SPE Argentina

SPE de Argentina Asociación Civil

CLUSTERS DESIGN, DIVERSION EFFECTIVENESS AND DIAGNOSTIC TECHNOLOGIES

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LEAGUE OF SPE VOLUNTEERS

JEP CONSULTING

Source: Tim Singley, 2015

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Initial Quote

"The good thing about science is that it's true whether or not you believe in it".

Source: brainpickings.org

Neil deGrasse Tyson

Some Definitions

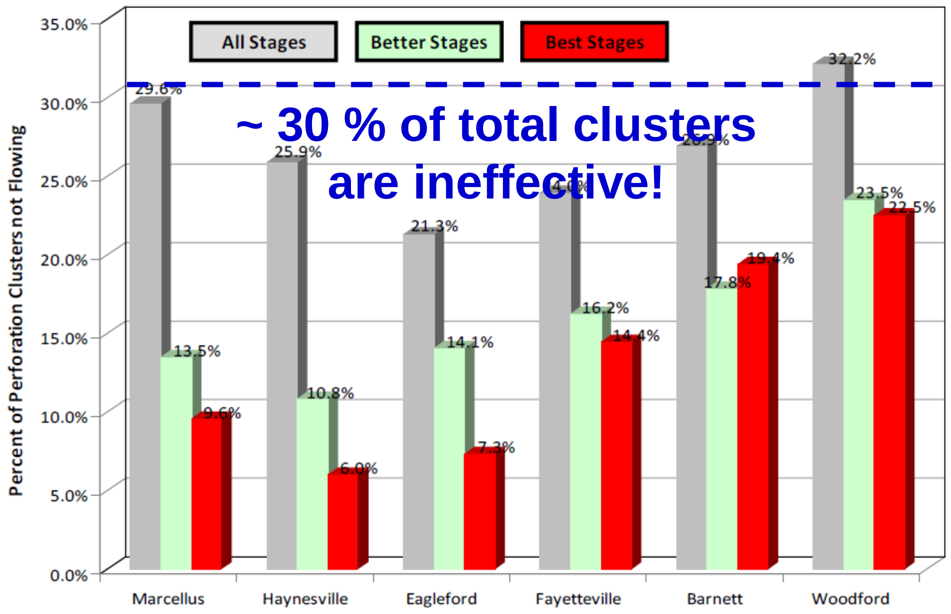
✓Cluster:

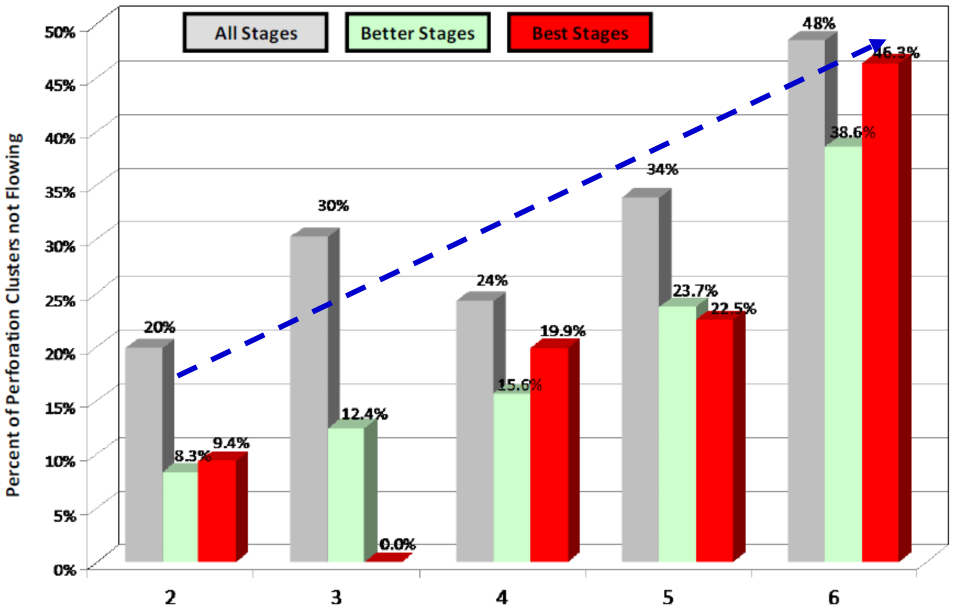
- From Wikipedia: "…a group of similar things or people positioned or occurring closely together…"

- My definition in context: "…a group or bunch of perforations positioned along a fracturing stage intended to get ***uniform flow distribution*** while pumping an ***engineered stimulation treatment*** with the hope of making ***evenly distributed production*** from each one of them…"

Ambitious expectations!

Some Hard Facts!





Source: SPE 144326

✓Production performance = f(cluster effectiveness):

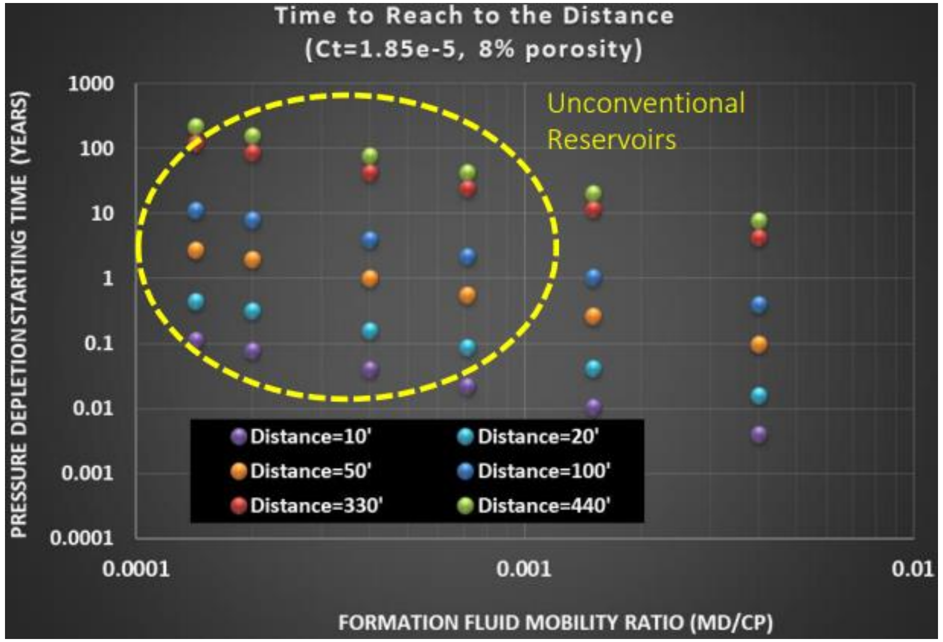
- ~2/3 of the total clusters are not producing. Current technologies are fixing part of the problem but still away from optimum. Why?
- The greater the number of clusters per stage, the lower the clusters effectiveness. Why?

Why do We Want to Optimize Clusters Design?

- ✓ Some answers:
  - To maximize reservoir contact
  - To make more efficient reservoir fluids recovery
  - To optimize well spacing
  - To accelerate development pace
  - To maximize production and monetize it
  - To reduce completion costs
  - To avoid fracture interference
  - To reduce operational issues while pumping hydraulic fractures
- ✓ In summary: right well spacing and optimal cluster design will maximize recovery and improve well economics and company value
- ✓ It is prohibitive the field trial-error approach!

Fundamentals Behind Tighter Clusters Design

- ✓ Fracture production:
  - Function of contacted area
  - Larger fracture surface area for higher rate, but large fractures are difficult to preserve along time as conductivity is continuously degraded
  - Tighter clusters spacing may result in faster depletion and higher recovery
  - Completion cost, geomechanical and operational constraints impact cluster design
- ✓ Tradeoff of multiple variables to get an optimum design
- ✓ Basis for high density completions (HDC)



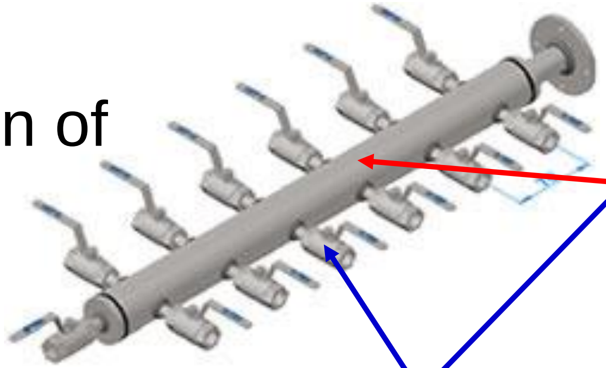
Source: SPE 189855, SPE 194367

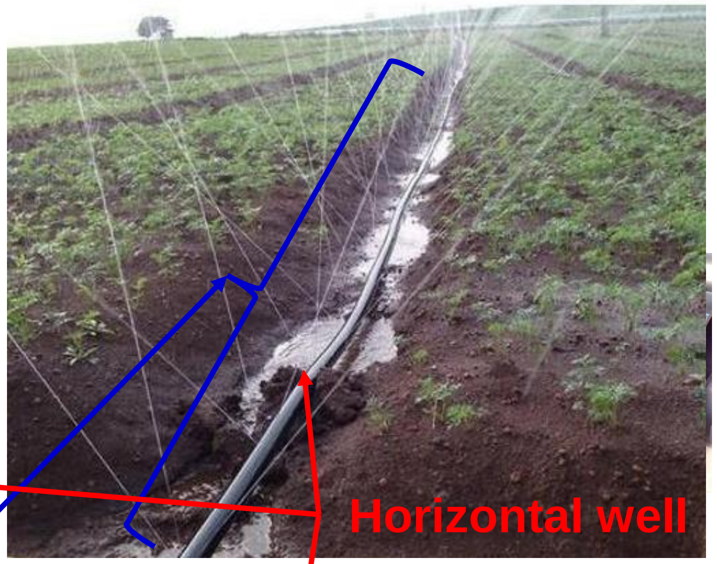
Completion

$$q \approx \sqrt{\frac{\phi C k_m}{\mu B^2}} * \boxed{A\sqrt{k}} * \Delta p * \frac{1}{\sqrt{t}}$$

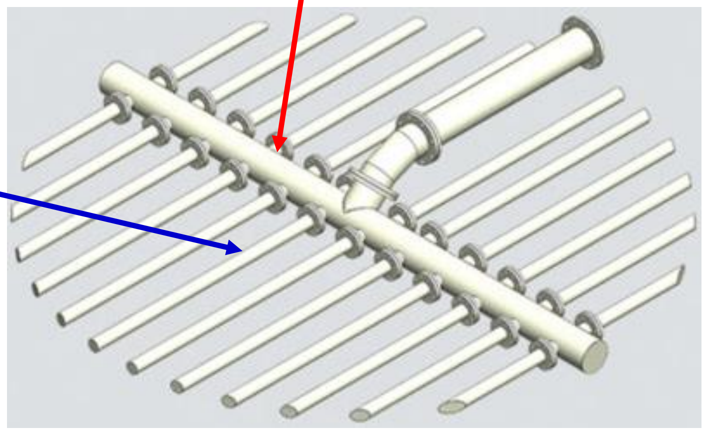
Resemblance to Other Industrial Applications

- ✓ Other applications face similar challenges to distribute fluids evenly. All successfully implemented
- ✓ Irrigation:
  - Objective: provide even distribution of water at required rate
- ✓ Distribution manifolds:
  - Objective: distribute fluid volume mostly equally in each outlet
- ✓ Liquid distributors:
  - Objective: spread fluid in each branch at the same rate





Source: indiamart.com



Source: www.enexio-water-technologies.com

What do They Share in Common?

	Clusters	**Other *Successful* Applications**
Physics	Not well understood, simplistic	Well known
Fluid	Multiphase (frac fluid + proppant)	Single phase
Fluid rheology & regime	Non-Newtonian, always turbulent?	Newtonian, turbulent
Slip between phases	Yes	No
Slip at pipe wall	Yes (friction reduction)	No
Sedimentation	Partial	No
External stress	Variable (rock stress along stage)	Constant (atmospheric pressure)
Pipe external boundaries	Yes (cement, perforation channel, reservoir)	Yes (atmosphere)
Type of orifices & phasing	Jet perforations, 0, 60, 120, 0 - 360	Drilled holes, multiple options
Uniform hole size	Close to uniform with special charges	Yes
Holes breakdown	Yes	No
Erosion	Yes (important)	No

✓ Need to tackle every issue if we want to improve current results!

Fundamentals of Limited Entry Treatments (LET)

✓ Some history:

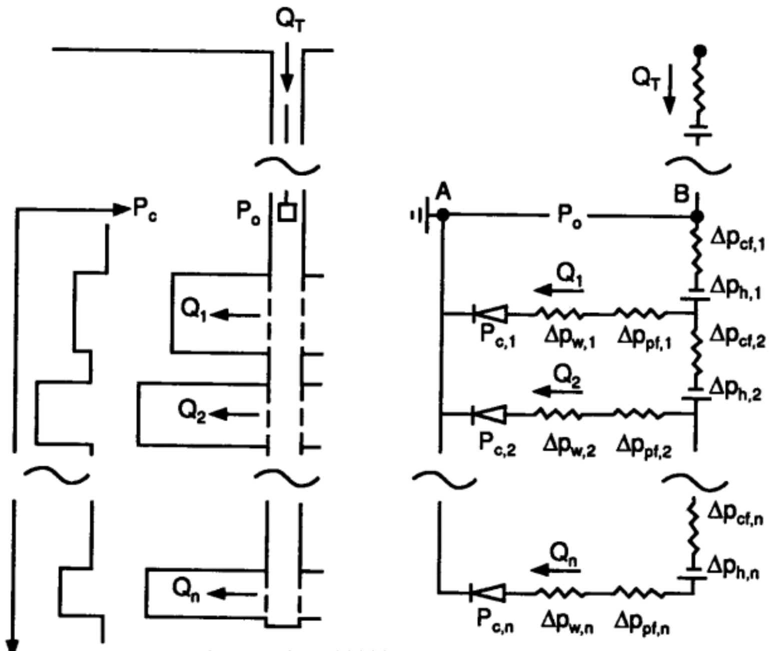
- Firstly reported in a paper in 1963 by Lagrone and Rasmussen (SPE 530)

✓ Physics:

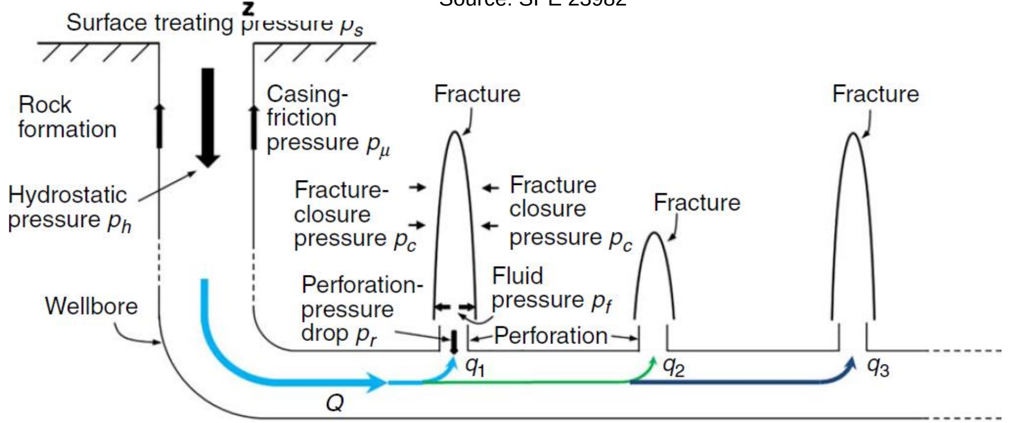
- High perforation friction to ensure that pressure during injection is greater than the highest stress in the layers or along stage
- False assumption as other parameters such as H_f, YM, leak off rate and area affect net pressure which impact stresses

✓ Math behind rate distribution:

- Use of Kirchhoff’s laws for fluid distribution
- Currently coupled to fracture model



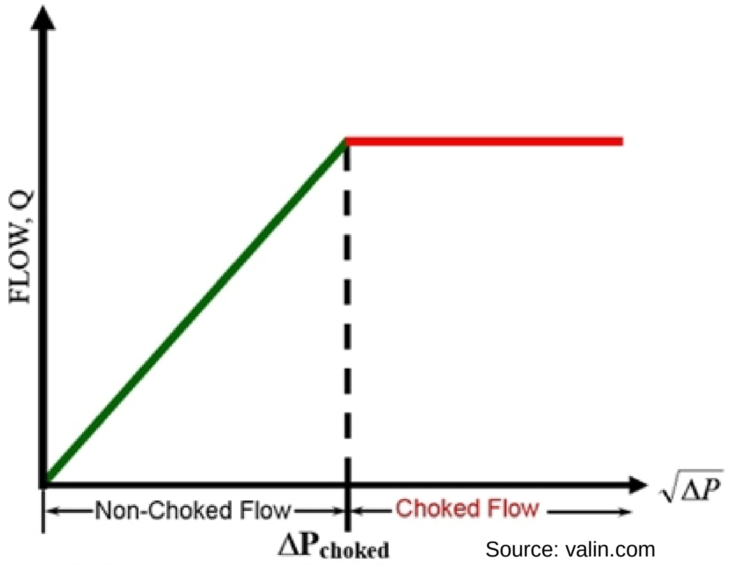
Source: SPE 23982



Source: Zhao et al., 2021

Limited Entry Treatments

- ✓ Limited entry design equation:
  - Based on choked flow theory. Abusive utilization of flow equation through chokes but still useful
  - If pressure drop across choke or orifice (perf) is high enough, downstream rate is constant
- ✓ Practical application
  - Possible to pump multiple fractures at different entry points
  - Firstly applied in vertical tight wells and now a common practice in unconventional horizontal wells
- ✓ Main observation from real treatments
  - Not all perforations take fluid, process is not 100 % efficient



Source: valin.com

Orifice Flow Equation

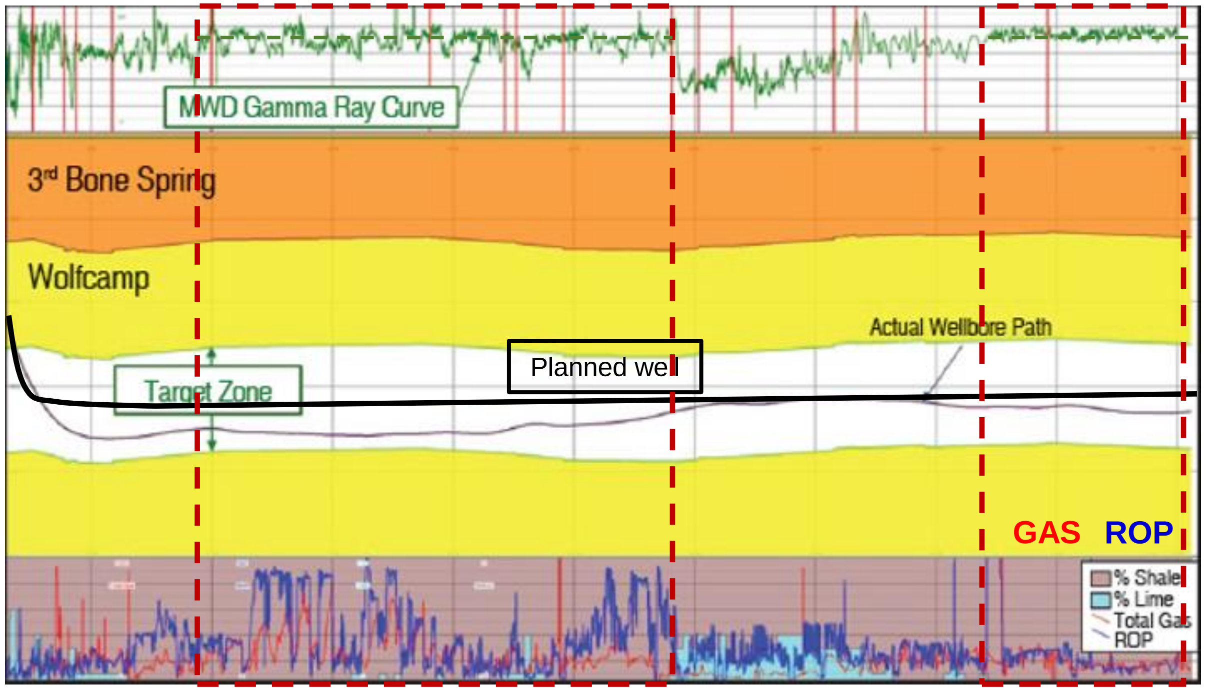
$$\Delta P_{perf} = \frac{0.237\,\rho Q^2}{D^4 C^2}$$

Where:

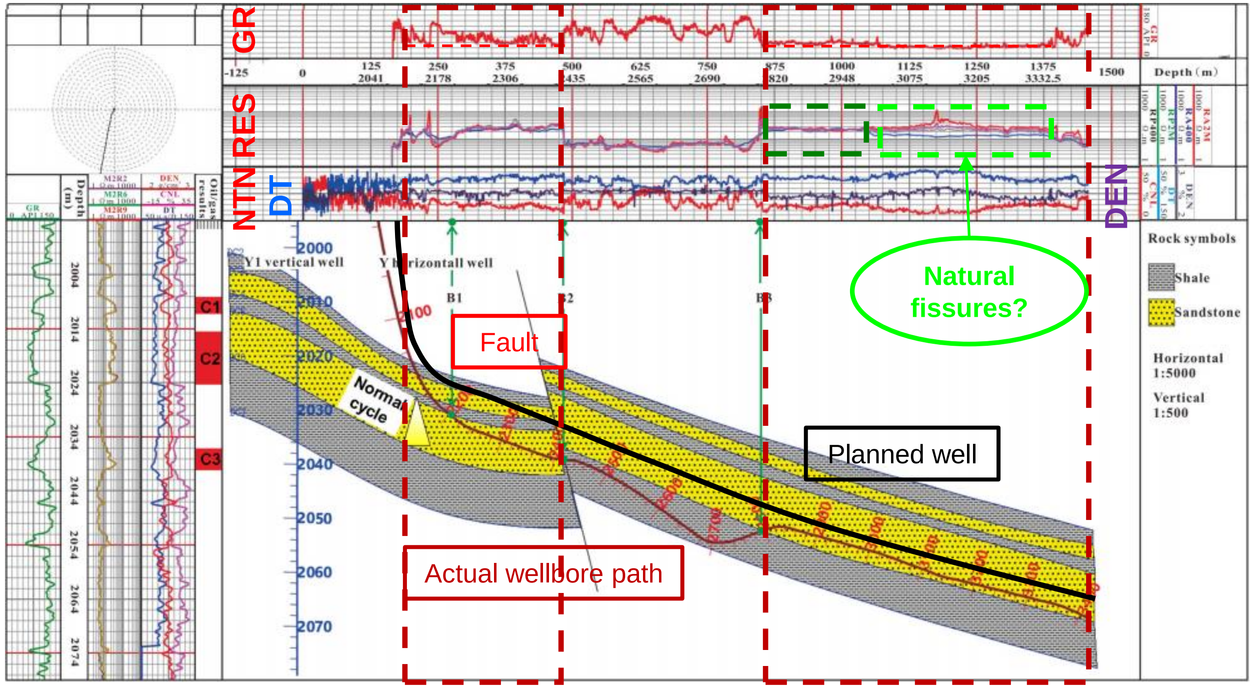
ΔP_{perf} = Total perforation friction, psi
Q = Flow rate through each perforation, BPM/perf
D = Diameter of perforation, in.
C = Perforation coefficient (.095, for round perforation)
ρ = Fluid density, lbs/gal

Limited Entry in Times of COVID-19

Reservoir and Wellbore Construction – Plan vs Reality



Source: AOGR, March 2018



Source: Quin et al., 2017

✓Observations

- Actual wellbore path rarely matches planned trajectory. Unexpected faults
- Geosteering is not easy, it is mostly a reactive operational technique
- GR alone can not be used to define zones with similar stresses. Instead define stages by selecting zones with similar rock and geomechanical properties

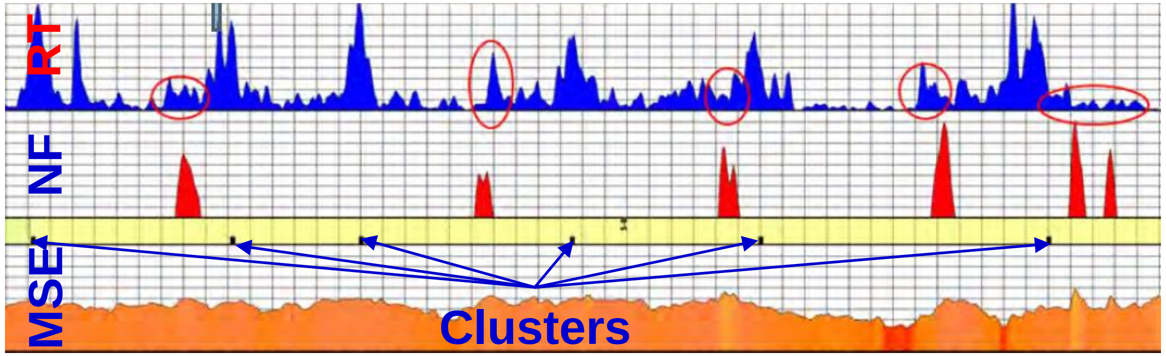
Geomechanical Variability Impact

✓Engineered completions:

- Stages designed to minimize stress difference between clusters
- Number of clusters and separation defined as per operator’s completion strategy

✓Additional input (if present):

- Natural fissures (if able to be activated)



Source: modified from SPE 204208

✓Takeaways:

- In zones with active natural fissures, perforations placed on these zones will take more fluid than perforations located outside the fissured zone leading to early screen-outs and reduced contacted area
- Perforation scheme must include this important variable
- If logs are not available other proxies can be used instead

How Much Limited Entry Pressure is Really Needed?

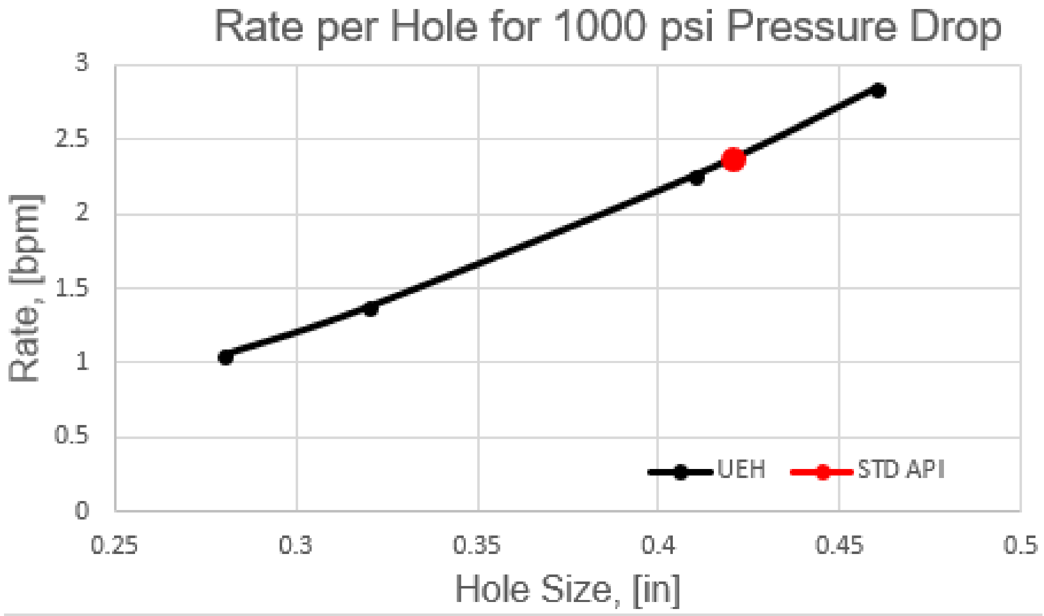
- ✓ Limited Entry Treatments (LET) have evolved in designs where increased pressure drop is required, but is there a limit?
- ✓ Higher pressure = higher hydraulic power = higher costs and quick equipment deterioration
- ✓ Main factors:
  - Perforating
  - Fracture initiation pressure
  - Stresses and stress regime
  - Fracture extension net pressure
  - Near wellbore complexity
  - Stress shadow effects
  - Economics!

Increase

$$\textbf{ROI} = \frac{\textbf{Production}}{\textbf{Cost} + \textbf{Cycle Time}}$$

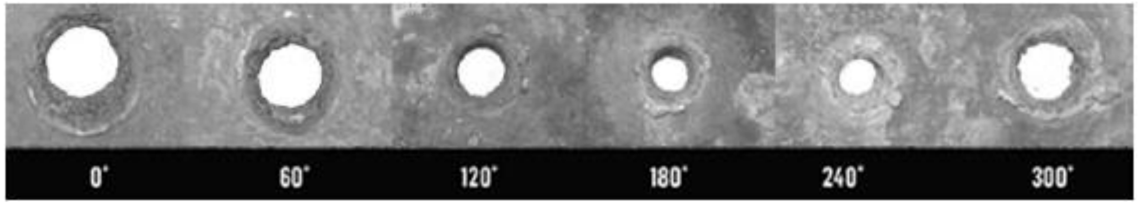
Reduce **Improve**

Perforations Entry Hole Size Effects

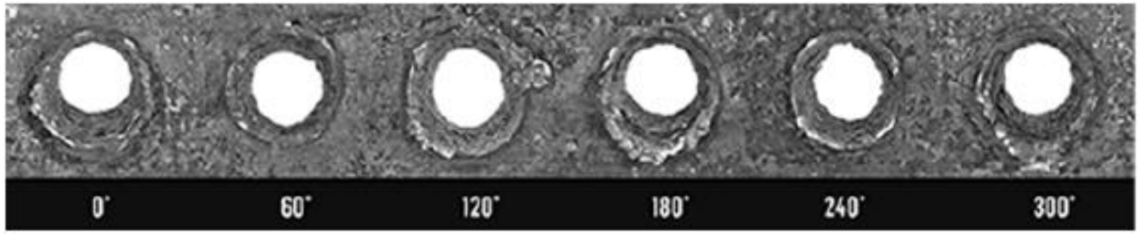


Source: SPE 188478

Standard API charges



Uniform Entry Hole



Shot No.	1	2	3	4	5	6	7
Phase	0	60	120	180	240	300	360
Clearance	0.00	0.26	0.90	1.30	0.90	0.26	0.00
API EHD	0.42	0.42	0.42	0.42	0.42	0.42	0.42
EHD (P110)	**0.46**	**0.41**	**0.32**	**0.28**	**0.32**	**0.41**	**0.46**
DP vs. Design	67%	109%	304%	477%	304%	109%	67%

✓Observations

- If all holes have the same ID, therefore pressure drop is the same in all of them
- If holes are of different size, pressure drop is the same for all holes but rate per hole is variable. This assumption is no longer valid if geomechanics is considered. Stress behind each hole is not the same

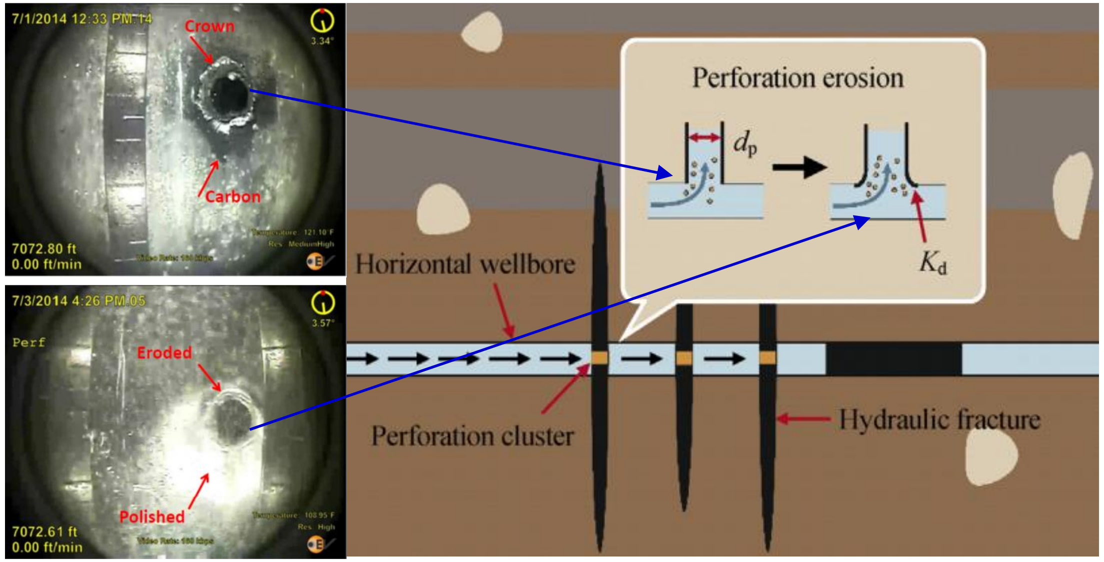
Perforation Erosion

✓Observations:

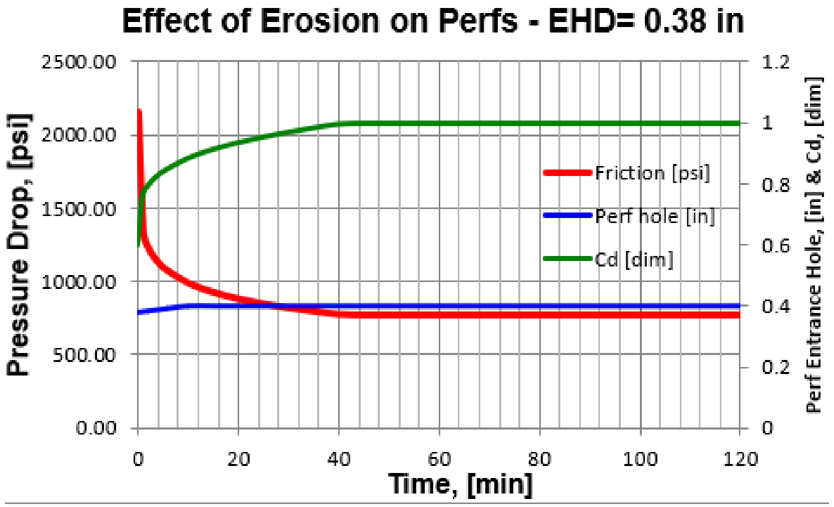
- Perforation erosion is time dependent
- Function of proppant size, concentration, fluid rate, erosion rate, etc.
- Typical range: 0.004 – 0.008 in/1,000 lb_m
- Erosion is not a linear process
- Erosion process is not totally understood so it is not well described physically nor mathematically. Efforts in place

✓Consequences:

- Friction pressure is poorly estimated
- Limited entry treatments are jeopardized!



Source: Yongming et al., 2018



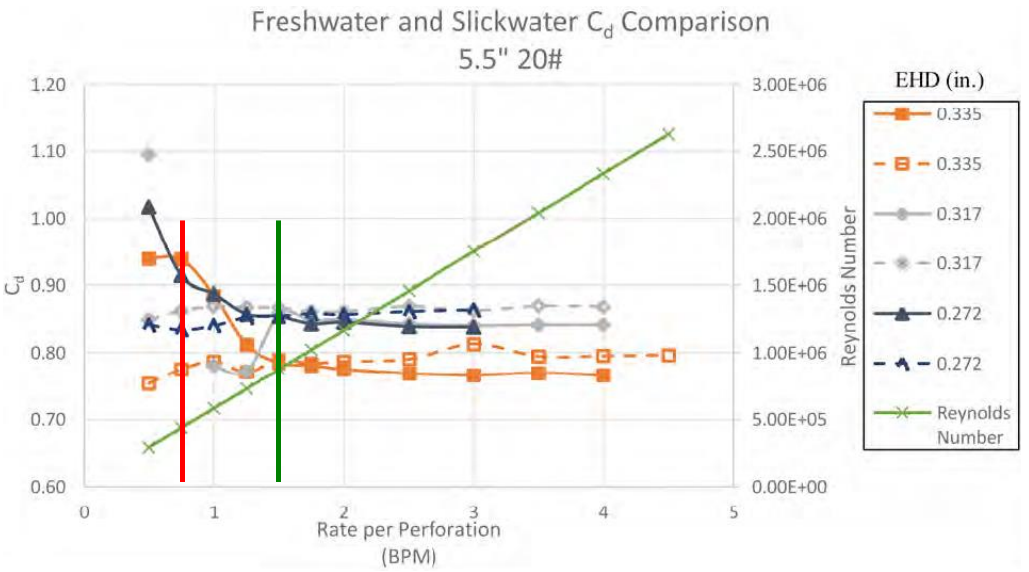
Cd Variation – Recent Research Studies

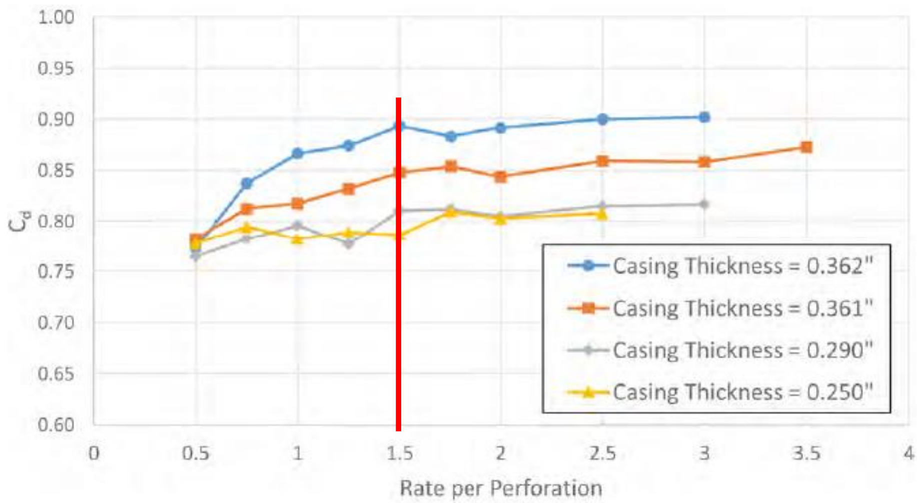
✓ Impact on pressure drop:
- Squared and inversely proportional

✓ Rate impact:
- Actually, it depends on Re's number
- Above ~1.5 bpm/hole values are constant

✓ Fluid type impact:
- Viscous and HVFR increases minimum rate to get constant Cd values

✓ Casing thickness:
- ~10 % variation in Cd = ~20 % variation in pressure drop
- Constant Cd values above ~1.5 bpm/hole

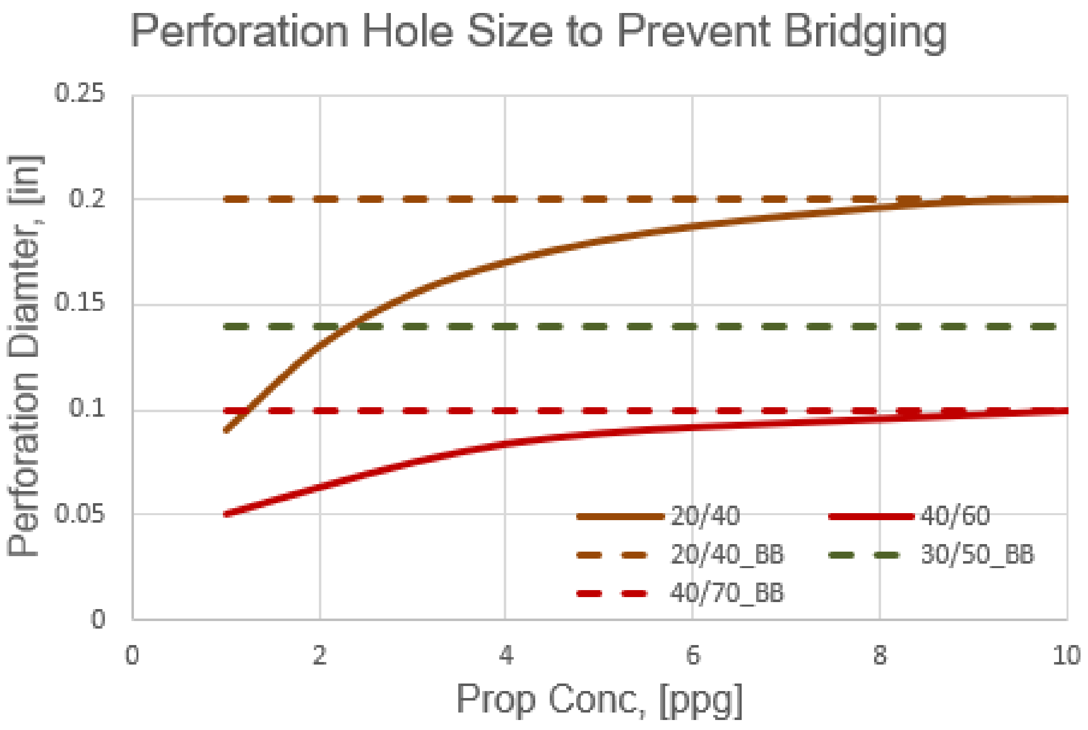




Source: SPE 204178

Maximum Proppant Size Through a Hole

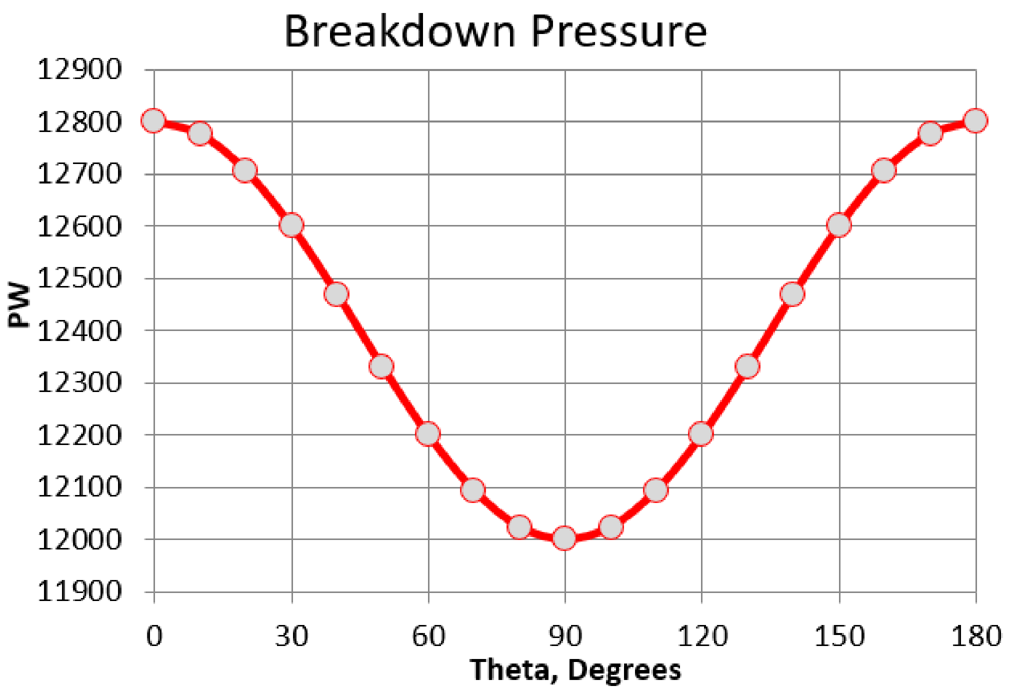
- ✓ An old graph but still useful:
  - From experiments if D_perf > 6 D_prop, then bridging is unlikely
  - Overlay of Bob Barree's recommendation matches values at 10 ppg (safe side)
- ✓ Takeaways:
  - For unconventional fracs where maximum prop size is 20/40 and prop concentration is < 5 ppg, minimum hole size (EHD) could be ~0.18 in
  - Justification for smaller hole size in XLE but too small might cause production issues such as scaling, choking, etc



Geomechanics Impact on Perforations Breakdown

✓Observations

- In real wells, stress around the wellbore is not equal as considered before in basic analyses
- In strike-slip stress regime, first perforations to breakdown will be those close to the 90 +/- 15 degrees (~horizontal)
- If we want to breakdown all perforations an excess of pressure and friction is required above the minimum breakdown pressure
- Minimum rate is no longer a rule of thumb of 2 – 2.5 bpm/hole. It needs to be calculated!
- One of the reasons why only 2/3 of perforations are reported broken down



Frac Initiation in Cased and Cemented Perforated Wells

✓Fact:

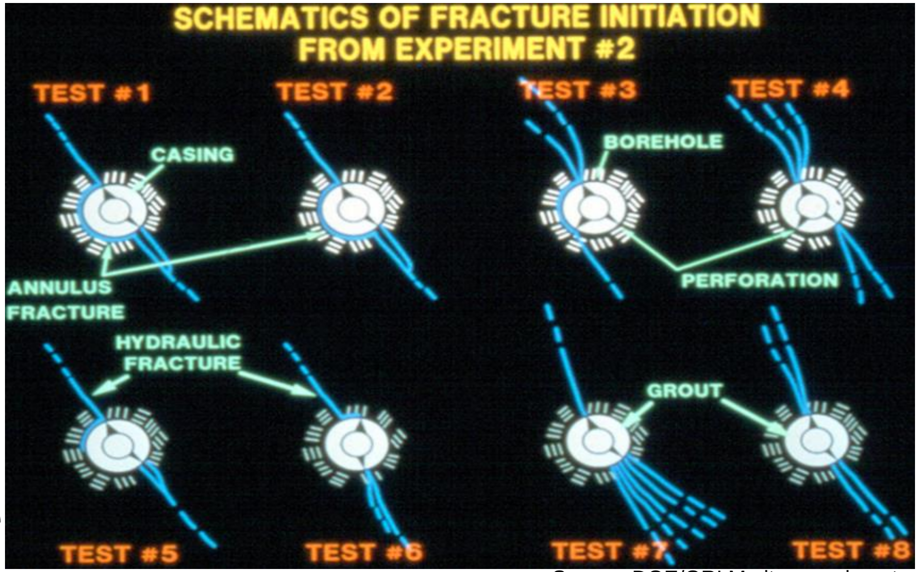
- Fractures rarely initiate at tip of perforation tunnels leading to tortuosity or NWC

✓Reasons:

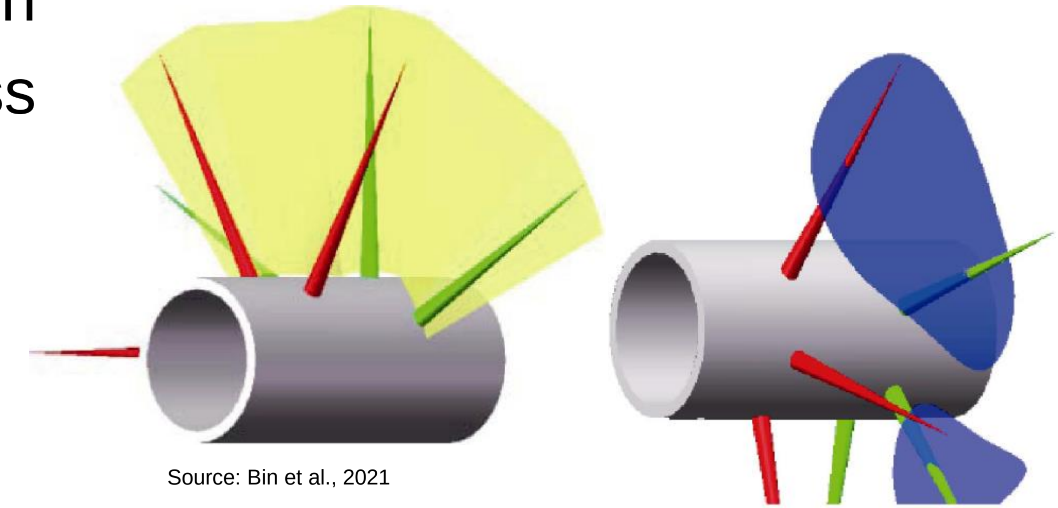
- Cementing job is not perfect in horizontal wells
- Charges create a tunnel with a compacted zone with higher strength than surrounding region
- Misalignment of perfs and max. horiz. stress
- Disconnected fracture planes

✓Takeaways:

- No need of deep penetration charges
- Uniform hole size and short clusters



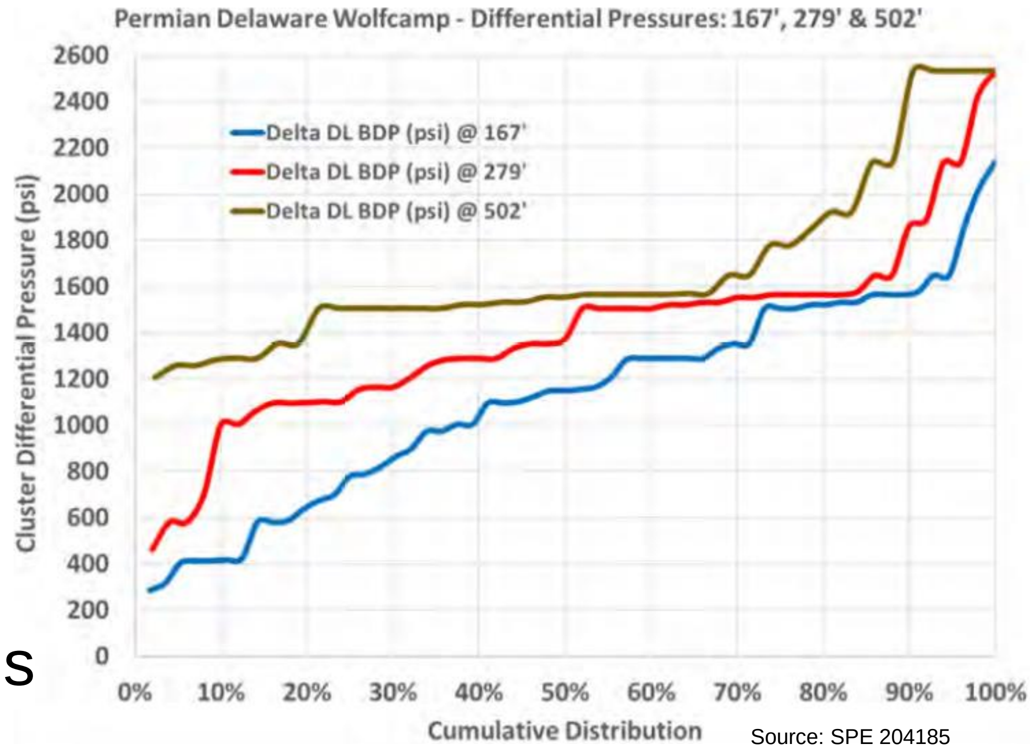
Source: DOE/GRI M-site experiments



Source: Bin et al., 2021

Differential Pressure to Initiate Clusters

- ✓Physics:
  - Stresses around wellbore are not equal
  - Perforations mostly aligned with maximum stress will breakdown firstly
  - Extra differential pressure required to breakdown remaining perforations
  - Initially, breakdown is done at low rate (minimum friction), but differential pressure is only obtained if higher rates are attained
- ✓Limiting factors (most important ones):
  - Frac stage length, near wellbore complexity, perforation entry holes, ***EROSION***, etc.

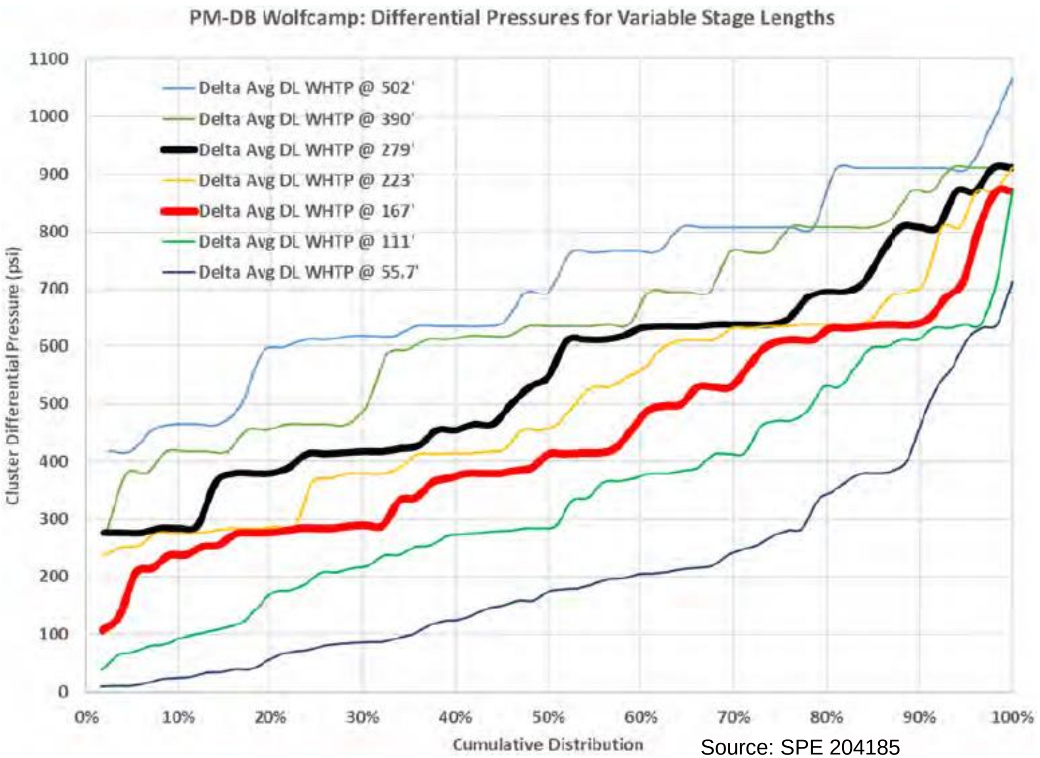


Source: SPE 204185

Precautionary note: this graph is only valid for the region where data was acquired, as geomechanics and other factors govern the outcomes

Differential Pressure to Keep Clusters Active

- ✓ Physics:
  - As frac treatment progresses, erosion causes an important decrease in pressure drop. Not a linear function!
  - Holes are enlarged and Cd increases
- ✓ Frac stage length impact:
  - The larger the frac stage, the larger the pressure drop required to keep all clusters active during the whole treatment.
  - Need to understand erosion process
  - One approach is to pump at maximum allowable pressure at variable rate



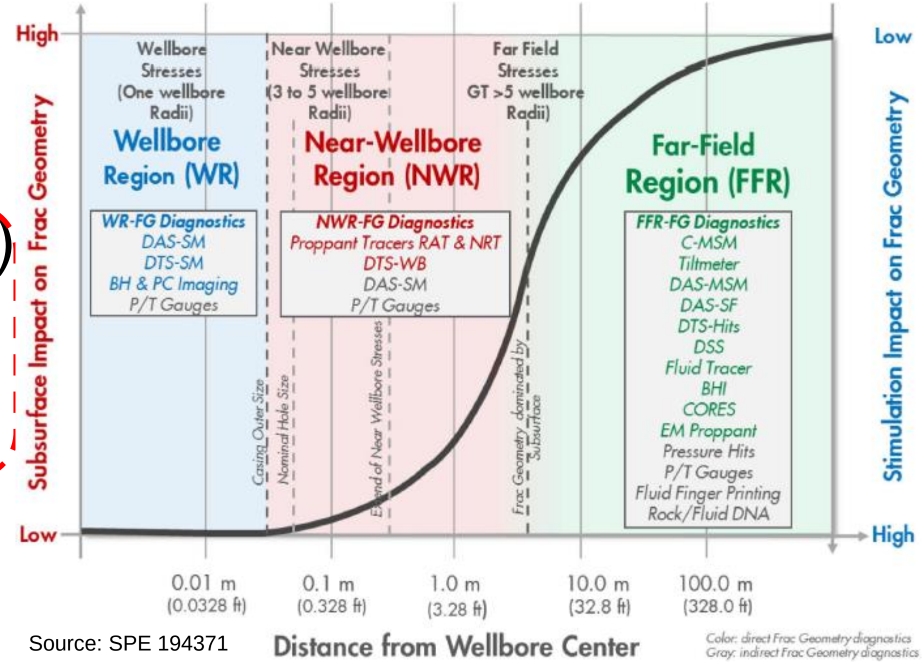
Source: SPE 204185

Precautionary note: this graph is only valid for the region where data was acquired, as geomechanics and other factors govern the outcomes

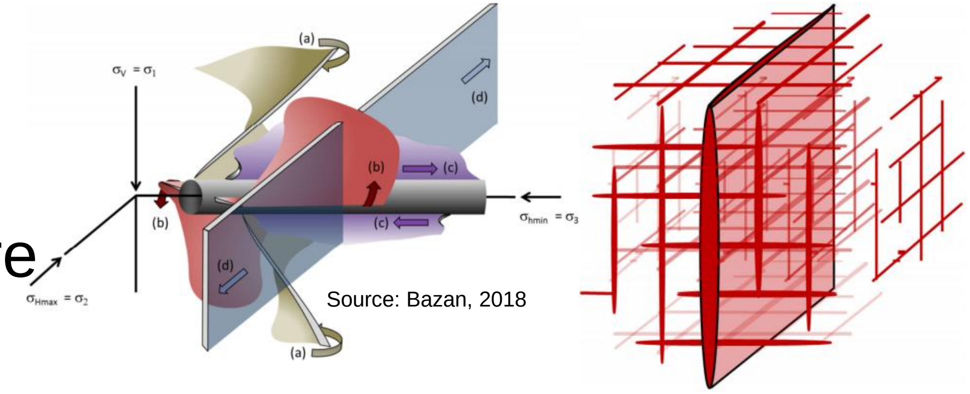
Fracture Behavior in Laminated / Fissured Rocks

✓ Fracture regions:
- Wellbore (WR) – 1 r_w
- Near-wellbore (NWR) – 3 to 5 r_w (10’s of inches)
- Mid-field (MFR) – 5 to 10 r_w (10’s of feet)
- Far-field (FFR) – >10 r_w (100’s of feet)

✓ Behavior
- Simple, tortuous and complex fractures
- Initially swarms of fractures, then dominant mostly planar fractures
- Unique pressure signature of each region
- Possible to decouple in width-opening pressure (true P_{net}), complex back stress (stress shadowing) and mid-field complexity



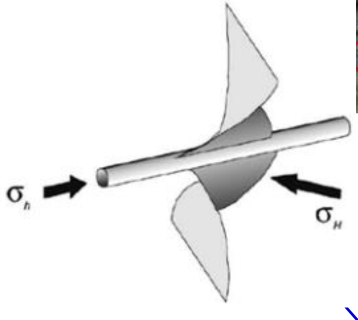
Source: SPE 194371



Source: Bazan, 2018

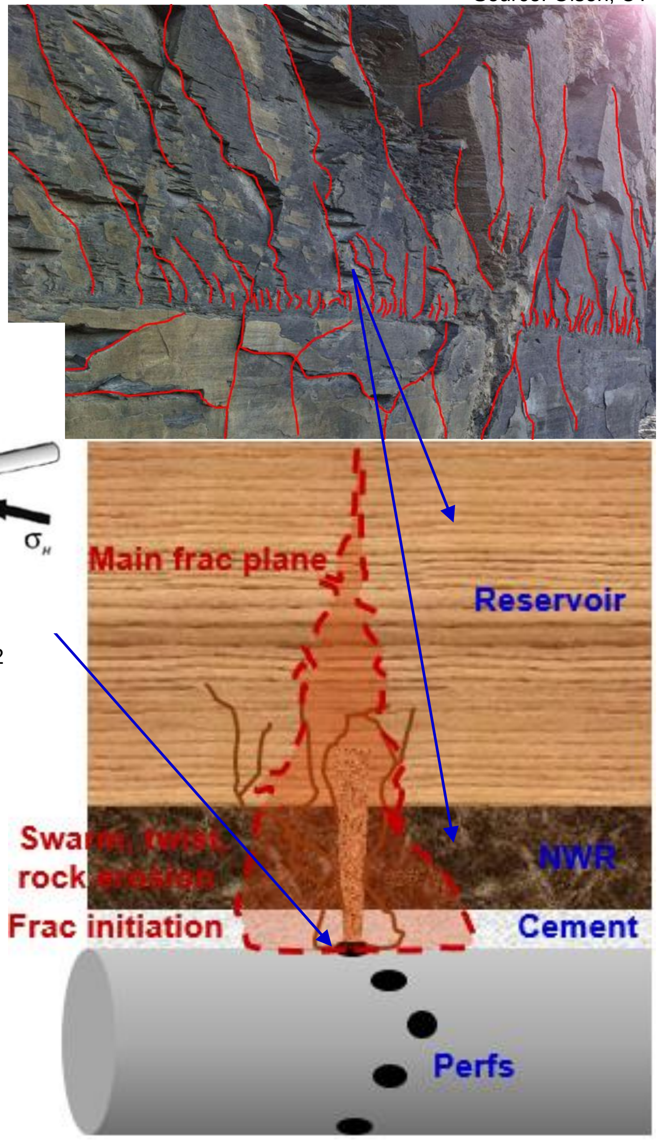
Near Wellbore Region (NWR) Complexity & Pressure Drop

- ✓ Facts:
  - Initial “tortuosity” of no less than ~500 psi, being ~1,500 – 2,000 psi a good average
- ✓ Characteristics of NWR:
  - Virgin rock disturbed by wellbore construction
  - Region where fracture initiate, initially grow, create a swarm, coalesce or branch, twist, etc.
  - Erosion of cement and rock. Formation of tortuous flow channel. Pressure drop changes abruptly with no particular law
  - Variations in flow paths dimensions cause pressure variations that might dominate completely fluid partitioning leading to dominating fractures



Source: Rahman, 2002

Source: Olson, UT



Differential Pressure Effects on Clusters – No NWC

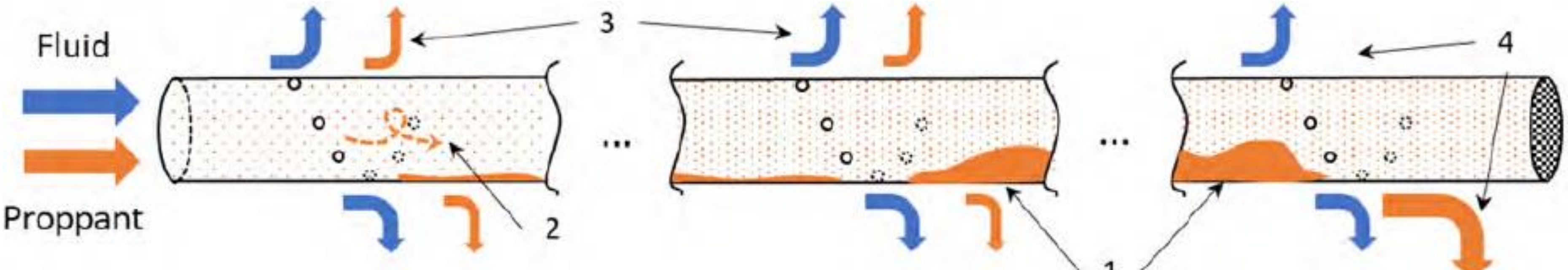
Case	Clusters	SPF	Total perfs	EHD [in]	Prop Conc [ppg]	Press Drop [psi]	Rate [bpm]	Remarks
Baseline – no erosion	5	6	30	0.38	0	1,000	**58**	Old school
Baseline – w/ erosion	5	6	30	0.38	4	1,000	**78**	Old school
Case 1 – no erosion	10	6	60	0.38	0	1,000	**116**	Old school
Case 1 – w/ erosion	10	6	60	0.38	4	1,000	**156**	Old school
Case 2 – w/ erosion	5	6	30	0.38	4	2,000	**110**	XLE
Case 3 – w/ erosion	10	6	60	0.38	4	2,000	**221**	XLE
Case 4 – w/erosion	10	2	20	0.38	4	2,000	**74**	XLE
Case 5 – w/erosion	15	2	30	0.38	4	2,000	**110**	XLE
Case 6 – w/erosion	15	2	30	0.34	4	2,000	**87**	XLE
Case 7 – w/erosion	15	1	15	0.38	4	2,000	**55**	XLE
Case 8 – w/erosion	20	1	20	0.38	4	2,000	**74**	XLE

Assumptions: initial Cd: 0.6 (no erosion), final Cd: 0.9 (eroded), all active perforations, no near wellbore complexity

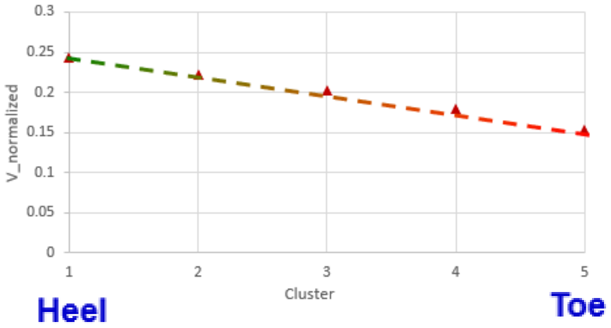
Proppant Transportation & Distribution in Clusters

✓ Observations from DAS/DTS, camera imaging and other technologies:
- Heel-biased proppant distribution
- Decrease in axial velocity from heel to toe leading to potential proppant settling
- Settling cause alterations of frictional pressure drop along the stage
- Bottom perforations received more proppant but they may screen out

✓ Causes (not in order):
- Multiphase flow, fluid viscosity, slip between phases, settling, stratified flow, velocity variation and proppant inertia (momentum)



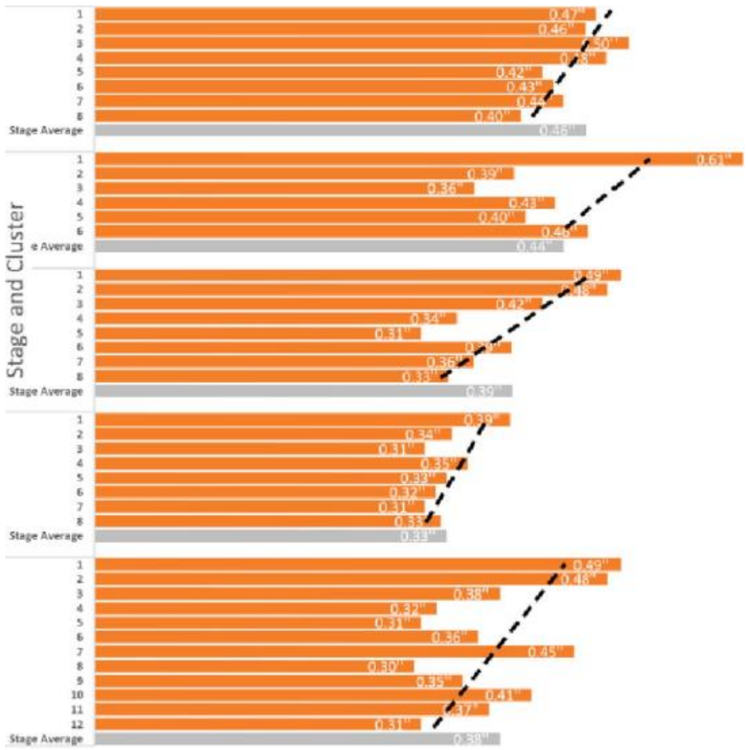
Source: SPE 204207



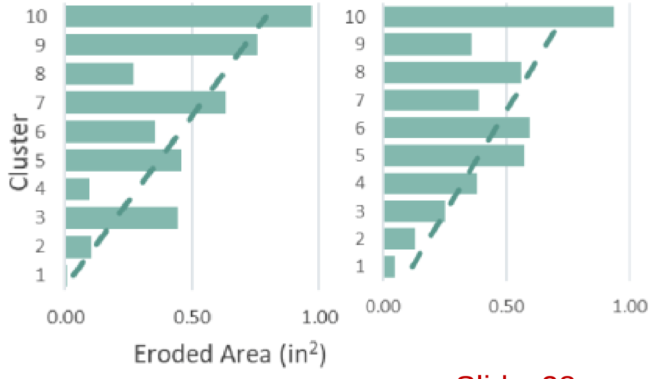
Proppant Transportation & Perforations Locations

✓Observations:

- Gravity has an important effect on proppant distribution
- Clusters close to the heel receive more momentum than remaining ones
- Fluid velocity decreases from heel to toe. Impact on shear-thinning fluids
- Slurry has two phases with completely different inertia so easier for proppant to overpass heel cluster but for fluid is easier to go into those perforations. Once erosion process starts proppant is dragged and transported so its distribution is heel-biased
- 0 – 180 top-bottom perforations receive different amount of proppant if not designed properly

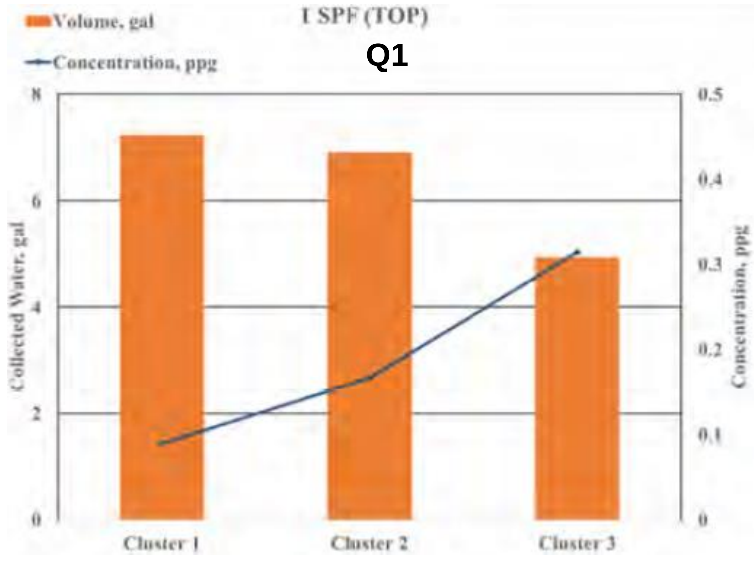


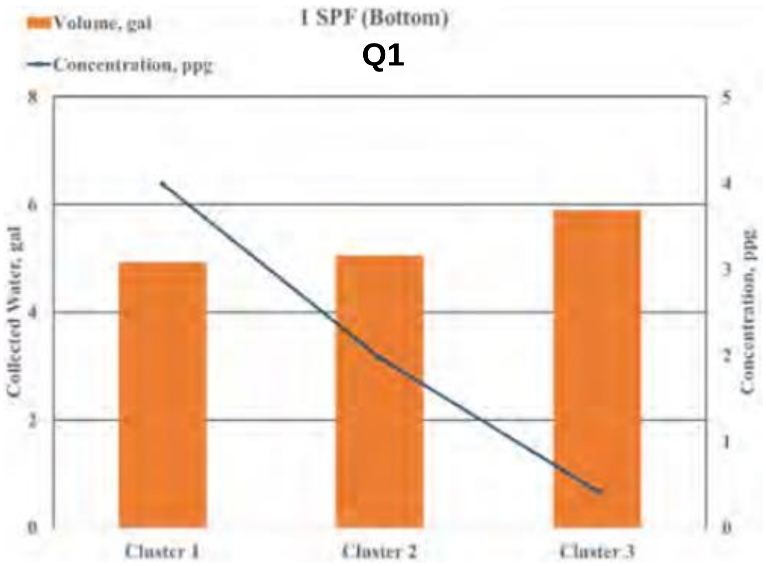
Source: SPE 194334

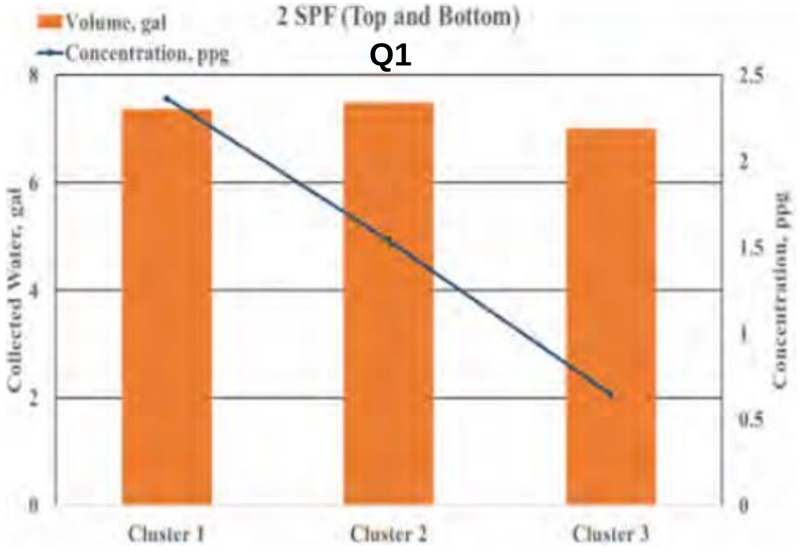


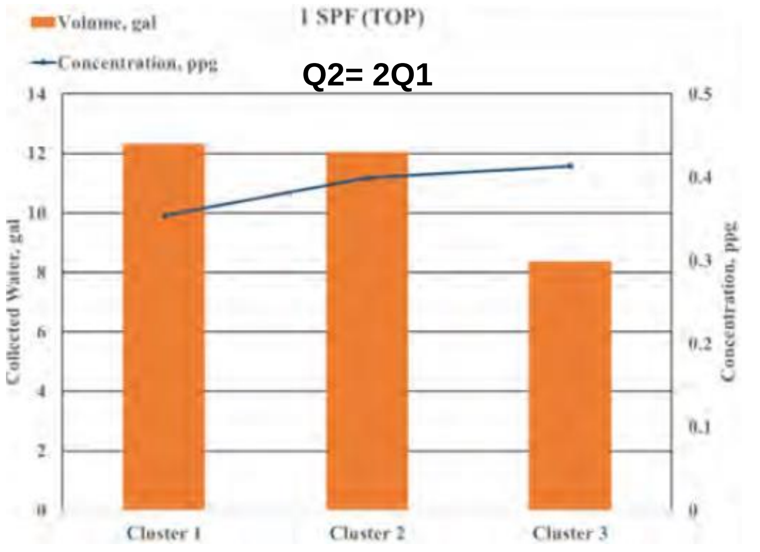
Source: SPE 204186

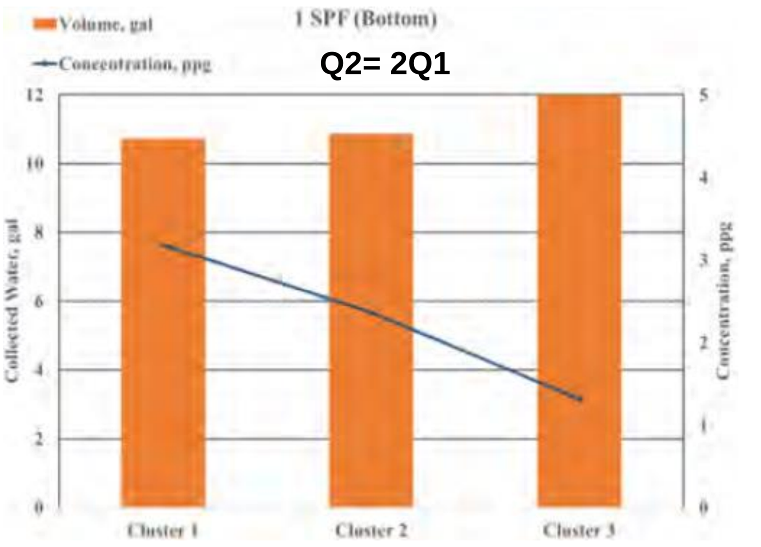
Proppant Transportation & Perforations Locations

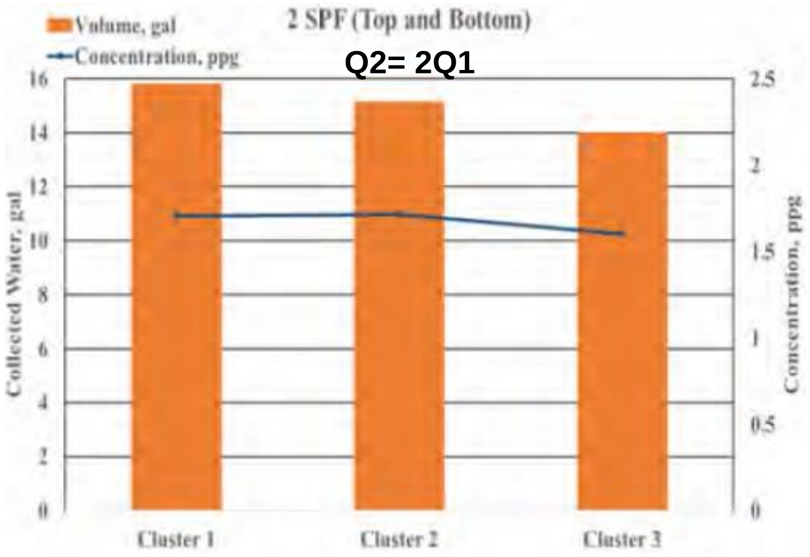












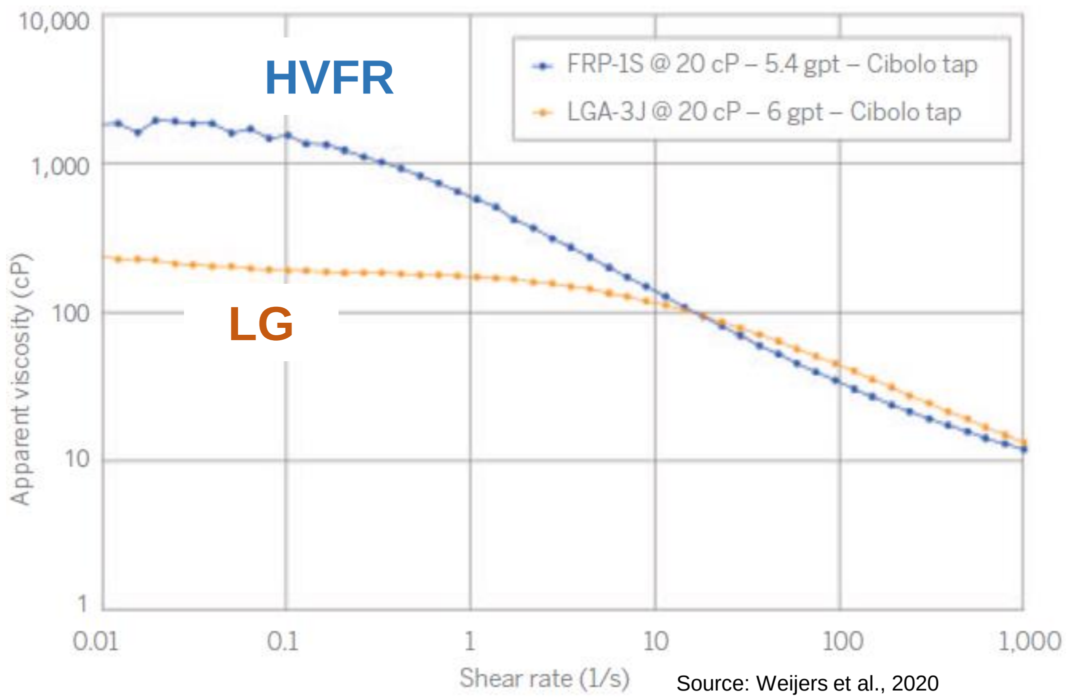
Frac Fluid Apparent Viscosity Comparison

✓Facts:

- Frac fluids are non-Newtonian therefore viscosity is shear-rate depending

✓Observations:

- Both have similar apparent viscosity at 511 1/s – S-1 (standard testing)
- Above 10 1/s both have similar friction
- Below 10 1/s (perforations and fractures) HVFR has advantages as it has better transporting capabilities
- Useful in multi-clusters applications where axial velocity is low close to the toe

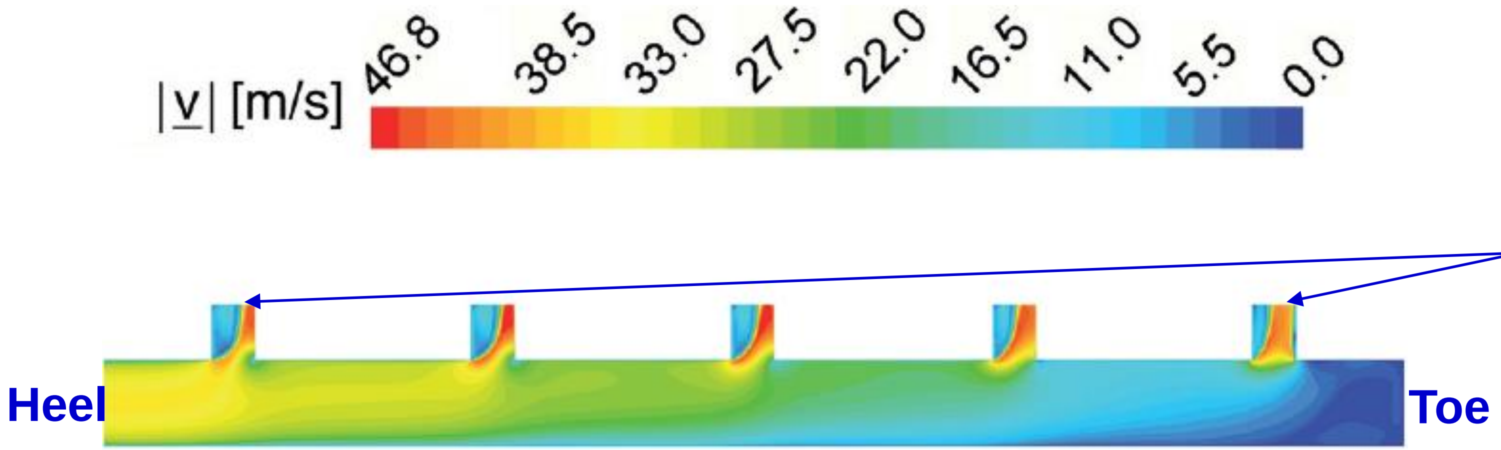


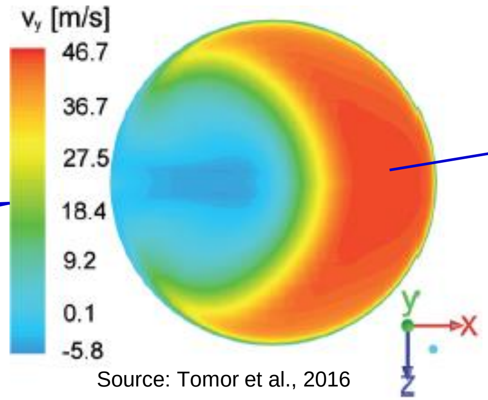
Source: Weijers et al., 2020

Local Velocities Along Frac Stage – Top Perforations

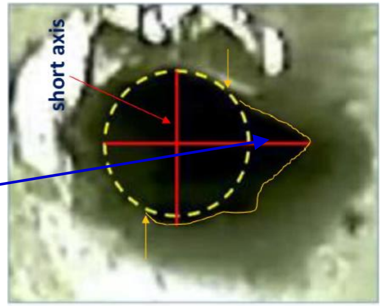
✓Findings from CFD analysis of geometrically distributed holes:

- Axial and lateral velocities are not uniform at the cross-section
- Much higher velocities close to the heel and in the upper section of the pipe
- Lower velocity in the bottom of the pipe leading to potential settling at the toe
- Higher velocities inside hole onto the toe direction leading to uneven erosion
- Very low velocity close to the toe
- Flow area available at each entry point must be modified. More holes at the toe

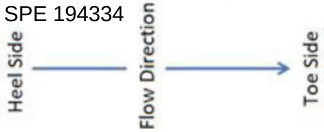




Source: Tomor et al., 2016



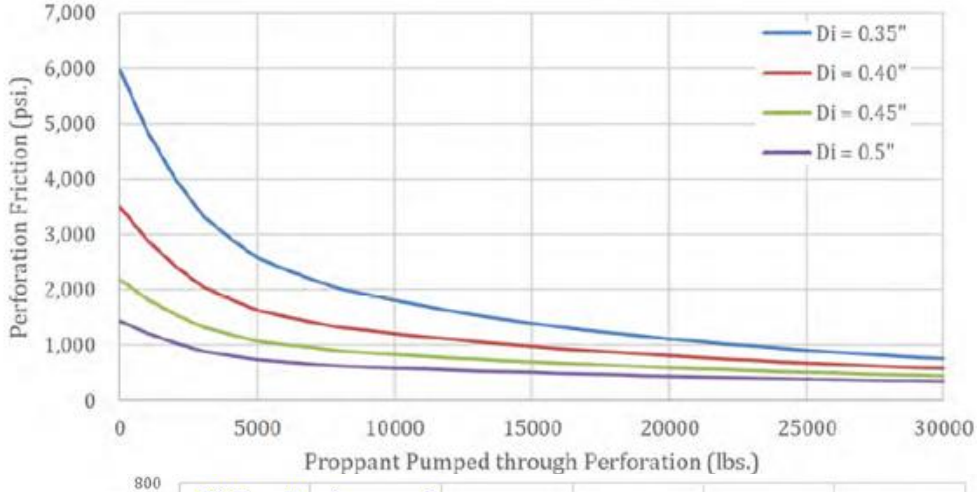
Source: SPE 194334

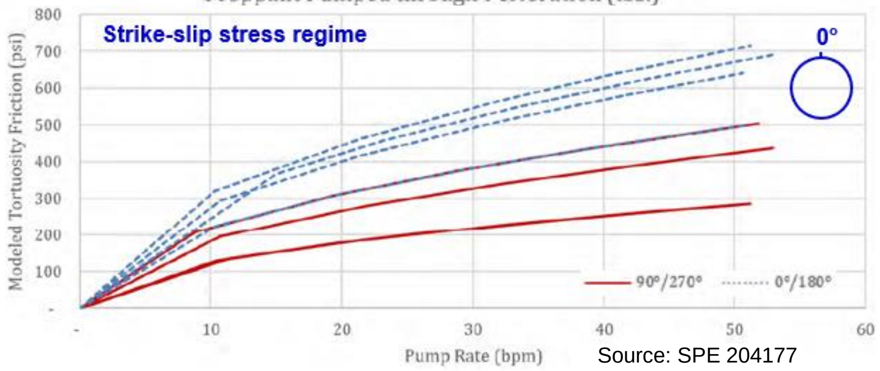


Downhole Imaging Diagnostic

Source: SPE 194334

- ✓Findings:
  - Pre-treatment perforations entry hole were highly variable even with uniform entry hole charges
  - Charges performance is lower than reported
  - Not all charges perform the same
  - Smaller holes erodes faster and converges to the same pressure drop of bigger holes
- ✓Erosion rate:
  - Not linear as function of proppant pumped
- ✓Stress regime:
  - Perforating into the plane of maximum horizontal stress reduces tortuosity



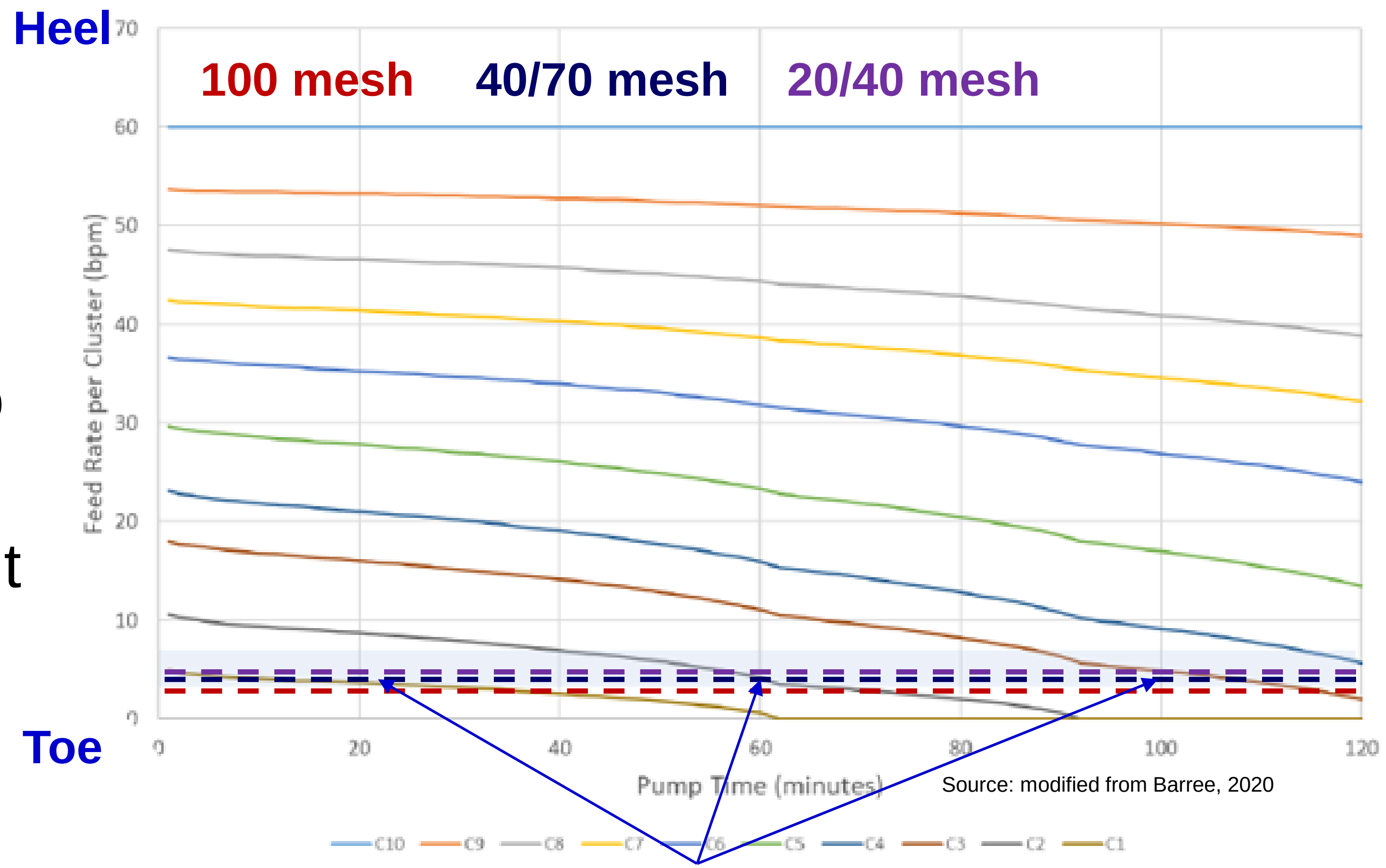


Source: SPE 204177

Rate per Cluster & Proppant Transportation

✓ Observations:

- Only clusters close to the heel see high fluid energy
- Velocity reduction is larger along time for clusters close to the toe
- Rate per cluster is not constant along time
- Depending on proppant type, size and frac fluid apparent viscosity some clusters might face settling effects and would not receive too much proppant



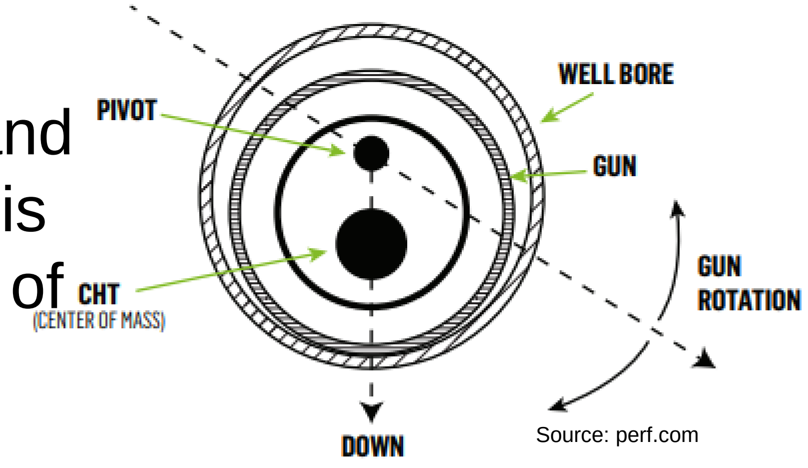
Source: modified from Barree, 2020

Clusters 1, 2 and 3 will suffer settling problems

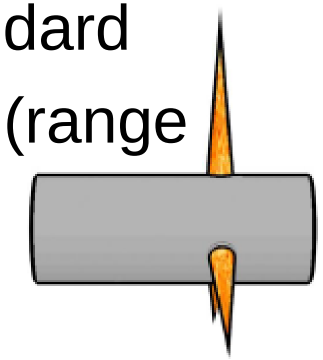
Clusters Perforating

✓Based on studies and observations:

- Based on downhole camera images, DAS logging and CFD analysis current trend in normal stress regime is to go for 0 – 180° or 0° phasing when large number of clusters is used. Number of holes limited to 2 – 5
- For 0° phasing top-oriented casing guns are used
- Uniform entry hole charges are the new standard
- Smaller hole size charges are now common (range 0.22 to 0.38 in are now standard sizes)



Source: perf.com



Source: geodynamics, 2019

✓New developments:

- Reliable and cheap oriented casing guns
- Single plane uniform entry hole
- Still UEH charges need improvement (<4 % variability)

Tapered Perforating Scheme

✓Fact from observations:

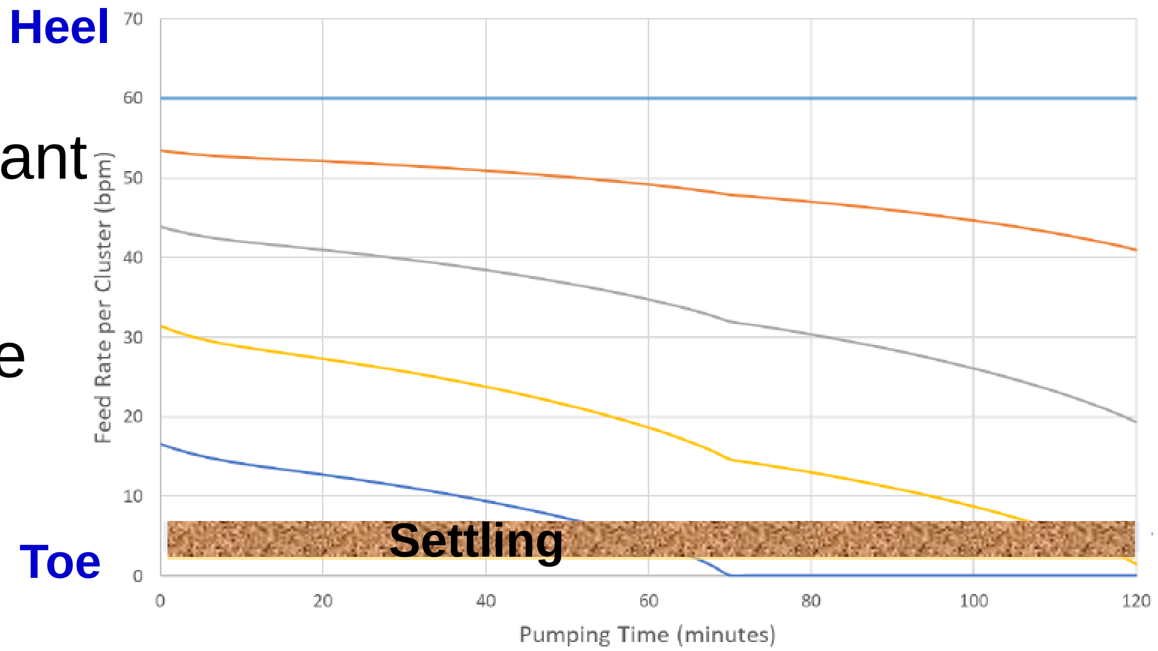
- Clusters close to toe receive less proppant

✓Approach to fix the problem:

- More holes of same size close to the toe

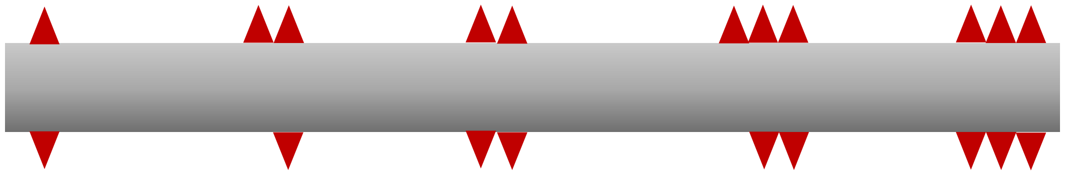
✓Results:

- Impossible to keep constant rate per cluster. It helps with proppant transport
- As the number of holes increase, it is more difficult to control pressure drop = erosion
- Erosion is more a function of proppant concentration than pumping rate
- Hole distribution still on evaluation



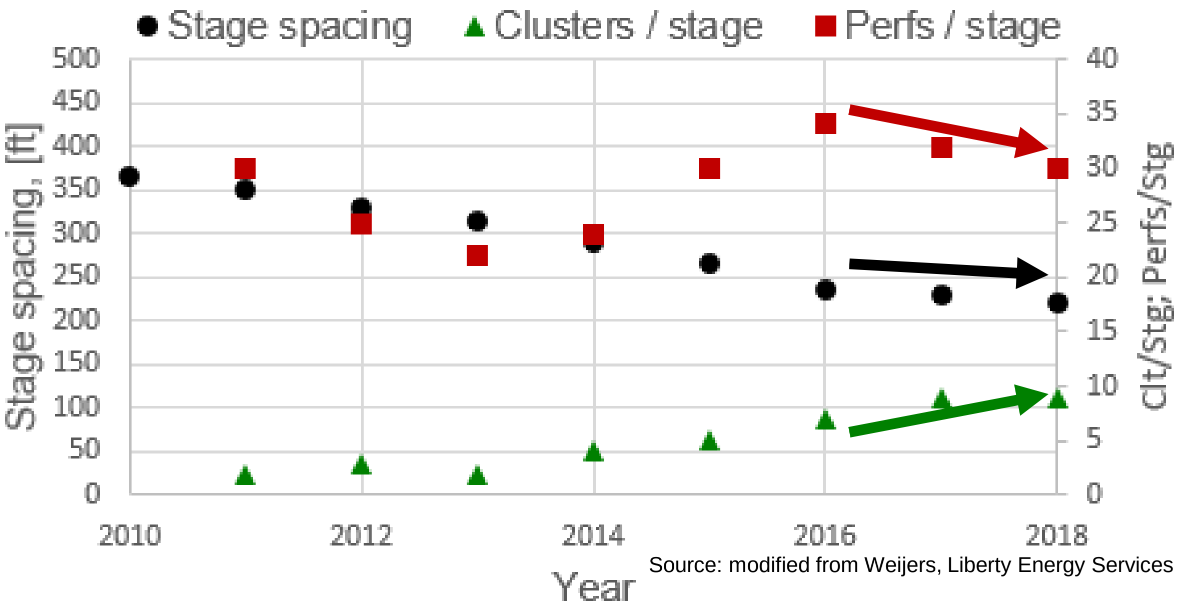
C-5 (2 h); C-4 (3 h); C-3 (4 h); C-2 (5 h); C-1 (6h)

Source: Barree, 2020



Evolution of Cluster Design

- ✓ Cluster spacing:
  - Originally long stages. Low number of clusters. Great number of holes. Poor results
  - Evolution to shorter stages, increased number of clusters and less holes
- ✓ Rate and friction pressure at perfs:
  - Rate has increased from ~60 to 120 bpm. New blender designs
  - Friction at perforations have evolved up to 2,500 psi in XLET
- ✓ Diverters
  - Use of diverters on a regular basis



Source: modified from Weijers, Liberty Energy Services

Design parameter	LET	XLET
Friction at perfs [psi]	1,000 -1,500	2,000 – 2,500
Rate/perf	2 – 3 bpm/perf	>3 bpm/perf

Step Rate Down Test During P&P Completions

✓Objectives:

- Estimate perforation efficiency
- Assess NW tortuosity

✓Execution:

- One SRT during pad and another during flushing

✓Improved methodology:

- Based on better understanding of the process

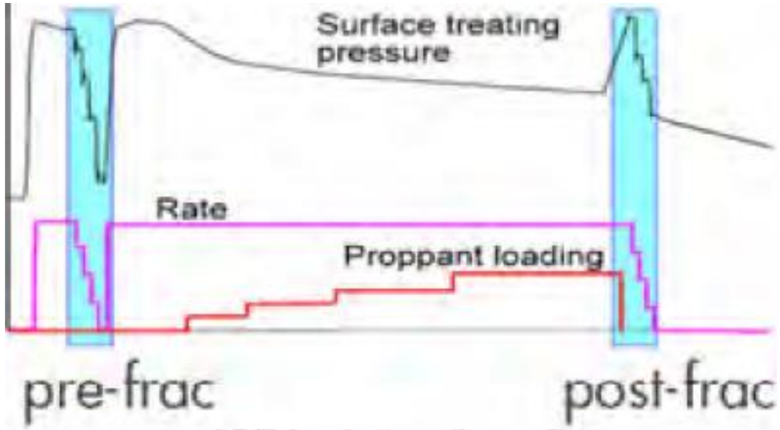
$$\Delta P_{entry} = \Delta P_{perf} + \Delta P_{nwbt} = \underbrace{k_{perf} Q^2}_{perforation friction} + \underbrace{k_{nwbt} Q^{\beta}}_{near-wellbore tortuosity friction}$$

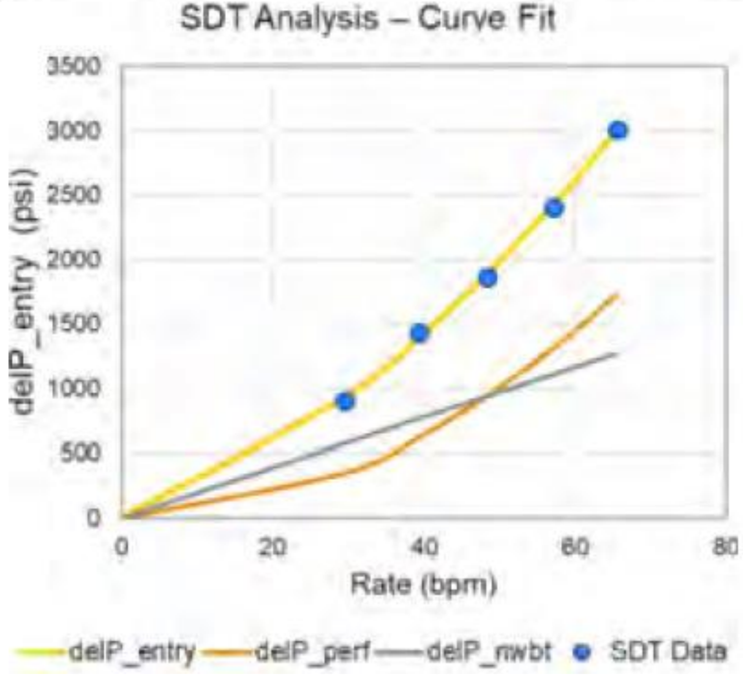
Old Eq

$$\Delta P_{entry} = \Delta P_{perf} + \Delta P_{nwbt} = \underbrace{k_{perf} Q^2}_{perforation friction} + \underbrace{k_{slot}}_{slot-type nwb} + \underbrace{k_{tort} Q^{0.5}}_{tortuous-type nwb}$$

New Eq

$$N_{perfs\ open} = N_{perfs\ shot} \sqrt{\frac{\Delta p_{perfs\ shot}}{\Delta p_{perf,\ measured}}}$$



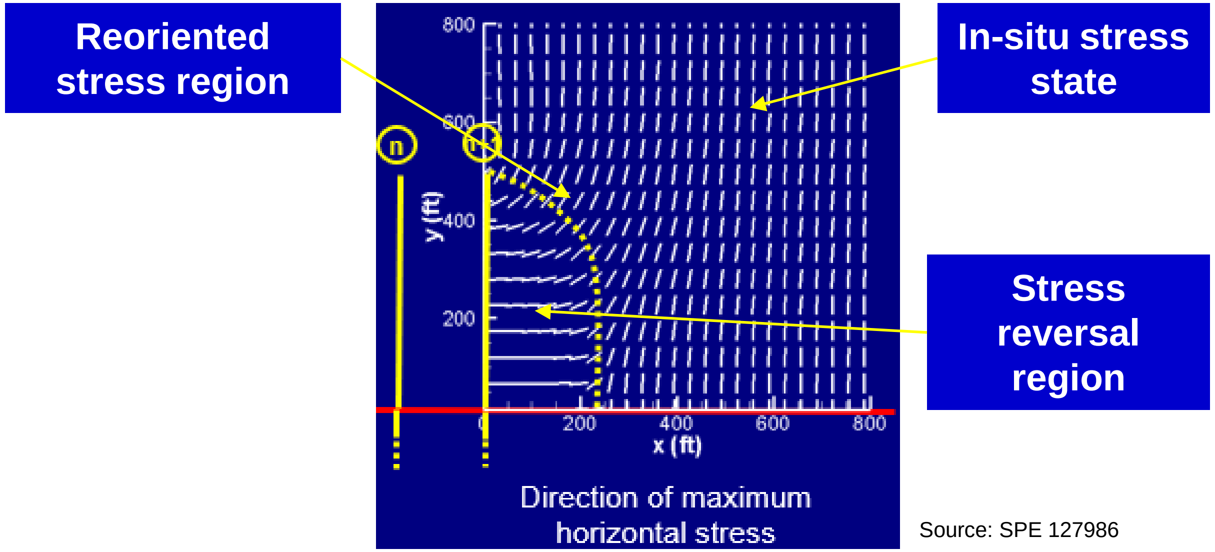


Source: SPE 204147

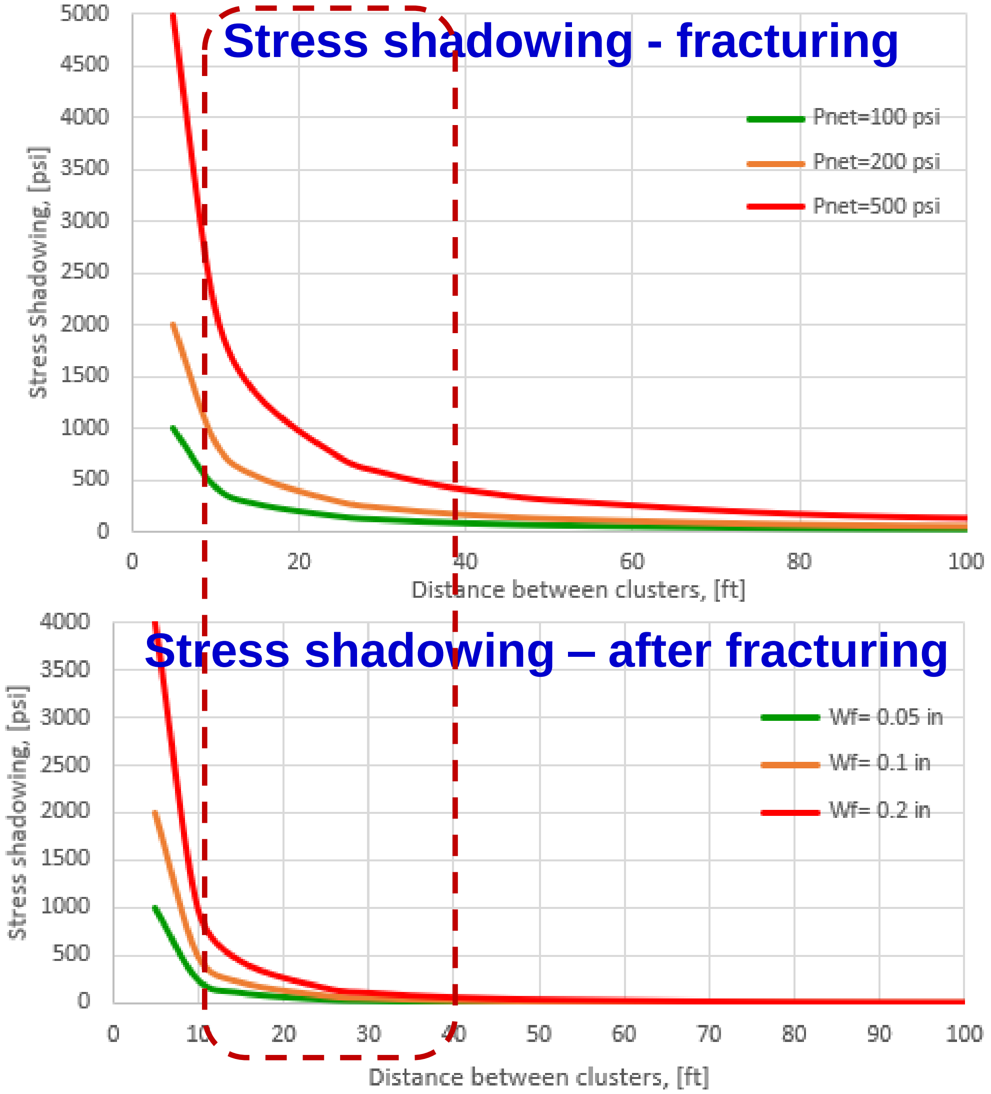
Stress Shadowing

✓ Stress interference acts during and after fracturing:

- Although closely spacing provides higher IP it also creates high stresses causing interaction between fractures that might lead to coalescence into dominant fractures
- Potential stress reversal. Bad for fracturing



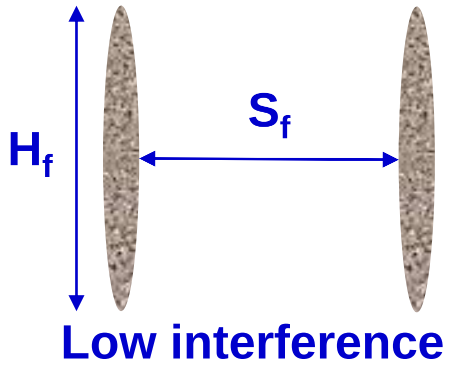
Source: SPE 127986

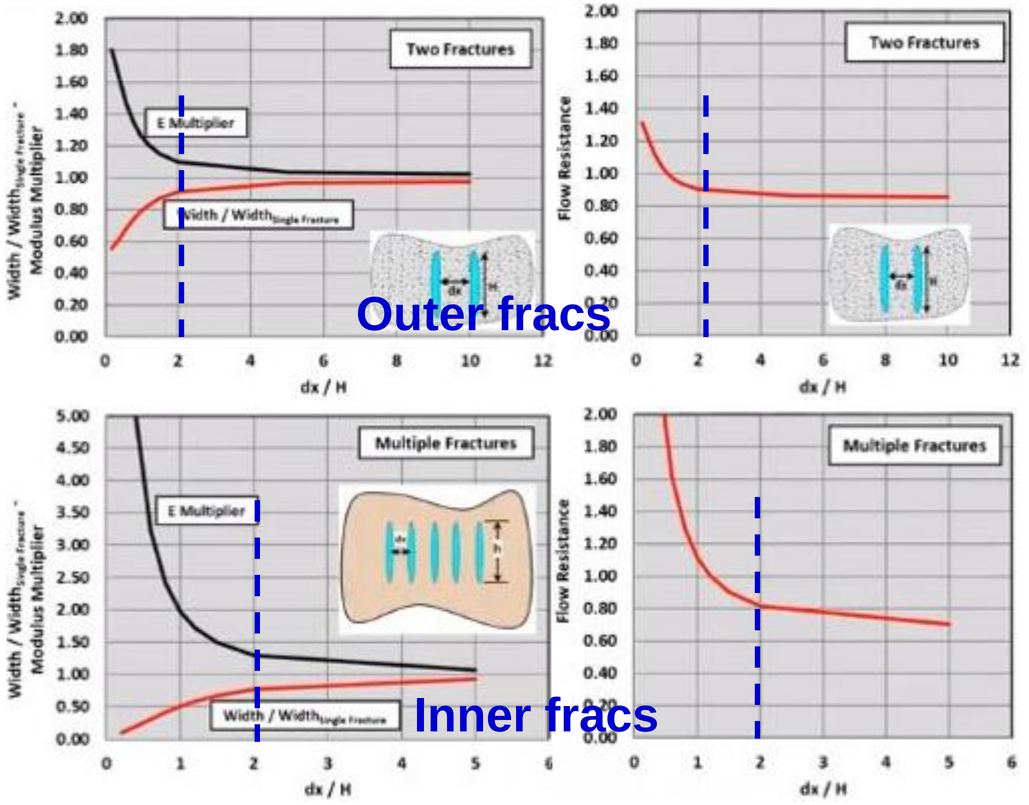


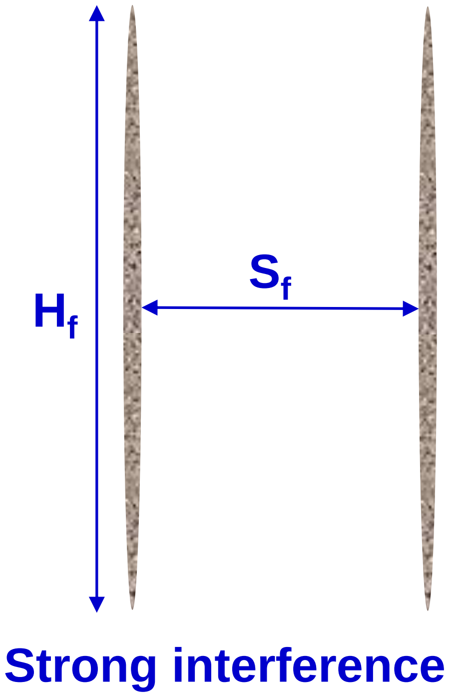
Stress Shadowing is not as Simple as 1-2-3

✓ Stress shadowing = stress interference:

- S.I. = 1 / Separation^{n} is not a good representation
- Complex interference may be beneficial for close cluster spacing
- Not only function of spacing but also fracture height
- For outer fracs if $S_f > 2H_f$ minimum effect on flow resistance and W_f
- For inner fracs if $S_f > 2H_f$ minimum effect on flow resistance but on W_f
- No limit for maximum interaction, fractures will tend to compensate each other while growing





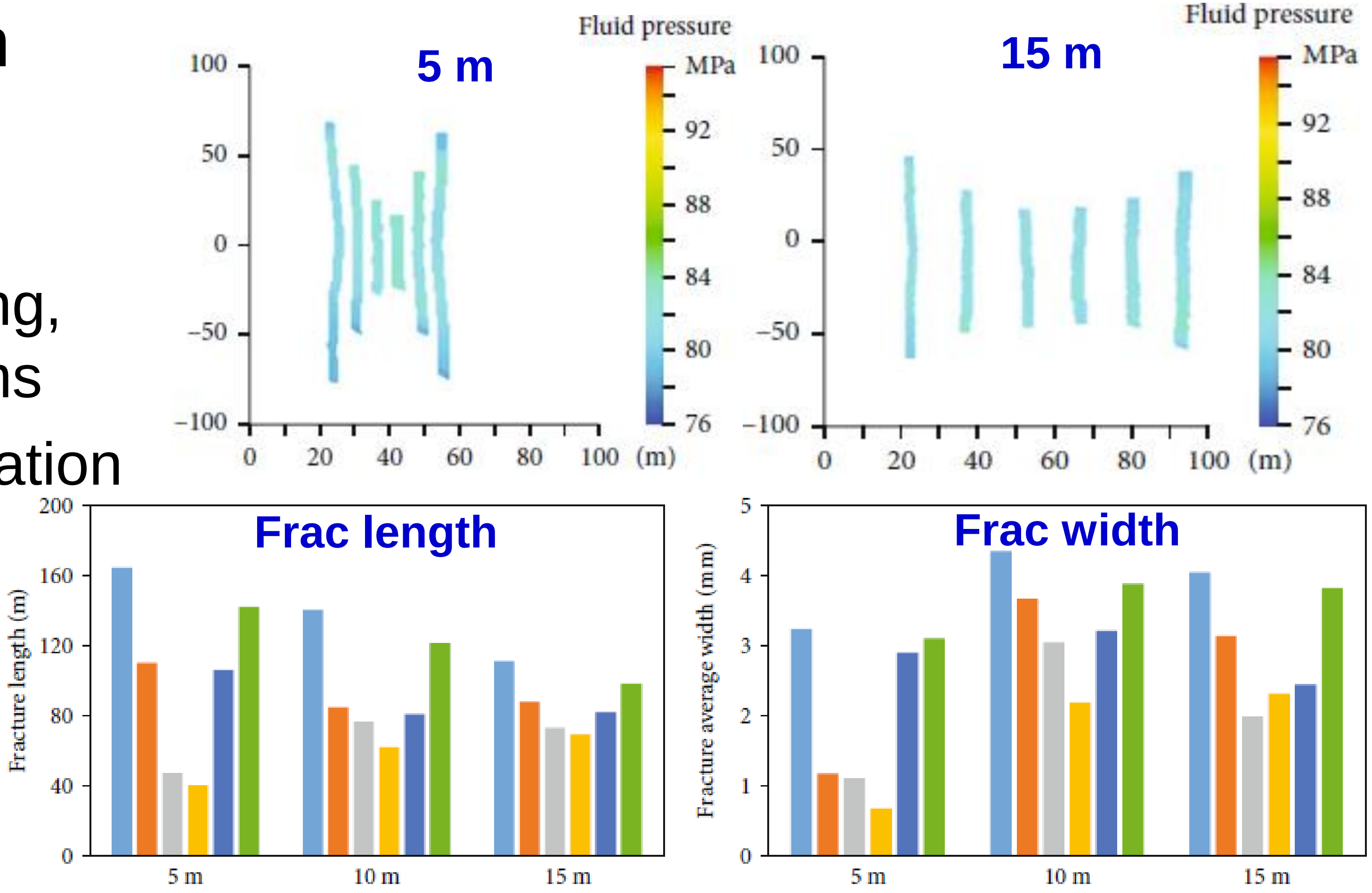


Source: NSI Frac course

Stress Shadowing

✓ Stress interference between fractures propagating from clusters in a single stage:

- Stresses inversions, branching, coalescence, choking, swarms
- Fracture competition and creation of lengthy dominant fractures
- Non-productive longitudinal fractures
- Asymmetric fractures
- Early production interference
- Potential frac hits



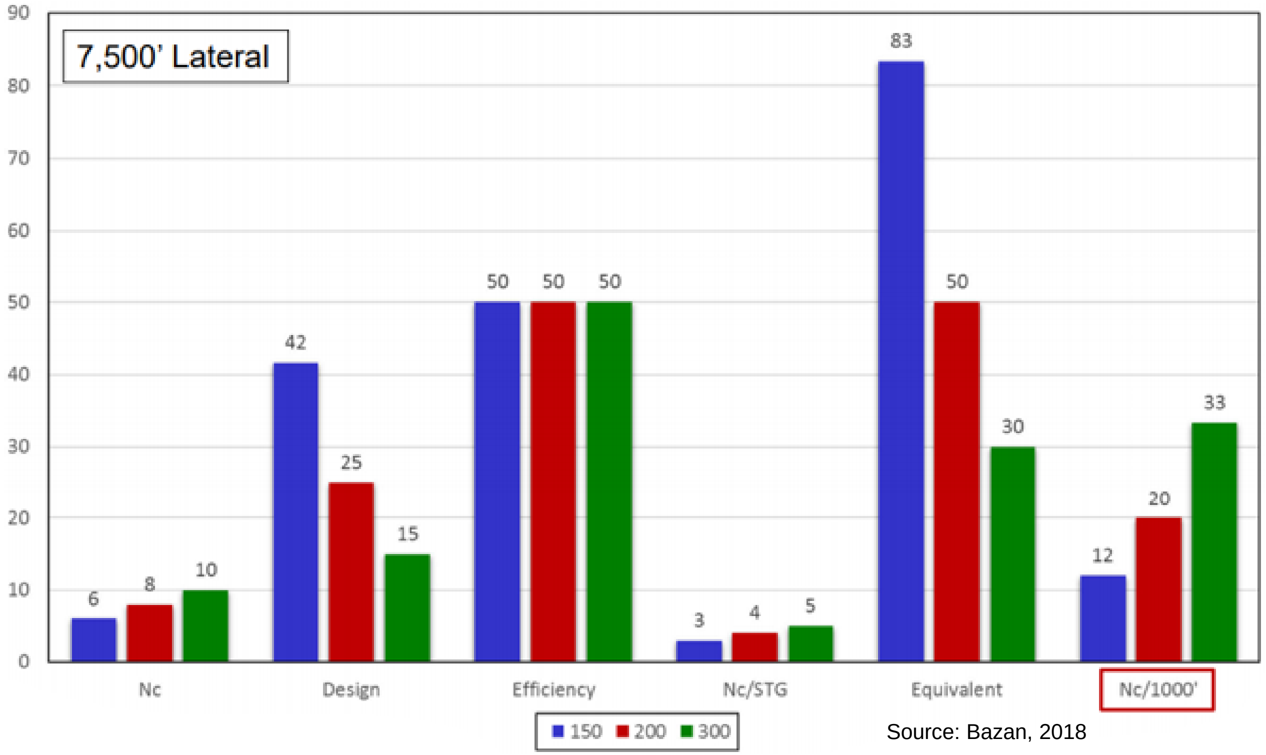
Source: Zhao et al., 2021

Cluster or Diversion Effectiveness

- Definitions:
  - Execution: “actual number of ***successfully*** treated clusters over the number of designed clusters”. Need to define what is a successful treatment
  - Production: “actual number of clusters that contribute ***most of the production*** over designed or executed clusters”. Need to define production indicator
- Some facts (average effectiveness):
  - Standard LET: ~65 %
  - Enhanced LET: ~70 – 80 %
  - XLET: ~80 – 95 %
- Observations (DTS/DAS):
  - Clusters contribution to production decreases with time
  - New designs must be focused not only on initial or early production

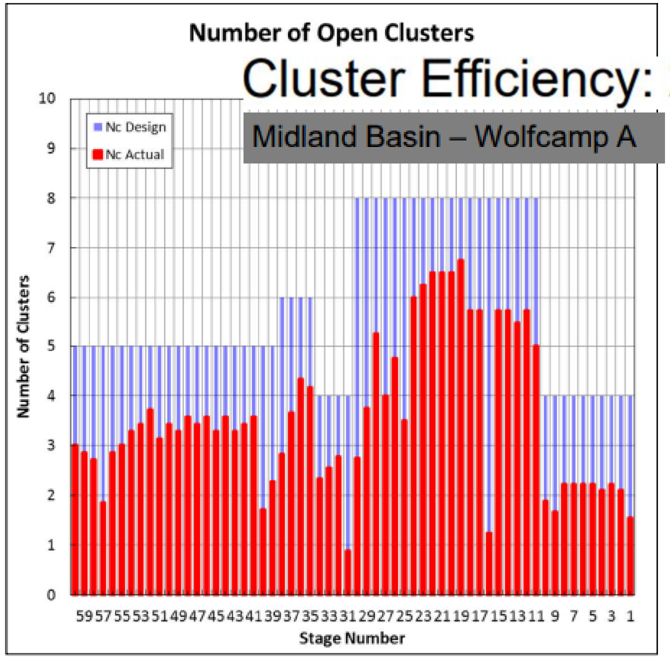
Clusters Metrics

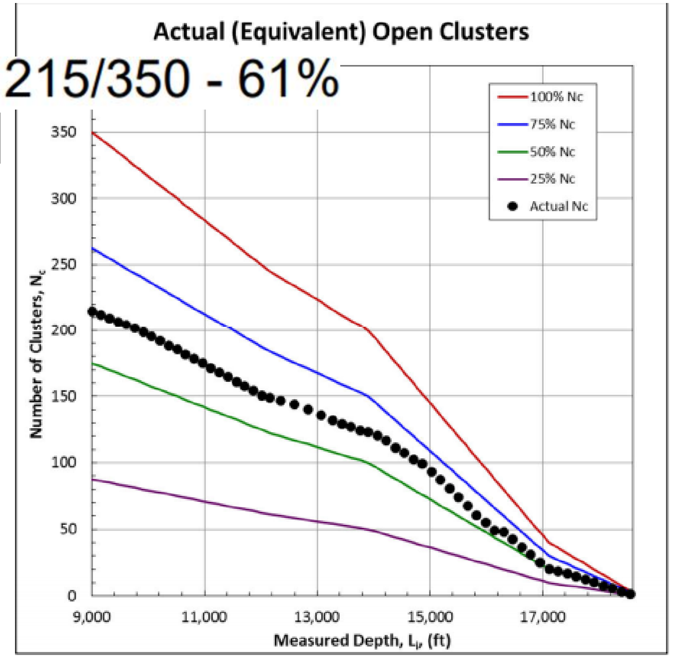
- ✓Intra-well analysis:
  - Clusters per stage
  - Cluster spacing
  - Cluster efficiency
  - Equivalent cluster spacing
  - Incremental cost per barrel
- ✓Inter-well analysis:
  - Previous kpi's
  - Clusters number/normalized length
- ✓Magic numbers behind metrics:
  - Number of fractures created that might produce
  - Minimum well cost that maximize production

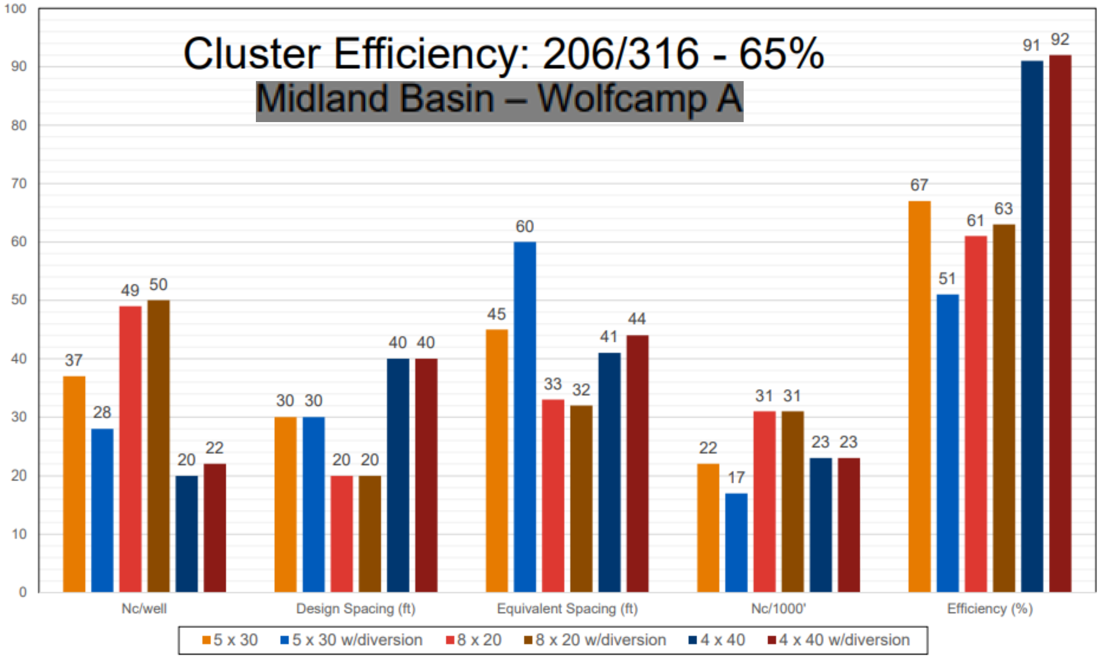


Source: Bazan, 2018

Clusters Efficiency – Case Studies







Source: Bazan, 2018

✓Observations:

- Evaluate clusters efficiency within a well and create correlations with formation properties and/or completion practices. Define base line for future optimizations
- Do not try to change many variables at a time. Statistically it will be difficult to analyze and might lead to wrong answers

Some Medicines to Difficult Zones – High Entry Friction

✓Facts

- Some zones are difficult to frac
- When due to high perforation friction, tortuosity or both there are options to save the day!
- SRDTs are highly useful
- At least four steps to get decent data for SRDT analysis

✓Objectives:

- Improve the number of successful treatments
- Enhance diversion effectiveness

✓High perforation friction:

- Spot acid
- Ball out perforations
- Reperforate

✓Tortuosity:

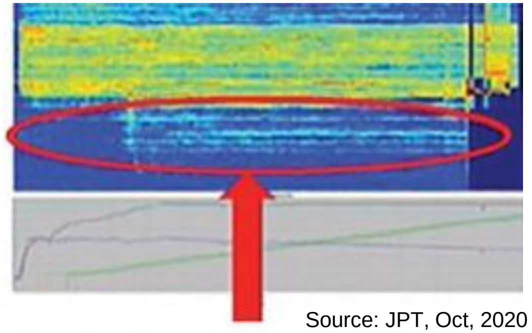
- Low concentration proppant slugs
- Initiate with high viscosity fluids
- Increase rate

✓When nothing works:

- Have an exit plan, do not waste your time and money
- Rethink you perforation strategy

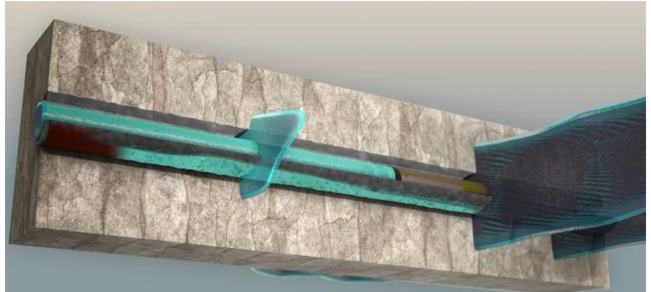
Overlooked Problems

- ✓ Plug/ball leakage:
  - If there is a leak, DAS evidence suggests that in average ~ 50 % of the treatment is lost into the previous stage
- ✓ Cement channeling:
  - All your diversion efforts are gone if fluid paths are connected behind pipe
- ✓ Casing erosion:
  - ~50 % of the wells suffers a point close to a plug where significant erosion is observed
  - Casing breaches are not uncommon
  - High rates, turbulence and plug design are part of the problem

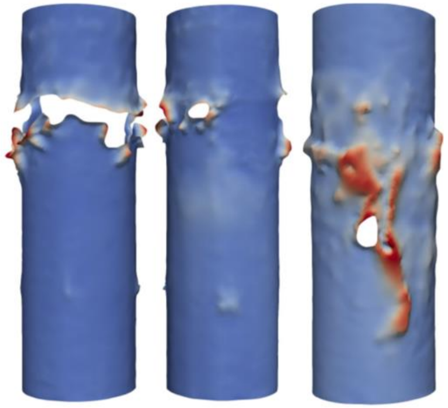


Source: JPT, Oct, 2020

Streaks of green show plug is leaking



Source: World Oil, SLB Tech Talk



Source: Robinson et al., 2020

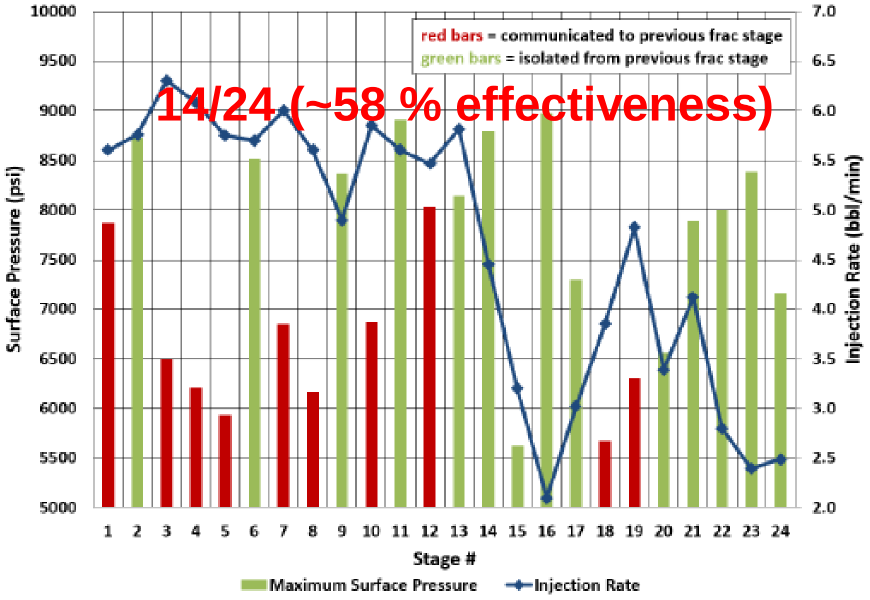
Isolation Effectiveness – is it Good Enough?

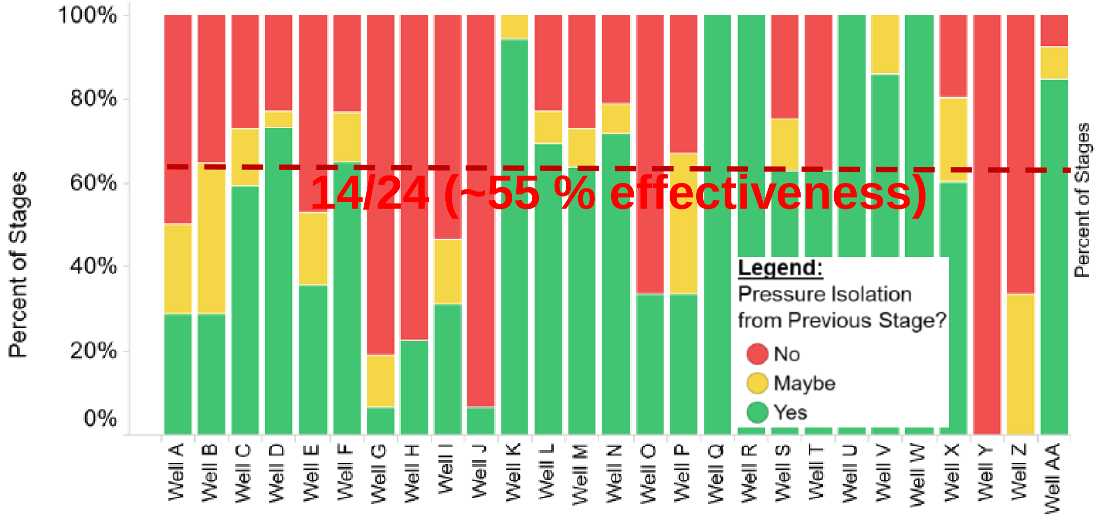
✓External isolation:

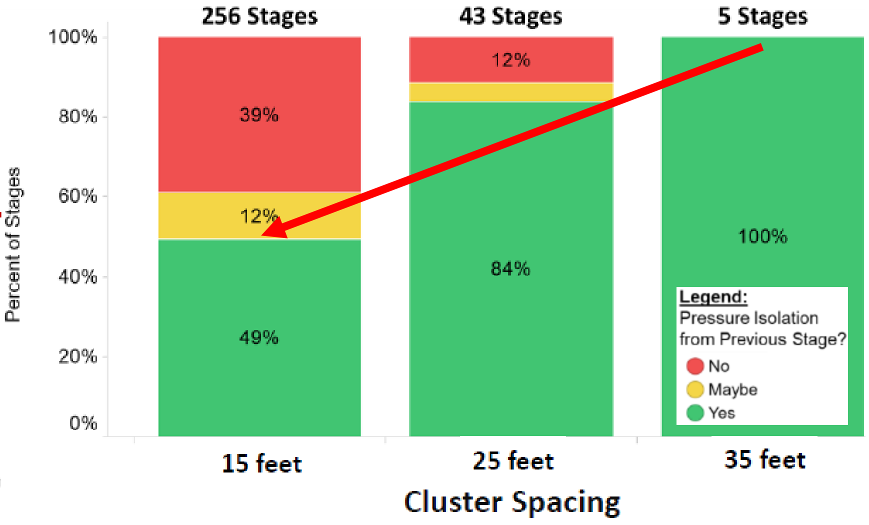
- Cement sheath. Isolation is not as good as we think (~50 – 60 % effectiveness)
- Reduced cluster spacing worsens the case

✓Impact on production and evaluations:

- Lower production
- Biased interpretations, wrong decisions







Source: SPE 201376

Diverting Agents

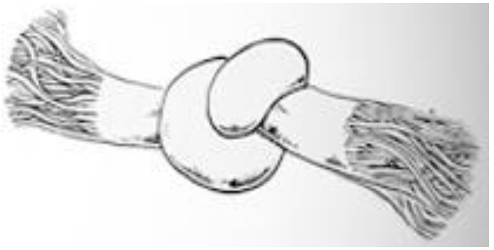
✓Objective:

- Plug dominant fractures in order to open new perforations and propagate new fractures from inactive clusters
- Enhance slurry distribution among perforations

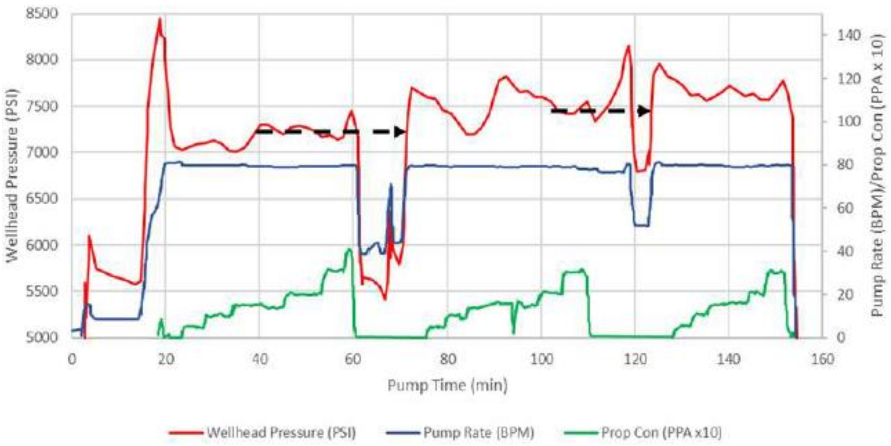
✓The technology:

- Mostly degradable particulates, of different shape and size that can sustain appreciable differential pressure through perforations while pumping but of quick dissolution during production
- Solutions for near wellbore and far-field region
- Multiple cycles per stage

Source: SPE DL, Van Domelen, 2020



Source: slicfrac.com



Source: drill2frac.com

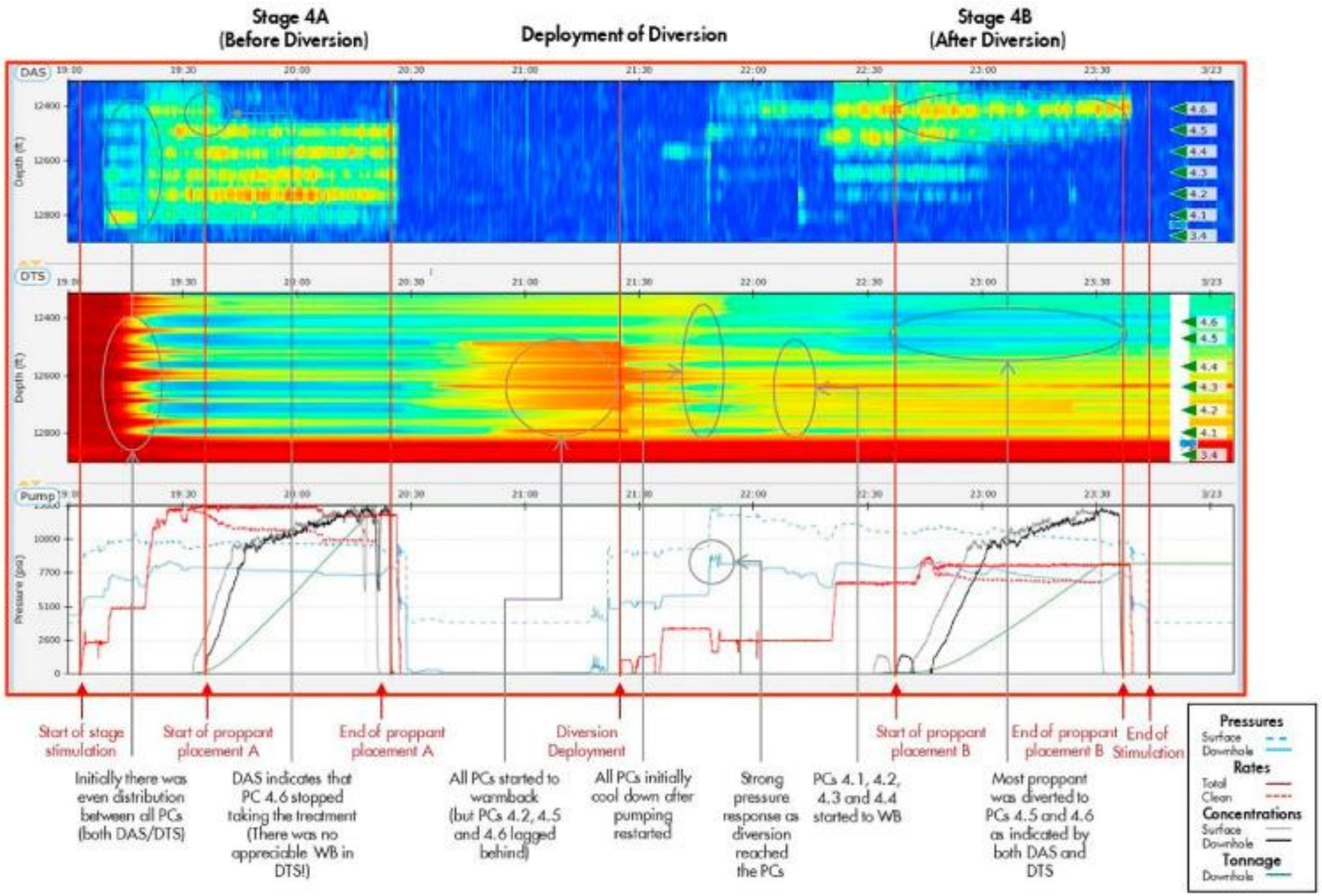
Is Diversion Effective? – How to Measure it?

✓Evaluation tools:

- Pressure increment after each diverter treatment deployment
- DAS/DTS
- Production per stage as compared to previous diverting strategy either by chemical tracers or actual production

✓Conclusion:

- In general it improves diversion effectiveness



Source: Shah et al., 2020

Diverting Agents as Plugs

✓Objective:

- Reduce or eliminate the utilization of conventional plugs either drillable or degradable
- Reduce completion cycle cost

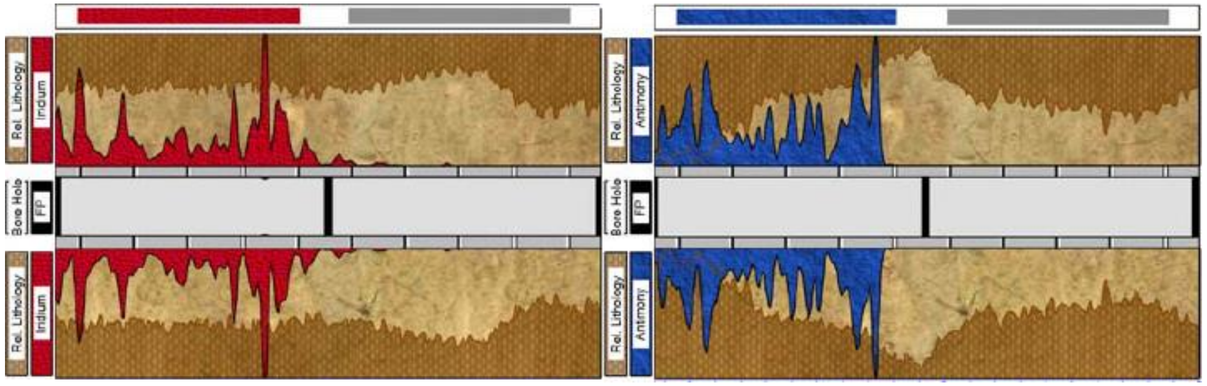
✓The technology:

- Pieces of degradable rope tied as a single knot called “pod”. Different sizes
- One pod per perforation

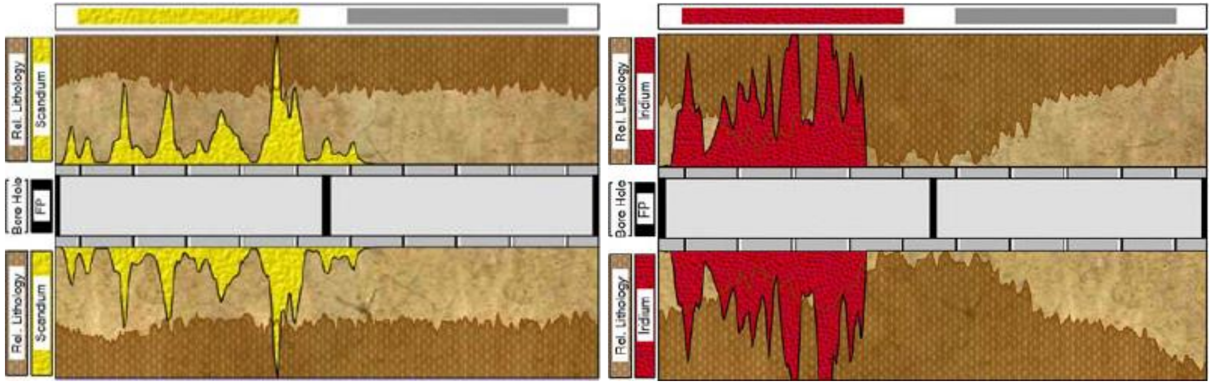
✓Results:

- Tested successfully in several plays

Bridge plugs – successful isolation



Pods – successful isolation



Source: SPE 189900

Source: slicfrac.com

Diagnostic Technologies Overview

- ✓Chemical tracers:
  - Production performance, cleanup efficiency
- ✓Radioactive proppant tracers:
  - Qualitative indicator of near wellbore fracture network (~2 ft)
  - Potential interstage communication
- ✓DAS + DTS:
  - Acoustic and temperature details. Proxy for individual cluster production
  - Possible to observe changes while pumping or producing in each cluster
- ✓Downhole camera:
  - Image of perforations conditions pre or post fracture
  - Proxy to evaluate perforation strategy

Chemical Tracers Diagnostic Technology – Case Study

✓Water-soluble tracers:

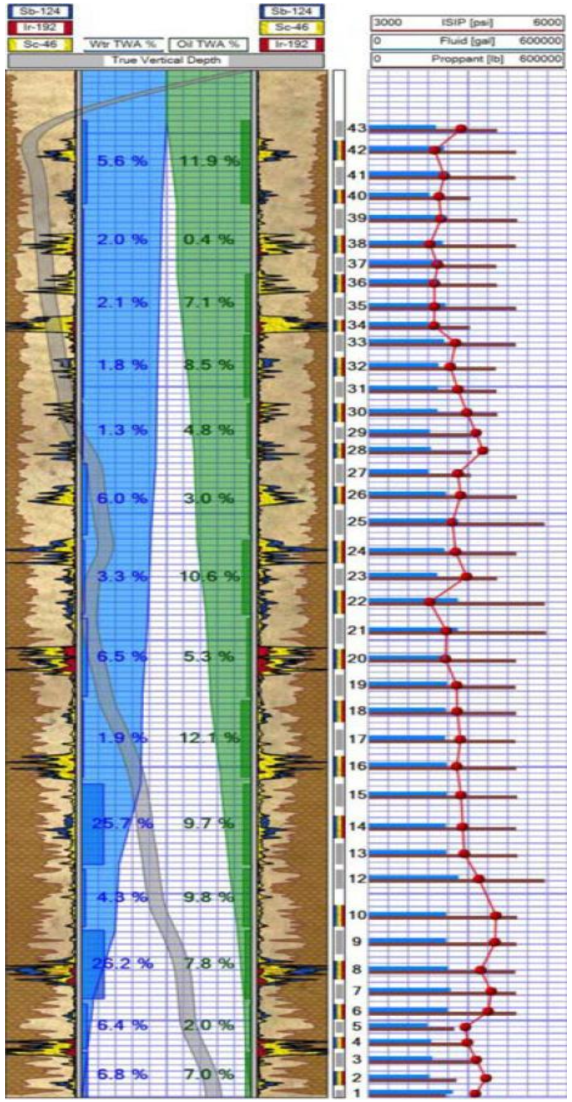
- Production per stage, uniformity of production
- Cleanup efficiency
- Potential communication with neighbor wells

✓Hydrocarbon-soluble tracers:

- Production related to propped zone over time
- Production performance in newly treatments

✓Clusters analysis:

- Difficult to evaluate clusters efficiency
- Possible to evaluate relative changes in completion design
- Integration with other technologies allows evaluating clusters efficiency



Source: SPE 204169

Downhole Camera Diagnostic & DAS Integration

✓DAS:

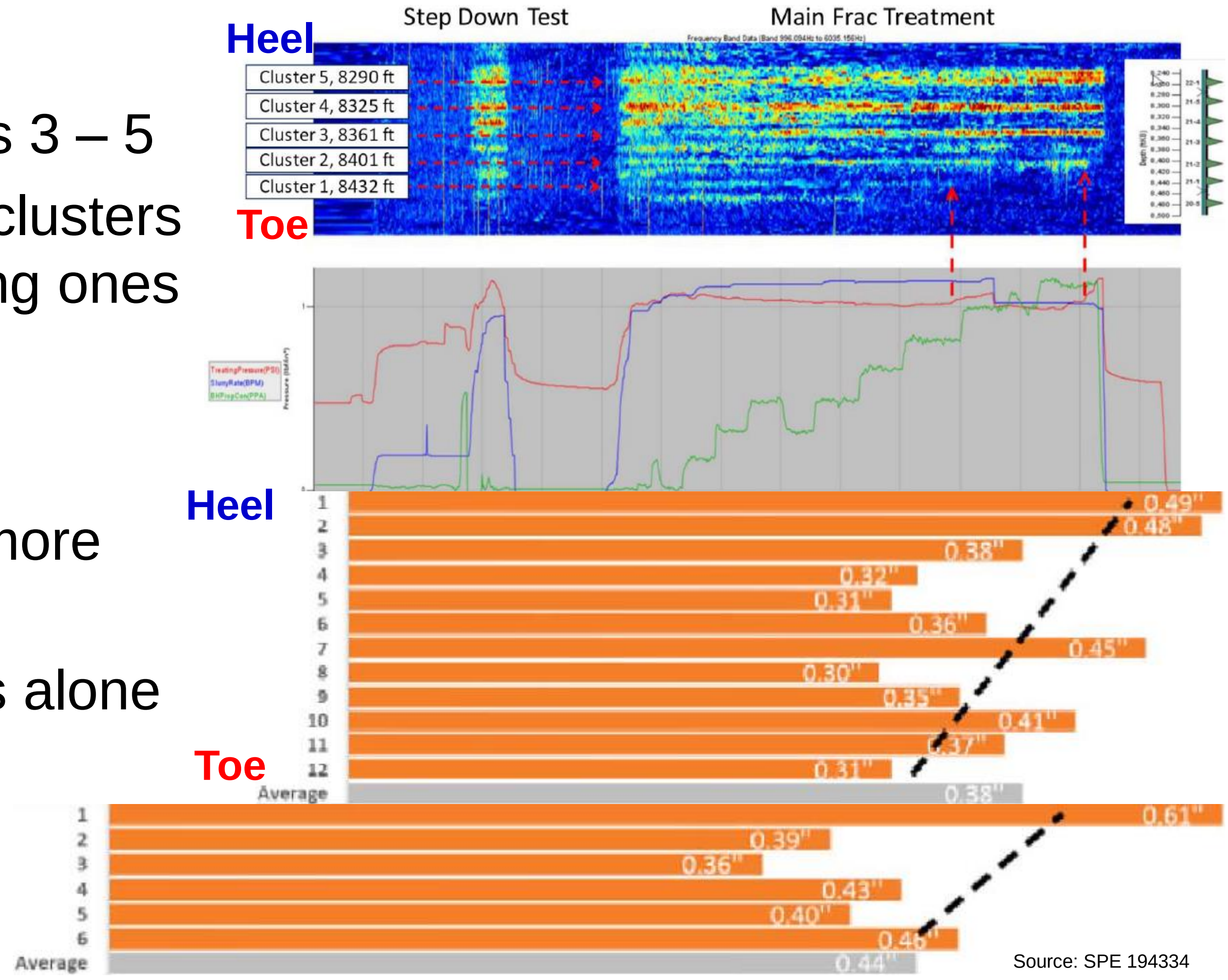
- SRDT shows activity in clusters 3 – 5
- Main frac: mostly all activity in clusters 3 – 5. Some activity in remaining ones
- Very common observation

✓Downhole camera analysis:

- Clusters close to the heel are more eroded (heel bias)
- Reasons not clear from images alone

✓Integrated analysis:

- Clusters 3 – 5 received most part of the total treatment



Source: SPE 194334

Clusters Number Impact on Production – Case Study

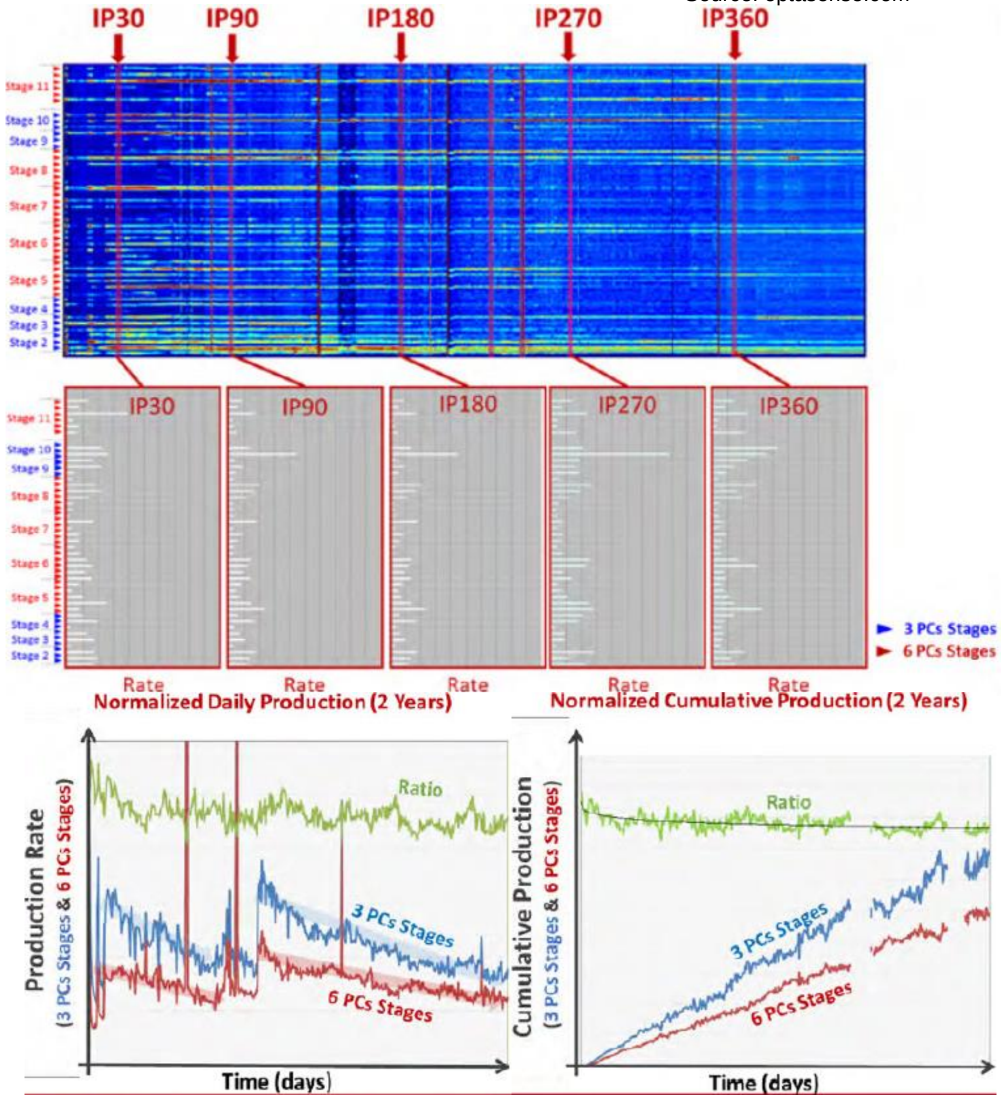
✓Challenge:

- Assess how completion design affects production and recovery
- Same well, similar geology and treatment volumes but different number of clusters

✓Observations:

- DSA/DTS permanent fiber provided continuous production data per cluster
- 6 clusters overperformed 3 clusters/stage
- Production trend sustained at least for the first two years
- Final decision based on economics

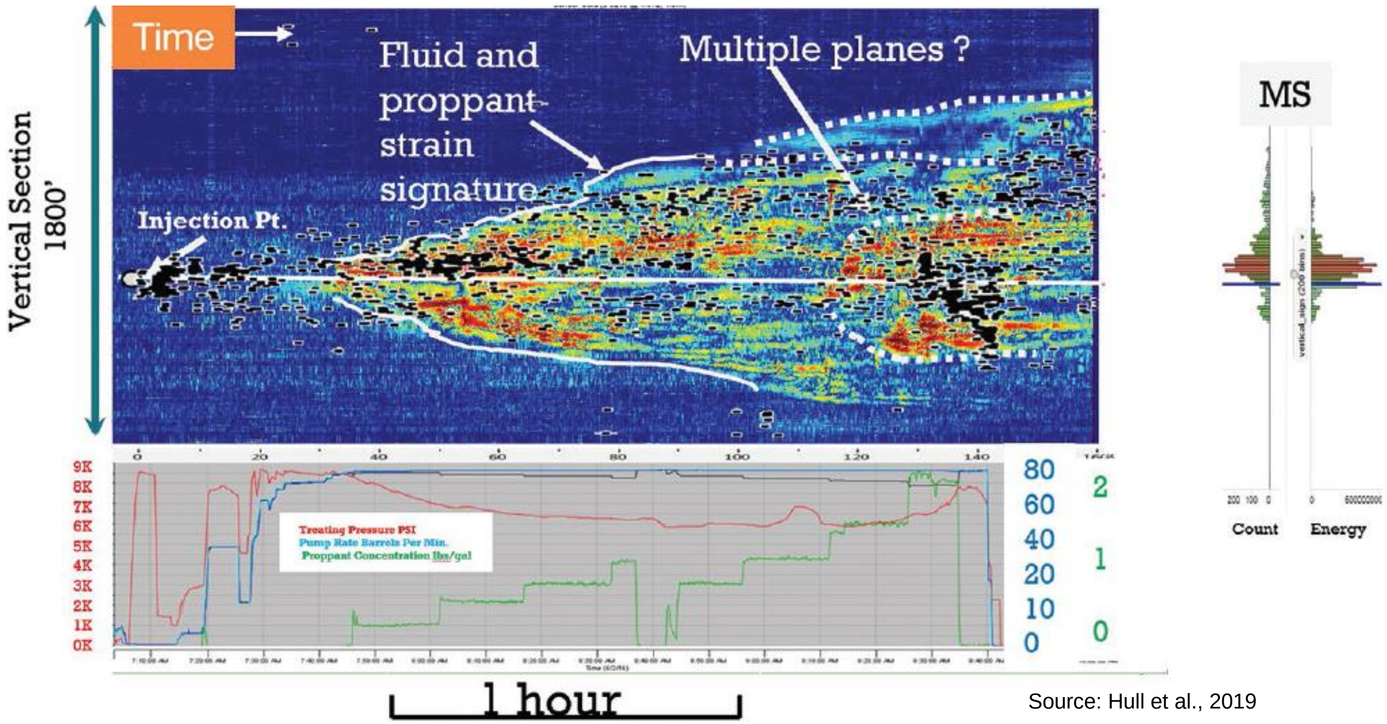
Source: optasense.com



Strain Rate Measuring While Fracturing

✓Technology:

- DAS. Low-frequency strain measurement
- Strain relates to poroelastic effects and stress changes
- Efforts to better distinguish fluid from proppant



Source: Hull et al., 2019

✓Observations:

- Fracture growth in height is not continuous. It takes some time to accumulate energy until it breaks into a new zone (lamination and carbonate layers effect)
- Better estimation of fracture dimensions compared to microseismic mapping

Final Quote

"If you think it's expensive to hire a professional, wait until you hire an amateur".

Source: oklahomaminerals.com

Q&A

Source: rotary-ribi.org

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