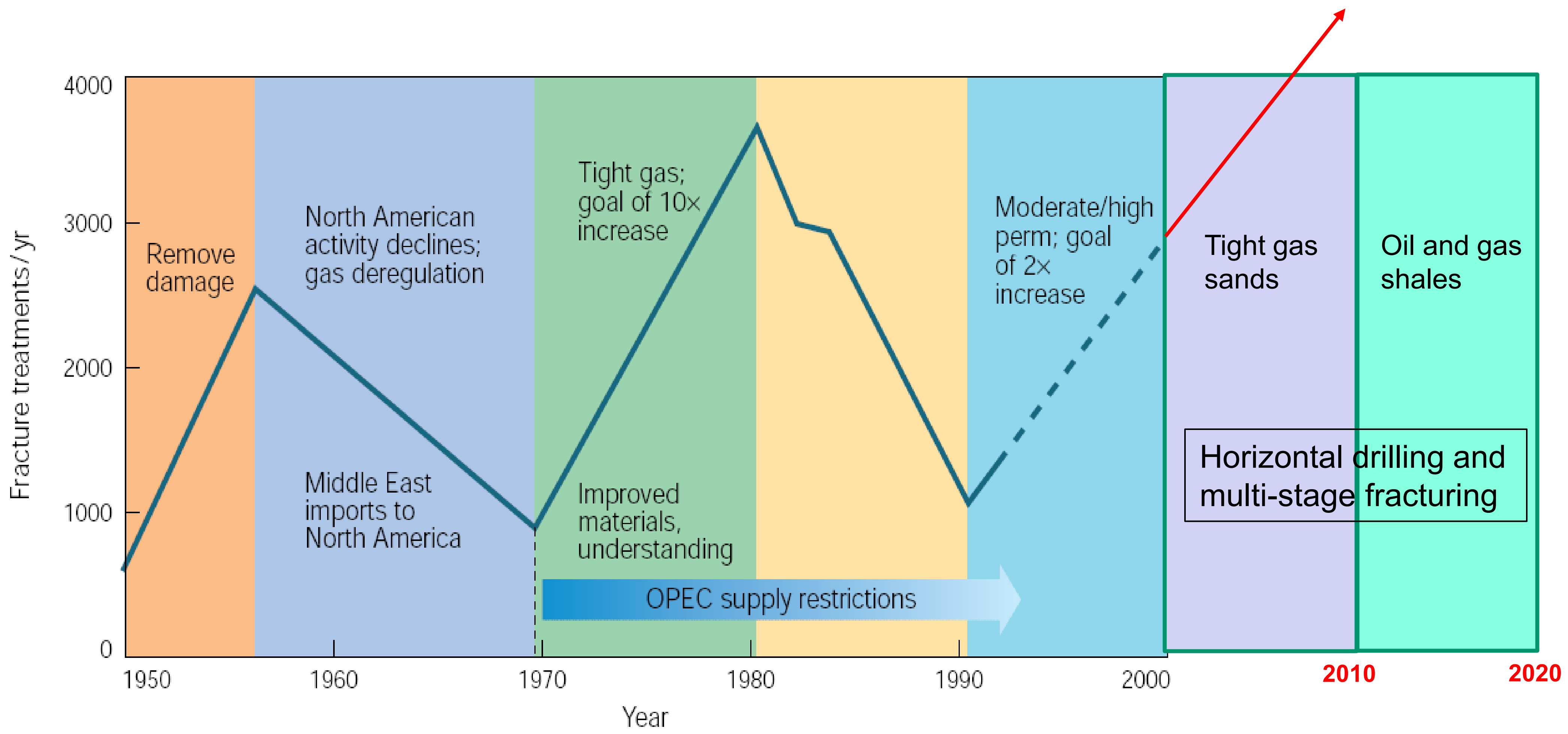
Changing Motivations for Hydraulic Fracturing



Courtesy: SLB

Standard Practices, 1980-2000

- Primary motivation was to bypass near wellbore formation damage
- Conventional formations with modest permeability
- Mostly single stage fracs in vertical wells
- High viscosity frac-fluids (cross-linked and linear gels) to prevent proppant settling and improve proppant coverage
- Breakers widely used to break down gel during flowback
- Low pumping rates (10-30 BPM)
- Large diameter, highly conductive, crush resistant proppant used.
- High proppant concentrations
- Small fluid volumes
- Large number of perforations

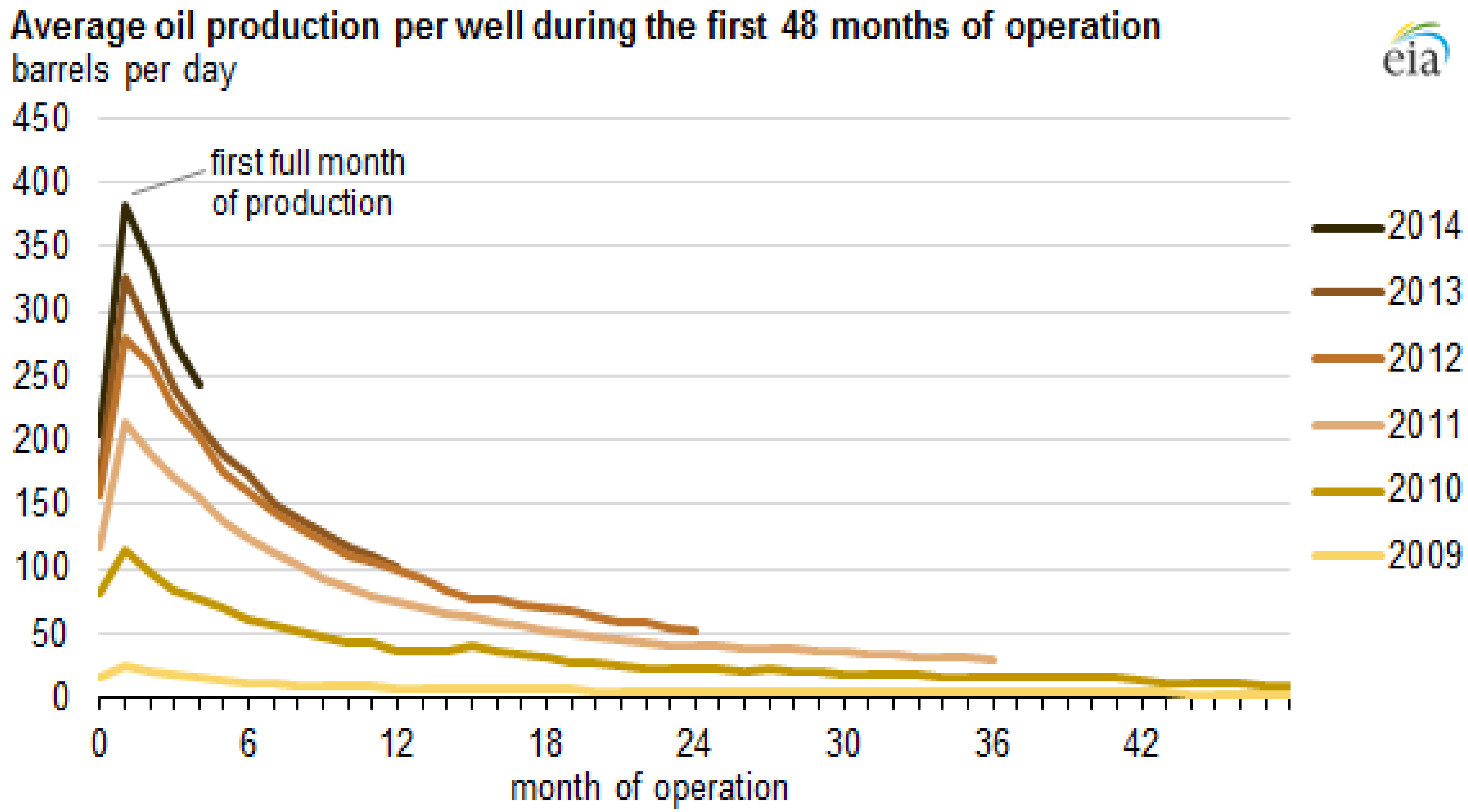
Standard Practices 2010-Today

Almost Exactly the Opposite of pre-2000 Practices

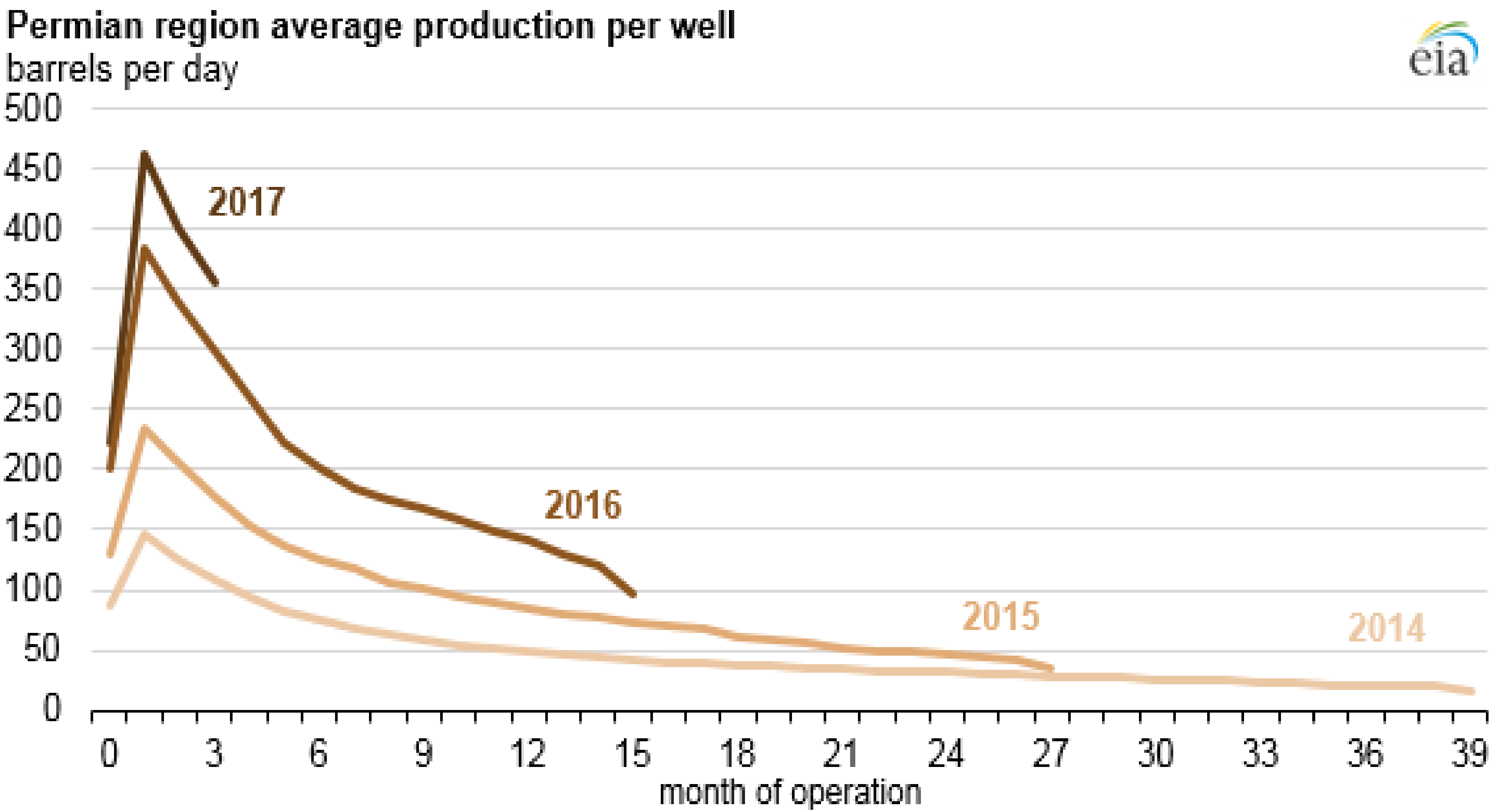
- Primary motivation is to increase surface area of contact between the fracture and the rock by 1 million times.
- Target: All formations (1 D to 10 nD)
- Multi-stage fracs in horizontal wells (hundreds of fracs per well)
- Low viscosity frac-fluids (slick water) to maximize fracture length
- High pumping rates (90-110 BPM)
- Smaller diameter, low-cost proppant
  - For tight rocks FCD >100 even if fracture conductivity is low.
- Large volumes of sand and fluid used (over 10 MMlb of sand and 250Mbbl of slick water per well)
- Low concentrations of proppant.
- Smaller number of perforations

Improvements In Well Production

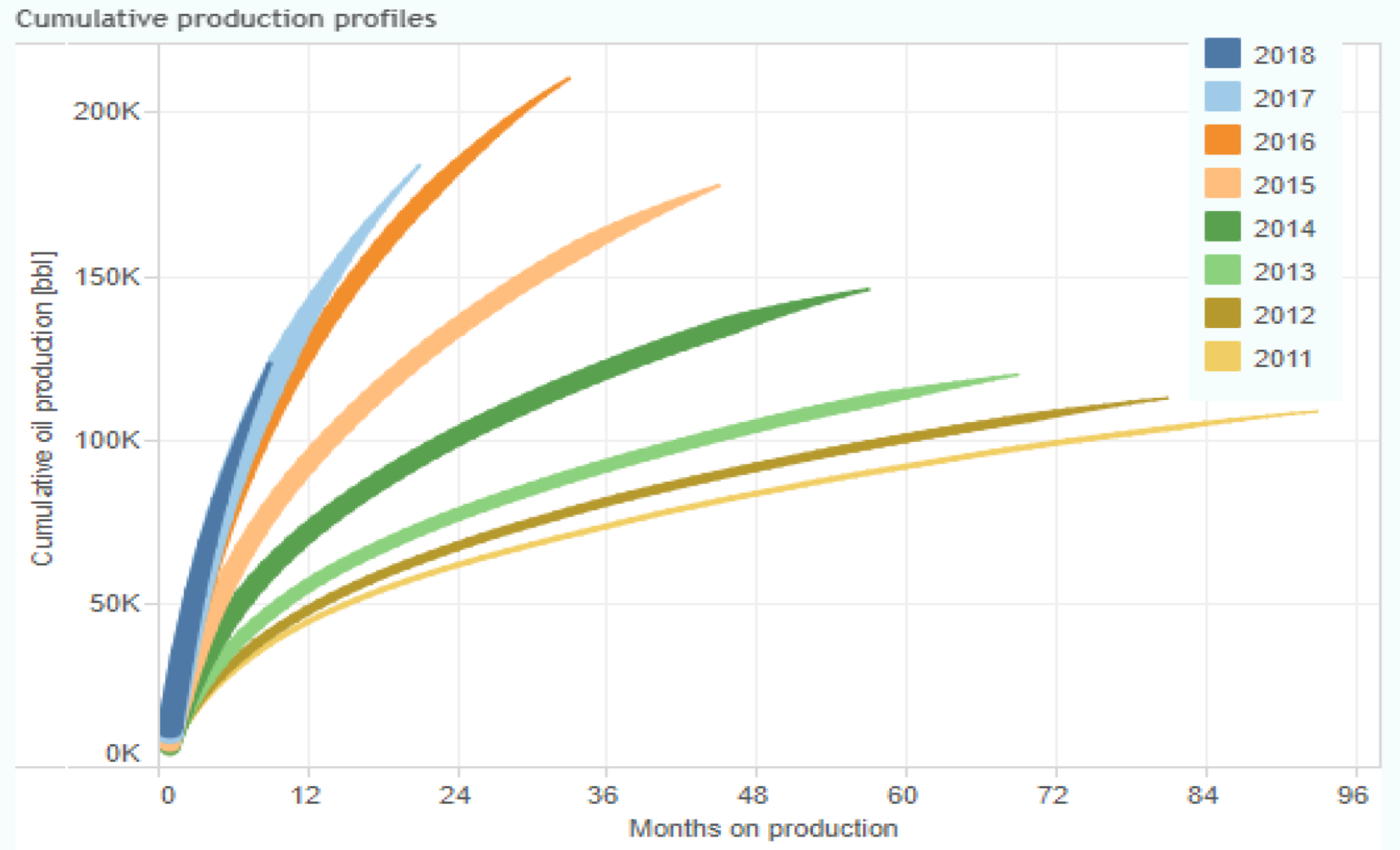
Source: U.S. Energy Information Administration



Improvements in Well Productivity



Well Production in the Wolfcamp Shale



Most Significant Changes in Fracturing

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3. Proppant and fluid selection
4. Refracturing
5. Fracture diagnostic techniques
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6. Interaction of fractures with natural fractures
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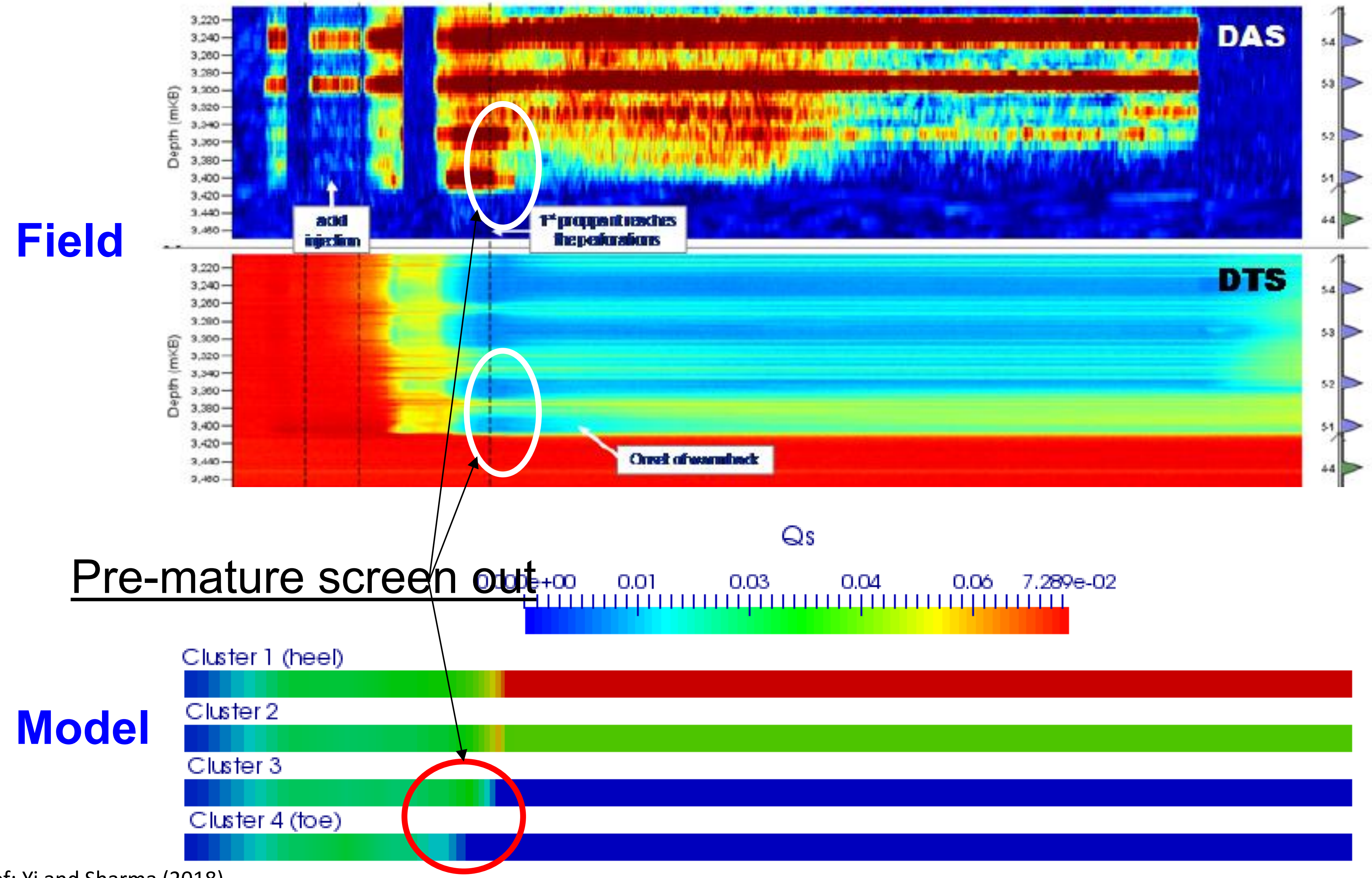
8. Proppant Placement

Extreme Limited Entry

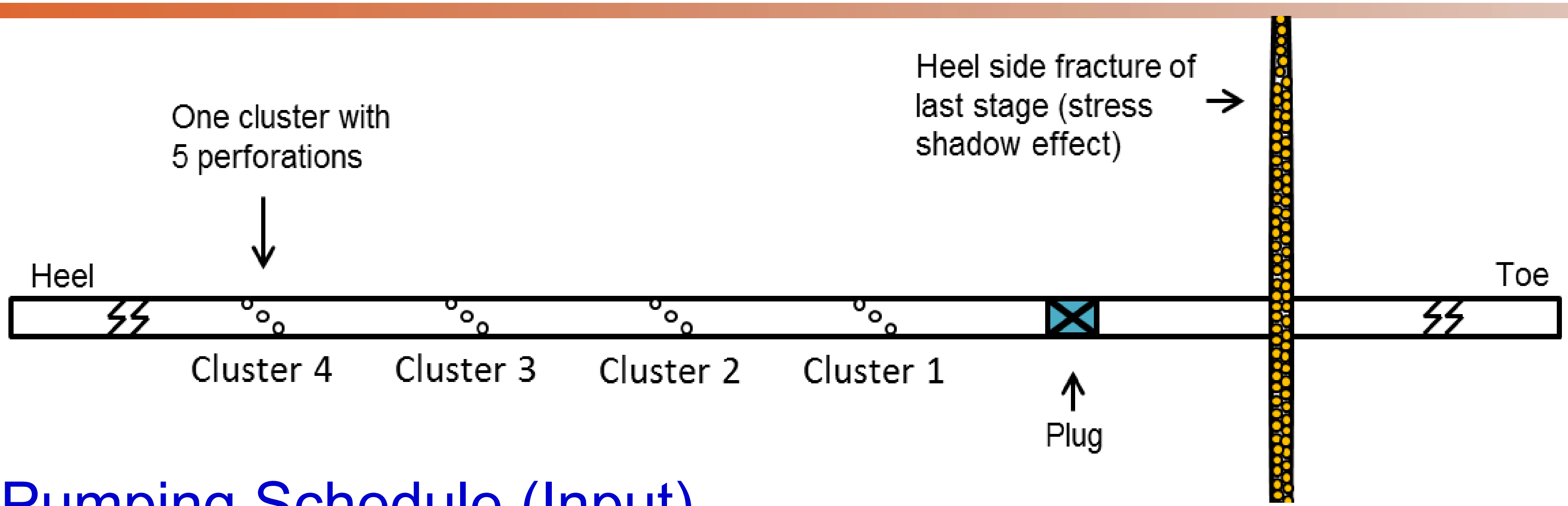
- Diversion of fluid into all clusters can be achieved by ensuring a large pressure drop (rate) through perforations.
- This implies that the number of perforations should be reduced
- Over many years the number of perforations per cluster has been reduced from 10-15 to 1-5.
- This has led to much better fluid distribution in perforations.
- Note that this does not guarantee uniform placement of proppant.

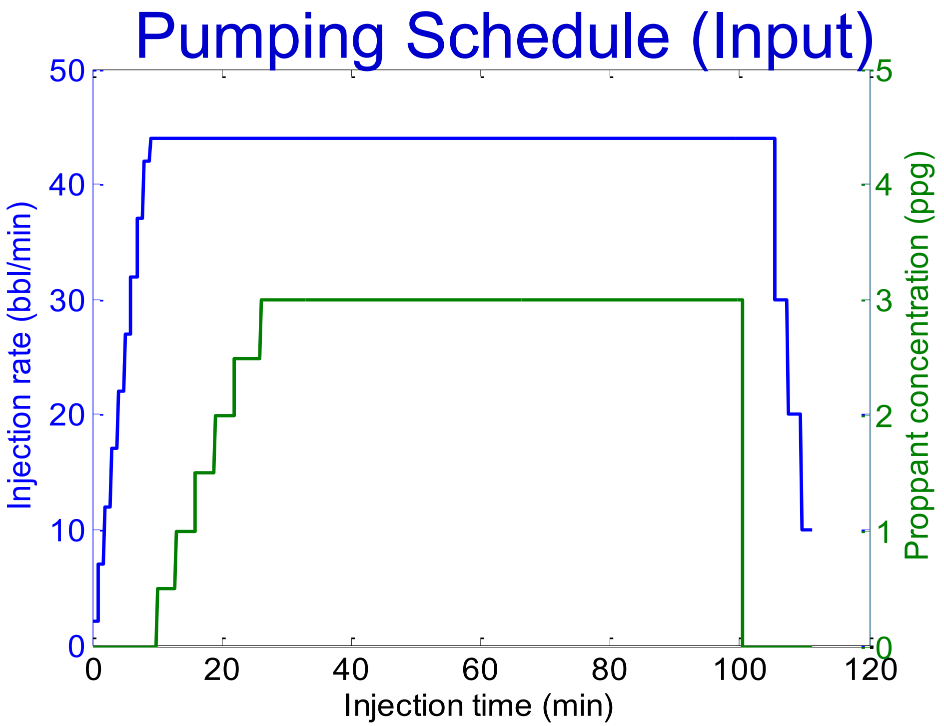
Non-Uniform Proppant Distribution

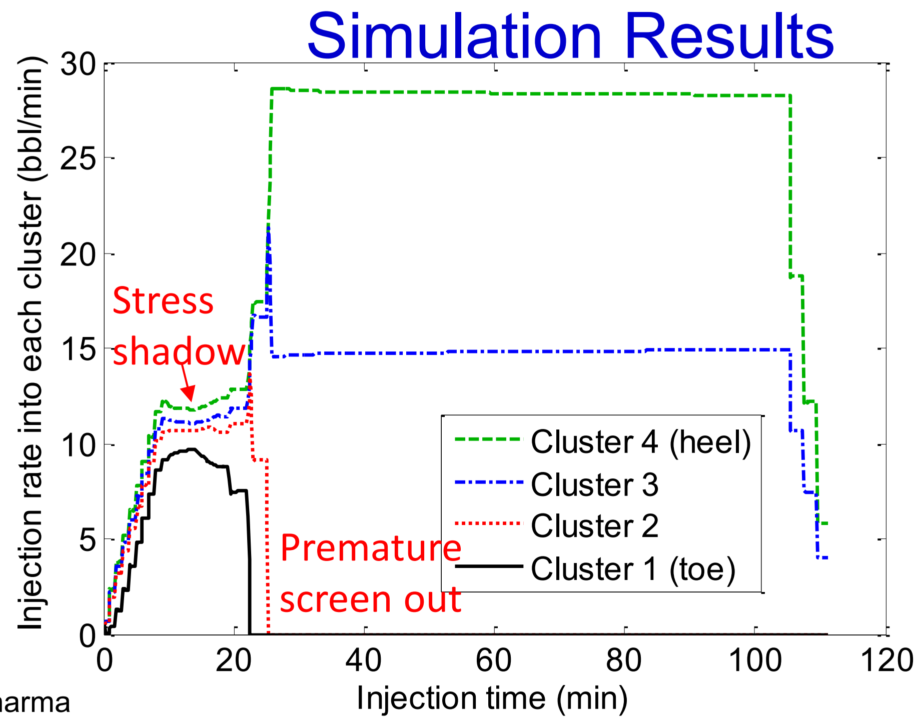


Ref: Yi and Sharma (2018)

Refracs with a Liner: Proppant Placement in New Perfs







Ref: Yi and Sharma (2018)

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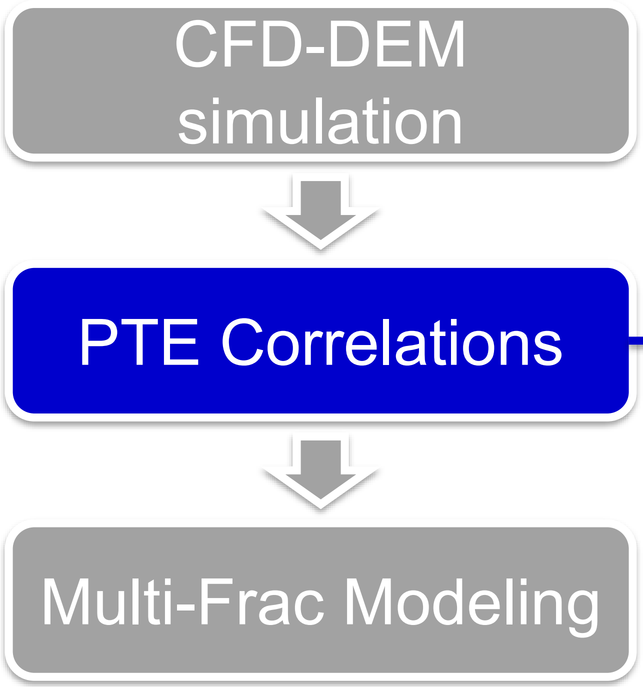
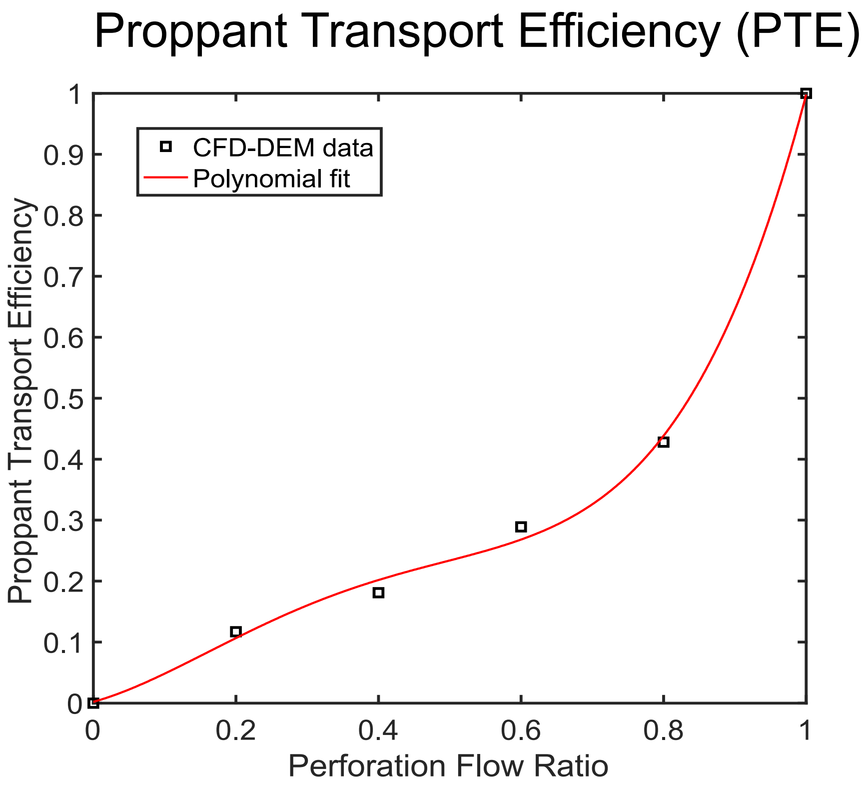




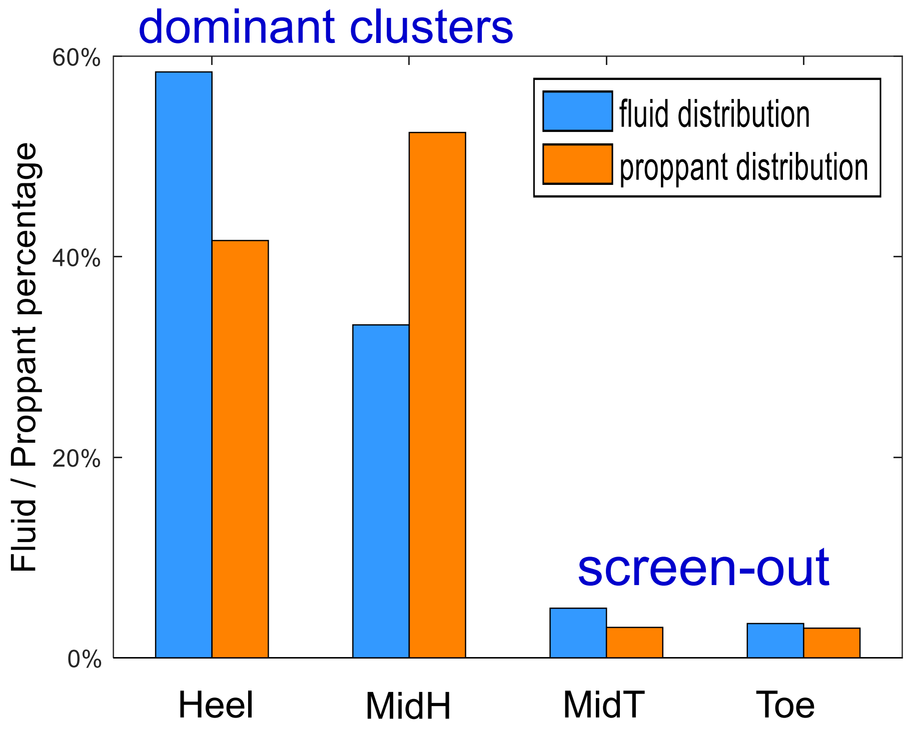
$$PTE = f(D_{well}, D_{perf}, c_{prop}, d_{prop}, \rho_{prop}, Q)$$

Yi, S. S., and M. M. Sharma, "A new method to calculate slurry distribution among multiple fractures during fracturing and refracturing", Journal of Petroleum Science and Engineering, vol. 170, pp. 304-314, 11/2018.

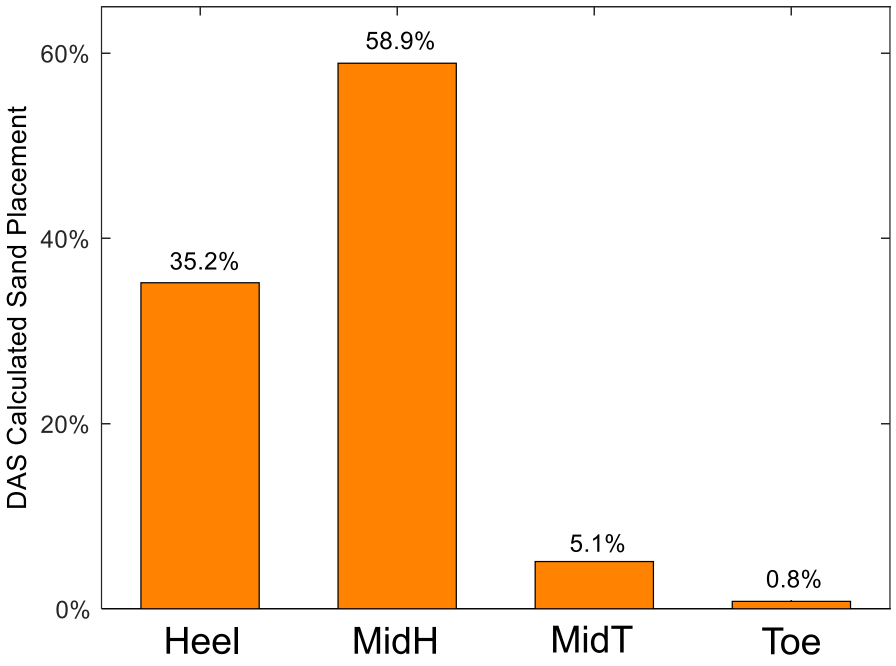
Yi, S. S., C-H. Wu, and M. M. Sharma, "Proppant Distribution Among Multiple Perforation Clusters in Plug-and-Perforate Stages", SPE Production & Operations, vol. Preprint, 03/2018.

Non-Uniform Proppant Distribution

Simulation (Fluid & Proppant)



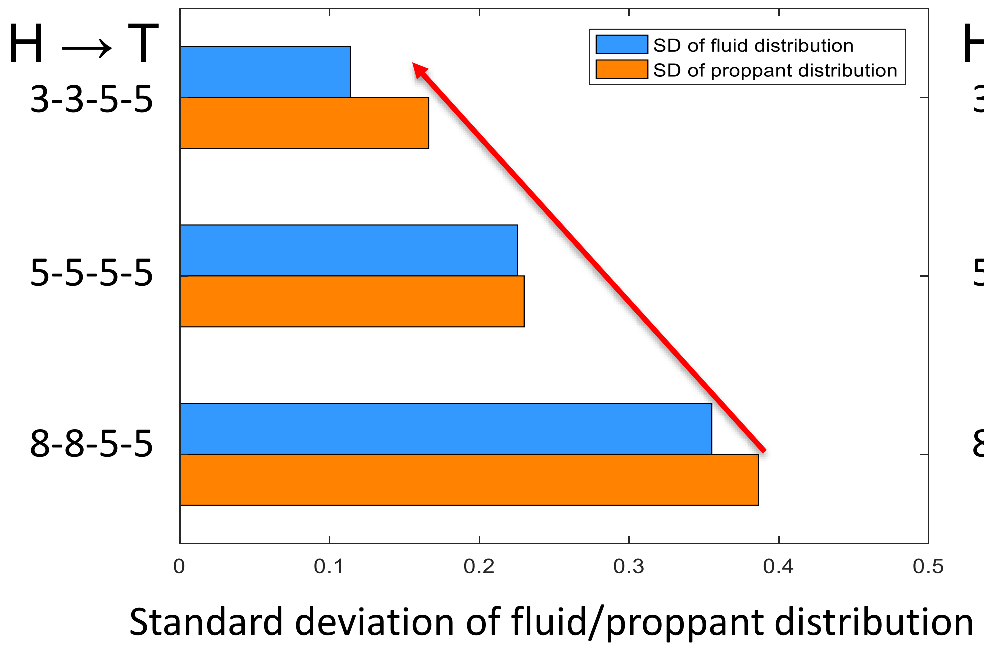
From DAS(Proppant)

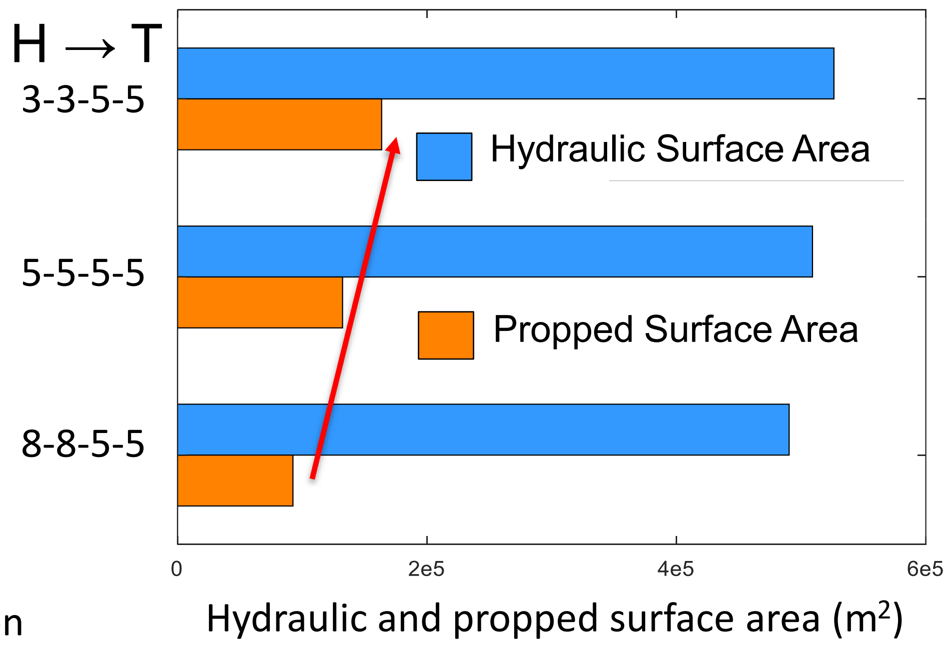


Ref: Yi and Sharma (2018); Molenaar & Cox (2013)

Perforation Design for Uniform Proppant Placement

- Fewer perforations near heel √
- More perforations near heel X
- Uniform distribution -> more propped surface area





Publications Related to Proppant Placement

- Yi, S. S., C-H. Wu, and M. M. Sharma, "Optimization of Plug-and-Perforate Completions for Balanced Treatment Distribution and Improved Reservoir Contact", SPE Journal, vol. 25, issue 02, pp. 558-572, 04/2020.
- Wu, C-H., and M. M. Sharma, "Modeling Proppant Transport Through Perforations in a Horizontal Wellbore", SPE Journal, vol. 24, issue 04, pp. 1777-1789, 08/2019.
- Yi, S. S., R. Manchanda, M. M. Sharma, and N. P. Roussel, "Preventing Heel Dominated Fractures in Horizontal Well Refracturing", SPE Hydraulic Fracturing Technology Conference & Exhibition, The Woodlands, February 5-7, 2019.
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- Yi, S. S., C-H. Wu, and M. M. Sharma, "Proppant Distribution Among Multiple Perforation Clusters in Plug-and-Perforate Stages", SPE Production & Operations, vol. 33, issue 04, pp. 654-665, 11/2018.
- Shrivastava, K., and M. M. Sharma, "Proppant Transport in Complex Fracture Networks", SPE Hydraulic Fracturing Technology Conference and Exhibition, The Woodlands, Texas, U.S.A., January 23-25, 2018.
- Wu, C-H., S. S. Yi, and M. M. Sharma, "Proppant Distribution Among Multiple Perforation Clusters in a Horizontal Wellbore", SPE Hydraulic Fracturing Technology Conference and Exhibition, The Woodlands, Texas, U.S.A., January 24-28, 2017.
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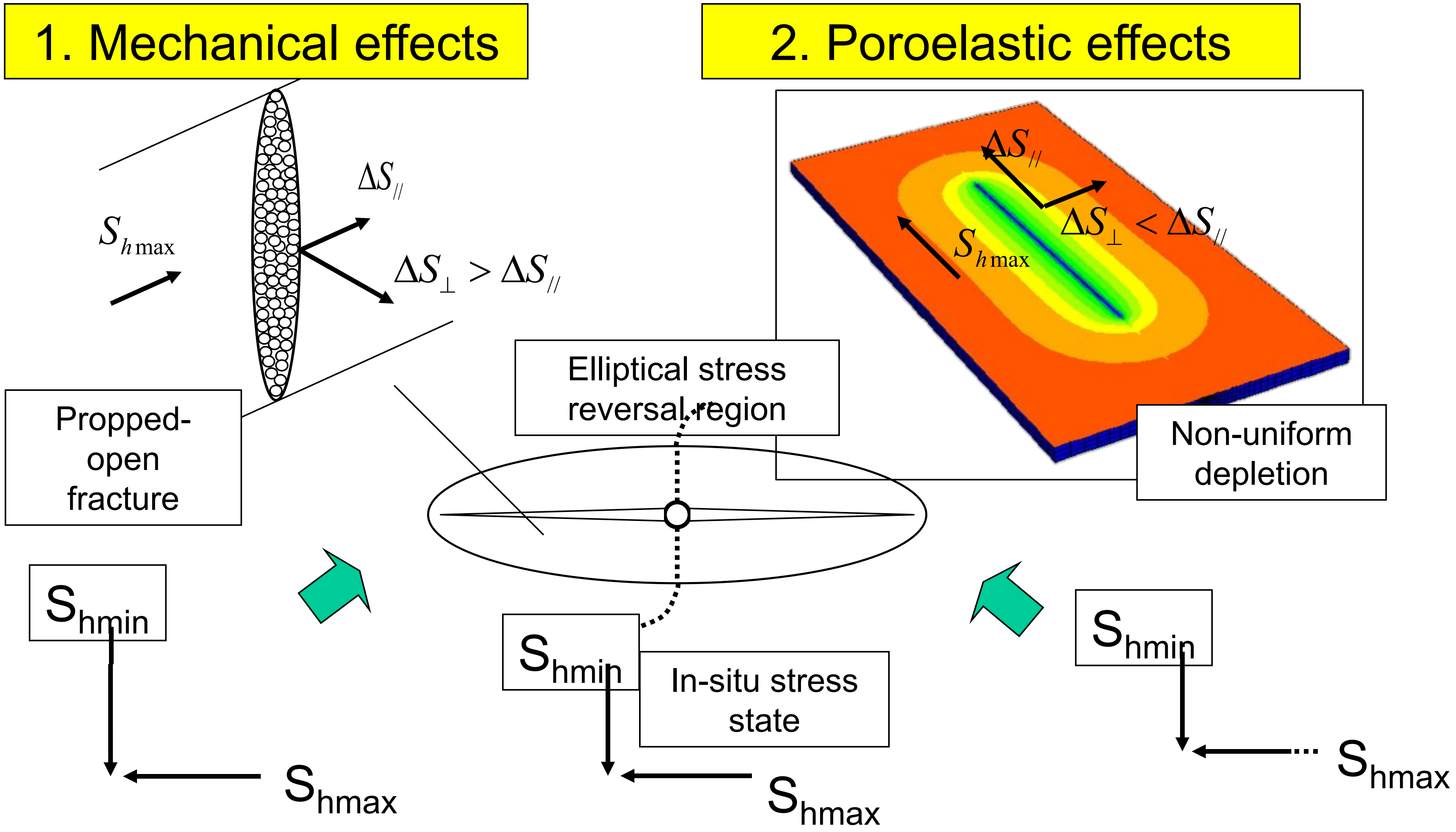
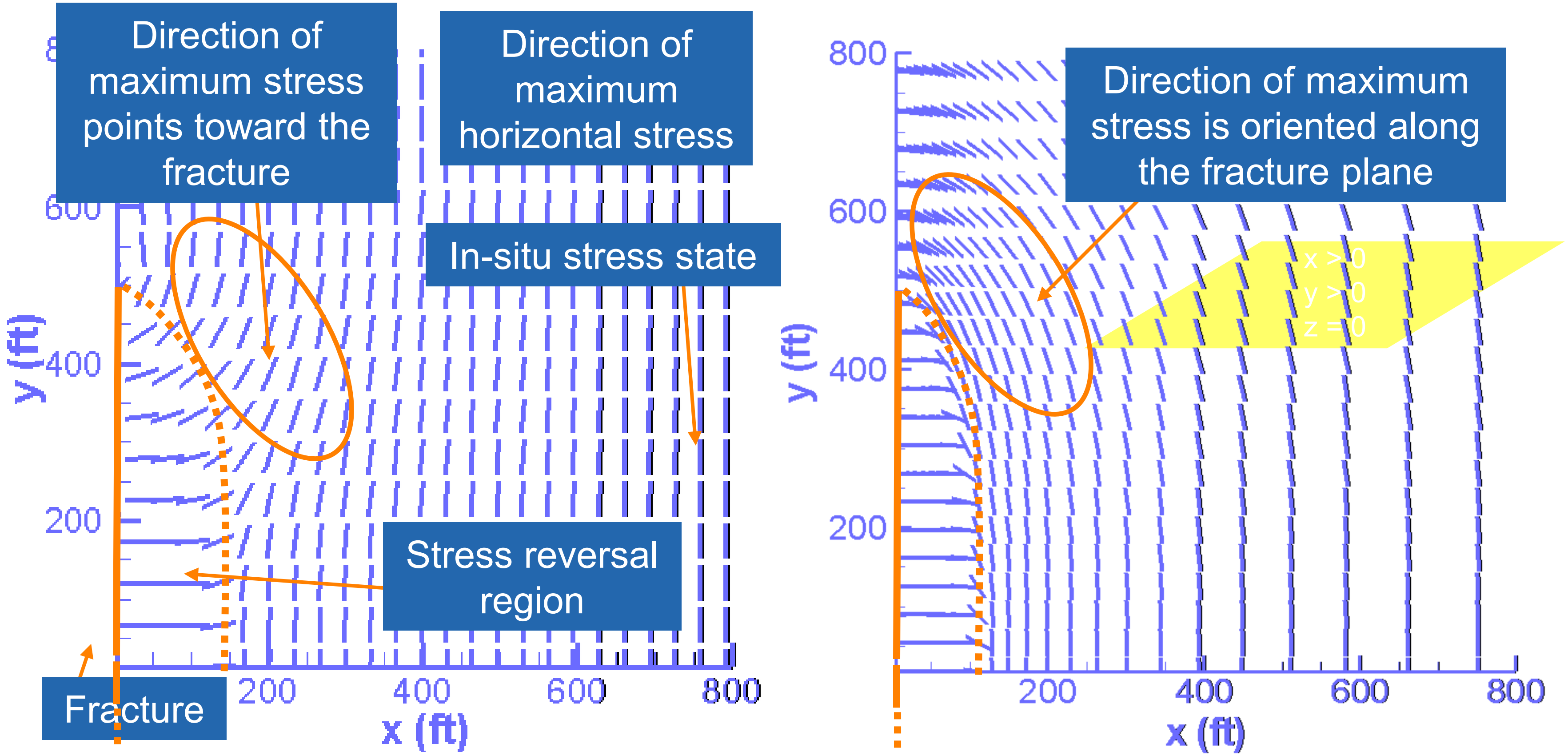
Two Contributors to Stress Reorientation



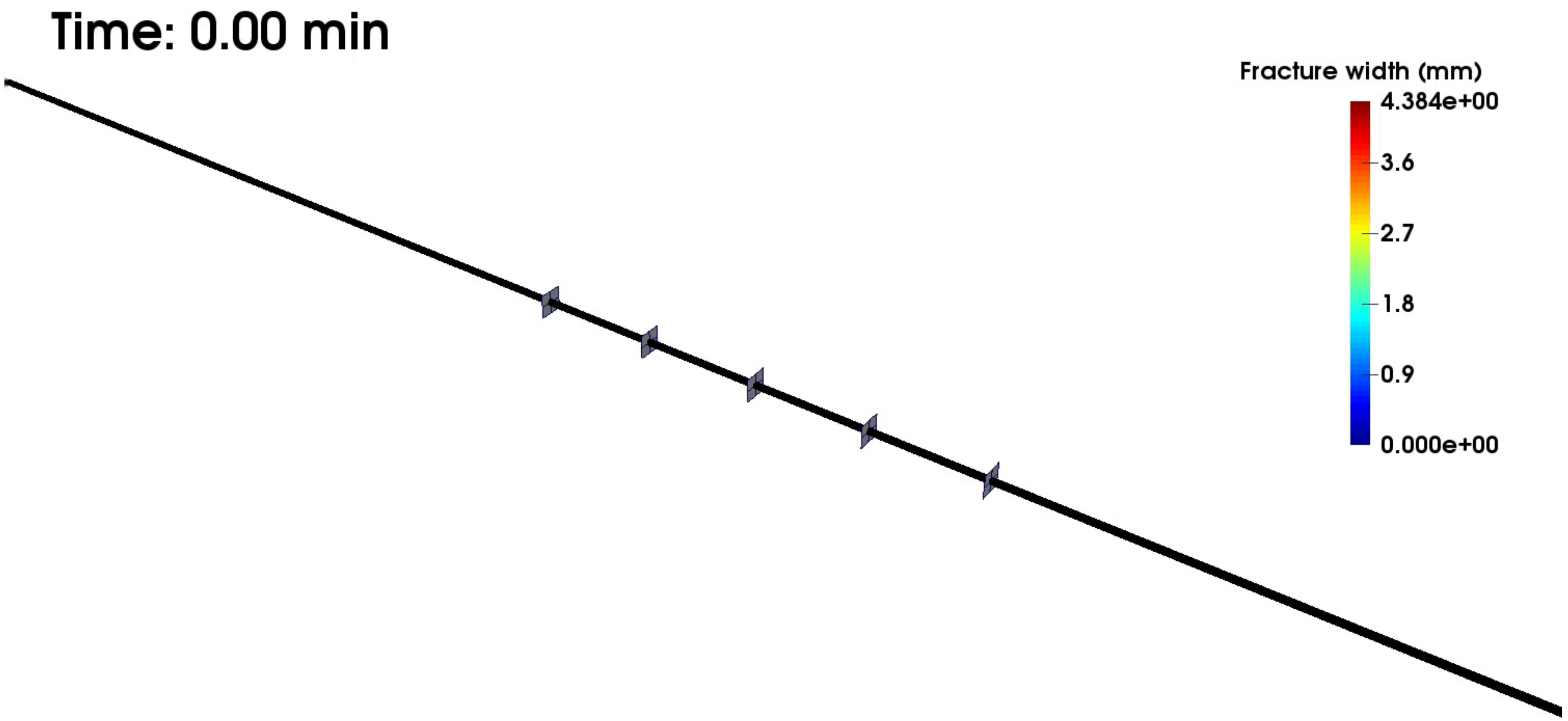
Mechanical and Poroelastic Stress Reorientation



Mechanical Effects
(fracture opening)

Poroelastic Effects
(production well)

Five P-n-P Fractures Propagating Simultaneously

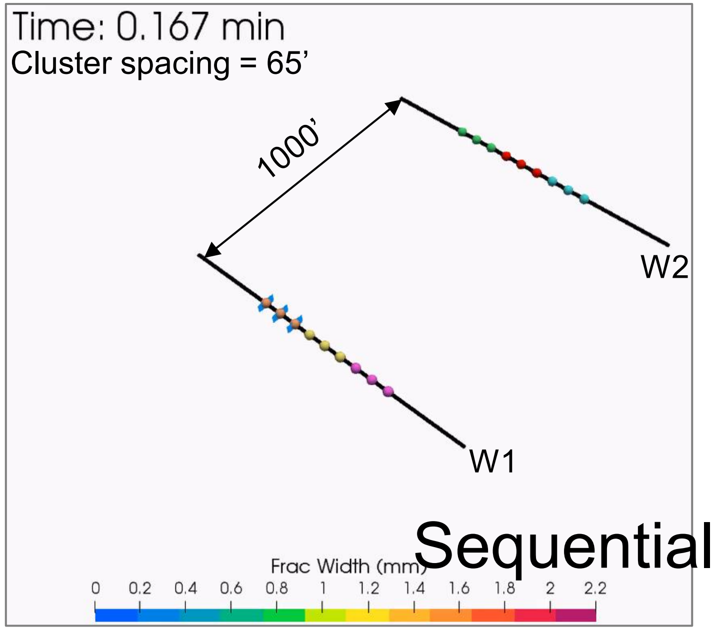


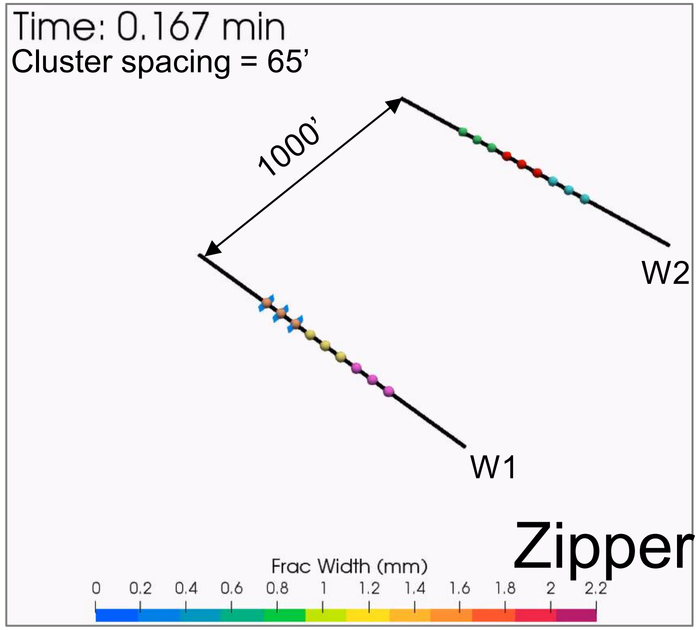
- Simulation results from Multi-Frac-3D (2017)
- The axis along the well has been stretched 3 times for visualization purposes

Multiple Well-Stage Fracture Propagation

Sequential vs. zipper fracturing

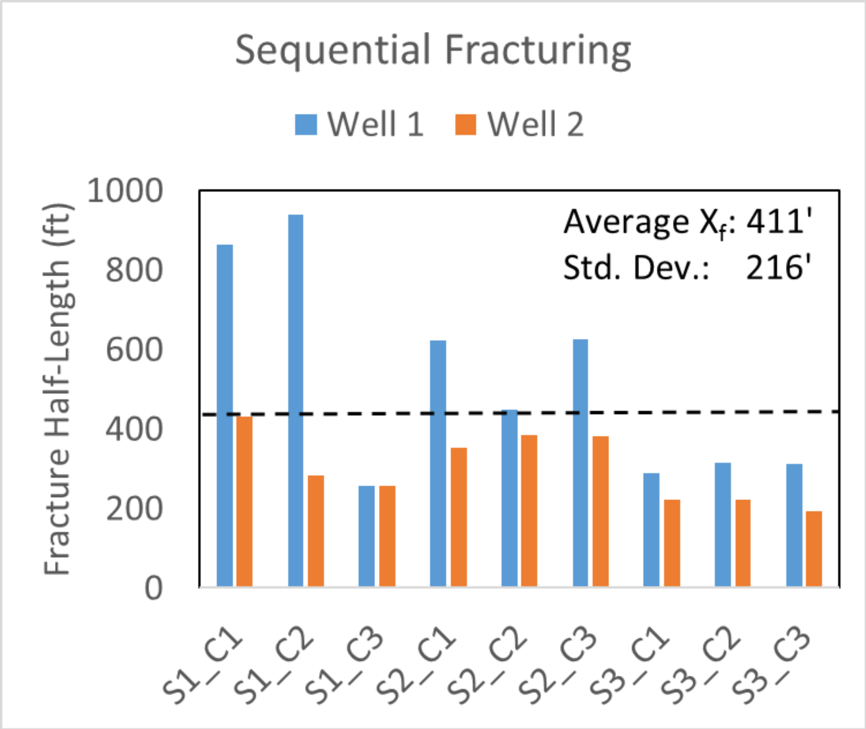
- Zipper fracturing reduces stress shadow (orthogonal fractures).
- Staggering clusters by ~30' reduces stress interference (longer fractures)
- Zipper fracturing also significantly reduces the time needed to fracture both wells
- 2 to 4 well zipper fracs are now routinely done and are found to be more productive.
- In multi-well pads, the sequence of fracturing matters (and we now understand why).

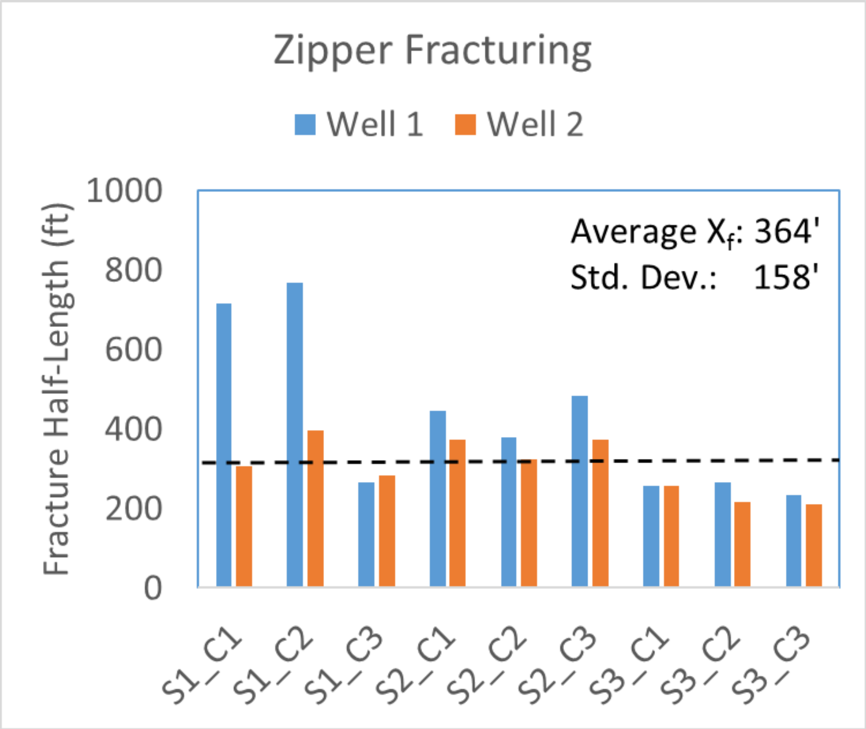




Multiple Well-Stage Fracture Propagation

Impact of fracture sequencing

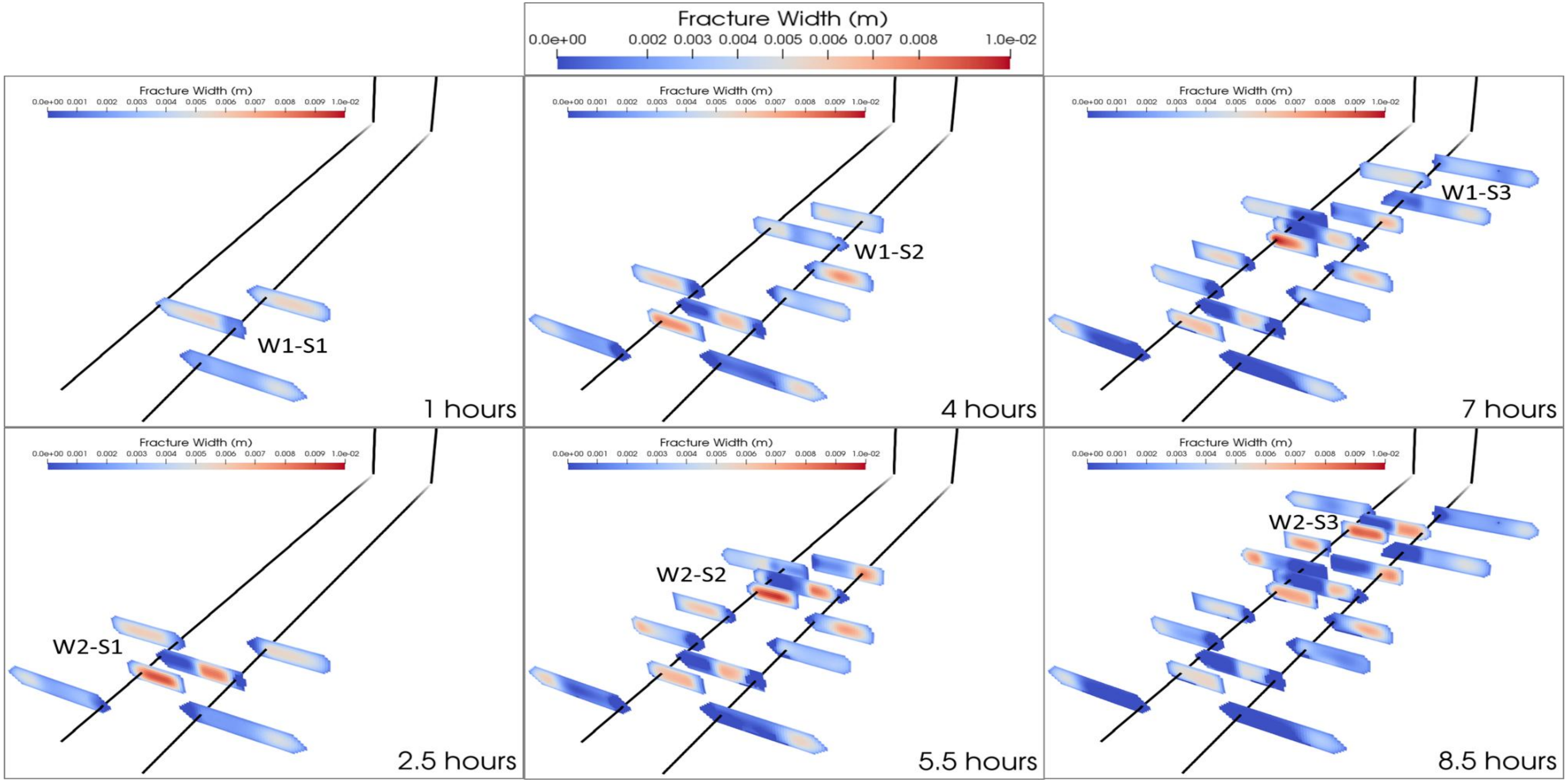




- Longer fractures with sequential fracturing.
- More uniform fractures with zipper fracturing sequence.
- More stress shadow in zipper fracturing induces smaller lengths.
- Second well’s fractures are shorter than the first well’s fractures.

Multiple Well-Stage Fracture Propagation

Staggering zipper fractured wells

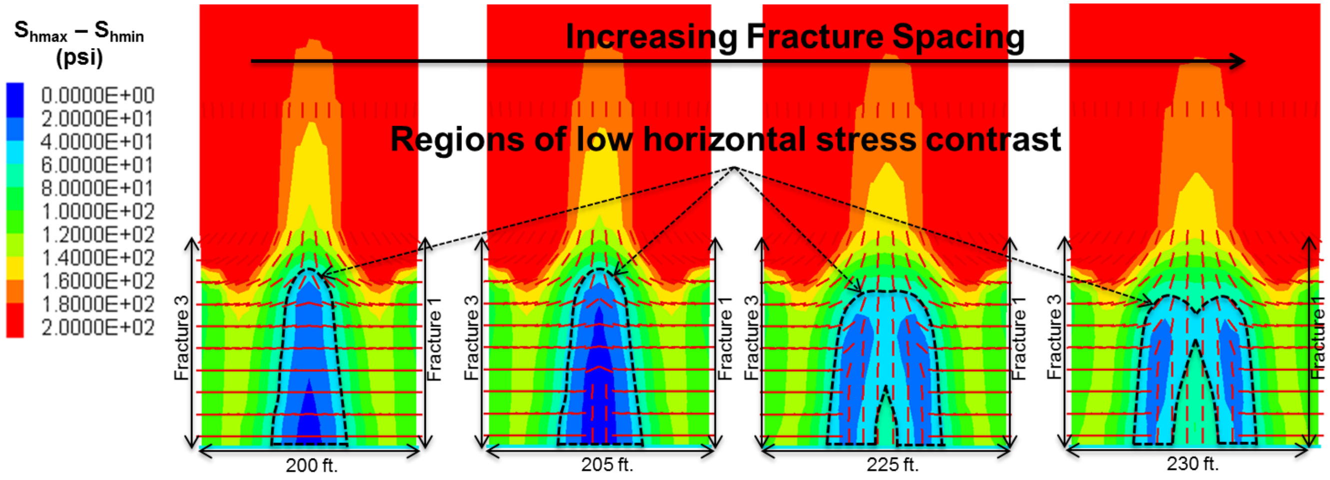


Simulation results from Multi-Frac-3D (2018)

Multiple Well-Stage Fracture Propagation

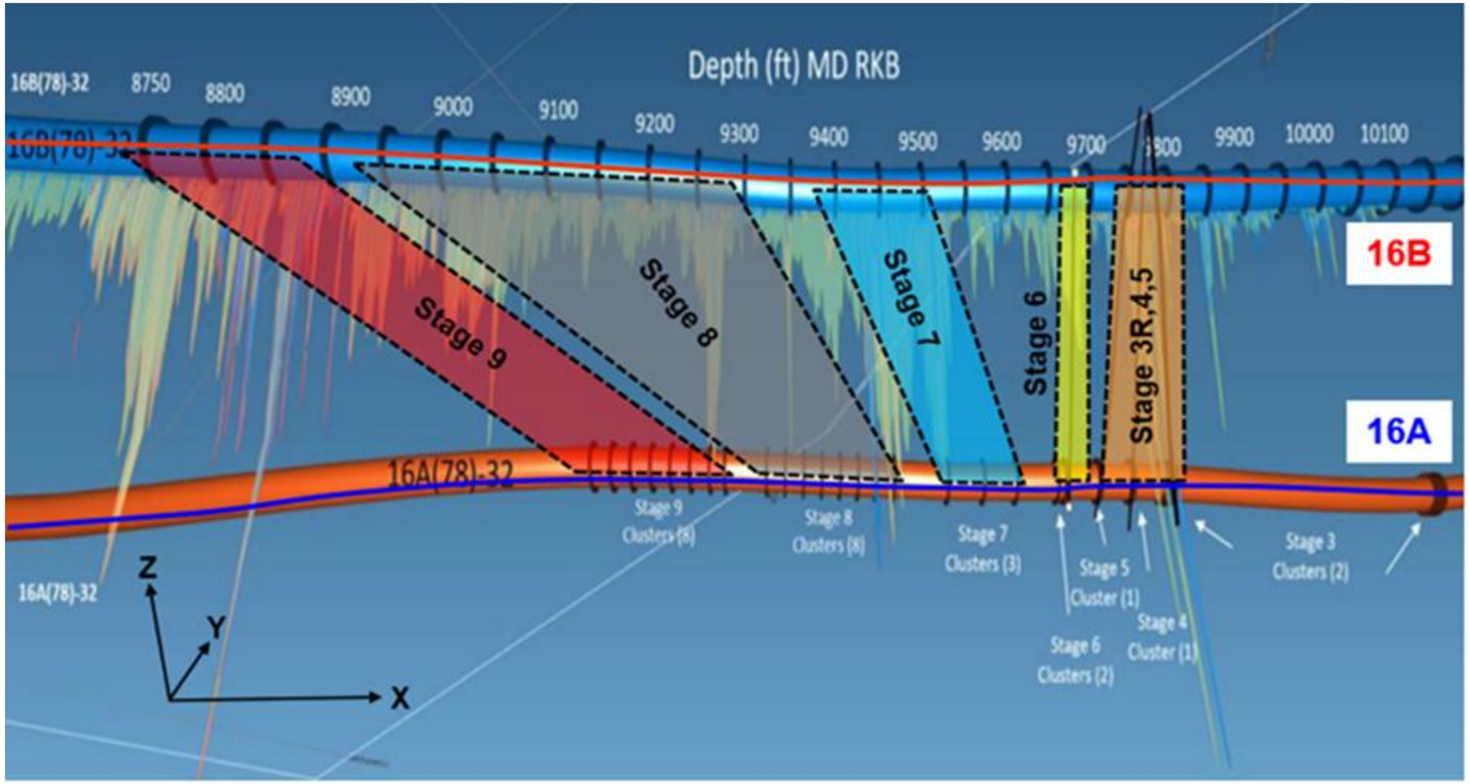
Texas-Two-Step fracturing

- Texas-Two-Step fracturing (Roussell and Sharma, 2011) refers to a strategy of fracture sequencing in which the fracture in the middle of two fractures is stimulated after the outer fractures have been stimulated.
- Texas two-step can be a very efficient strategy to create orthogonal fractures and improve the complexity of the fractures created in a well to improve its overall productivity.
- The opening of the outer fractures can induce a region of low horizontal stress contrast in the middle of the fractures. Regions of low horizontal stress contrast can induce fracture complexity. The optimal scenario suggests an outer fracture spacing of 205 ft for the formation.



Application to Geothermal Well Pairs

- The University of Texas - Shell - Neubrex team monitored and interpreted RFS-DSS data recorded by the fiber we installed at Forge (Ou, et. al., 2025)
- This strain change data formed the basis for locating perforations in the 16B well in near real time.
- Hydraulic fractures clearly undergo significant reorientation and turning during multi-stage stimulation.



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- Roussel, N.P. 2011. Stress Reorientation in Low Permeability Reservoirs. PhD dissertation, University of Texas at Austin, Austin, Texas (August 2011).
- Manchanda, R., Roussel, N.P. and Sharma, M.M. 2012. Factors Influencing Fracture Trajectories and Fracturing Pressure Data in a Horizontal Completion. Paper presented at 46th US Rock Mechanics / Geomechanics Symposium.
- Manchanda, R., Sharma, M.M., and Holzhauser, S. 2013. Time Dependent Fracture Interference Effects in Pad Wells. Paper SPE 164534 presented at SPE URC.
- Manchanda, R. and Sharma, M.M. 2013. Time-Delayed Fracturing: A New Strategy in Multi-Stage, Multi-Well Pad Fracturing. Paper SPE 166489 presented at SPE ATCE.
- Manchanda, R. and Sharma, M.M. 2014. Impact of Completion Design on Fracture Complexity in Horizontal Shale Wells. *SPE Drill & Compl.* **29**(1): 78-87

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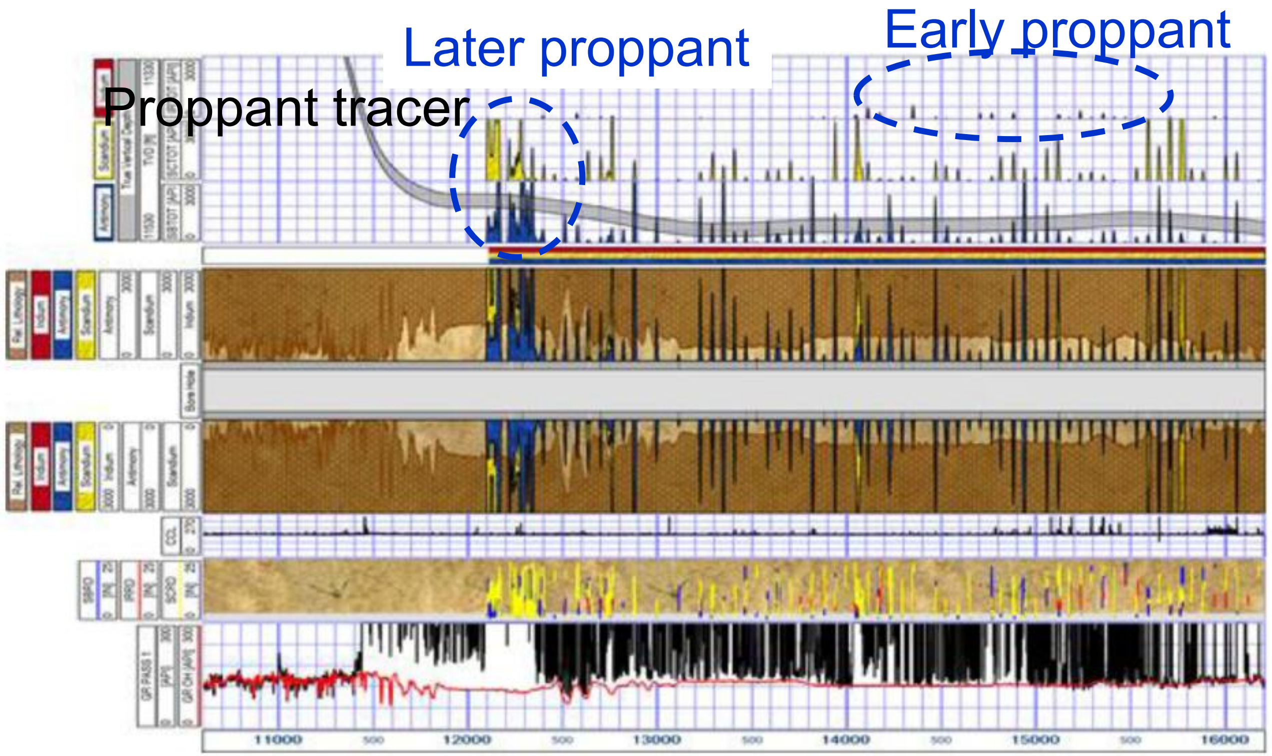
Where Does the Proppant Go: Refracturing with No Liner

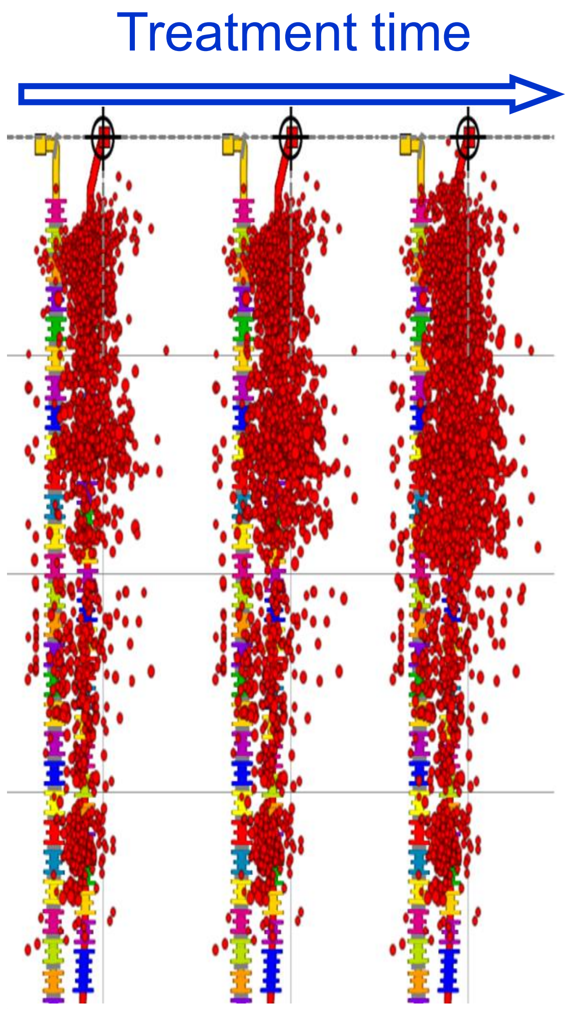
Refrac mainly treated the heel section of the well

- Micro-seismic mapping
- Proppant tracer
- Production logging
- …

Main challenge in refracs is to avoid the preferential treatment of the heel

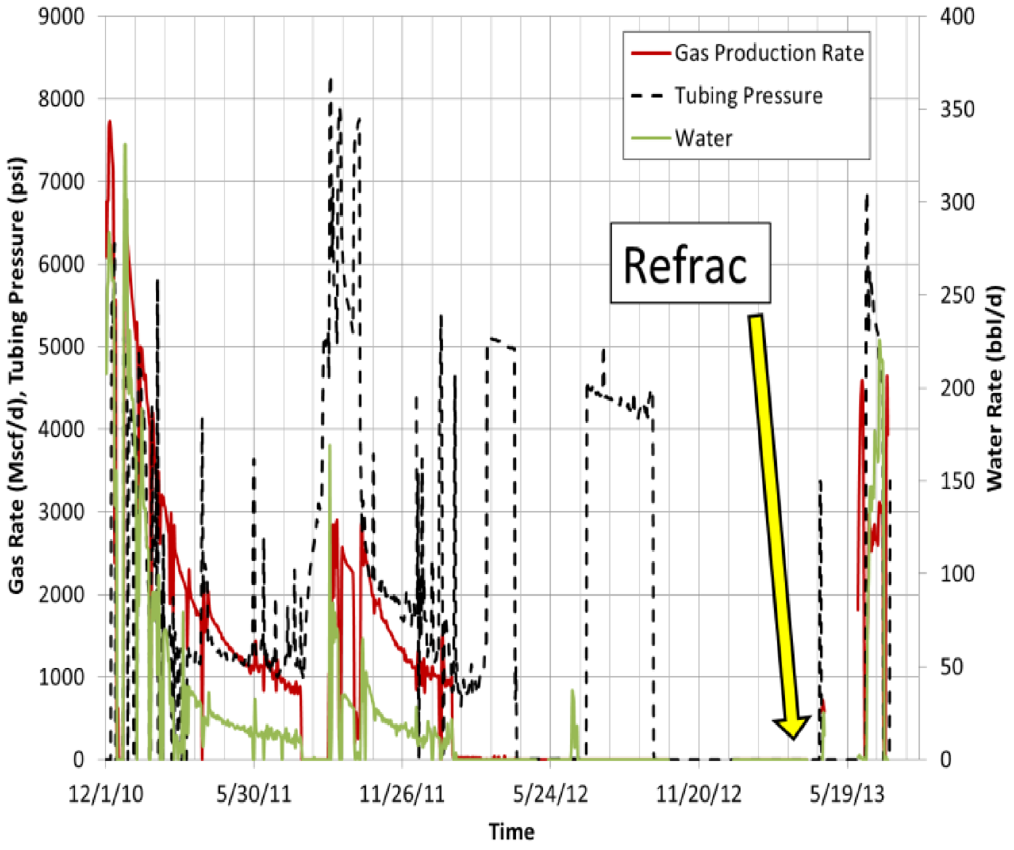


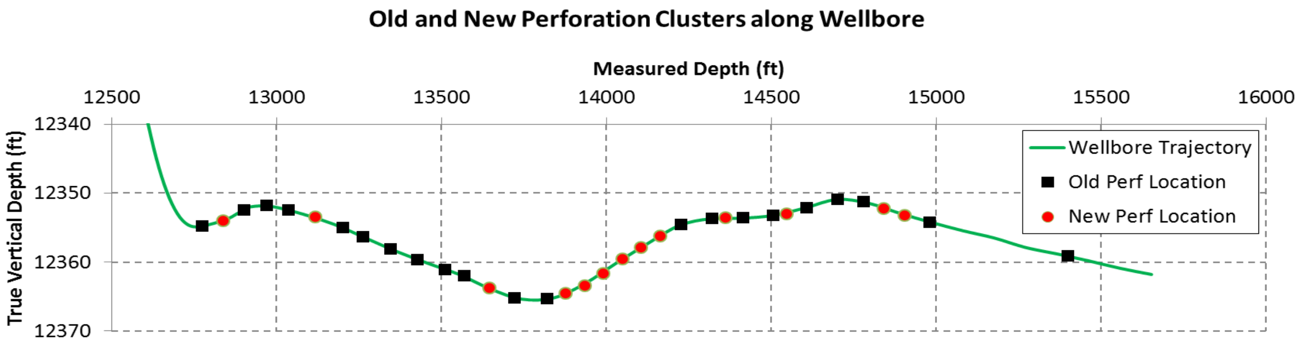
Ref: Evans et al. (2016)



Micro-seismic mapping

Haynesville Shale Refracturing Case Study # 1





New perforations were added before re-fracturing

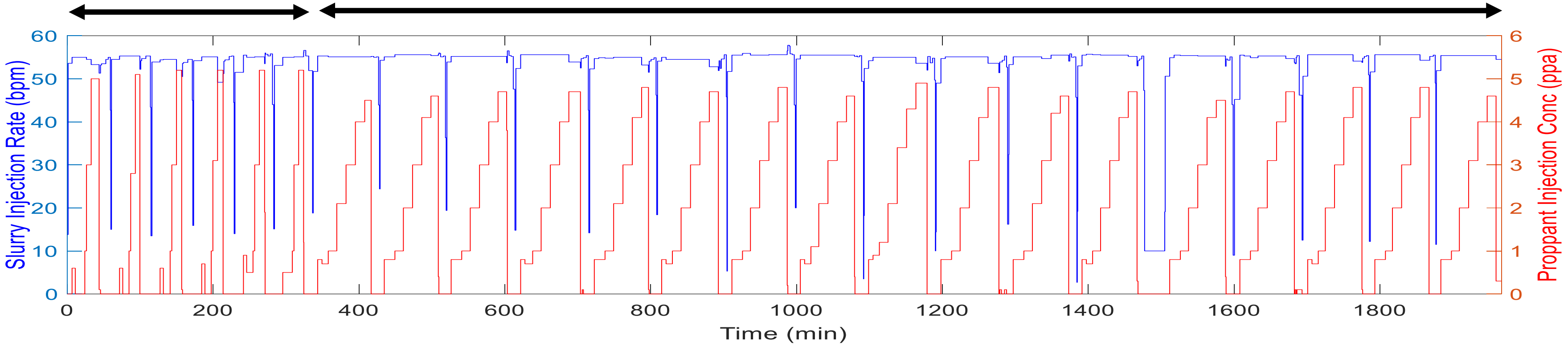
SPE-181795-MS• A Model for Refracturing Operations in Horizontal Wells Employing Diverting Agents • Yi & Sharma

Refrac Simulation

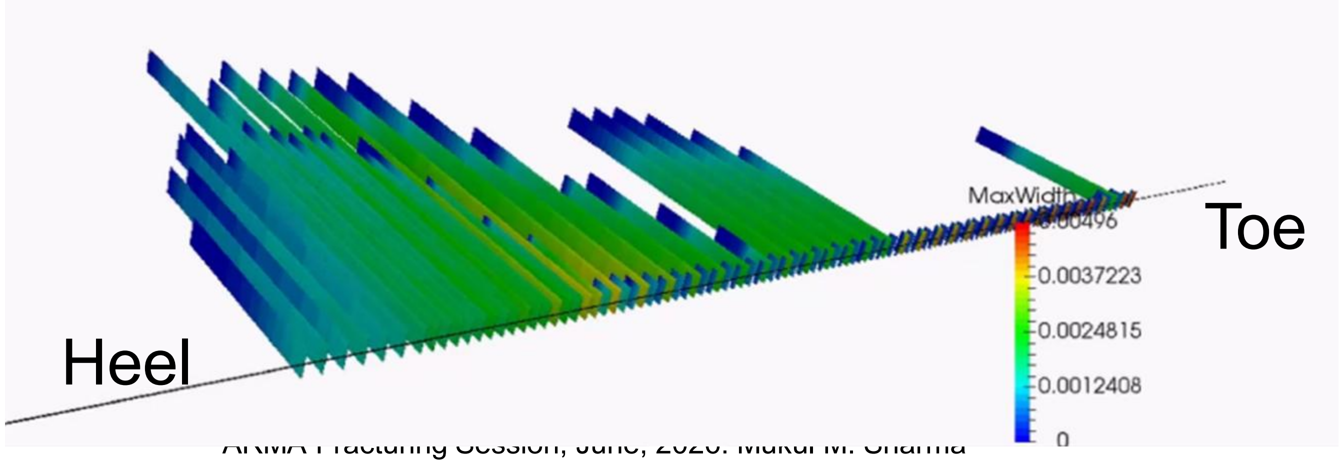
6 short cycles
~ 40 min each

17 long cycles
~ 100 min each

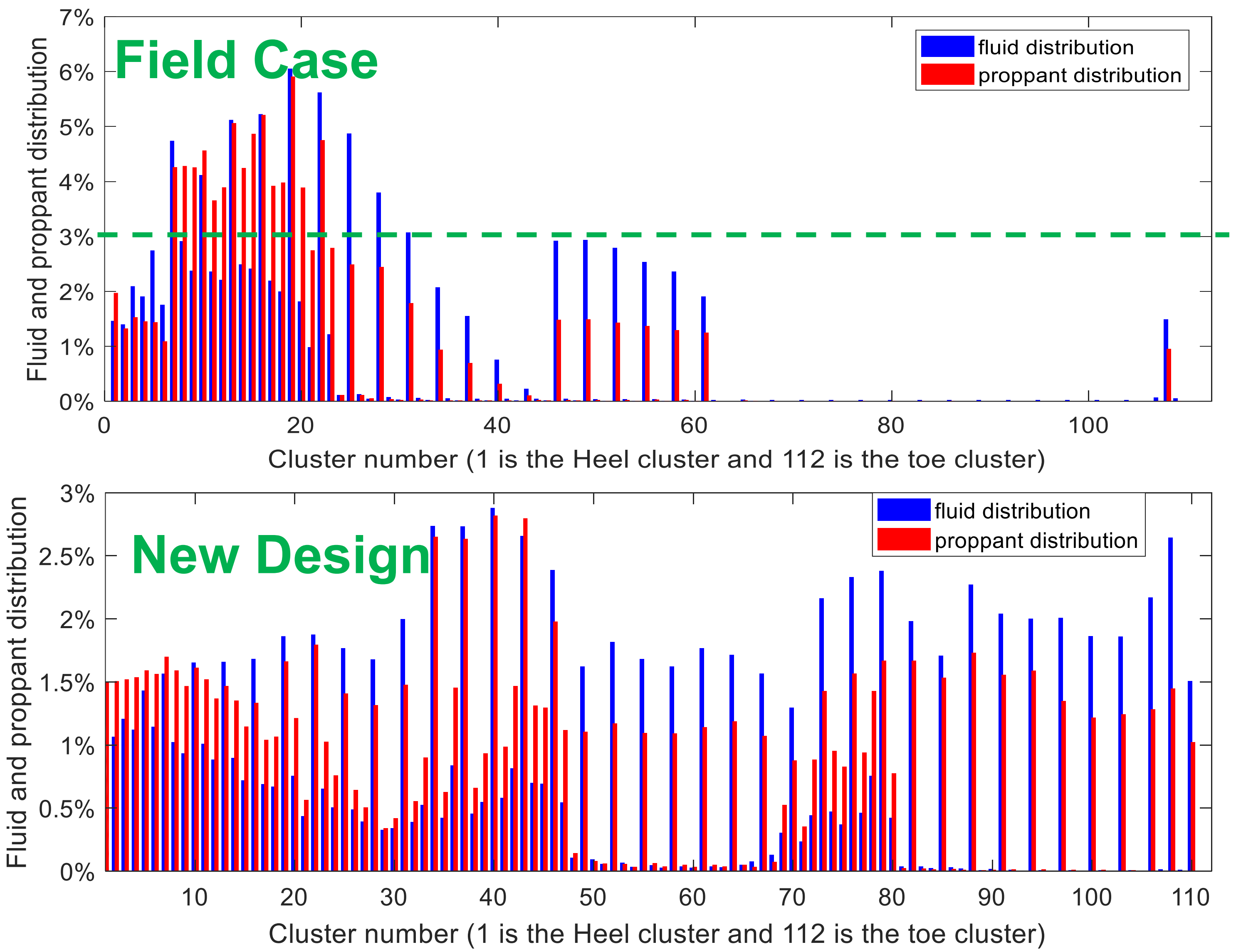
Diverting agent is pumped
between every cycle



Simulated fracture geometry



Shorter Stages with More Frequent Diversion



Refrac Candidate Well Selection
Criteria that Influence Refrac Success

1. Reservoir quality
   – Initial decline rate → D_{iD}
   – Recovery factor
2. Extent of fracture reorientation
   – Stress contrast and drawdown → Π_{mech}, Π_{poro}
   – Mechanical properties of the rock
3. Quality of the initial completion → F_{co}
   – Initial fracture design and implementation
4. Extent of reservoir depletion → R_{dep}
   – Cumulative production from adjacent wells

Publications Related to Refracturing

S. S. Yi, R. Manchanda, M. M. Sharma, and N. P. Roussel, “Preventing Heel Dominated Fractures in Horizontal Well Refracturing”, in *SPE Hydraulic Fracturing Technology Conference & Exhibition*, The Woodlands, TX, U.S.A., February 5-7, 2019: Society of Petroleum Engineers, 2019. doi: 10.2118/194341-MS.

S. S. Yi and M. M. Sharma, “A new method to calculate slurry distribution among multiple fractures during fracturing and refracturing”, *Journal of Petroleum Science and Engineering*, vol. 170, pp. 304–314, 2018, doi: https://doi.org/10.1016/j.petrol.2018.06.048.

D. P. Gala and M. M. Sharma, “Effect of Fluid Type and Composition on Changes in Reservoir Stresses due to Production: Implications for Refracturing”, in *51st U.S. Rock Mechanics Symposium*, San Francisco, CA, U.S.A., June 25-28, 2017: American Rock Mechanics Association, 2017.

S. S. Yi and M. M. Sharma, “A Model for Refracturing Operations in Horizontal Wells Employing Diverting Agents”, in *SPE Asia Pacific Hydraulic Fracturing Conference*, Beijing, China, August 24-26, 2016: Society of Petroleum Engineers, 2016. doi: http://dx.doi.org/10.2118/181795-MS.

N. P. Roussel and M. M. Sharma, “Selecting Candidate Wells for Refracturing Using Production Data”, *SPE Production & Operations*, vol. 28, no. 01, pp. 36–45, 2013, doi: http://dx.doi.org/10.2118/146103-PA.

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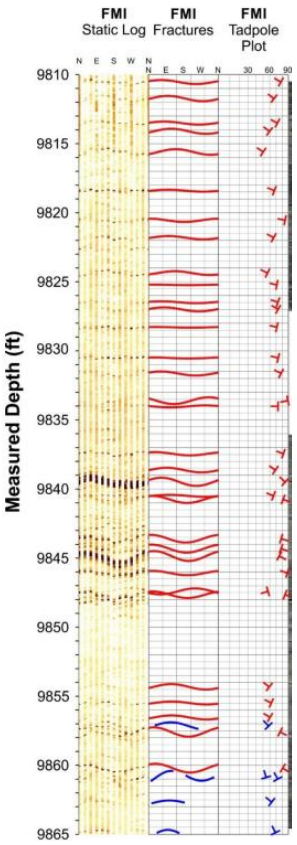
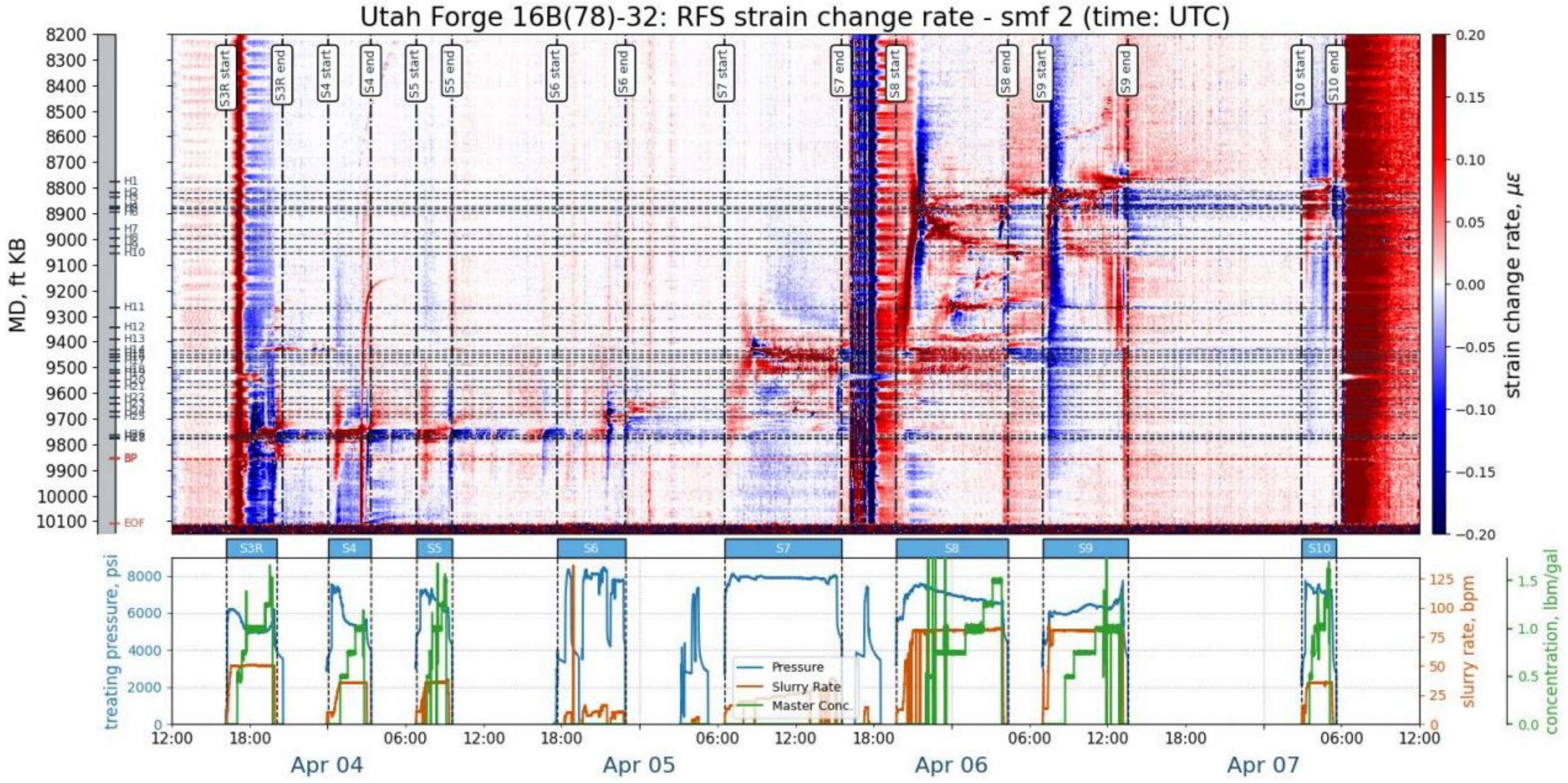
Integration of Fiber Optic Data with FMI Log (Forge)

- Formation micro-resistivity imaging (FMI) log was employed during the drilling process of 16B to detect pre-existing fractures and faults along the producer (Jones et al., 2025).
- Pre-existing fractures from FMI log were compared to fracture-driven interactions from FO data to better understand the development of EGS fracture network.

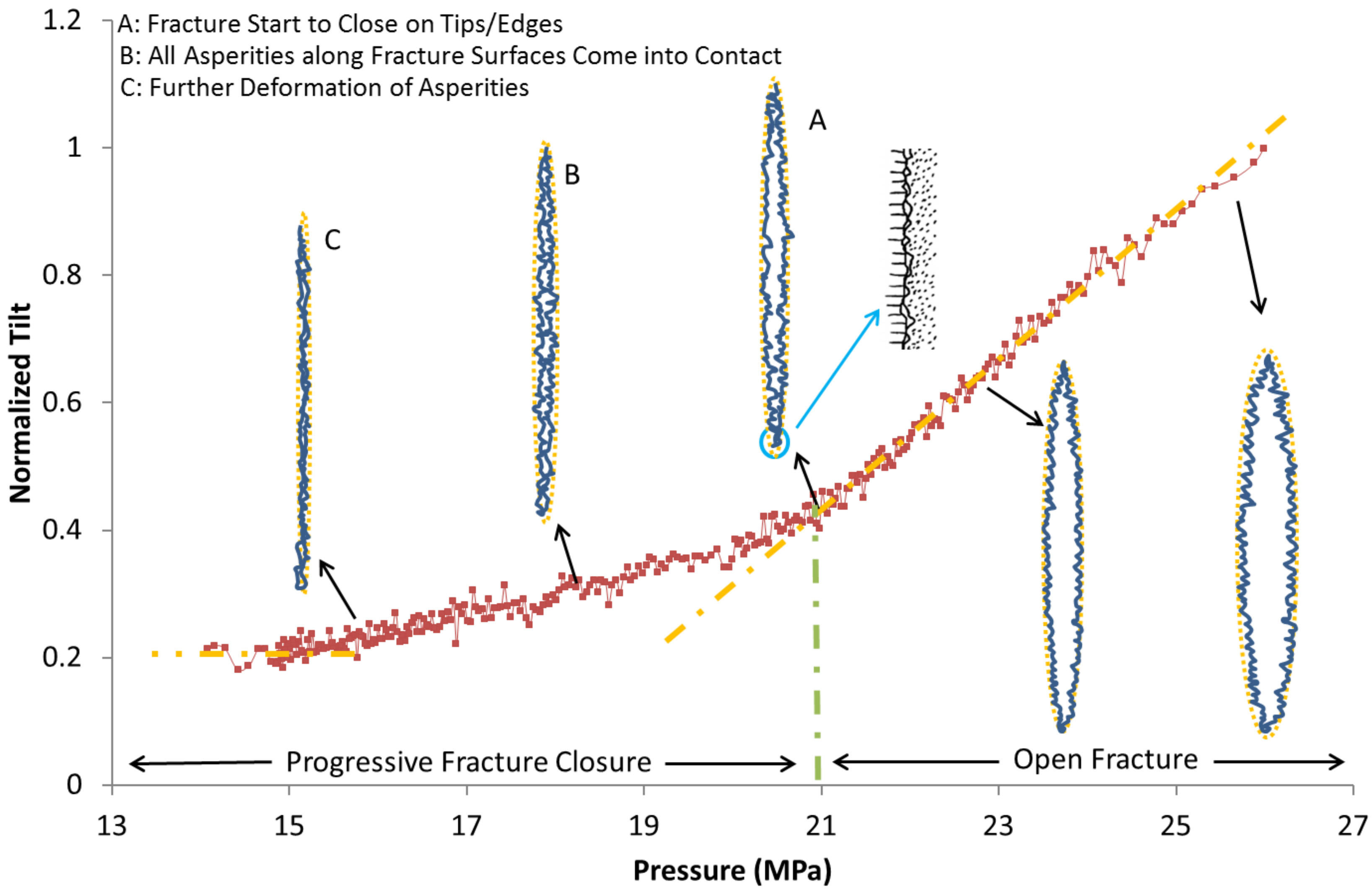
FMI logging data along producer 16B (Jones et al., 2025)



FO data along producer 16B (Jurick et al., 2025)



Pressure Diagnostics:
Where do we define Closure Stress?



Different Methods to Estimate Minimum In-Situ Stress

Scenarios		Conventional Method		Compliance Method		Variable Compliance Method	
		Estimated σ_{hmin} (MPa)	Absolute(MPa)/ % Error	Estimated σ_{hmin} (MPa)	Absolute(MPa)/ % Error	Estimated σ_{hmin} (MPa)	Absolute(MPa)/ % Error
Base Case		32.3	-2.7 / -7.71%	37.3	2.3 / 6.57%	35.3	0.3 / 0.86%
Modified Base Case	w_0=1 mm	32.7	-2.3 / -6.57%	36.7	1.7 / 4.86%	35.1	0.1 / 0.29%
	w_0=3 mm	31.7	-3.3 / -9.43%	38.2	3.2 / 9.14%	35.0	0 / 0.00%
	σ_{ref}=2 MPa	32.4	-2.6 / -7.43%	36.9	1.9 / 5.43%	35.2	0.2 / 0.57%
	σ_{ref}=8 MPa	32.2	-2.8 / -8.00%	37.3	2.3 / 6.57%	35.1	0.1 / 0.29%
	h_f=5 m	31.3	-3.7/ -10.57%	39.3	4.3 / 12.29%	35.4	0.4 / 1.14%
	h_f=15 m	32.5	-2.5 / -7.14%	36.8	1.8 / 5.14%	35.1	0.1 / 0.29%
	k=0.005 md	32	-3 / -8.57%	37.4	2.4 / 6.86%	35.2	0.2 / 0.57%
	k=0.05 md	31.8	-3.2 / -9.14%	37.5	2.5 / 7.14%	35.3	0.3 / 0.86%
	V_w=50 m^3	32.7	-2.3 / -6.57%	37.1	2.1 / 6%	35.3	0.3 / 0.86%
	V_w=100 m^3	32.8	-2.2 / -6.29%	37.1	2.1 / 6%	35.2	0.2 / 0.57%
	P_0=8 MPa	30	-5 / -14.29%	37.4	2.4 / 6.86%	35.3	0.3 / 0.86%
	P_0=28 MPa	34.3	-0.7 / -2.00%	NA	NA	NA	NA

References for Estimating In-Situ Stress

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- Wang, H and Sharma, M.M. 2018. Modelling of Hydraulic Fracture Closure on Proppants with Proppant Settling. Journal of Petroleum Science and Engineering, Vol(171):636-645.
- Wang, H., Yi, S., and Sharma, M.M. 2018. A Computationally Efficient Approach to Modeling Contact Problems and Fracture Closure Using Superposition Method. Theoretical and Applied Fracture Mechanics, Vol(93): 276-287.
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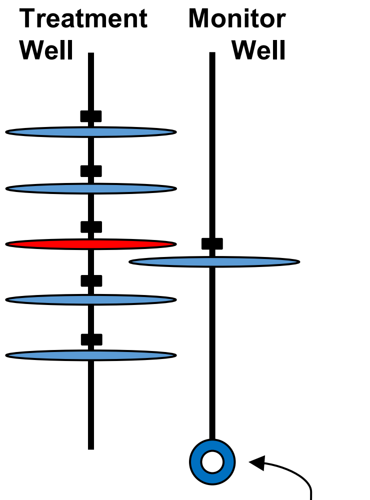
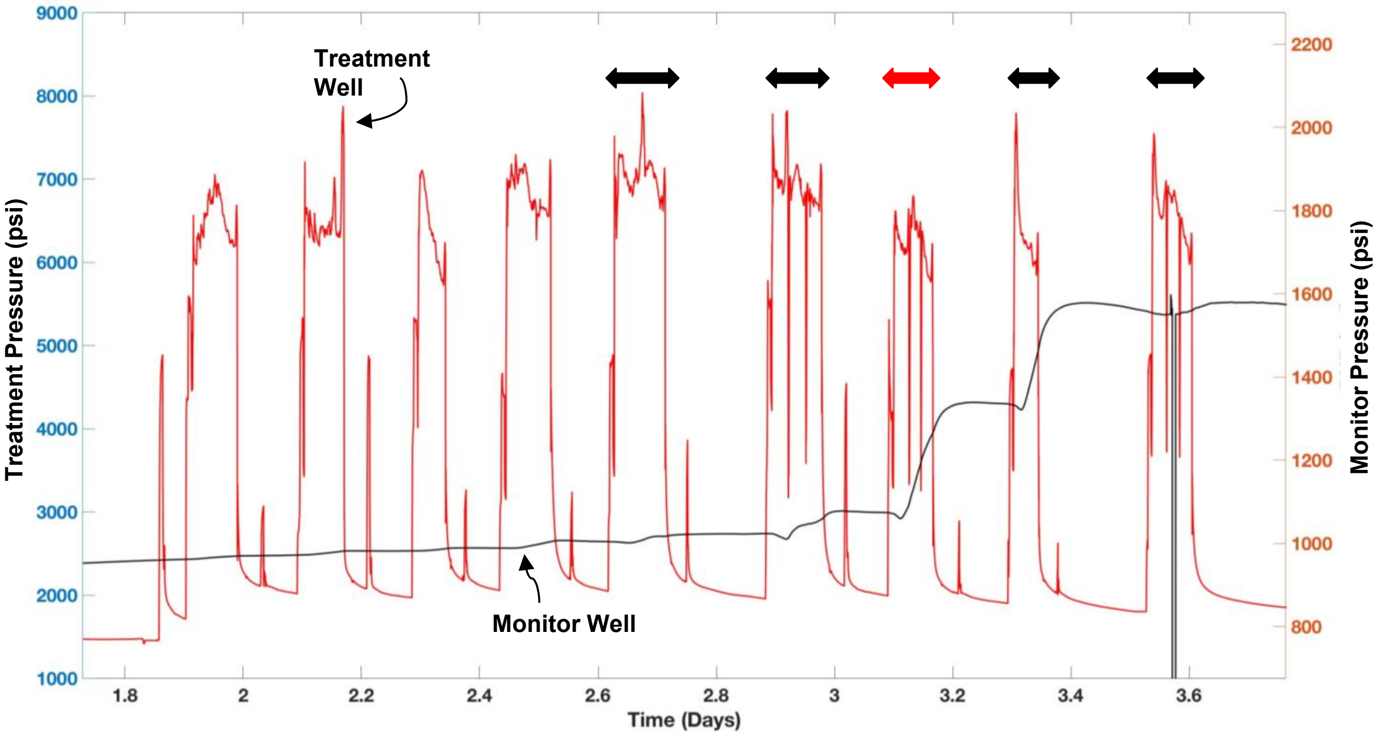
- Wang, H and Sharma, M.M. 2017. New Variable Compliance Method for Estimating Closure Stress and Fracture Compliance from DFIT data. Paper SPE 187348 presented at the *SPE Annual Technical Conference and Exhibition* held in San Antonio, TX, USA, 09 – 11 October.
- Zheng, S., Manchanda, R., Wang, H. and Sharma, M.M., 2020. DFIT Analysis and Interpretation in Layered Rocks. In *SPE Hydraulic Fracturing Technology Conference & Exhibition*.

Pressure Interference during Stimulation in Unconventional Reservoirs

- During stimulation, fractures propagating towards the monitor well can cause pressure changes in an offset monitor well.



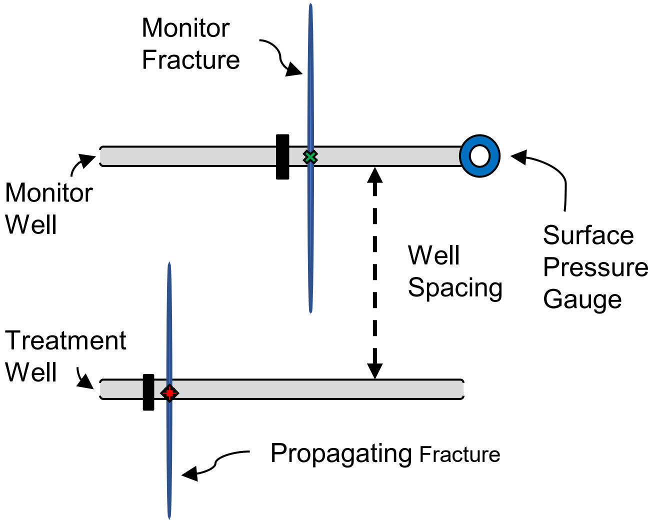


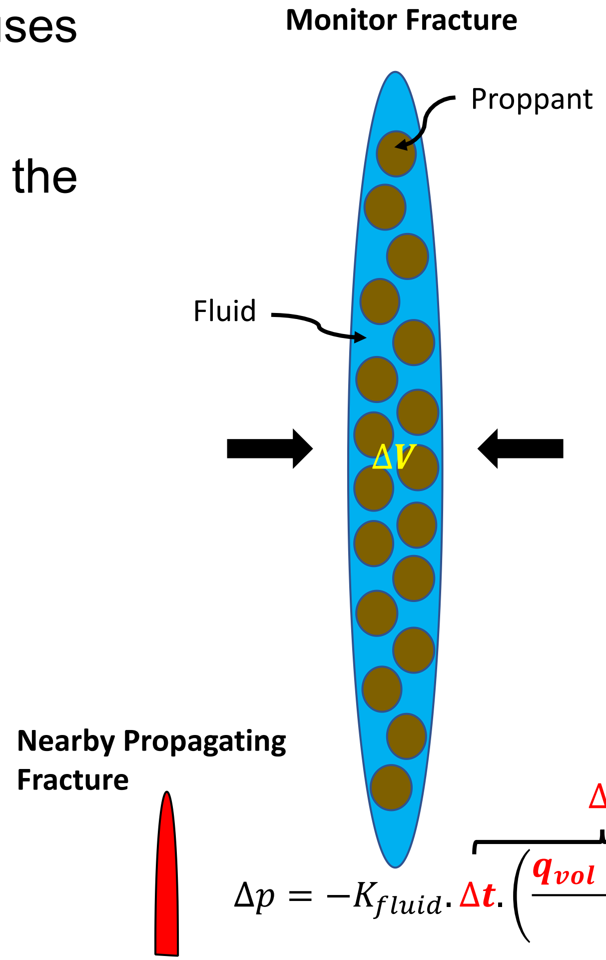
Pressure data from the Permian Basin

- Pressure response can be due elastic interactions between the fractures or due to hydraulic communication (fluid migration).

Pressure Response at the Monitor Well due to Stress Shadow

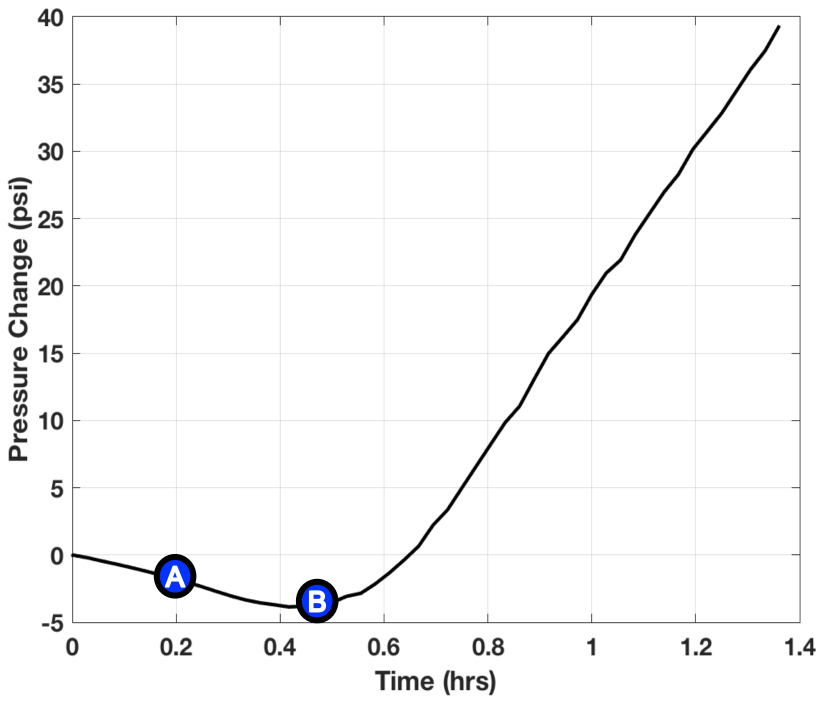
- Hydraulic fracture propagation in the treatment well causes mechanical deformation (stress alterations).
- This mechanical deformation compresses or dilates the fluid inside the monitor fracture which results in a pressure change.

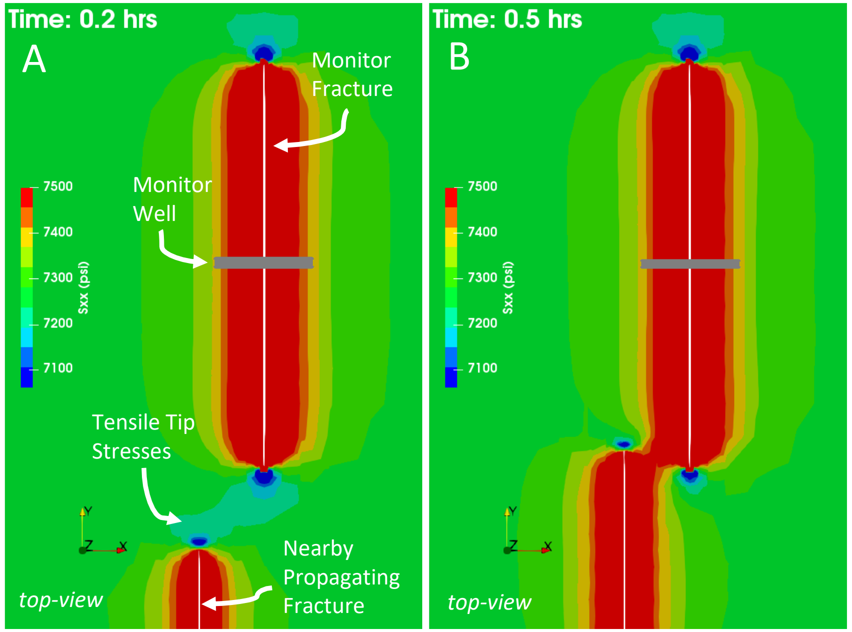




$$\Delta p = -K_{fluid}.\underbrace{\Delta t.\left(\frac{q_{vol} + q_{leakoff}}{V_{fluid}}\right)}_{}\quad \text{where } \Delta V = \Delta t.\,(q_{vol} + q_{leakoff})$$

Monitored Pressure Response during Hydraulic Fracture Propagation from the Treatment Well



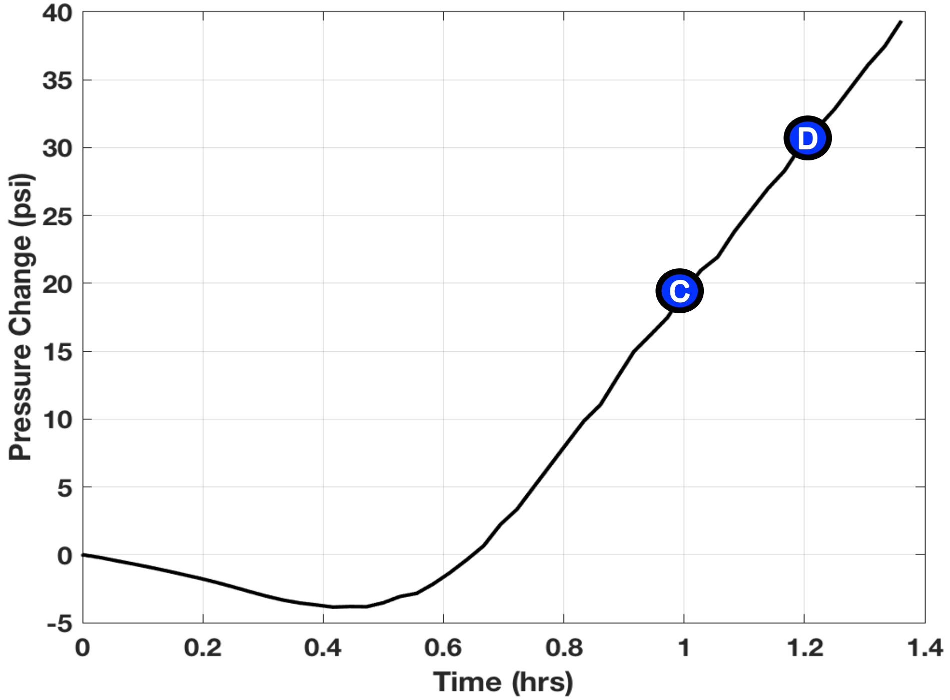


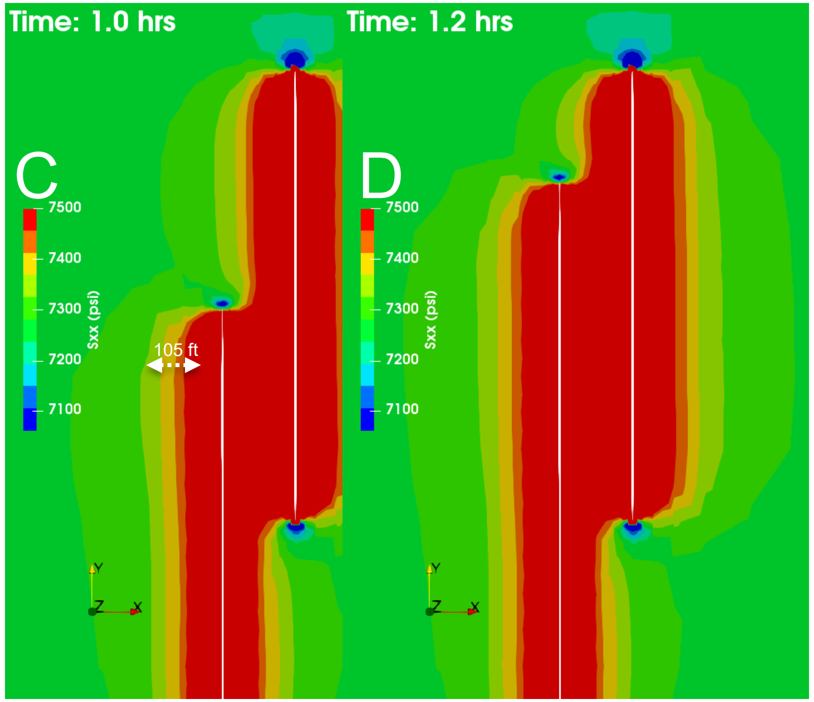
Seth et al., 2018

Up to point B, the tensile stress ahead of the propagating fracture tip dilates the fluid inside the monitoring fracture, resulting in a decrease in pressure.

Ref: SPE 191492 • Estimating Fracture Geometry by Analyzing the Pressure Interference between Fractured Wells • Seth & Sharma, 2019.

Monitored Pressure Response during Hydraulic Fracture Propagation from the Treatment Well

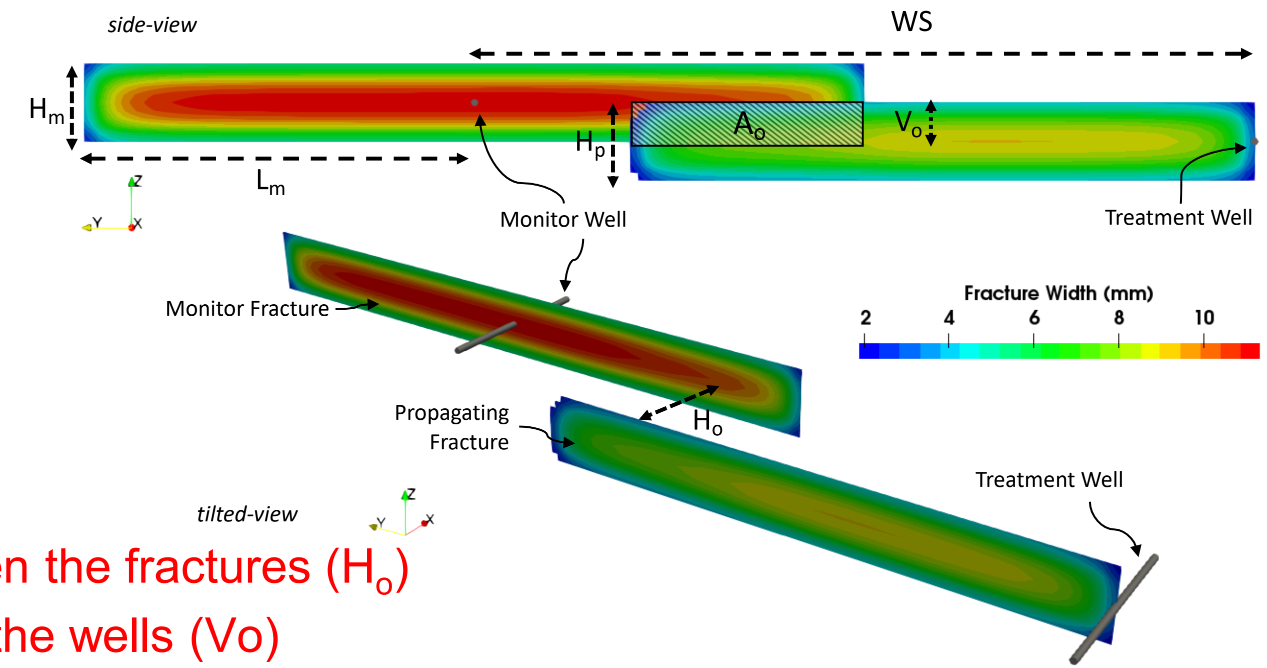




After point B, the propagating fracture starts squeezing the monitor fracture, thereby compressing the fluid inside it, resulting in an increase in pressure.

Ref: SPE 191492 • Estimating Fracture Geometry by Analyzing the Pressure Interference between Fractured Wells • Seth & Sharma, 2019.

Sensitivity Study Model Parameters

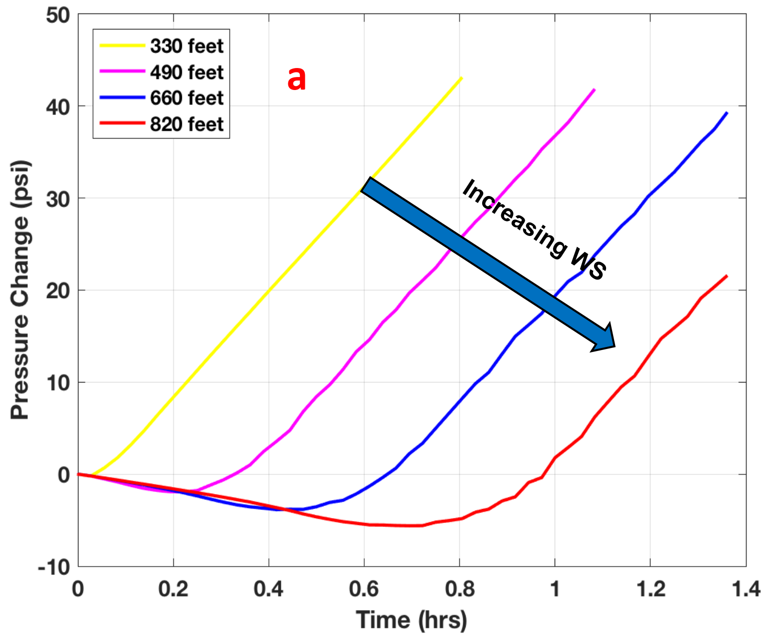


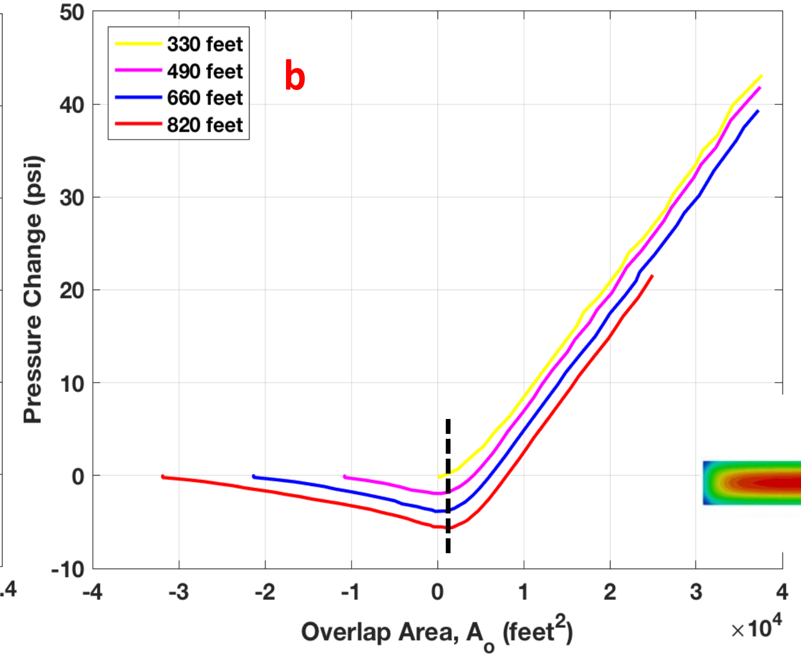
- Well Spacing (WS)
- Horizontal Offset between the fractures (H_o)
- Vertical Offset between the wells (Vo)
- Propagating Fracture Height (H_p)
- Injection Rate
- Monitor Fracture Height (H_m)
- Monitor Fracture Half-Length (L_m)
- Monitor Fracture Proppant Mass (M_p)
- Monitor Fracture Initial Porosity (ϕ_m)

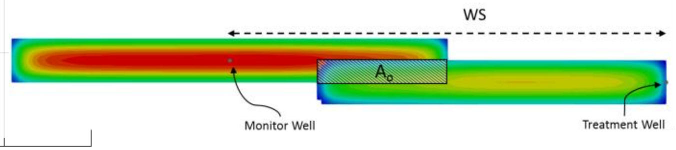
→ Pressure Response at the Monitor Well

Ref: SPE 191492 • Estimating Fracture Geometry by Analyzing the Pressure Interference between Fractured Wells • Seth & Sharma, 2018.

Impact of Well Spacing (WS)







Seth et al., 2018

Ref: SPE 191492 • Estimating Fracture Geometry by Analyzing the Pressure Interference between Fractured Wells • Seth et. al., 2018.

- With increasing Well Spacing (WS):
  - Pressure increase is lower in magnitude.
  - Occurs later in time.
  - Takes more time for the propagating fracture to overlap with the monitor fracture.
- For Pressure Change Vs Overlap Area (A_o):
  - The curves for different WS values nearly collapse into a single curve
  - The pressure starts to increase at the same value of A_o.

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Seth, P., R. Manchanda, A. Kumar and Sharma, M.M. 2018. Estimating Hydraulic Fracture Geometry by Analyzing the Pressure Interference Between Fractured Horizontal Wells. **SPE-191492**. In SPE ATCE, Dallas, Texas.

Seth, P., R. Manchanda, B. Elliott, S. Zheng and M.M. Sharma. 2019. Diagnosing Multi-Cluster Fracture Geometry Using Dynamic Poroelastic Pressure Transient Analysis. **URTeC (1092)**. In Proceedings of the 7th URTeC, Denver, Colorado.

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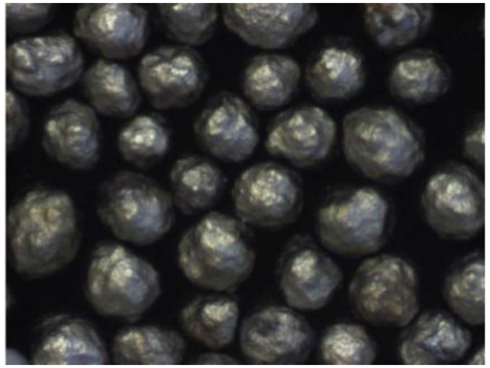
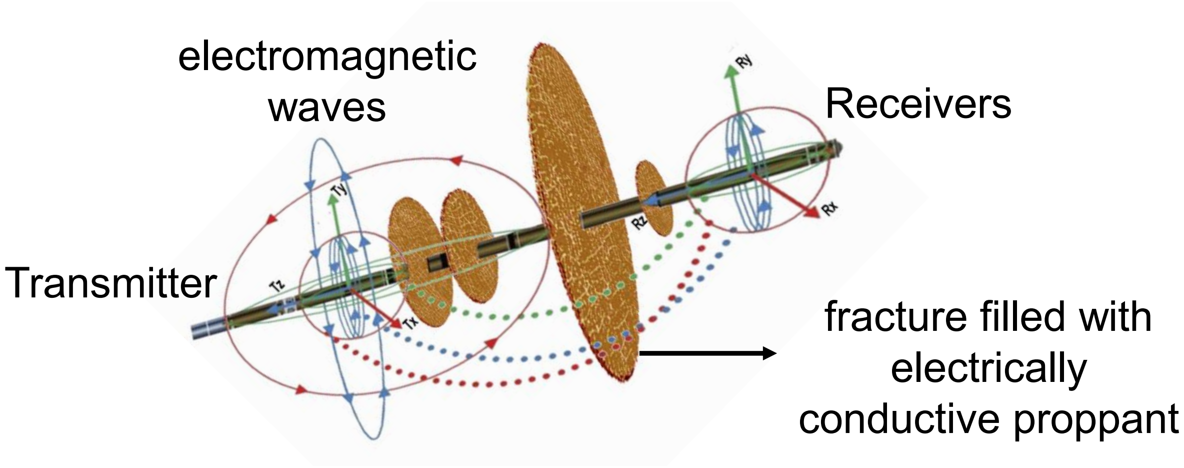
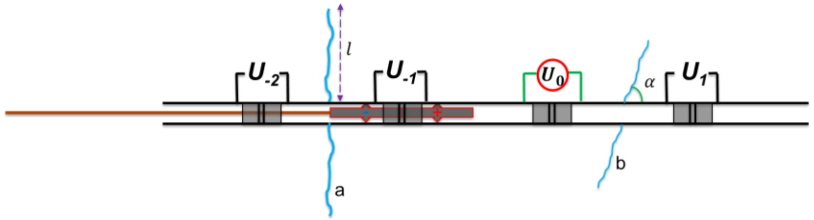
Seth, P., B. Elliott, T. Ingle, A. Kumar, S. Zheng and M.M. Sharma. 2020. Are We Over-Stimulating Our Laterals? Evaluating Completion Design Practices Based On Field Offset Well Pressure Measurements. **SPE-201346**. SPE ATCE, Houston, Texas (2020).

Fracture Diagnostics with Electrically Conductive Proppant

- Transform a hydraulic fracture into an electrically conductive plane using conductive proppants.
- Install source and receivers downhole to improve signal to noise ratio:

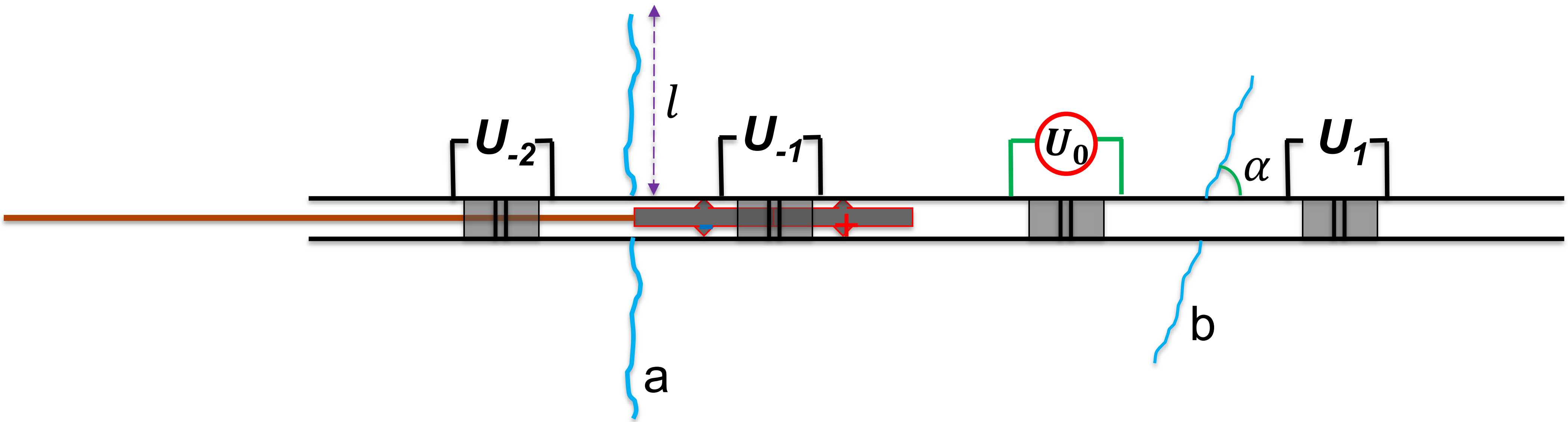






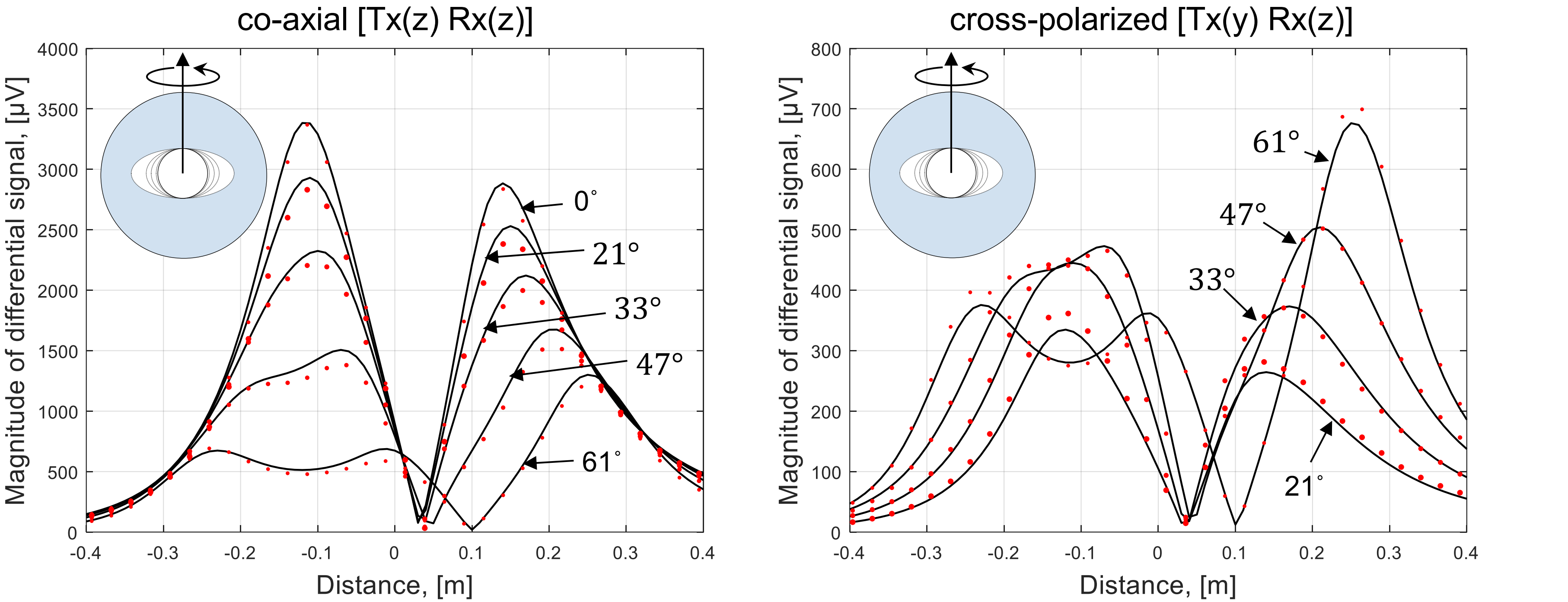
- Limited in the fracture properties that can be recovered
- Designed for cased-hole completions

Measurements in Cased Wells



- Insulating gaps are placed between standard casing sections (30') to form both transmitter and receiver pairs
- A voltage source is applied across one of the gaps (#0) from inside the casing
- Voltages across other gaps (#1,2…) are measured and recorded

Results – Lab Measurements



Parameters	Co-Axial	Co-Planar	Cross-Polarized
Surface Area	Strong	Moderate	Weak
Aspect Ratio	Strong	Moderate	Weak
Dip Angle	Strong	Strong	Strong

- Dots show measured signals
- Solid lines show simulated results

Publications

[1] Zhang, P., Brick, Y., et al. "Numerical Study of an Electrode-Based Resistivity Tool for Fracture Diagnostics in Steel-Cased Wellbores." *Geophysics*, 83(2), pp.1-33.

[2] Shiriyev, J., Brick, Y., Zhang, P., et al., 2018. "Experiments and Simulations of a Prototype Tri-axial Electromagnetic Induction Logging Tool for Hydraulic Fracture Diagnostics." *Geophysics*, 83(3), pp.1-37.

[3] Zhang, P., Sen, M.K., et al. "Modeling of Low Frequency Downhole Electrical Measurements for Mapping Proppant Distribution in Hydraulic Fractures in Cased-Hole Wells." *SPE Journal*, SPE-189884-PA.

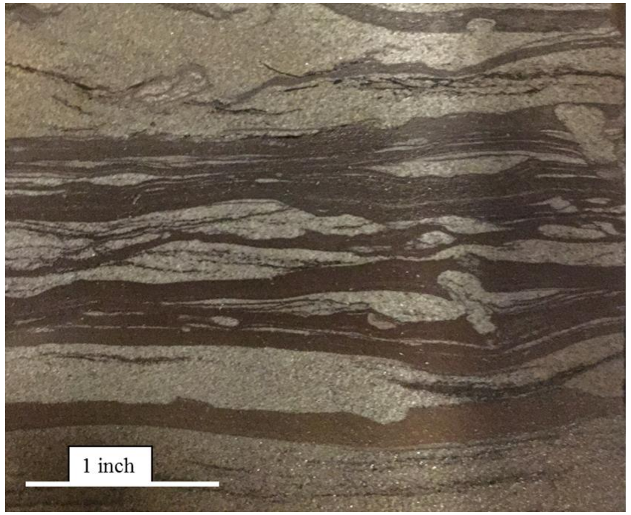
[4] Zhang, P., Brick, Y., et al., 2016. "Fracture Diagnostics Using a Low Frequency Electromagnetic Induction Method." 50th US Rock Mechanics/Geomechanics Symposium, American Rock Mechanics Association.

Most Significant Changes in Fracturing

1. Improving cluster efficiency (distributing proppant efficiently)
    i. Extreme limited entry
    ii. Perforation cluster design
2. Fracture spacing and sequencing
3. Proppant and fluid selection
4. Refracturing
5. Fracture diagnostic techniques
    i. Fiber optics
    ii. DFIT analysis
    iii. Pressure interference between wells
    iv. Electrically conductive proppant
6. Interaction of fractures with natural fractures
7. Parent-child wells
8. Proppant Placement

What Are Induced Unpropped (IU) Fractures?

- IU fractures are fractures created by the process of propagation of the main propped fracture.
- IU fractures include natural fractures, but also include many other types of fractures created by failure along planes of weakness by stresses induced by the opening of the propped fracture.
- Fracture widths are too narrow to allow proppant to enter them.



Eagle Ford shale heterogeneity at a core scale (Ouchi and Sharma, 2015).

Eagle Ford shale heterogeneity seen in an outcrop, large scale planes of weakness are evident (Durham, 2013).

Ref: The Role of Induced Un-propped (IU) Fractures in Unconventional Oil and Gas Wells, Mukul M. Sharma, and R. Manchanda, SPE-174946-MS, SPE Annual Technical Meeting, Houston, TX, 2015.

Evidence of the Presence of IU Fractures

- Six independent pieces of evidence presented to conclusively show the creation of induced unpropped fractures in most wells:
  - Direct visual evidence in HFTS 1 core
  - Fate of the injected fracturing fluids
  - Micro-seismic data,
  - Production history matching,
  - Tracer data,
  - Pressure communication between wells.
- These IU fractures close over time.
- IU fractures must be considered when designing fracture treatments and during short-term and long-term production.

Ref: The Role of Induced Un-propped (IU) Fractures in Unconventional Oil and Gas Wells, Mukul M. Sharma, and R. Manchanda, SPE-174946-MS, SPE Annual Technical Meeting, Houston, TX, 2015.

Consequences of the Presence of IU Fractures

- Creation of a stimulated rock volume (SRV) with enhanced permeability around the main hydraulic fracture.
- Created fracture area being much larger than “effective” fracture area.
- Closure of unpropped fractures over time (after fracturing)
- The use of smaller mesh size proppant to ensure that the proppant is placed in some of the IU fractures.
- Use of acid or other chemicals to etch the surface of the IU fractures.
- Selecting cluster spacing and well spacing to maximize the creation of IU fractures and fracture conductivity.
- Selecting the proper zippering sequence for fracs in the pad based on a recognition that the IU fracs are closing.
- ….

Publications Related to Natural Fractures

- M. Cao and M. M. Sharma, “The Effect of Variations of Fluid Pressure in Natural Fractures on the Geometry of Fracture Networks and Well Productivity”, in The Unconventional Resources Technology Conference, Denver, Colorado, USA, 13-15 June 2023: URTeC, 2023. doi: https://doi.org/10.15530/urtec-2023-3864802.
- M. A. Tammar, T. E. Alotaibi, M. M. Sharma, and C. M. Landis, “ Laboratory Imaging and Phase Field Modeling of the Interaction of Hydraulic Fractures with Well Cemented Natural Fractures”, in SPE Kuwait Oil & Gas Show and Conference, Kuwait: 2019. doi: 10.2118/198086-MS.
- H. Wang and M. M. Sharma, “Determine In-Situ Stress and Characterize Complex Fractures in Naturally Fractured Reservoirs from Diagnostic Fracture Injection Tests”, Rock Mechanics and Rock Engineering, 2019, doi: https://doi.org/10.1007/s00603-019-01793-w.

- H. Wang and M. M. Sharma, “Determine In-Situ Stress and Characterize Complex Fractures in Naturally Fractured Reservoirs from Diagnostic Fracture Injection Tests”, Rock Mechanics and Rock Engineering, 2019, doi: https://doi.org/10.1007/s00603-019-01793-w.

- S. Agrawal, K. Shrivastava, and M. M. Sharma, “Effect of Shear Slippage on the Interaction of Hydraulic Fractures with Natural Fractures”, in SPE Hydraulic Fracturing Technology Conference & Exhibition, The Woodlands, TX, U.S.A., February 5-7, 2019. doi: https://doi-org.ezproxy.lib.utexas.edu/10.2118/194361-MS.
- K. Shrivastava and M. M. Sharma, “3-D Interactions of Hydraulic Fractures with Natural Fractures”, in SPE International Hydraulic Fracturing Technology Conference & Exhibition, Muscat, Oman, October 16-18, 2018: Society of Petroleum Engineers, 2018.
- K. Shrivastava, J. Hwang, and M. M. Sharma, “Formation of Complex Fracture Networks in the Wolfcamp Shale: Calibrating Model Predictions with Core Measurements from the Hydraulic Fracturing Test Site”, in SPE Annual Technical Conference, Dallas, Texas, U.S.A., September 24-26, 2018:
- K. Shrivastava and M. M. Sharma, “Mechanisms for the Formation of Complex Fracture Networks in Naturally Fractured Rocks”, in SPE Hydraulic Fracturing Technology Conference and Exhibition, The Woodlands, Texas, U.S.A., January 23-25, 2018: doi: https://doi.org/10.2118/189864-MS.
- W. Wu and M. M. Sharma, “A Model for the Conductivity and Compliance of Unpropped and Natural Fractures”, SPE Journal, vol. 22, no. 06, pp. 1893–1914, 2017, doi: https://doi.org/10.2118/184852-PA.
- H. Ouchi, A. Katiyar, J. T. Foster, and M. M. Sharma, “A Peridynamics Model for the Propagation of Hydraulic Fractures in Naturally Fractured Reservoirs”, SPE Journal, vol. 22, no. 04, pp. 1082–1102, 2017, doi: https://doi.org/10.2118/173361-PA.
- N. P. Roussel and M. M. Sharma, “Strategies to Minimize Frac Spacing and Stimulate Natural Fractures in Horizontal Completions”, in SPE Annual Technical Conference and Exhibition, Denver, Colorado, U.S.A., October 30-November 2, 2011. doi: http://dx.doi.org/10.2118/146104-MS.

Most Significant Changes in Fracturing

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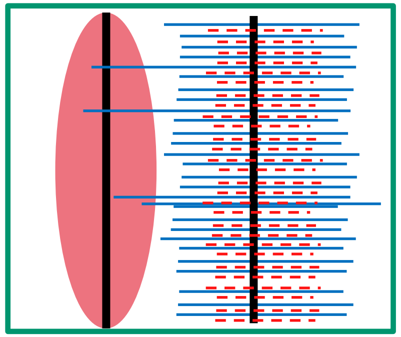
Parent-Child Well: Completion Strategies

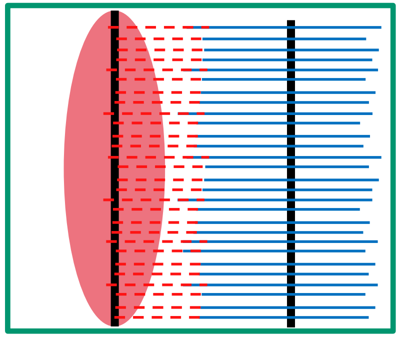
Child Completion Smaller



Target/Outcome: Reduce Capital to Offset Performance & Reduce Interaction

Risk: Under-Stimulation

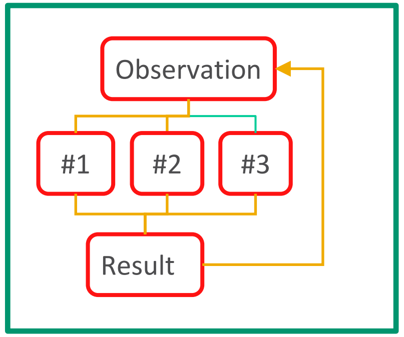
Alter Child Completion Larger



Target/Outcome: Reduce Asymmetry with Larger pad Volume on Child Wells

Risk: Over - Capitalization

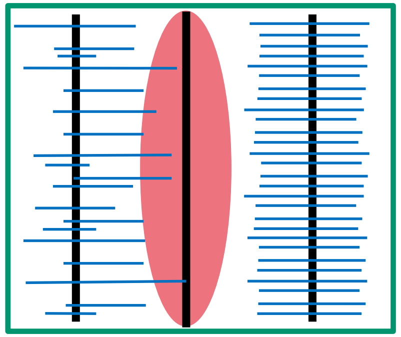
On the Fly Changes



Target/Outcome: Adjust Completion to Variability Along Lateral

Risk: Time and Tools Required to Inform Field Effectively and Scalability

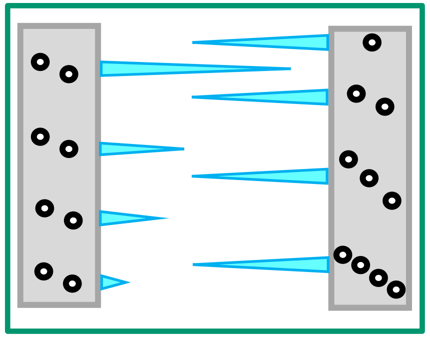
Pinpoint/CoilFrac



Target/Outcome: Single Clusters for more Controllable Frac Lengths

Risk: Lower Limit on Reduced Cluster Spacing/ Total # Clusters

VSC & ELE

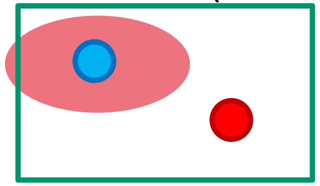


Target/Outcome: Improve Fluid Distribution, more NWB Stimulation

Risk: Pressure and Rate Limitation (equipment and tubulars) and Cost

Parent- Child Well: Depletion Mitigation

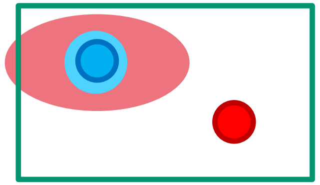
Base Case (nothing)



Parent Well:
Risk Cleanout, Sand Influx, Reduced Performance

Child Well:
Underperform 20-40% to Parent Well

Small Preload Parent*



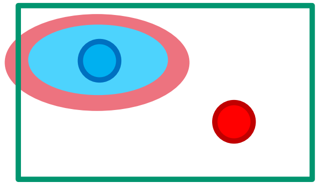
Parent Well:
Protects from Cleanout

Child Well:
Underperform 20-40% to 1st Order Offset

*Pushback Method

Chemical Remediation

Large Preload Parent

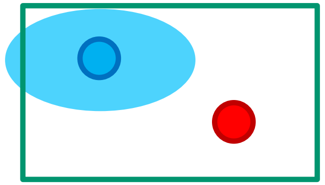


Parent Well:
Minimal Reserve Loss, Protect Parent Fracture Network

Child Well:
Underperform 15-35% to 1st Order Offset

*FFA

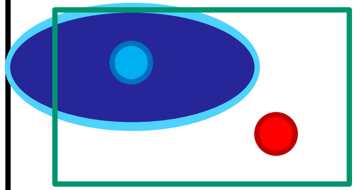
Recharge Parent



Parent Well:
Elevate Reservoir Stress & Pressure

Child Well:
Improve 1st Order Performance and Mitigate Frac Asymmetry

Refrac Parent



Parent Well:
Elevate Stress & Pressure, Incremental Reserve Adds

Child Well:
Optimal 1st Order Child Well

Increasing Cost and Planning Complexity →

Parent-Child Well Related Publications

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- Zheng, S., Manchanda, R., Gala, D.P., and Sharma, M.M., 2020. Pre-loading Depleted Parent Wells to Avoid Frac-Hits: Some Important Design Considerations. *SPE Drilling & Completion*. https://doi.org/10.2118/195912-MS
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- Agrawal, S., and M. M. Sharma, "Impact of Pore Pressure Depletion on Stress Reorientation and its Implications on the Growth of Child Well Fractures", Unconventional Resources Technology Conference, Houston, TX, U.S.A., July 23-25, 2018, Unconventional Resources Technology Conference (URTeC), 07/2018.
- Shrivastava, K., and M. M. Sharma, "Mechanisms for the Formation of Complex Fracture Networks in Naturally Fractured Rocks", SPE Hydraulic Fracturing Technology Conference and Exhibition, The Woodlands, Texas, U.S.A., January 23-25, 2018.
- Gala, D. P., R. Manchanda, and M. M. Sharma, "Modeling of Fluid Injection in Depleted Parent Wells to Minimize Damage due to Frac-Hits", Unconventional Resources Technology Conference, Houston, TX, U.S.A., July 23-25, 2018, Unconventional Resources Technology Conference (URTeC) , 07/2018.
- Manchanda, R., P. Bhardwaj, J. Hwang, and M. M. Sharma, "Parent-Child Fracture Interference: Explanation and Mitigation of Child Well Underperformance", SPE Hydraulic Fracturing Technology Conference and Exhibition, The Woodlands, Texas, U.S.A., January 23-25, 2018,
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Most Significant Changes in Fracturing

1. Improving cluster efficiency (distributing proppant efficiently)
   i. Extreme limited entry
   ii. Perforation cluster design
2. Fracture spacing and sequencing
3. Proppant and fluid selection
4. Refracturing
5. Fracture diagnostic techniques
   i. Fiber optics
   ii. DFIT analysis
   iii. Pressure interference between wells
   iv. Electrically conductive proppant
6. Interaction of fractures with natural fractures
7. Parent-child wells
8. Proppant Placement

Proppant Transport, Conductivity & Flowback Related Publications

- R. Manchanda, S. Zheng, S. Hirose, and M. M. Sharma, “Integrating Reservoir Geomechanics with Multiple Fracture Propagation and Proppant Placement”, SPE Journal, vol. 25, no. 02, pp. 662–691, 2020, doi: https://doi-org.ezproxy.lib.utexas.edu/10.2118/199366-PA.
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Challenges Still Remaining

- Parent-child well frac designs
- Optimum well spacing
- Refrac design
- Induced seismicity
- Proppant flowback
- Fracture diagnostics
- Understanding induced unpropped fractures
- ….

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