"Some Elements of Developing Ductile Shales: Description, Completions, Fracturing and Production"

Caney Town Hall Webinar

Tuesday, April 28th 10am CST

First in a Series of Webinars under DE-FE-0031776

- **Welcome & Introduction by Mileva Radonjic**
- **Presentation by George King**
- **During presentation attendees are encouraged to submit comments via the comment panel.**
- **We hope time allows for a live Q&A, however, if not written responses will be provided post webinar.**
- **Participants to include: DOE; NETL; Continental; OSU; OGS; Pittsburgh & Core labs**
- **Stay tuned for the May Town Hall Webinar – details to come**

Please join our Town Hall from your computer, tablet or smartphone.
https://global.gotomeeting.com/join/432608445
You can also dial in using your phone.
United States: +1 (786) 535-3211
Access Code: 432-608-445
New to GoToMeeting? Get the app now and be ready when your first meeting starts:
https://global.gotomeeting.com/install/432608445

Background image is SEM Micrograph of Caney Shale courtesy of OSU

George E. King, P.E. – CV Highlights

- 49-year veteran of the upstream Oil & Gas Industry
- Degrees in Chemistry (OSU) , Chem. Eng. & Petroleum Eng. (U of Tulsa)
- <u>28</u> Years with Amoco Production Research – field research on workovers, fracturing, underbalance perforating, acidizing, coiled tubing, foam fluids, sand control, water sensitive formations, training.
- <u>9</u> years with BP-Amoco and BP – Distinguished Advisor, annular pressure control, innovation trainer, sand control reliability for deep water
- <u>1</u> year with Rimrock – startup company in Barnett Shale – refining shale fracturing in multi-fractured horizontal wells
- <u>9</u> years with Apache – shale completions, fracturing, training
- <u>2</u> years consulting: DOE Geo-Thermal, well integrity, sand control, shale completions, well control, frac hits, failure analysis.

Technical Accomplishments

- Technical accomplishments include 95 technical papers,
- Advances in sand control, underbalance perforating, foam fluids, shale fracturing, well Integrity during fracturing
- Industry and Academia
  - 1985 - SPE Distinguished Lecturer on foam,
  - 1999 - SPE Completions Course Lecturer on horizontal wells
  - 1992 SPE Technical Chairman of Annual Meeting,
  - 1988-98 - adjunct professor at U of Tulsa (completions & fracturing)
- Awards:
  - 2015 SPE Distinguished member,
  - 2012 Engineer of the Year from Society of Professional Engineers – Houston Region,
  - 2004 Society of Petroleum Engineers' Production Operations Award
  - 1997 Amoco Vice President's Award for technology.

Some Elements of Developing Ductile Shales: Description, Completions, Fracturing and Production

George E. King, P.E.

April 28, 2020

GEK Engineering PLLC
Advisor to OSU's DOE-Funded Ductile Shale Project
Oklahoma State University

Outline of the Talk

1. Ductile shale description
2. Where is the oil and gas in ductile shales
3. How do oil and gas move through shales
4. Impact of net pressure changes and stress
5. Fracturing Ductile Shale
6. Completion Methods
7. Production
8. Ductile Shale Development overview

Focus for Today
28 April 2020

Effect of hydraulic fracturing on gas production in shale?

Three Curves:

- **Red** – Historical gas production from a MFHW well in core area of Haynesville.
- **Blue** – Simulated gas production rate from Model with 400 nano-Darcy matrix (no frac)
- **Green** - Simulated gas production rate from Model with 100 nano-Darcy matrix (no frac)

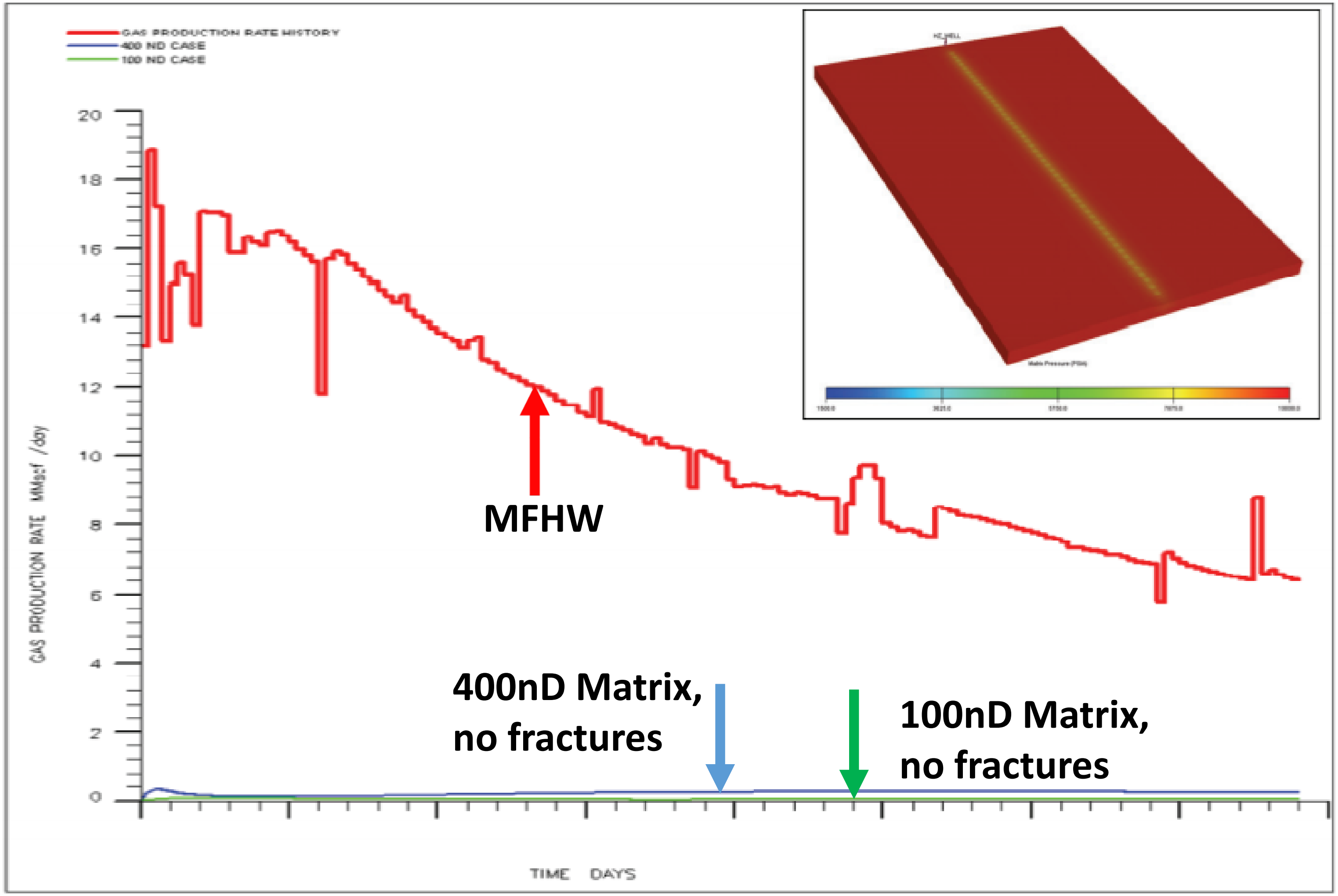
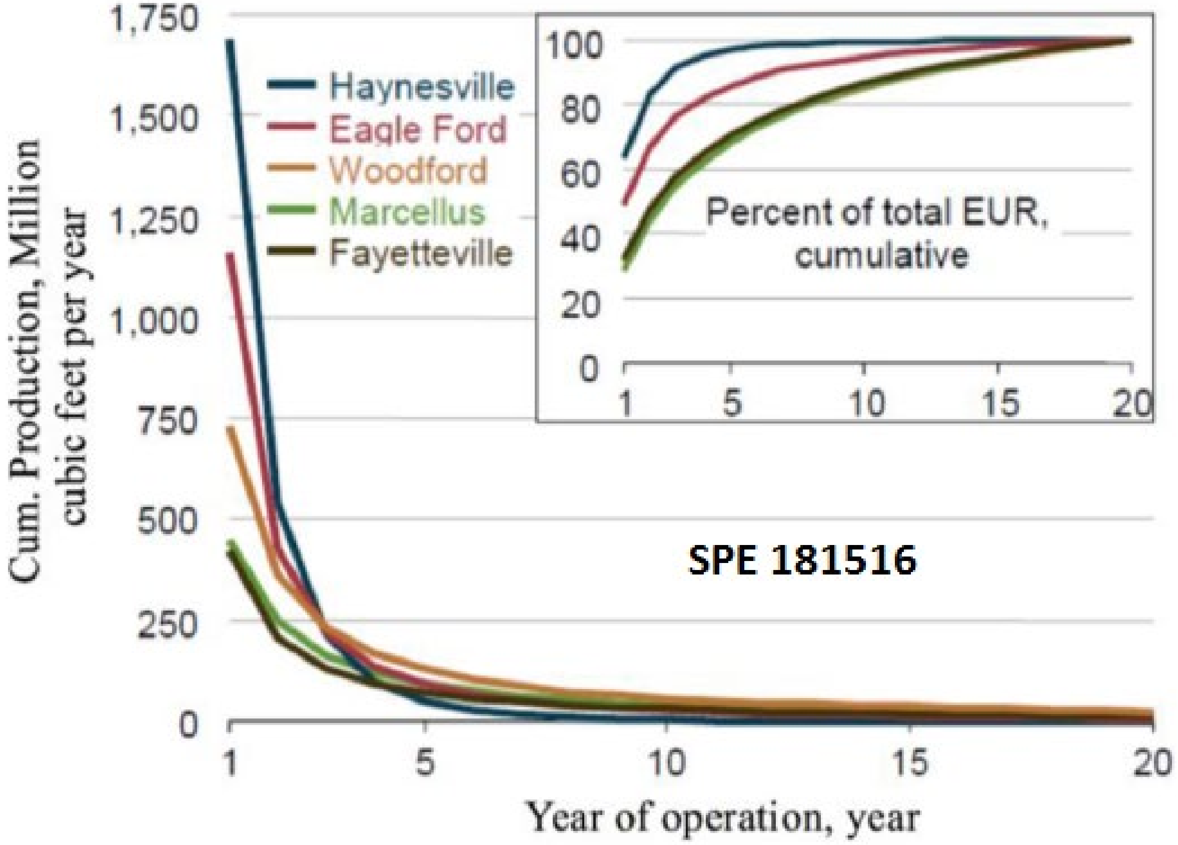


Fig. 5–Impact of shale matrix permeability on horizontal well gas production.

Thompson, J., Fan, L., Grant, D., Martin, R. B., Kanneganti, K. T., & Lindsay, G. J. (2011, June 1). An Overview of Horizontal-Well Completions in the Haynesville Shale. Society of Petroleum Engineers. doi:10.2118/136875-PA

Decline over time – Multiple Shales with Same Decline Shape – Flush Production & Slow Recharge or Flaw Paths Closing With Pressure Reduction?



Average production profile for major U.S. Shale plays (Borrowed from Baker Hughes).

Impacting Factors

- Matrix Perm
- Fluid Viscosity
- Reservoir Pressure
- Drawdown Speed
- Brittle or Ductile
- Proppant type/vol
- Nat. Fracs

Well Known North American Ductile Shales

- **Haynesville (gas)** ~700 TCF, northern Louisiana & East Texas. Depth 10,000 ft), BHT is 175 C, 350 F, and high pressure ~0.9 psi/ft. IP (24 hr) to 20+ mmscf/d. Gas requires treating to remove CO_2 and H_2S.
- **Fayetteville (gas)** ~13 bcf, central Arkansas, Depths 1400 to >4000 ft. Pressure ~ 0.4 psi/ft,
- **EagleFord (deep gas & shallow oil)** – 400 mile long x 50+ miles wide from northeast Mexico to NE Tx. Much higher carbonate percentage, (to~70% in S. Texas, becoming shallower & more shaly to NW. High% carbonate creates mixed brittle and ductile sections.
- **Caney** – southeastern Oklahoma along a common shale belt with Fayetteville, Woodford and Caney

Sweetspot fairway of North American shale plays - with total estimated (red) and producible (white) hydrocarbons in place.

Shale Components – one view

- **Brittle shales – easier initiation/propagation of hydraulic fracture - require little or no plastic deformation.**
- **Ductile shales tend to oppose fracture propagation – fracture closure (& healing) more likely.**
- **Silica and carbonate-rich shales exhibit brittle behavior while clay-rich shales "tend" to be ductile.**
- **Organic shale Petrophysical studies assume lithology is dominated by a few minerals, however, well logs are affected by mineral & pore structure variation.**

Adiguna, H., & Torres-Verdin, C. (2013, September 30). Comparative Study for the Interpretation of Mineral Concentrations, Total Porosity, and TOC in Hydrocarbon-Bearing Shale from Conventional Well Logs. Society of Petroleum Engineers. doi:10.2118/166139-MS

What causes ductility? Mostly soft materials in the formation – clays, chalks, weak sands, etc.

- "The clay content has to be less than 40% for a successful shale play (DMITRE, 2012b; Mckeon, 2011).
- However, evaluation criteria in China refer to clay contents less than 30% (Zou, 2013).
- <u>Increasing clay content leads to increasing ductility</u> of shale, which is <u>beneficial in terms of forming a better seal</u> to trap the gas within the reservoir, but <u>not in terms of hydraulic fracturing, as the shale will tend to self-heal.</u>
- As the hydraulic fluid is injected, the permeability will be further reduced due to clay content as the coherence of the matter is high, leading to a reduction in the extraction potential."

Yuan, Y., Jin, Z., Zhou, Y. *et al.* Burial depth interval of the shale brittle–ductile transition zone and its implications in shale gas exploration and production. *Pet. Sci.* **14,** 637–647 (2017). https://doi.org/10.1007/s12182-017-0189-7

Shales – Ductility and Brittleness

- Shear failure occurs when loading creates shear stresses that exceed shear strength.
- Fracturing is controlled by the ductility or brittleness of the material.
- Deformation can be brittle or ductile depending on shale properties and effective confining stress.
- Brittle deformation is characterized by dilation (becoming larger or wider) with sudden failure at a well-defined peak shear strength, followed by strain softening reduction to a residual shear strength.
- Brittle response can be accompanied by formation of distinct shear failure surfaces.
- <u>Ductile response usually produces less defined peak shear strength (and strain softening), with more diffused and large deformations and less distinct shear failure surface.</u>

Gutierrez, M., & Nygard, R. (2008, January 1). Shear Failure and Brittle to Ductile Transition in Shales from P-Wave Velocity. American Rock Mechanics Association.

Where do the UC Reservoirs fit?

URtec 2151959

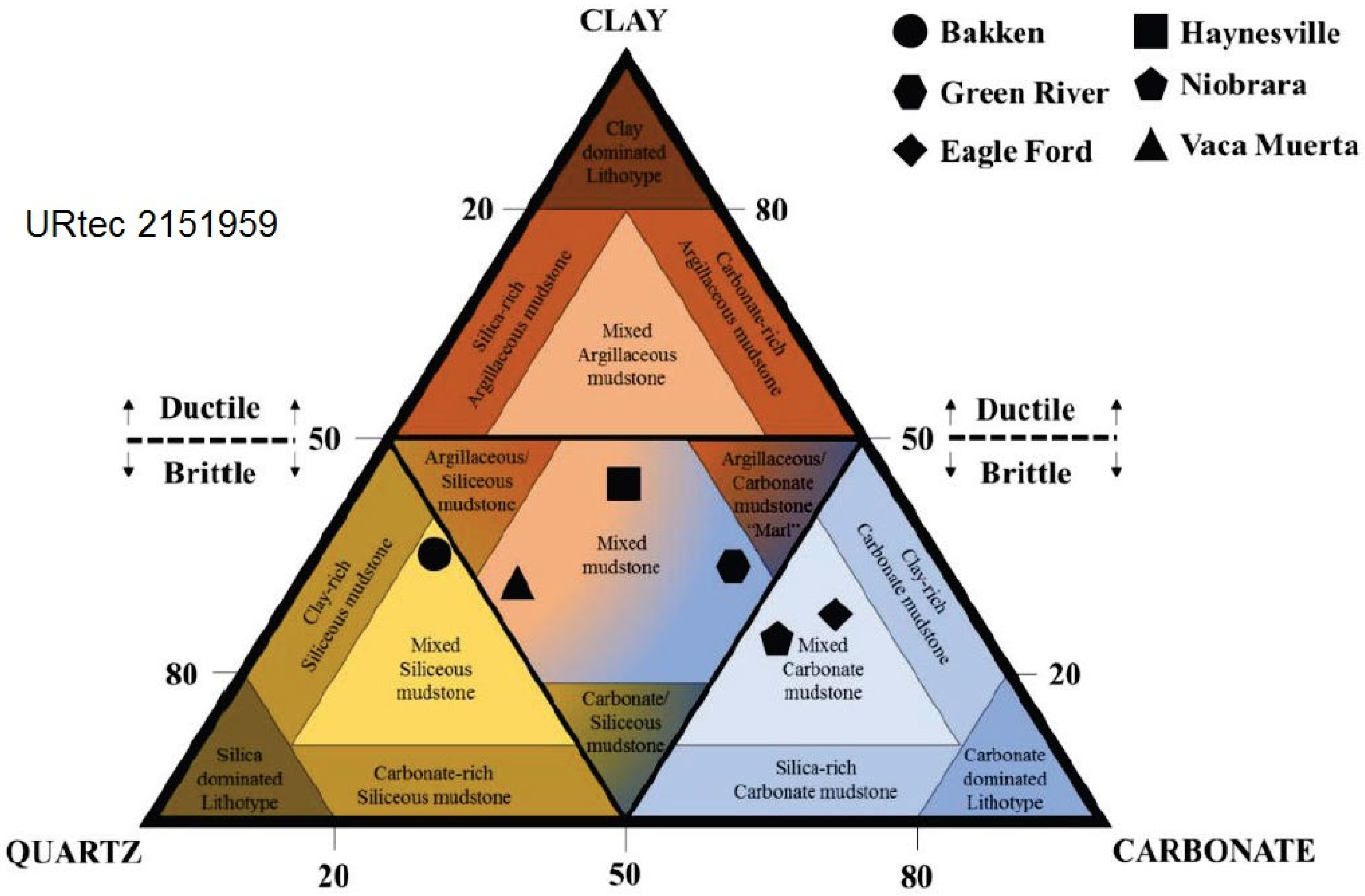
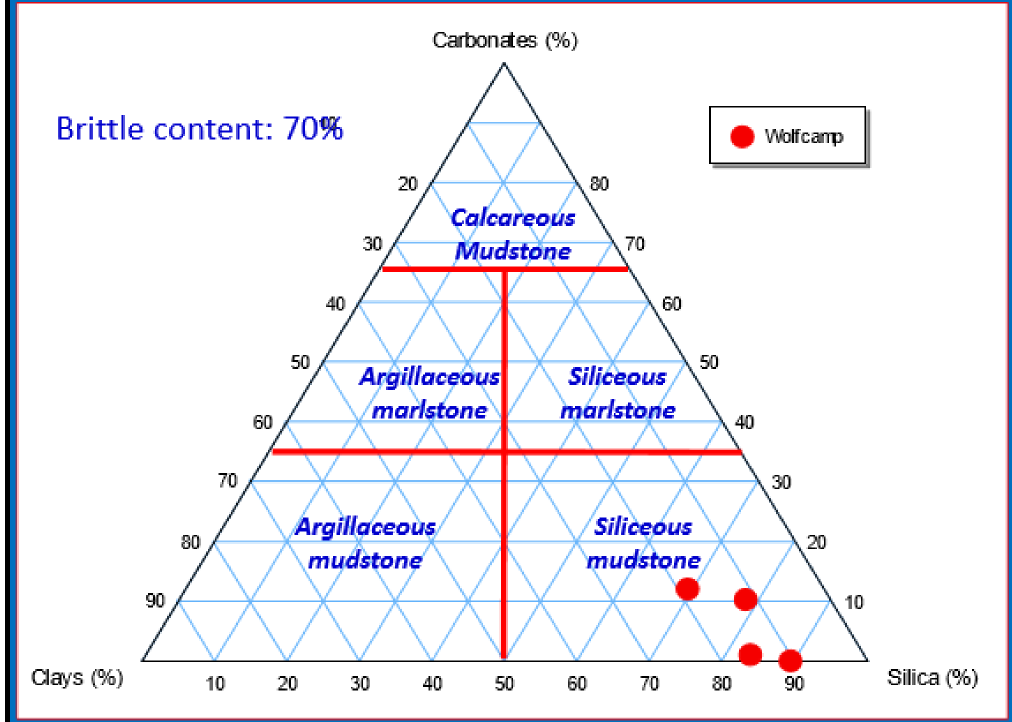
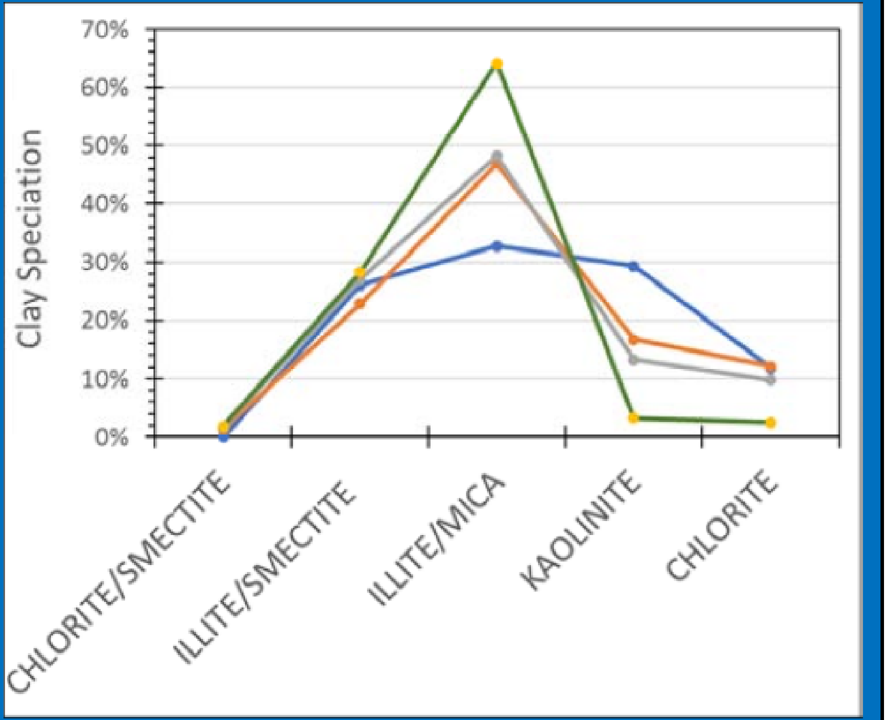


Figure 2: Ternary diagram highlighting the six organic-rich shales falling within different lithofacies. Notice the Eagle Ford and Niobrara are more carbonate dominated. The Bakken is more siliceous. Generally, all six organic-rich shales contain mixed mudstone facies (Ternary diagram modified from Diaz et al., 2012).

Clay Impacts

Mineralogy and Clay Speciation of select Wolfcamp samples at Fasken Ranch 36-1





Modified from Allix et al. (2010)

Delaware Basin Petroleum Systems, Jarvie et al., 2017 *AAPG 2017 Houston, Texas*

Minerals Present (Haynesville & Barnett)

Table 2: Average volumetric concentrations (in fraction of solid volume) of various minerals from XRD analysis performed in 8 wells with core samples in the Haynesville and Barnett shales. Main minerals are present in the form of V_{quartz}, $V_{p\text{-}feldspar}$, $V_{calcite}$, V_{illite}, $V_{chlorite}$, V_{mix}, and $V_{kaolinite}$. Accessory minerals include $V_{k\text{-}feldspar}$, $V_{dolomite}$, $V_{ankerite}$, V_{pyrite}, and $V_{fluorapatite}$.

Mineral	Haynesville Shale	Barnett Shale
Quartz (V_{quartz})	0.268	0.369
Potassium feldspar ($V_{k\text{-}feldspar}$)	0.004	0.021
Plagioclase feldspar ($V_{p\text{-}feldspar}$)	0.073	0.050
Calcite ($V_{calcite}$)	0.203	0.131
Dolomite ($V_{dolomite}$)	0.013	0.031
Ankerite ($V_{ankerite}$)	0.013	0.012
Pyrite (V_{pyrite})	0.020	0.031
Fluorapatite ($V_{fluorapatite}$)	0.018	0.015
Kerogen ($V_{kerogen}$)	0.055	0.086
Illite (V_{illite})	0.233	0.092
Chlorite ($V_{chlorite}$)	0.055	0.048
Mixed layer illite/smectite (V_{mix})	0.035 ?	? 0.110
Kaolinite ($V_{kaolinite}$)	0.010	0.004
Main minerals	0.877	0.804
Accessory minerals	0.068	0.110
Kerogen ($V_{kerogen}$)	0.055	0.086

My Comment - Mineral analysis by itself, is less import than the overall rock fabric.

Rock fabric - porosity, mineral type, location and structure, grain bonding, fissures, fractures and stresses are most important.

Adiguna, H., & Torres-Verdin, C. (2013, September 30). Comparative Study for the Interpretation of Mineral Concentrations, Total Porosity, and TOC in Hydrocarbon-Bearing Shale from Conventional Well Logs. Society of Petroleum Engineers. doi:10.2118/166139-MS

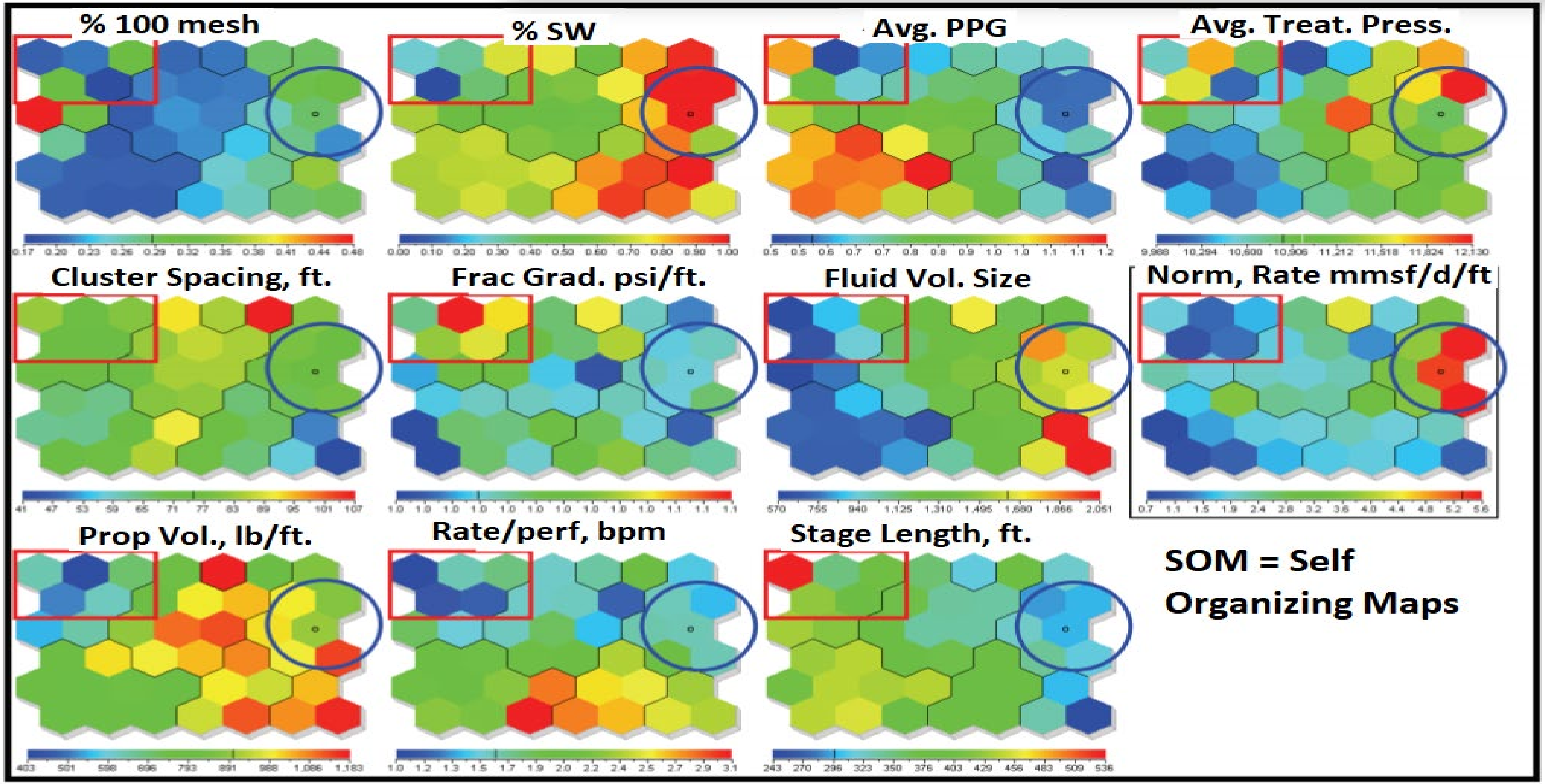


Fig. 13—SOM of Strait wells. The KPI map is outlined in the thin black rectangle. Blue circles indicate regions of higher production. Red rectangles indicate regions of lower production.

Thompson, J., Fan, L., Grant, D., Martin, R. B., Kanneganti, K. T., & Lindsay, G. J. (2011, June 1). An Overview of Horizontal-Well Completions in the Haynesville Shale. Society of Petroleum Engineers. doi:10.2118/136875-PA

Where to spot Frac Stages – one opinion

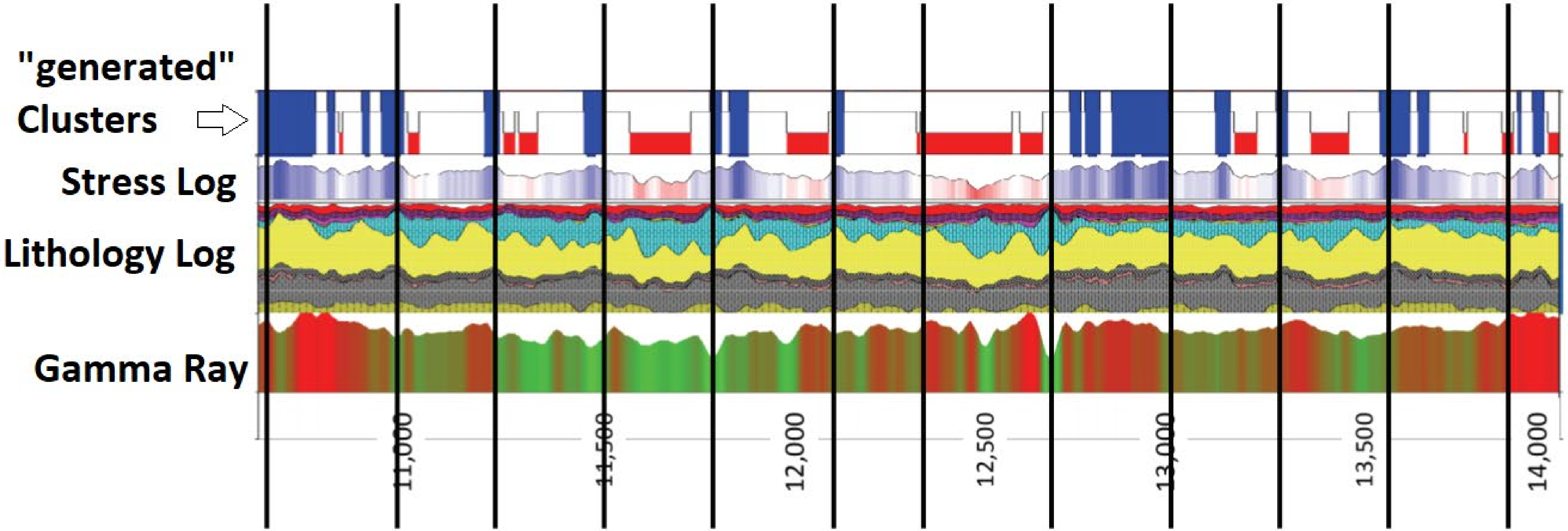


Fig. 9—Lateral staged by grouping "like" rock. Starting from the bottom, Track 1 is gamma ray, Track 2 is the lithology log, Track 3 is the stress log and Track 4 is the generated clusters. Vertical lines indicate plug depths.

Thompson, J., Fan, L., Grant, D., Martin, R. B., Kanneganti, K. T., & Lindsay, G. J. (2011, June 1). An Overview of Horizontal-Well Completions in the Haynesville Shale. Society of Petroleum Engineers. doi:10.2118/136875-PA

Drawdown Production Control

- In the early phase of cleanup, flow measurement and production in the ductile Haynesville wells, many wells were severely damaged or lost altogether by excessive drawdown during early production.
- The drawdown induced damage was directly correlated to high drawdown pressure differential, softness of the rock, and the very high initial reservoir pressures.
- Diligent control of cleanup and production drawdown is <u>absolutely essential</u> to preserve natural fracture and hydraulic fracture networks.
- Common damage of excessive drawdown include unpropped fracture closing, proppant embedment, proppant crushing & fines migration.

Thompson, J., Fan, L., Grant, D., Martin, R. B., Kanneganti, K. T., & Lindsay, G. J. (2011, June 1). An Overview of Horizontal-Well Completions in the Haynesville Shale. Society of Petroleum Engineers. doi:10.2118/136875-PA

Brittle and Ductile Behaviors Under Stress

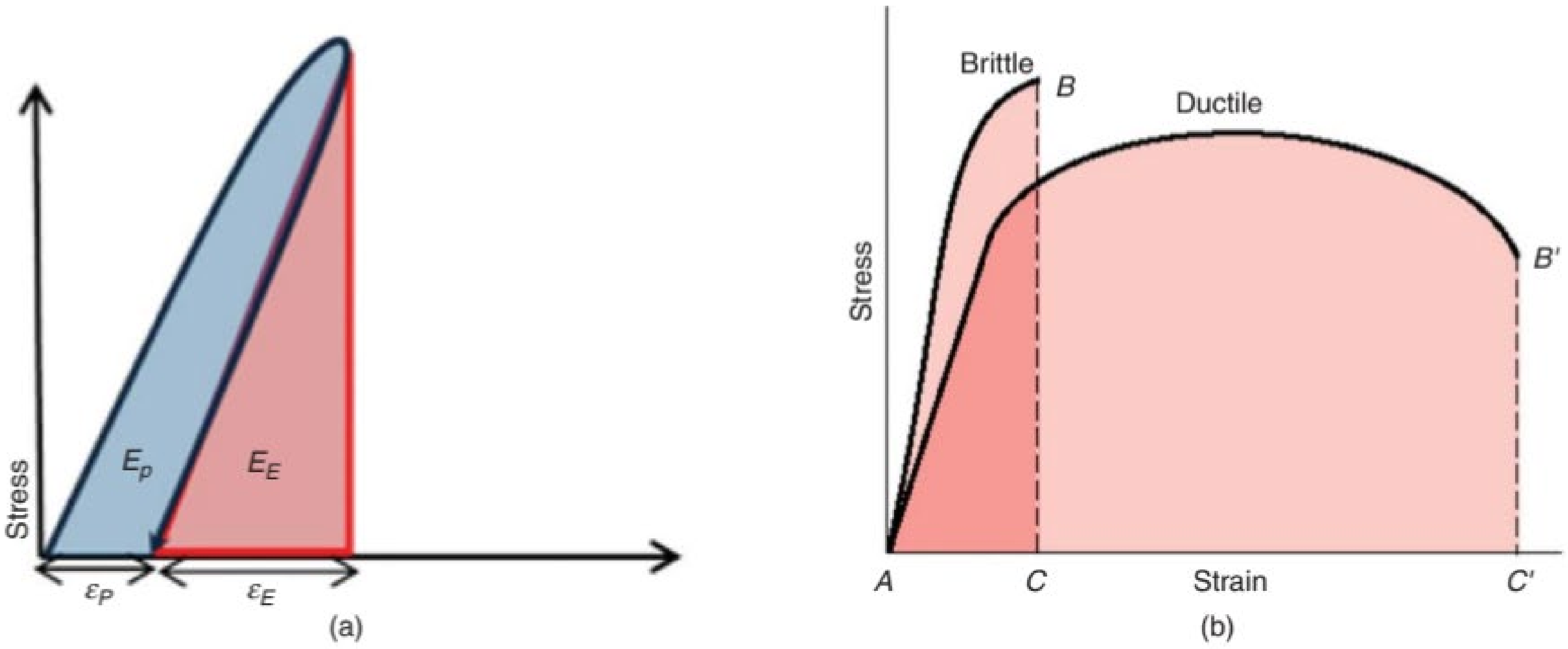


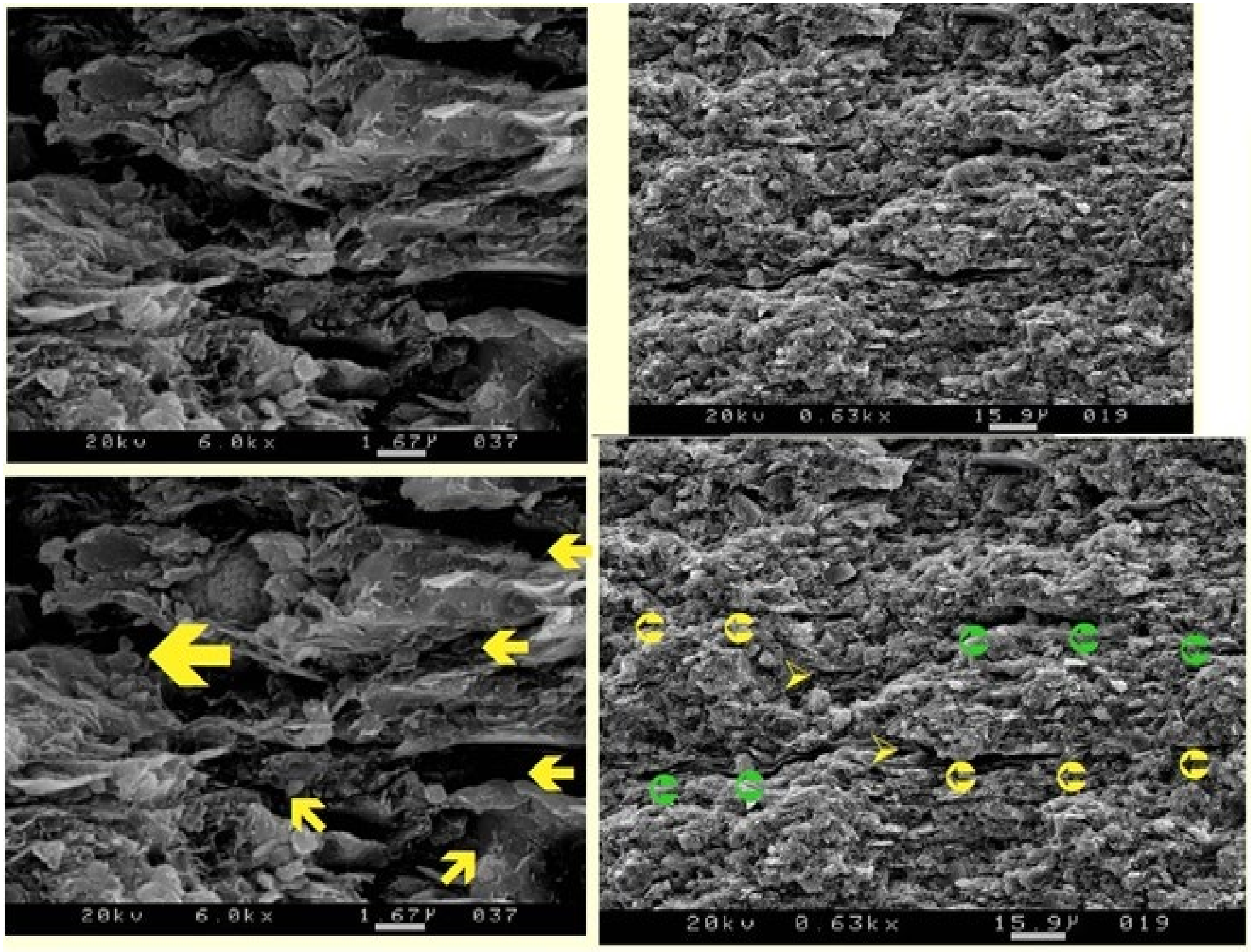
Fig. 2—(a) Elastic and plastic parts of deformation or energy obtained from a single-stress cycle: loading/unloading; (b) graph comparing typical stress/strain curves for brittle and ductile materials. Brittle failure causes fracture at lower strain levels, whereas material absorbs less energy (shaded area) and there is a significant drop from peak to residual. Conversely, ductile failure shows significant plastic strain. December 2015 SPE Journal

Safari, R., Gandikota, R., Mutlu, O., Ji, M., Glanville, J., & Abass, H. (2015, December 1). Pulse Fracturing in Shale Reservoirs: Geomechanical Aspects, Ductile/Brittle Transition, and Field Implications. Society of Petroleum Engineers. doi:10.2118/168759-PA.

Flow Path – Matrix

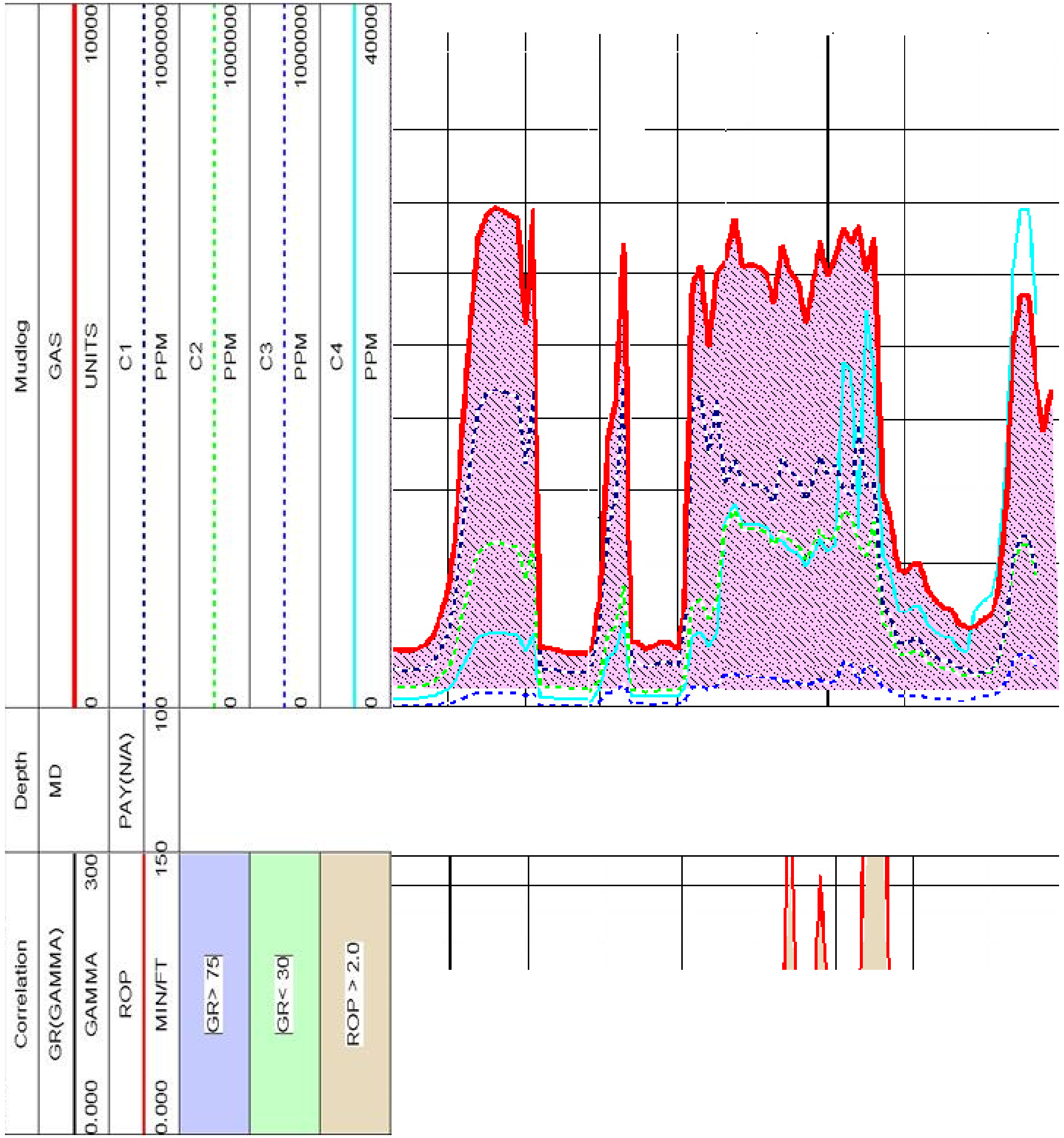
The fabric of productive shales does have channels of higher permeability than the very fine-grained material of the matrix.

The key to production is maximizing contact with these flow channels.



Roger M. Slatt, Prerna Singh, R. Paul Philp, K.J. Marfurt, and Y. Abousleiman, ConocoPhillips School of Geology and Geophysics, University of Oklahoma, and N.R. O'Brien, Department of Geology, State University of New York

Look for the Gas Shows



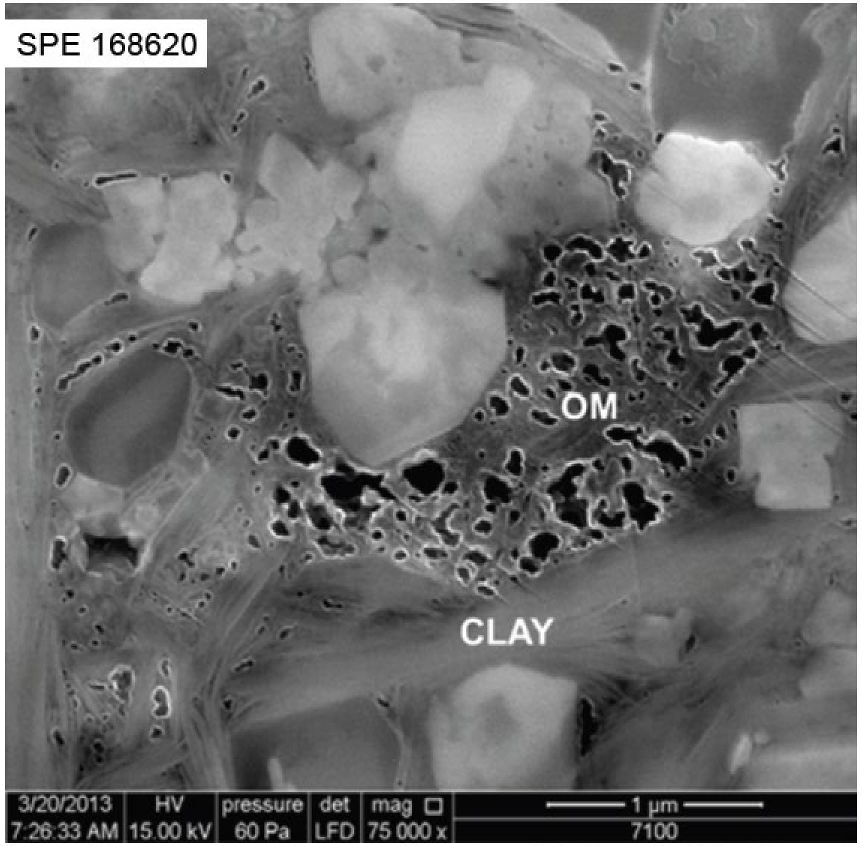
- Gas Show
  - Quantity
  - Ratio of gasses
  - Corresponding GR
- Other logs (CNL, Density) to help assess TOC
- Density for Brittleness
- Resistivity for water saturation and salinity
- ROP (rate of penetration)
- Is it a hot shale or a natural fracture?

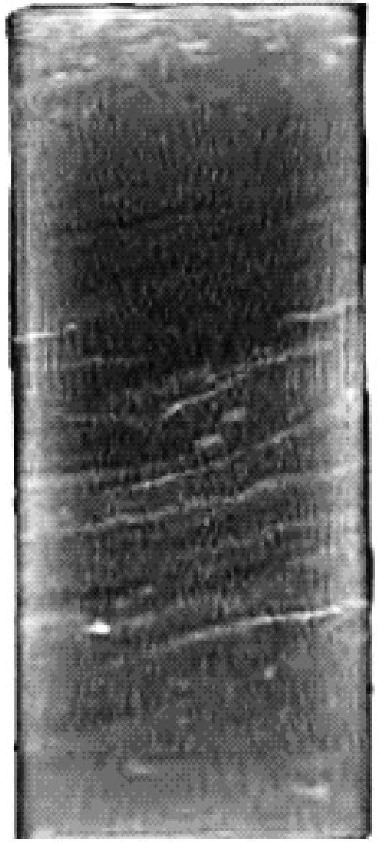
The objective is to align the perf clusters with natural fractures.

Mineralogy Effects on Porosity

Clay has ultra-low porosity. Thermally mature organic material often has a high porosity and may be surrounded by higher porosity and permeability rock.

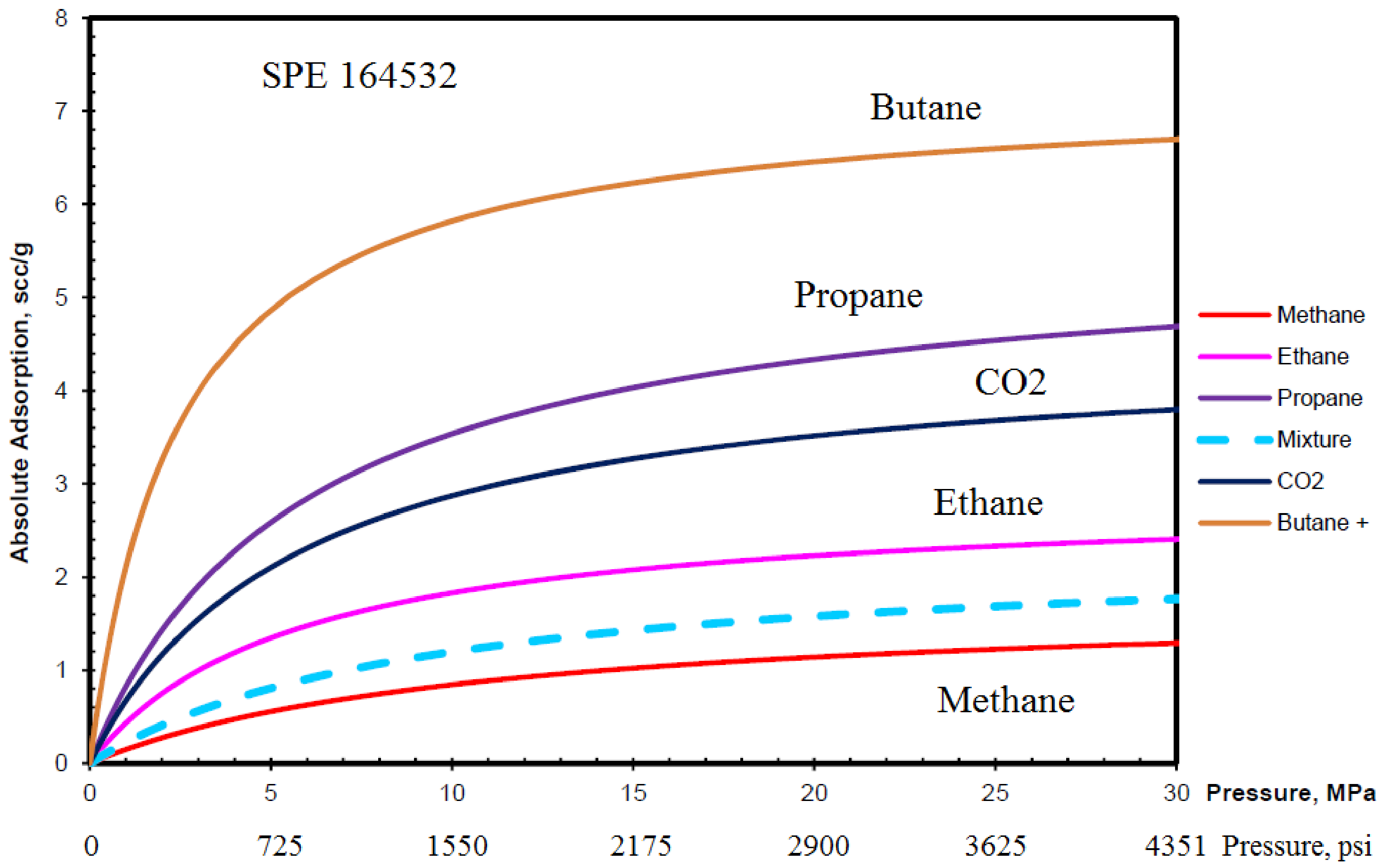
Bed-parallel microfractures may be found, and some researchers believe that microfractures are created by volume expansion.





Scanning electron image showing (a) the distribution of organic matter (OM) and clay in a shale gas sample (after Bertonecello et al. (2014)), and (b) CT-scan image of a similar sample, showing bed-parallel natural fractures.

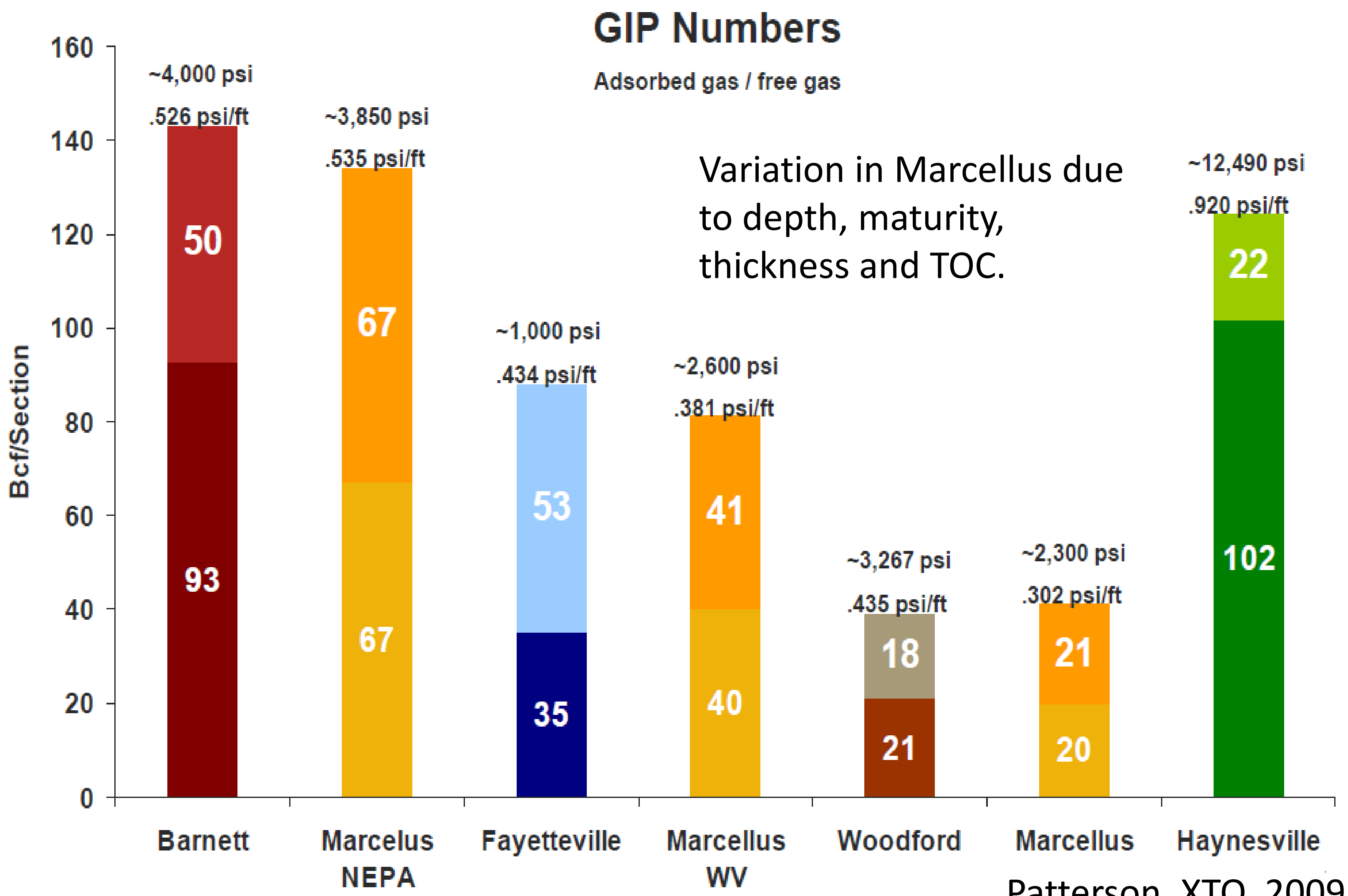
Relative Adsorption of Gases



Langmuir (absolute) adsorption isotherms for single-component gases obtained from dataset of Hartman et al. (2011).
The isotherms are provided courtesy of Chad Hartman.

Free and Adsorbed Gas

Remember – these are average numbers



Variation in Marcellus due to depth, maturity, thickness and TOC.

Patterson, XTO, 2009

Rock Creep with Time

Rock fabric deformation – creep may be several hundredths to several tenths of an inch of borehole diameter over a few months.

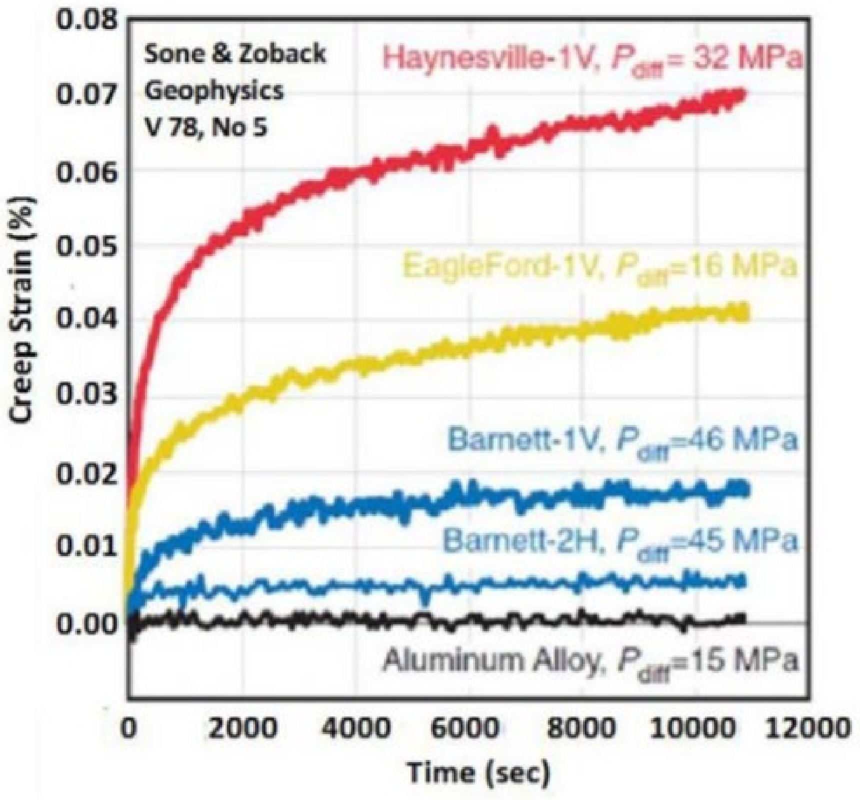


Figure 2—Rock Creep Under Load for three shale types

From (Sone & Zoback, Geophysics v78, no. 5)

Montgomery, C. T., Smith, M. B., An, Z., Klein, H. H., Strobel, W., & Myers, R. R. (2020, January 28). Utilizing Discrete Fracture Modeling and Microproppant to Predict and Sustain Production Improvements in Micro Darcy Rock. Society of Petroleum Engineers. doi:10.2118/199741-MS

Hiroki Sone, ; Mark D. Zoback (2013), Mechanical properties of shale-gas reservoir rocks — Part 1: Static and dynamic elastic properties and anisotropy, Geophysics (2013) 78 (5): D381–D392. https://doi.org/10.1190/geo2013-0050.1

Stress Changes Along the Wellbore

3D seismic interpretation by Rich and Ammerman, illustrating significant differences in seismic attributes between toe and heel of the lateral.

In their analysis, the natural fractures are parallel to fracture propagation in the toe. In the heel, the natural fractures are oriented perpendicular to hydraulic fracture direction.

An alternate interpretation is that the differences between σmin and σmax are decreasing in the heel and are in the range that both fracture sets could grow and complexity is developed.

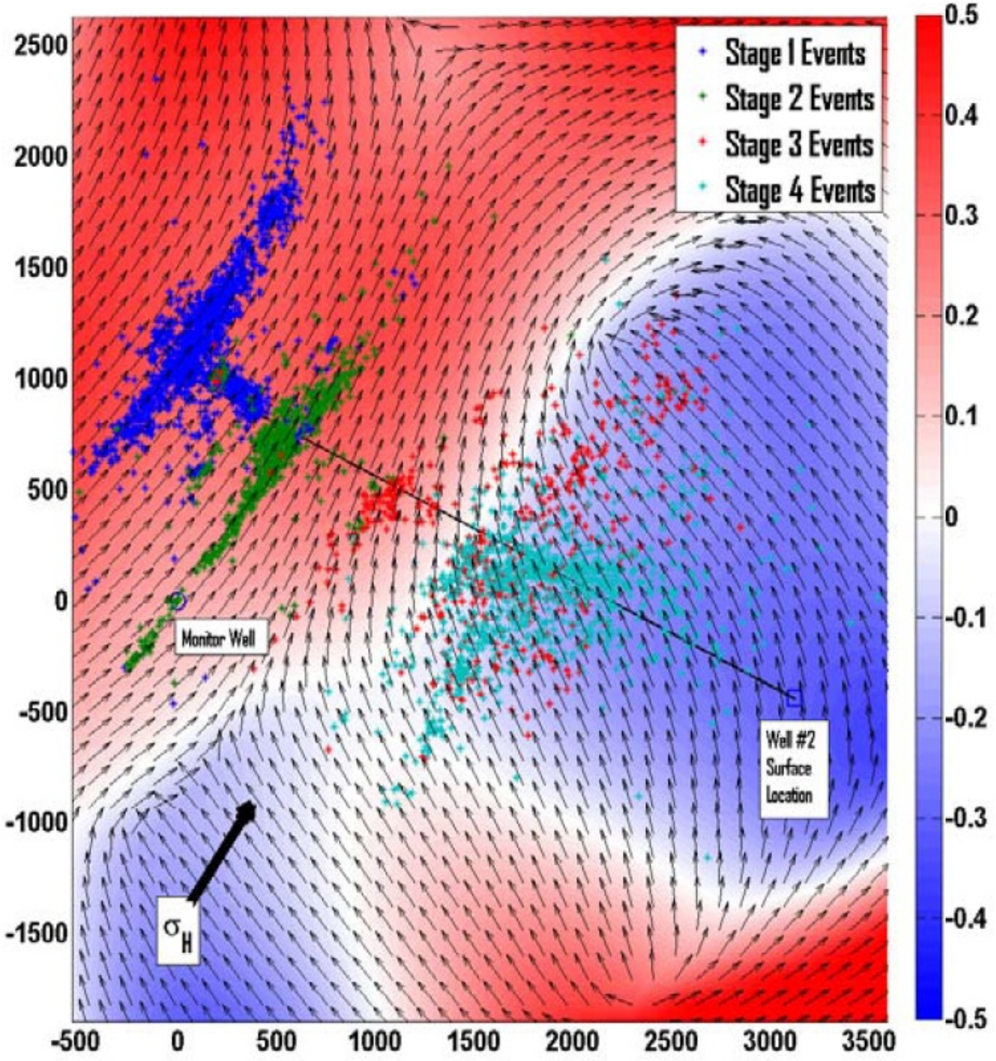
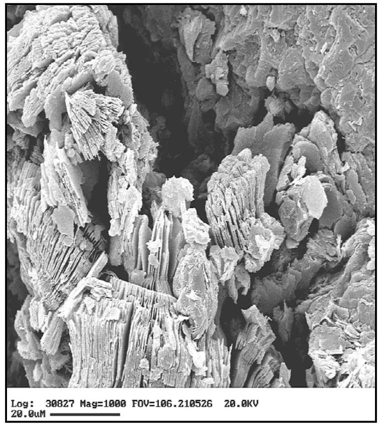
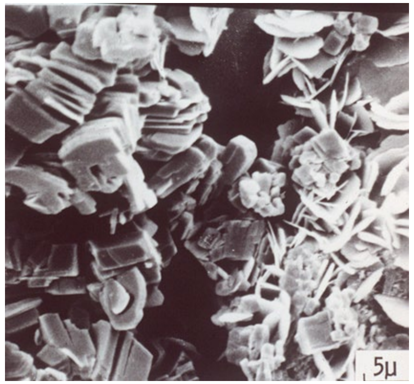


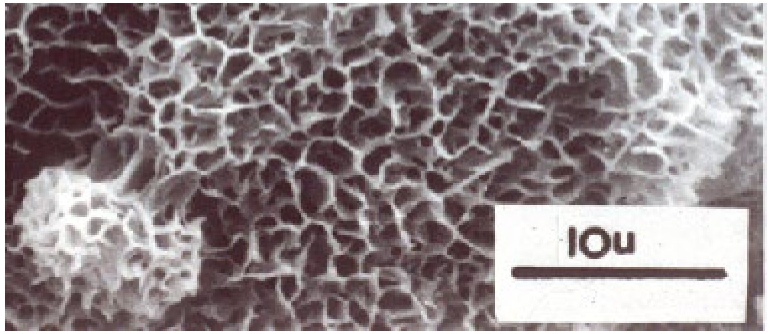
Figure 3 - Advanced seismic interpretation (from SPE 131779)

Clay Damage

- Will clay create a problem? Depends on clay type, form, location, what fluids are flowing and Insitu stresses.







Suggested Reference -Conway, M. W., Himes, R. E., & Gray, R. (2000, January 1). Minimising Clay Sensitivity to Fresh Water Following Brine Influx. Society of Petroleum Engineers. doi:10.2118/58748-MS

Suggested reference -Koteeswaran, S., Habibpour, M., Puckette, J., Pashin, J., Clark, P., (2018), Characterization of shale–fuid interaction through a series of immersion tests and rheological studies, Journal of Petroleum Exploration and Production Technology, 8:1273–1286 https://doi.org/10.1007/s13202-018-0444-5

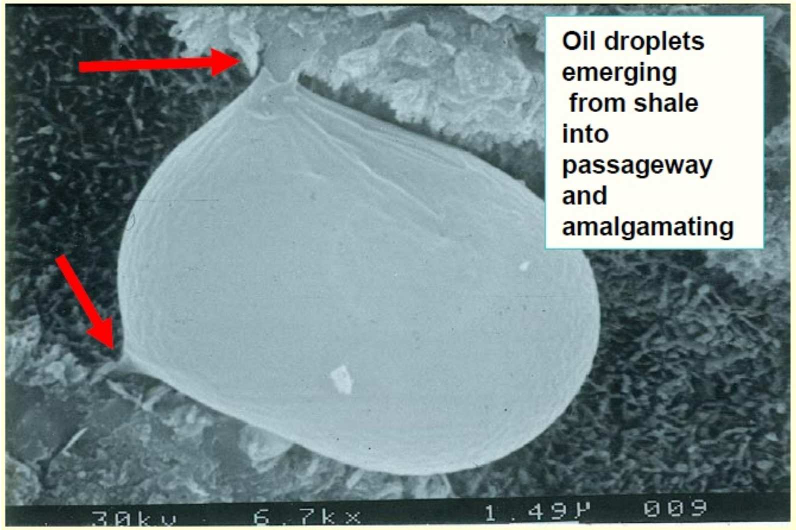
Reactivity of Clays

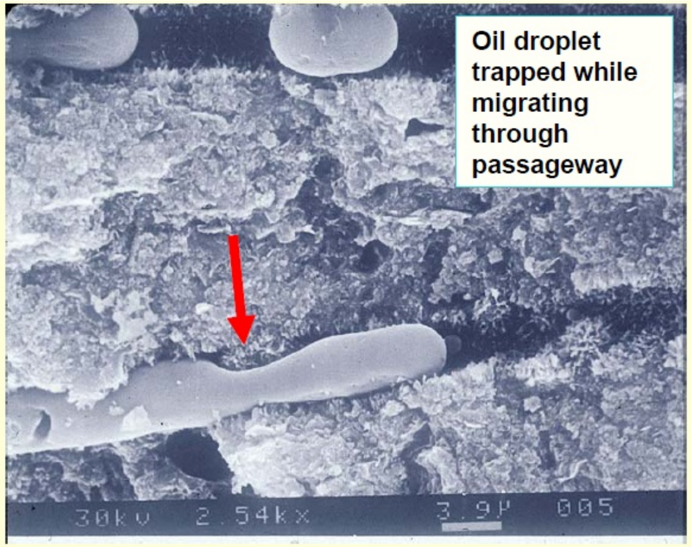
Biggest factors are contact area & location.

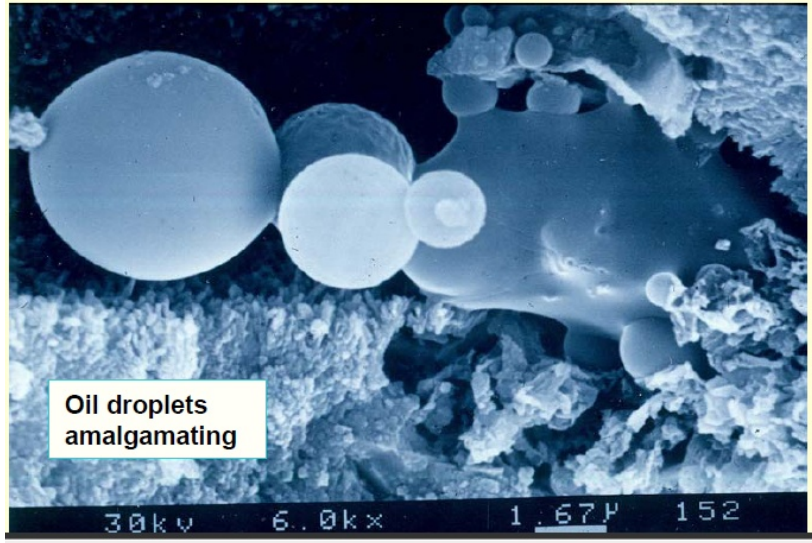
Mineral	Typical Area (M^2/g)	Cation Exchange Capacity (Meq/100 g)
Sand (up to 60 microns)	0.000015	0.6
Kaolinite	22	3 - 15
Chlorite	60	10 - 40
Illite	113	10 - 40
Smectite	82	80 - 150

Size ranges for clays depend on deposit configuration.
CEC's affected by coatings and configurations.

How Does Oil Move Through Shale?







O'Brien, N., G.D. Thyne, and R.M. Slatt, 1996, Morphology of hydrocarbon droplets during migration: visual example from the Monterey Formation (Miocene), California, AAPG Bull., v. 80, p. 1710-1718

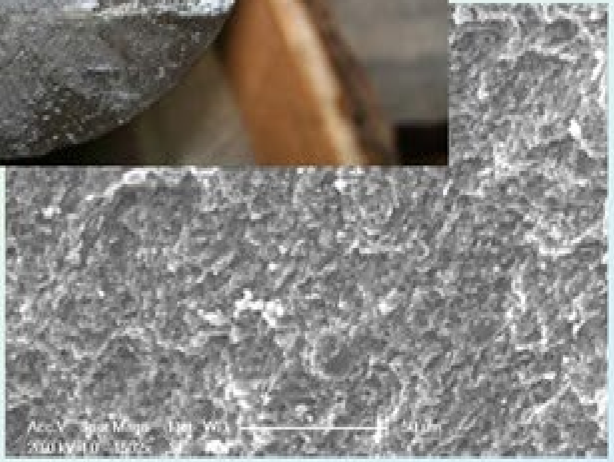
Source: Conoco-Phillips Slide

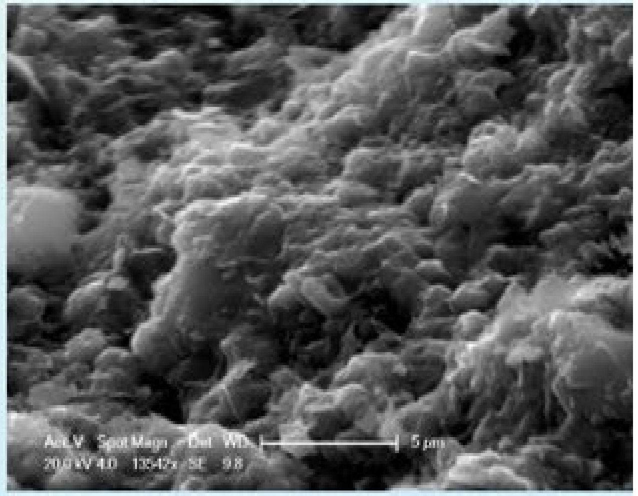
Roger M. Slatt, Prerna Singh, R. Paul Philp, K.J. Marfurt, *and* **Y. Abousleiman**, *ConocoPhillips School of Geology and Geophysics, University of Oklahoma, and* **N.R. O'Brien**, *Department of Geology, State University of New York*

Fabric Implications

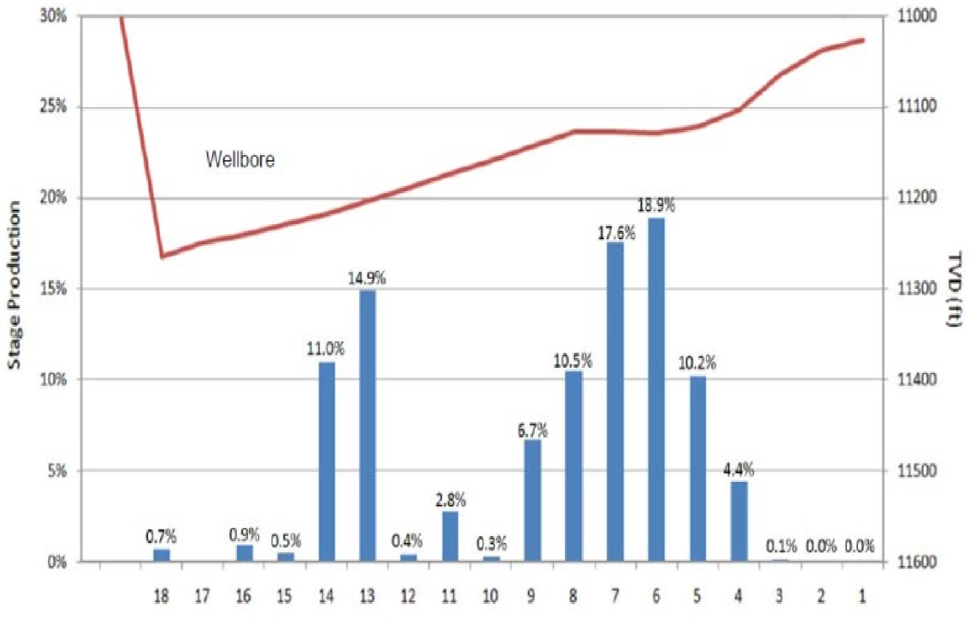
Woodford Shale – gas does not bleed out of the matrix uniformly despite the macroscopic homogeneity

Bustin, 2009





deliverability



Stage contribution (Well-1)

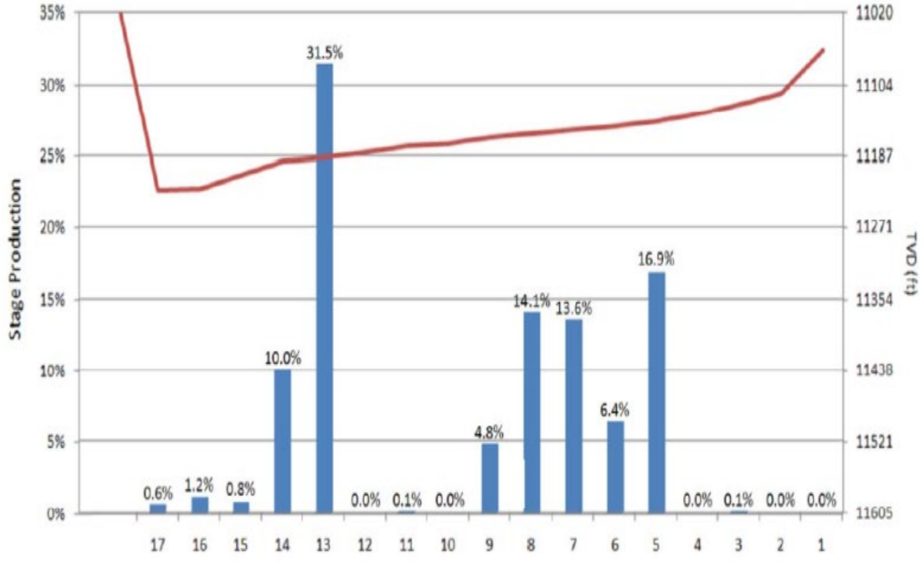
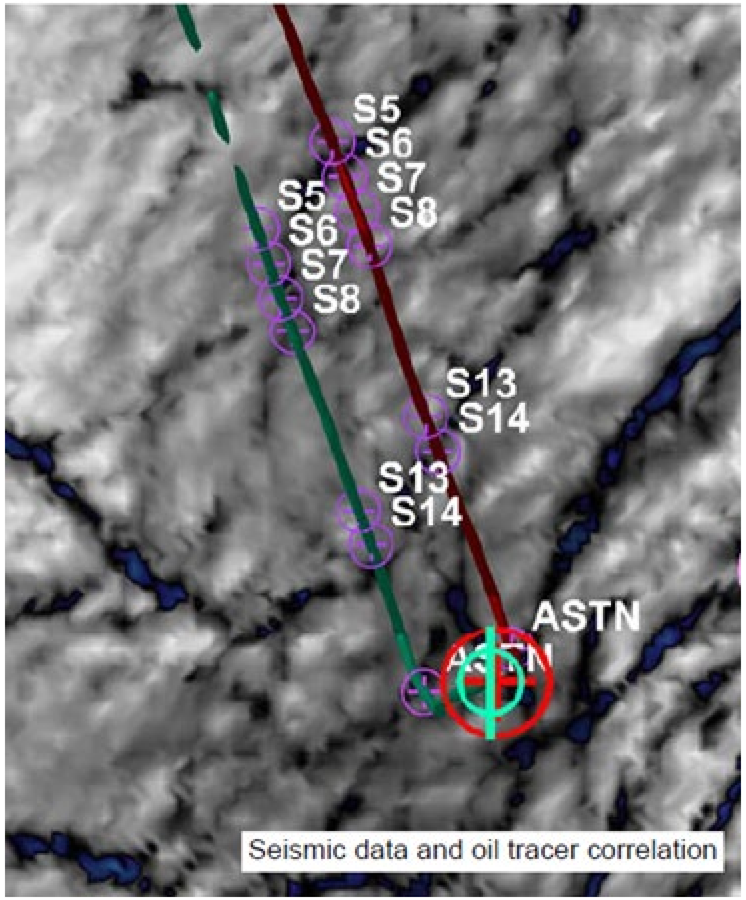


Figure 6. Stage contribution (Well-2)

How Many Fractures are Contributing?

Production highest from frac stages in areas of faulting – stress changes – natural fracs open?



Catlett, R. D., Spencer, J. D., Lolon, E., & Bucior, D. (2013, February 4). Evaluation of Two Horizontal Wells in the Eagle Ford Using Oil-Based Chemical Tracer Technology to Optimize Stimulation Design. Society of Petroleum Engineers. doi:10.2118/163846-MS

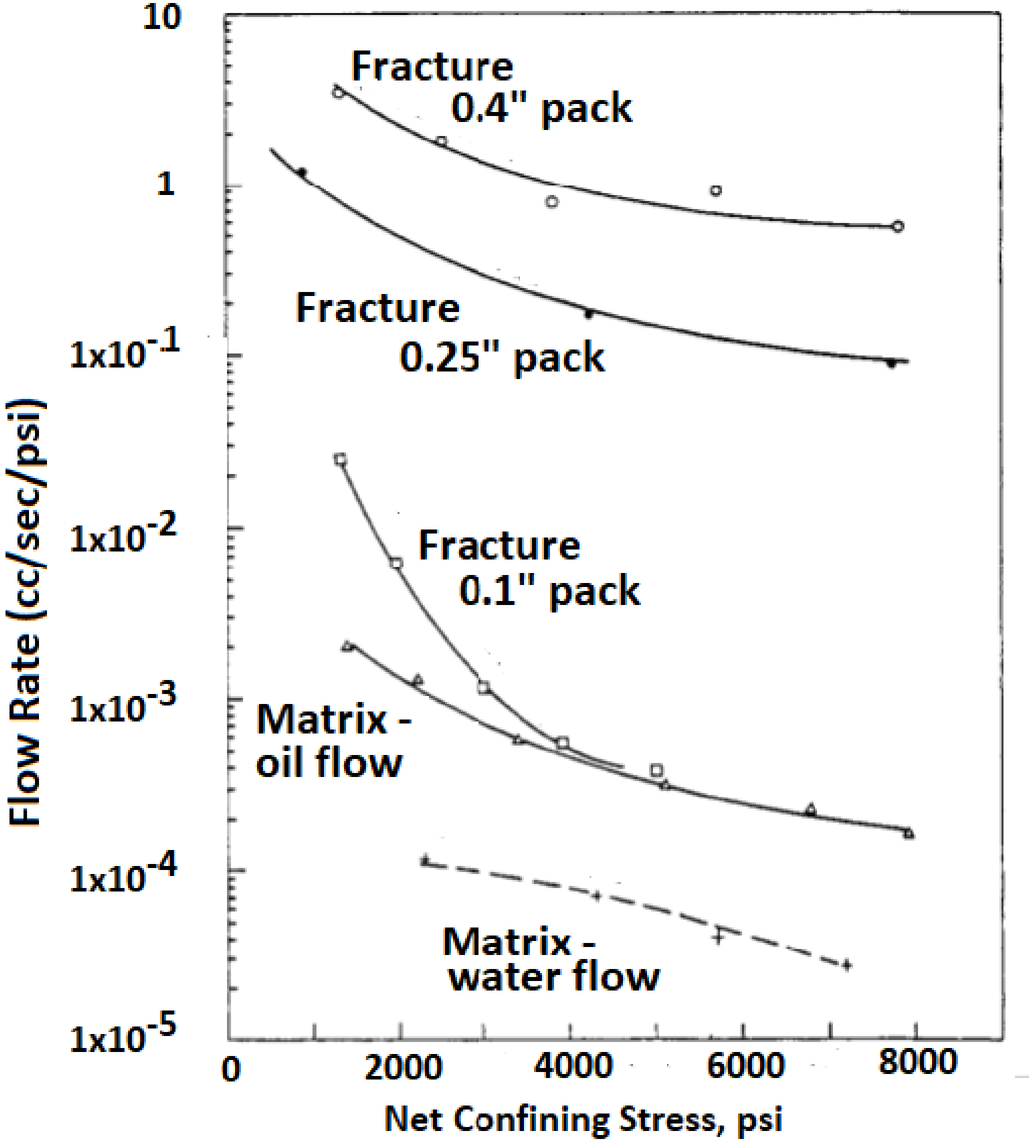
Effect on Proppant Packed Fracture Flow Capacity in Ductile Chalk Core as Net Pressure Increases – *(soft elements affect structure)*

All tests used 20/40 mesh sand proppant.

Note that the fracture with 0.1" thickness of proppant declined much faster as net pressure was increased.

Approx. embedment in soft chalks is ½ of a proppant grain, so embedment reduced flow space in the 0.1" pack by 1/3rd , while one proppant layer loss for the 0.25" pack is ~1/7th of capacity and the loss in the 0.4" pack is about 1/10th over the pressure range in the tests.

Changes in Fluid Flow for Proppant Packed Fractures As Net Confining Pressure Increases



Simon, D. E., Coulter, G. R., King, G., & Holman, G. (1982, November 1). North Sea Chalk Completions- A Laboratory Study. Society of Petroleum Engineers. doi:10.2118/10395-PA

From Where Does the Production Come?

(Kinetix-Intersect Modeling)

- **Variable recovery after 30 years of production,**
- **8.9% - near-wellbore dynamic nano-darcy region,**
- **2% - inter-hydraulic fracture,**
- **1.7 % external feeder regions for shale oil producer**
- **~ 2/3 total hydrocarbons from near-wellbore & fracs,**
- **Remaining 1/3 by external feeder region.**
- **Variable recovery factor & press depletion are basis for Enhanced Oil Recovery (EOR) techniques.**

Rodriguez, A. (2019, October 30). Inferences of Two Dynamic Processes on Recovery Factor and Well Spacing for a Shale Oil Reservoir. Society of Petroleum Engineers. doi:10.2118/197089-MS

Hydraulic Fracture Simulations by Modeling

- Classic hydraulic fracturing simulators based on Linear-Elastic Fracture Mechanics (LEFM):
  - Convenient to use, (but limited in shales)
  - Provide reasonable predictions for brittle formations,
  - Fail to predict fracturing pressures (e.g., breakdown, extension) and geometry (e.g., frac width and length), in formations that undergo plastic failures (e.g., ductile shales, soft chalks and poorly consolidated sands).

Wang, H., Marongiu-Porcu, M., & Economides, M. J. (2016, February 1). Poroelastic and Poroplastic Modeling of Hydraulic Fracturing in Brittle and Ductile Formations. Society of Petroleum Engineers. doi:10.2118/168600-PA

Fracture Initiation and Propagation

- Fracture propagation in ductile formations can introduce a significant plastic deformation around the fracture due to shar failure.
- A fracture will propagate when the energy-release rate in the “process zone” reaches a critical value.

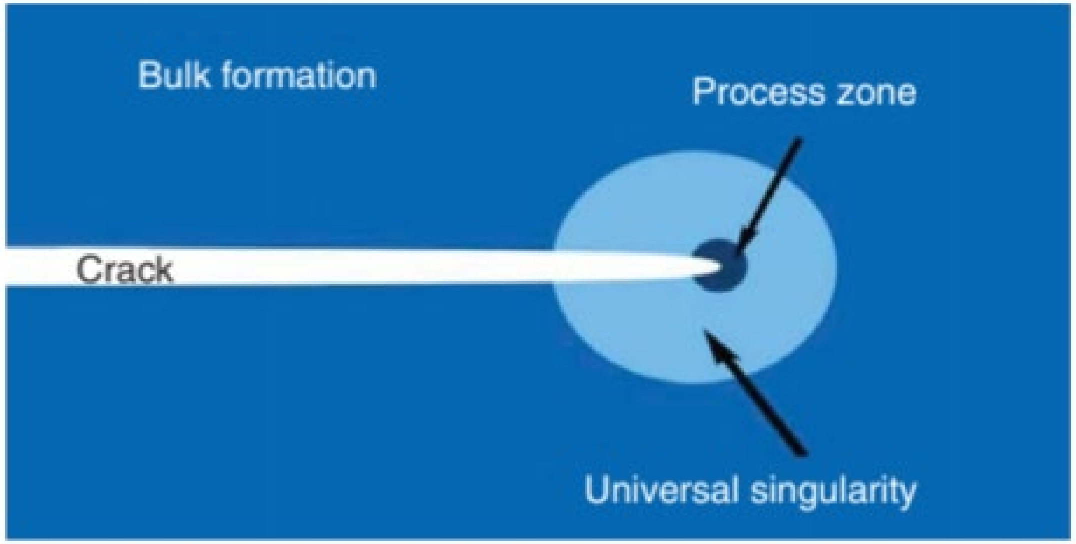


Fig. 1—Regions around the tip of a propagating crack.

The cohesive zone is a region ahead of the crack tip that can be characterized by microcracks that are the result of damage evolution created by changing stress (pressure, tensile failure or shear).

Wang, H., Marongiu-Porcu, M., & Economides, M. J. (2016, February 1). Poroelastic and Poroplastic Modeling of Hydraulic Fracturing in Brittle and Ductile Formations. Society of Petroleum Engineers. doi:10.2118/168600-PA

Fracture Extension in Ductile Formations

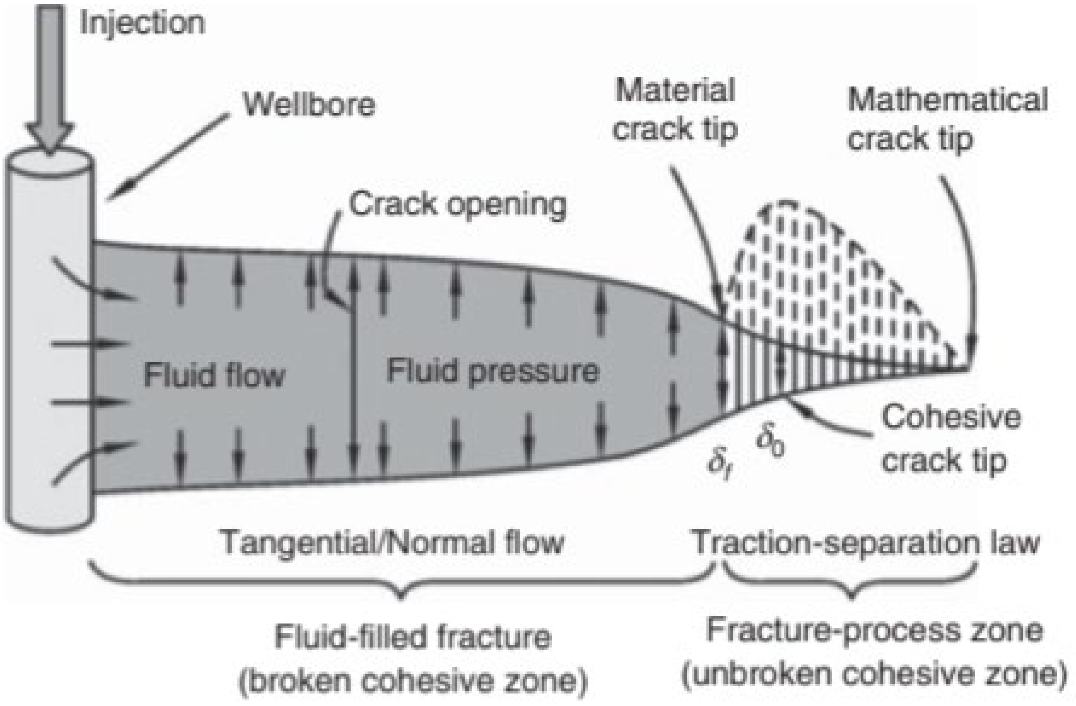
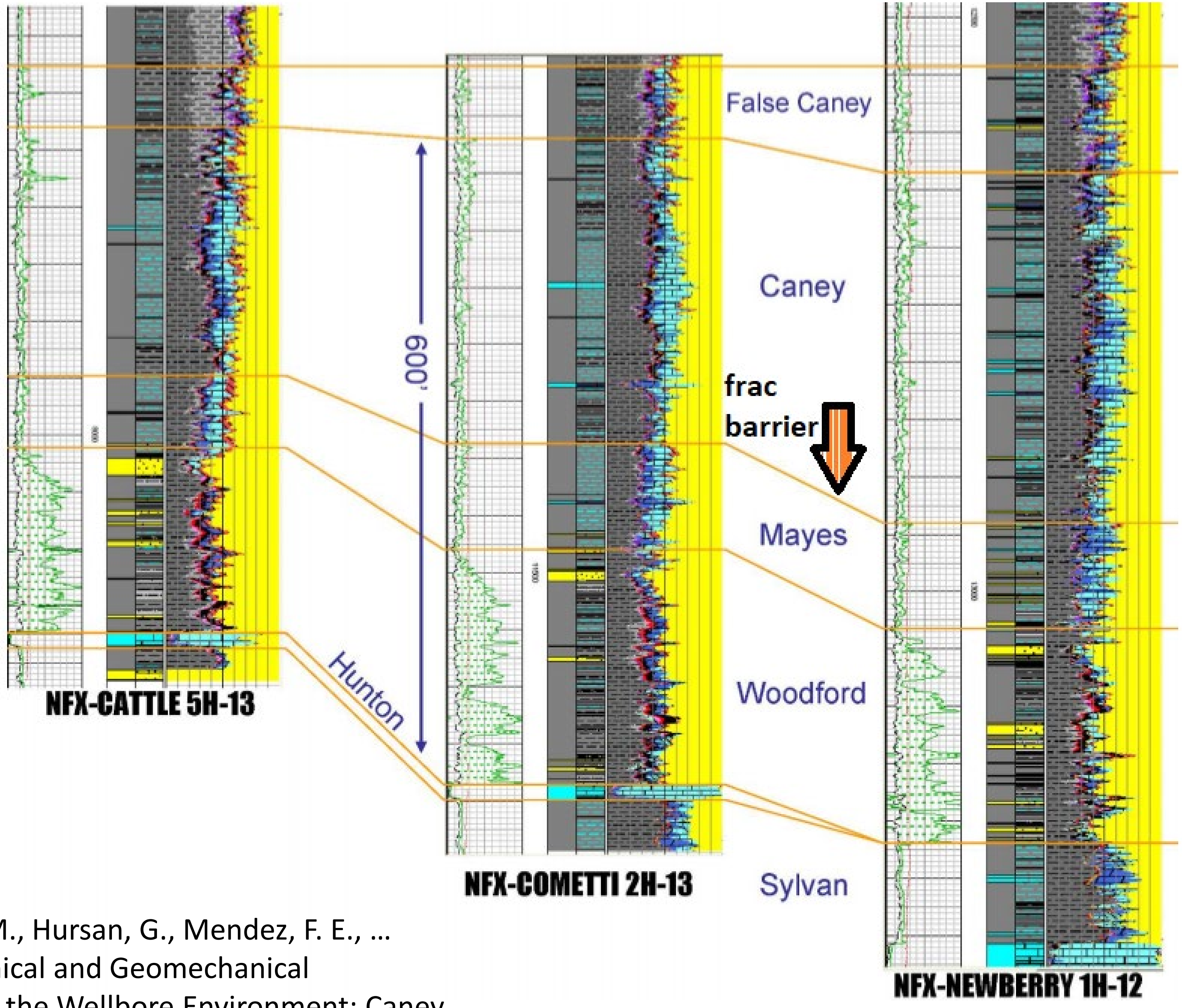


Fig. 4—Cohesive zone embedded along the fracture path (modified from Chen et al. 2009).

Wang, H., Marongiu-Porcu, M., & Economides, M. J. (2016, February 1). Poroelastic and Poroplastic Modeling of Hydraulic Fracturing in Brittle and Ductile Formations. Society of Petroleum Engineers. doi:10.2118/168600-PA

Potential Frac Barrier (Mayes)



Jacobi, D. J., Breig, J. J., LeCompte, B., Kopal, M., Hursan, G., Mendez, F. E., … Longo, J. (2009, January 1). Effective Geochemical and Geomechanical Characterization of Shale Gas Reservoirs From the Wellbore Environment: Caney and the Woodford Shale. Society of Petroleum Engineers. doi:10.2118/124231-MS

Lower Caney barriers to downward frac growth

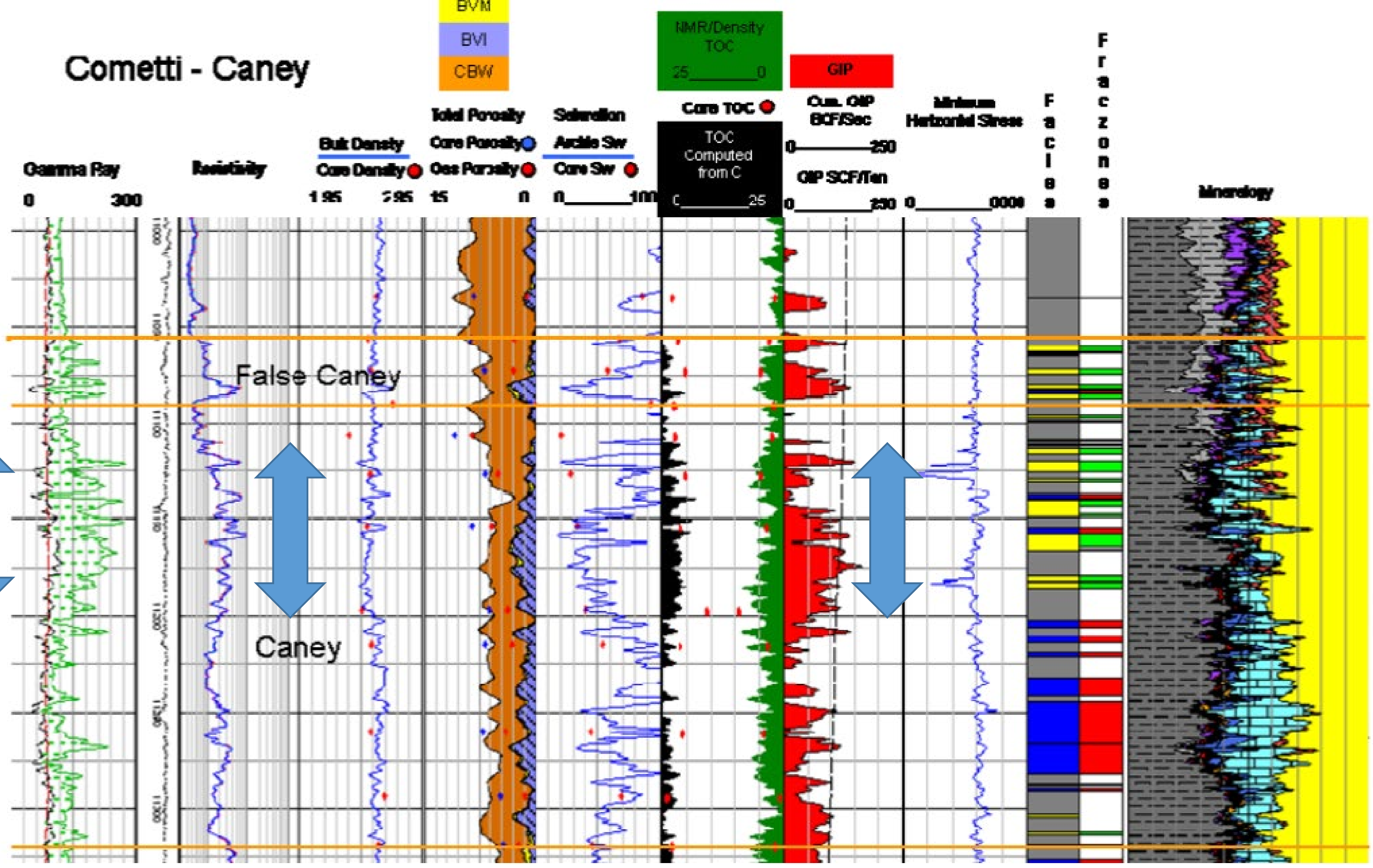


Fig. 17: Log of the Cometti displaying model results that show lithofacies of siliceous organic mudstones (black bars), carbonate mudstones (blue bars) siliceous mudstones (yellow bars), low organic mudstones (grey bars) (see Fig. 6 for legend). Also, see the corresponding favorable fracture zones (green bars) as opposed to potential fracture barriers (red bars) within both the Caney and False Caney. Note the significant thick barriers in the lower Caney that serve as containment for fractures induced into the sparse favorable zones of the upper Caney section.

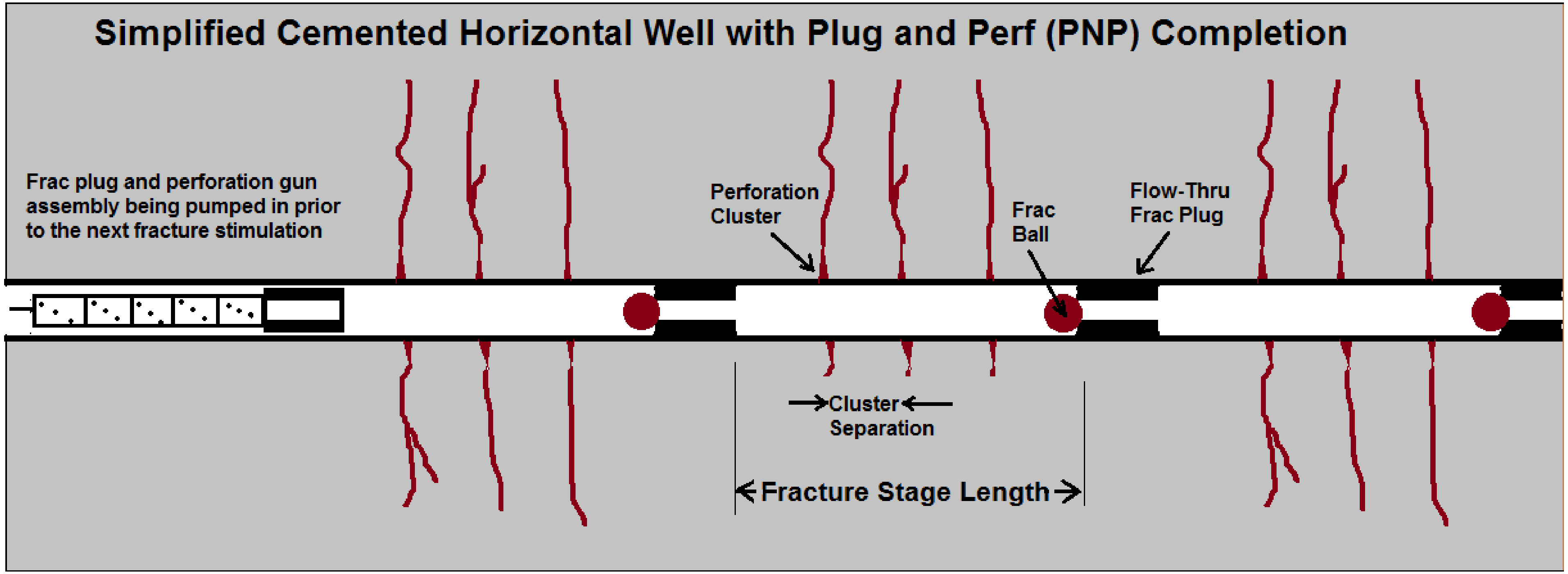
Jacobi, D. J., Breig, J. J., LeCompte, B., Kopal, M., Hursan, G., Mendez, F. E., … Longo, J. (2009, January 1). Effective Geochemical and Geomechanical Characterization of Shale Gas Reservoirs From the Wellbore Environment: Caney and the Woodford Shale. Society of Petroleum Engineers. doi:10.2118/124231-MS

An Opinion on Comparison of MFHW Completion Types

Completion Factor	Plug & Perf	Pkr. & Sleeve	CT Shifted Sleeve
Early Expense (before drilling)	Low	High	Moderate
Lead Time (order from mfgr.)	Low	High	Moderate
Casing/pkr run-to-frac time	Moderate	Moderate	Moderate
Landing accuracy Importance	Low	High	Moderate
Frac screenout occurrence	Low	Moderate?	Low
Potential for most frac entry points	Highest	Lowest	Moderate
Potential for missing stages	Low	Moderate	Low
Time between fracs	Moderate (2 hr)	Short (min.)	Short
High frac rates possible	Highest	Lowest	Moderate
Potential for missed stages	Low	Moderate?	Low
Gauge hole critical	Low	Yes	Low
Isolation quality btwn frac stages	Moderate	Low	Moderate
Proppant placement accuracy	Low	High	High
Equipment required during frac	Wireline Unit	None	Coiled Tubing Unit
Cleanout potential	High	Low	High
Workover Potential	High	Low	High
Flowback cntrl & entry shut-off	Low	Low	High
Field Knowledge of Technique	High	Moderate	Moderate
Freeze-up avoidance	Low	High	Moderate
Potential for refracs	High	Low	High
All -in - Cost	Lowest	Mod/High	High

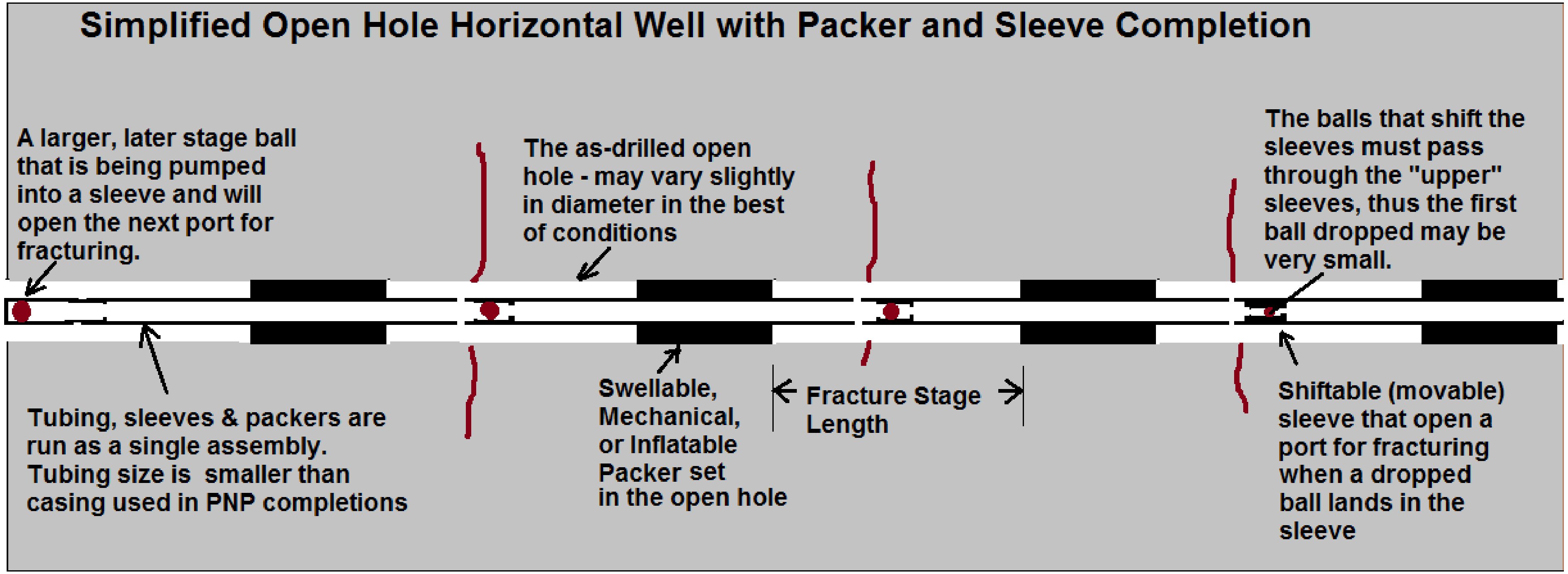
Source: George King, MFHW School Slides

Plug and Perf – Cemented Casing

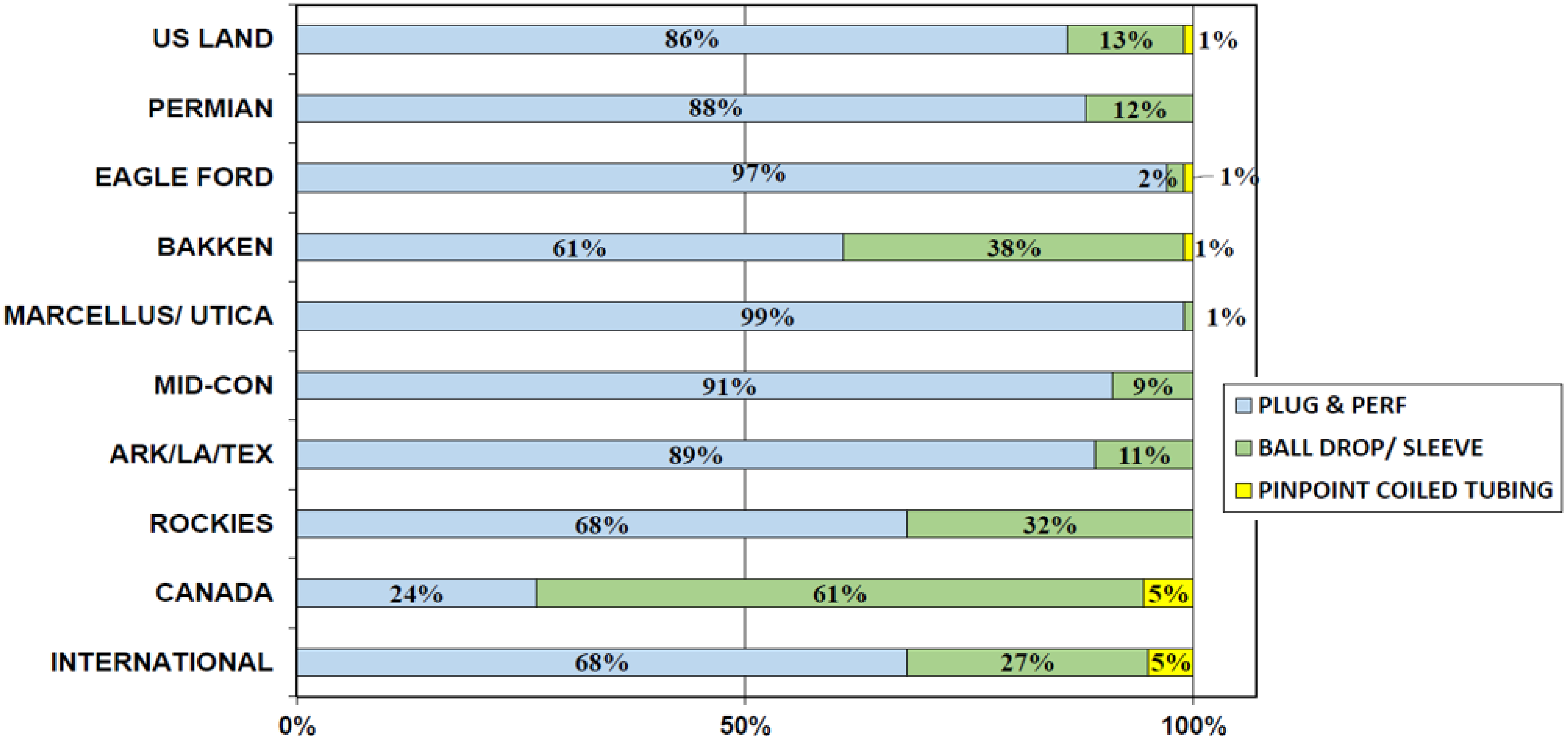


60 to 100 fractures along one wellbore create rock contact areas over 700,000 square feet each, + opening natural fractures→ about 10 million+ square feet of contact.

Packer and Sleeve – Open Hole



Approximate Distribution of Completion Types in Various Basins



Kimberlite International Oilfield Research

Karen Olson: SPE Unconventional Summit II

A recent high importance change - Hydraulic Diversion & Extreme Limited Entry (XLE)

- Number of perfs controls amount of hydraulic diversion when full injection rate reached.
- Achieving diversion while inj. rate is building to design rate requires diversion by other methods.
- Diversion by perforations involves number, diameter and flow efficiency of perfs
- Perf friction first seen when ratio of rate to perfs > 0.5 bpm/perf, but diversion begins when rate reaches at least 1.0 bpm/perf. Common today - effective diversion at 2.0 to 2.5+ bpm/perf?
- <u>XLE - New data suggests hydraulic diversion with 100 mesh sands at 8 bbl/min/perf – resembles pin-point injection.</u>

Effect of Proppant Embedment

Table 2—Baseline Conductivity and Proppant Embedment at 2,000 and 7,500 psi of Stress

SPE 191702

	Baseline Conductivities (md-ft.) @ 0.9 Damage Factor		Embedment – Change in Propped Fracture Width	
Stress (psi)	100 Mesh	40/70 White Sand	100 Mesh	40/70 White Sand
2,000	7.2	16.4	-1.4%	-2.5%
7,500	0.7	4.3	-6.5%	-11.1%
Loss of Fracture Conductivity %	-91%	-74%	-5.1%	-8.6%

A Bakken comparison of sand and ceramic proppant performance over time (no other controls)

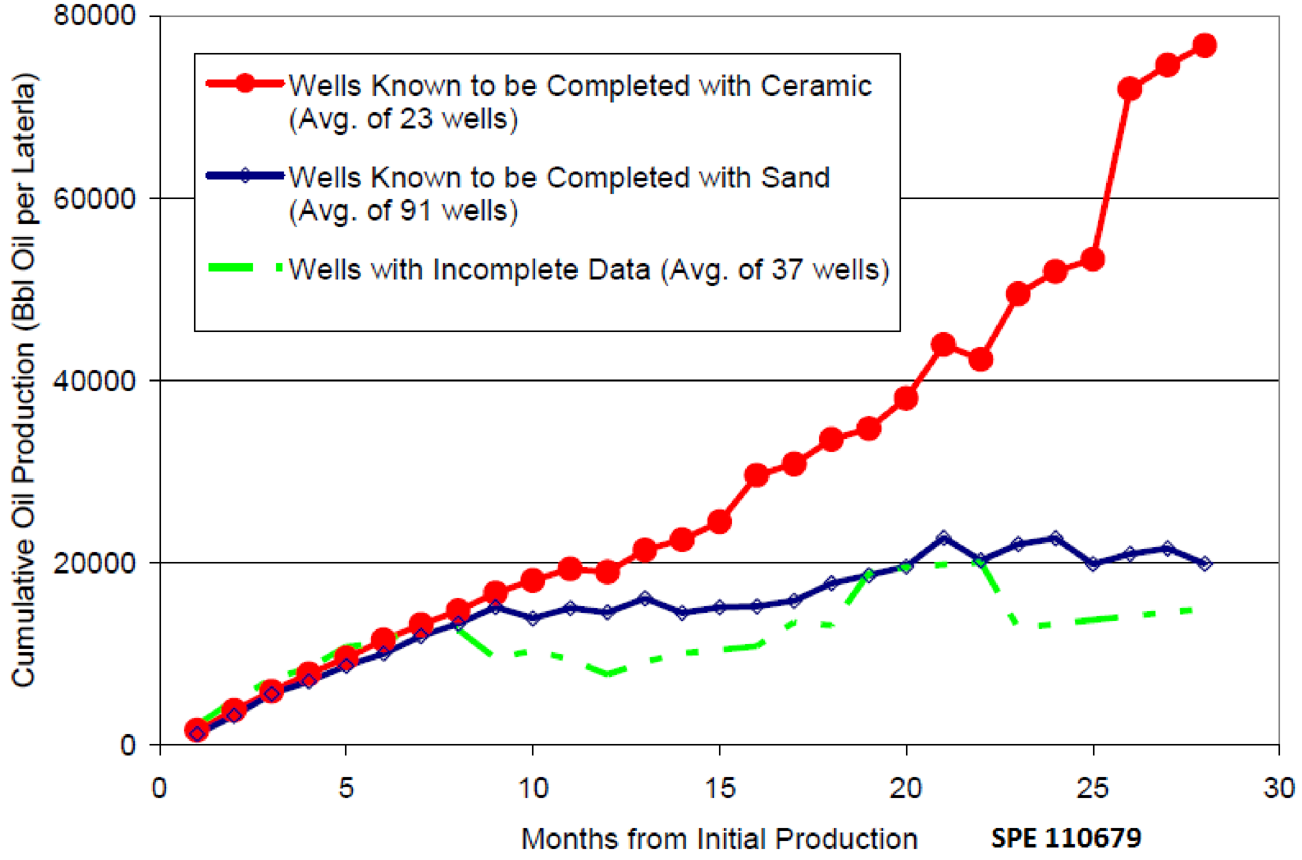


Figure 12 – Average cumulative Oil Production *per lateral* for Sand, Ceramic, and Unknown Completions in North Dakota

What is the difference?

- Larger/consistant prop size
- Better stability of ceramics
- Better strength of ceramics

What is the problem?

<u>Cost</u>

- sand \$0.06 to \$0.10 per lb.
- Ceramics ~\$0.35 to ~\$0.50/lb

Besler, M. R., Steele, J. W., Egan, T., & Wagner, J. (2007, January 1). Improving Well Productivity and Profitability in the Bakken--A Summary of Our Experiences Drilling, Stimulating, and Operating Horizontal Wells. Society of Petroleum Engineers. doi:10.2118/110679-MS

Average Cumulative BOE per 1000 ft. of Lateral – Micro-proppant

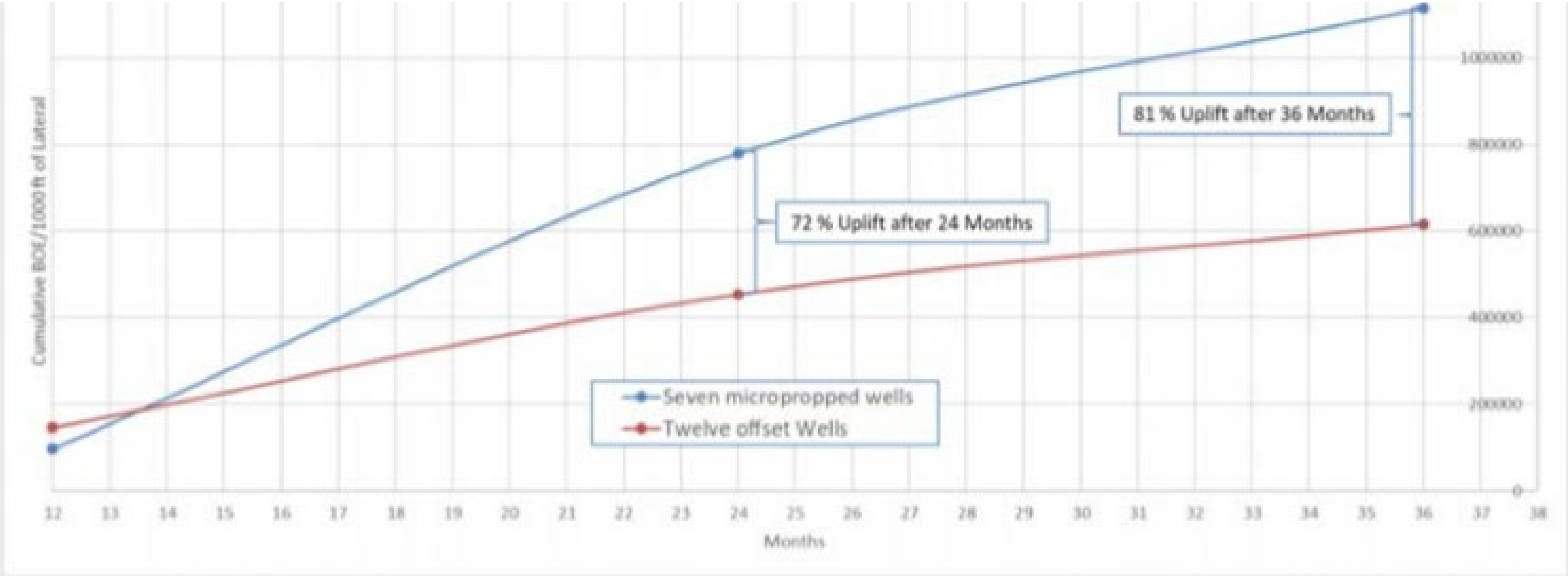
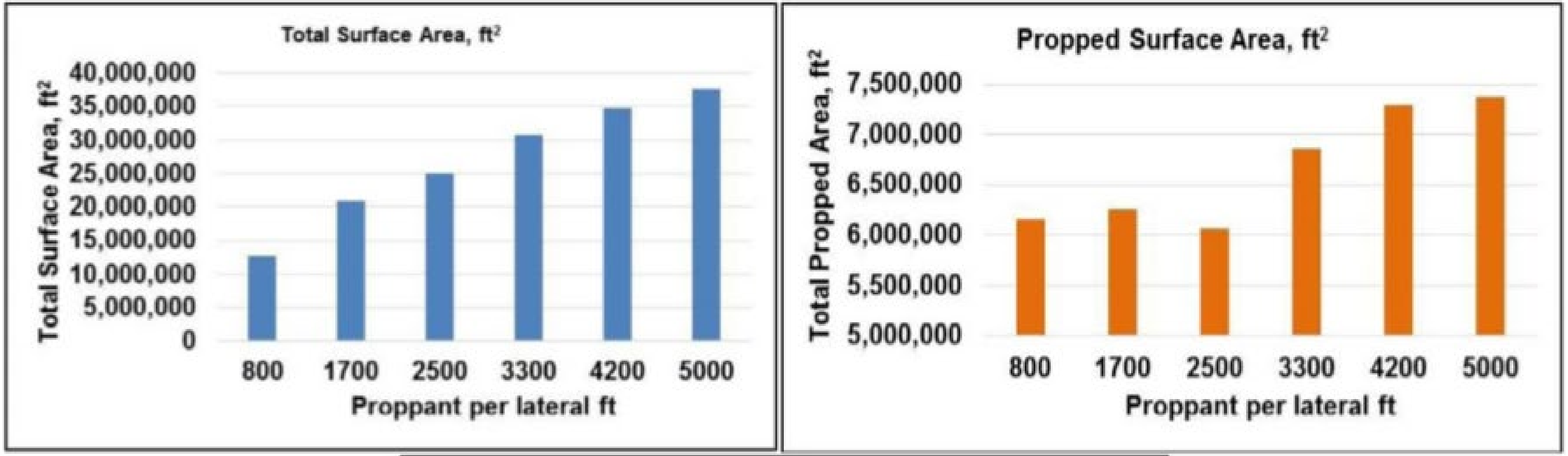
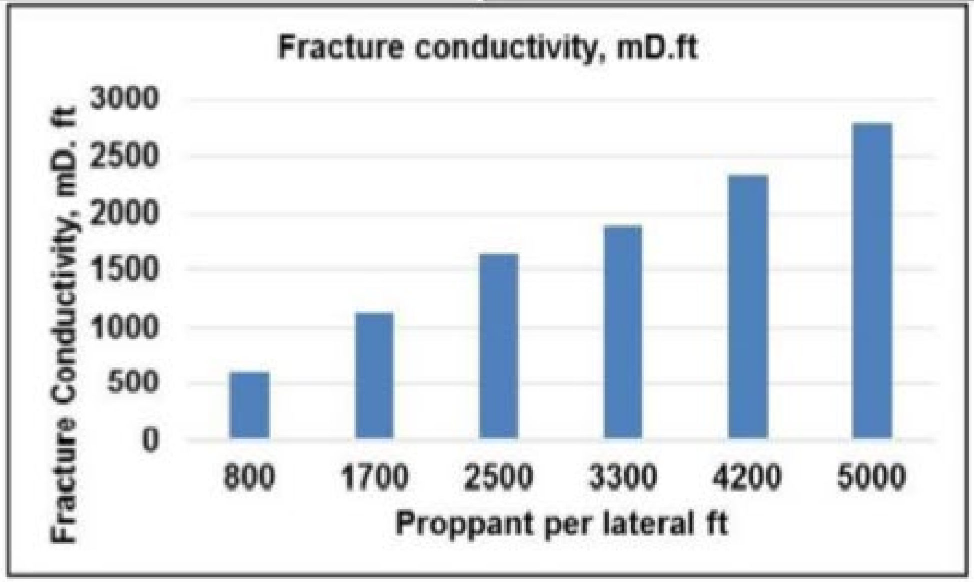


Figure 16—Woodford (SCOOP) averaged cumulative BOE/1000 foot of lateral for 7 MP wells and 12 offset wells

Montgomery, C. T., Smith, M. B., An, Z., Klein, H. H., Strobel, W., & Myers, R. R. (2020, January 28). Utilizing Discrete Fracture Modeling and Micropropppant to Predict and Sustain Production Improvements in Micro Darcy Rock. Society of Petroleum Engineers. doi:10.2118/199741-MS





SPE-191800-MS

Figure 24—Increasing proppant per lateral foot shows increase in the total propped surface area.

Srinivasan, K., Ajisafe, F., Alimahomed, F., Panjaitan, M., Makarychev-Mikhailov, S., & Mackay, B. (2018, August 28). Is There Anything Called Too Much Proppant? Society of Petroleum Engineers. doi:10.2118/191800-MS

Fracture Modeling – “All Models are Wrong, But Some are Useful” - British statistician George E. P. Box

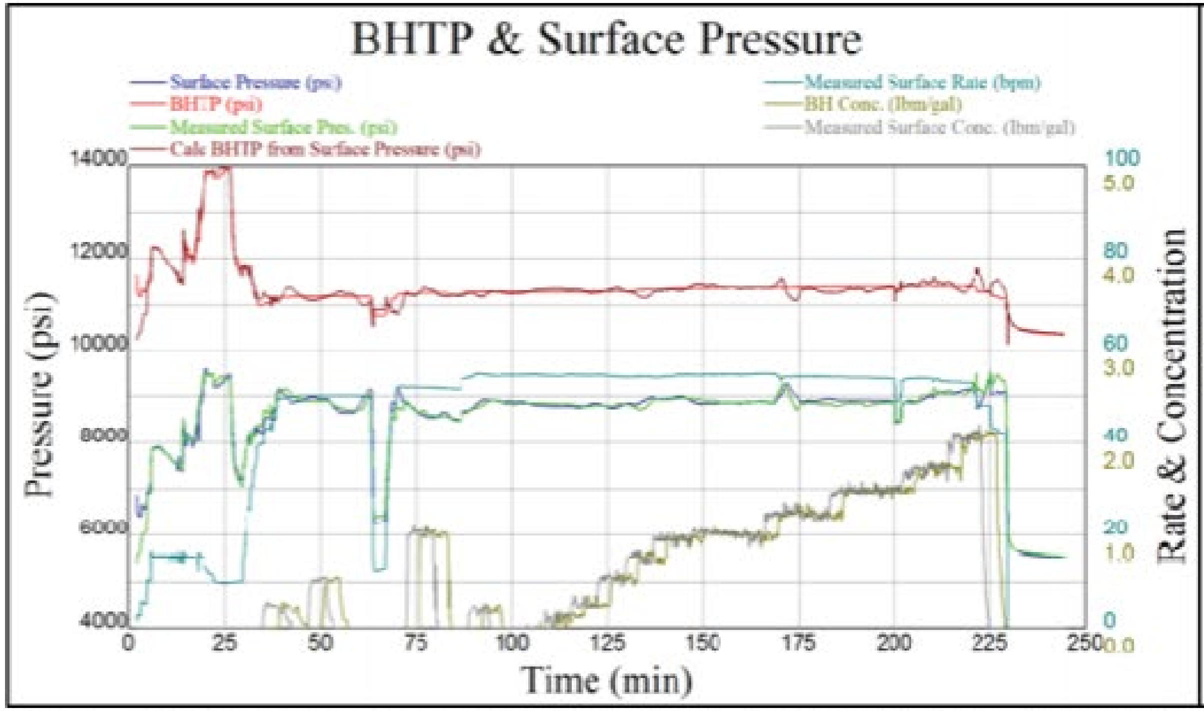


Fig. 8 – Pressure history match for Well A, (connected-cluster DFN).

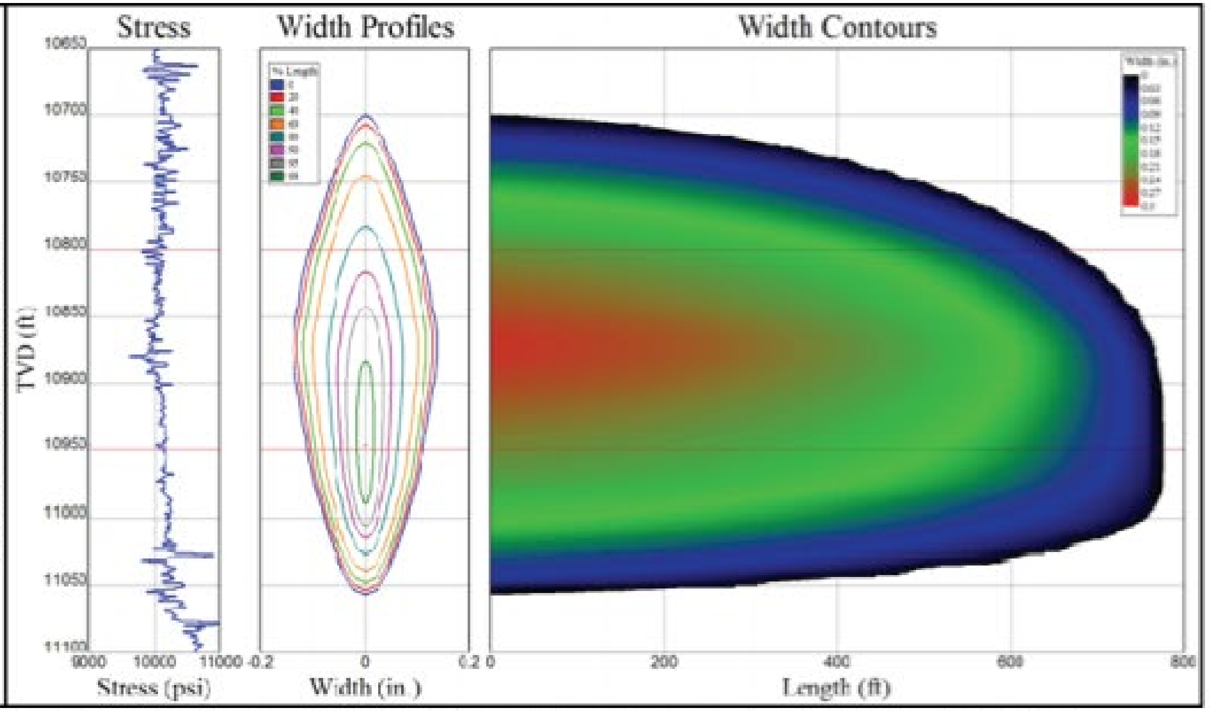


Fig. 9 – Stress, width contours and length for Well A, fracture half length is 776’, (connected-cluster DFN).

Bazan, L. W., Larkin, S. D., Lattibeaudiere, M. G., & Palisch, T. T. (2010, January 1). Improving Production in the Eagle Ford Shale With Fracture Modeling, Increased Fracture Conductivity, and Optimized Stage and Cluster Spacing Along the Horizontal Wellbore. Society of Petroleum Engineers. doi:10.2118/138425-MS

Where is the Proppant & is it Effective?

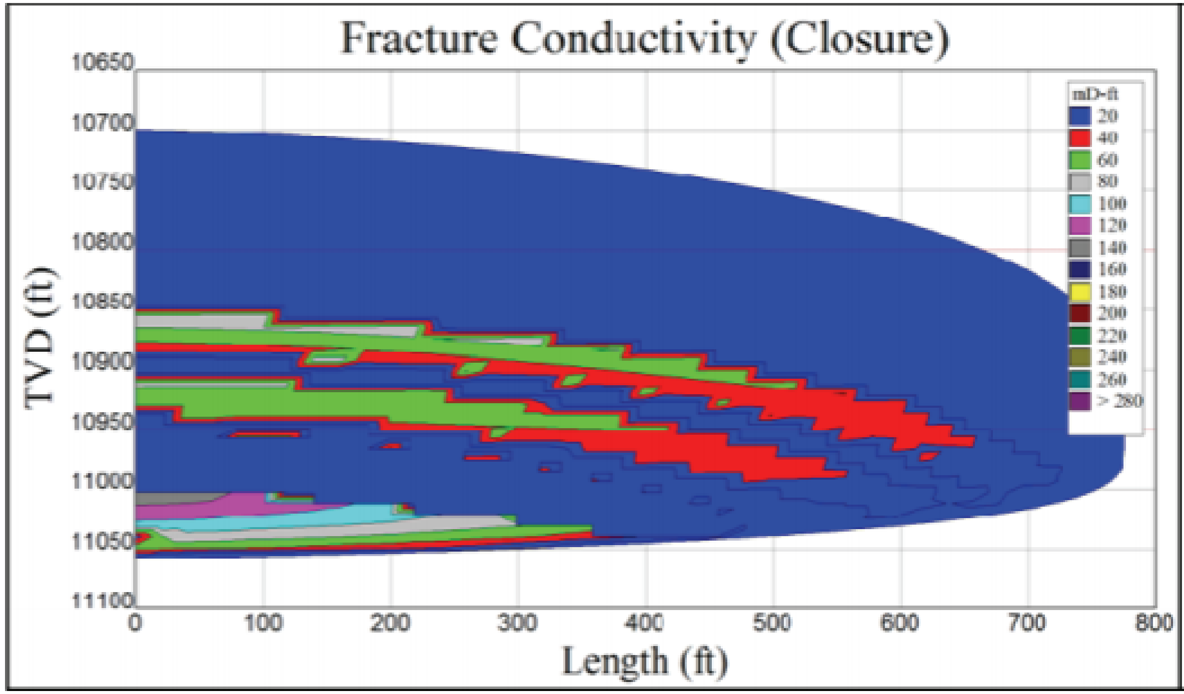


Fig. 10 – Fracture conductivity at closure for Well A showing 20-80 mD, (connected-cluster DFN).

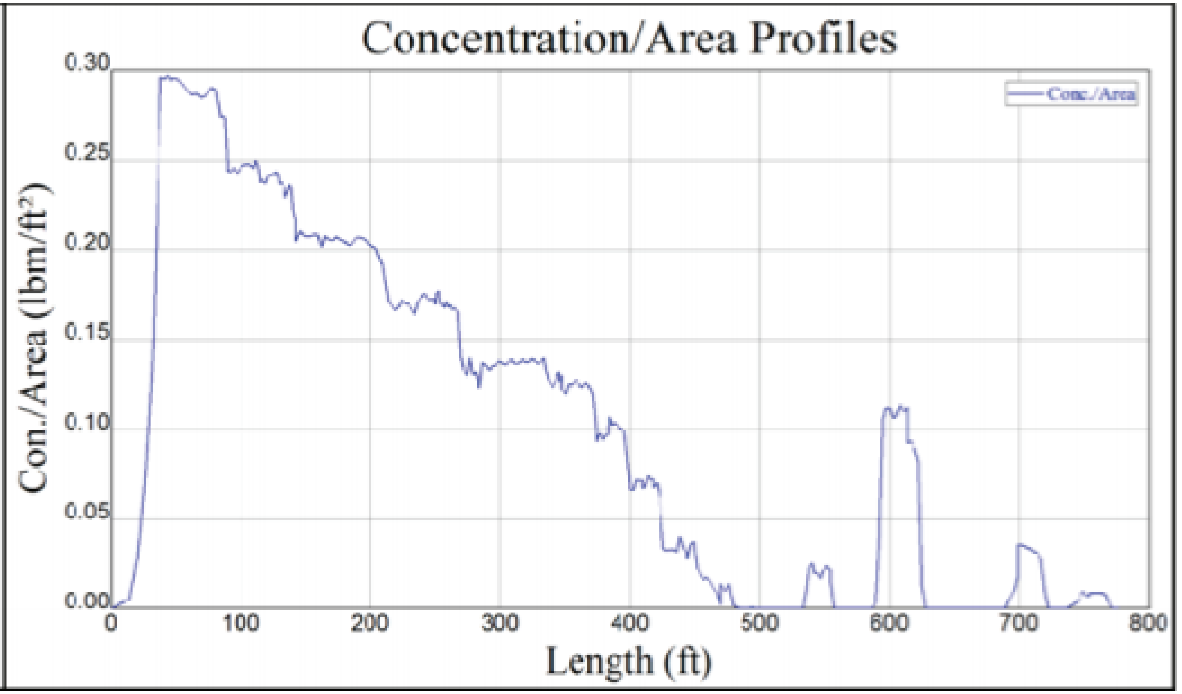
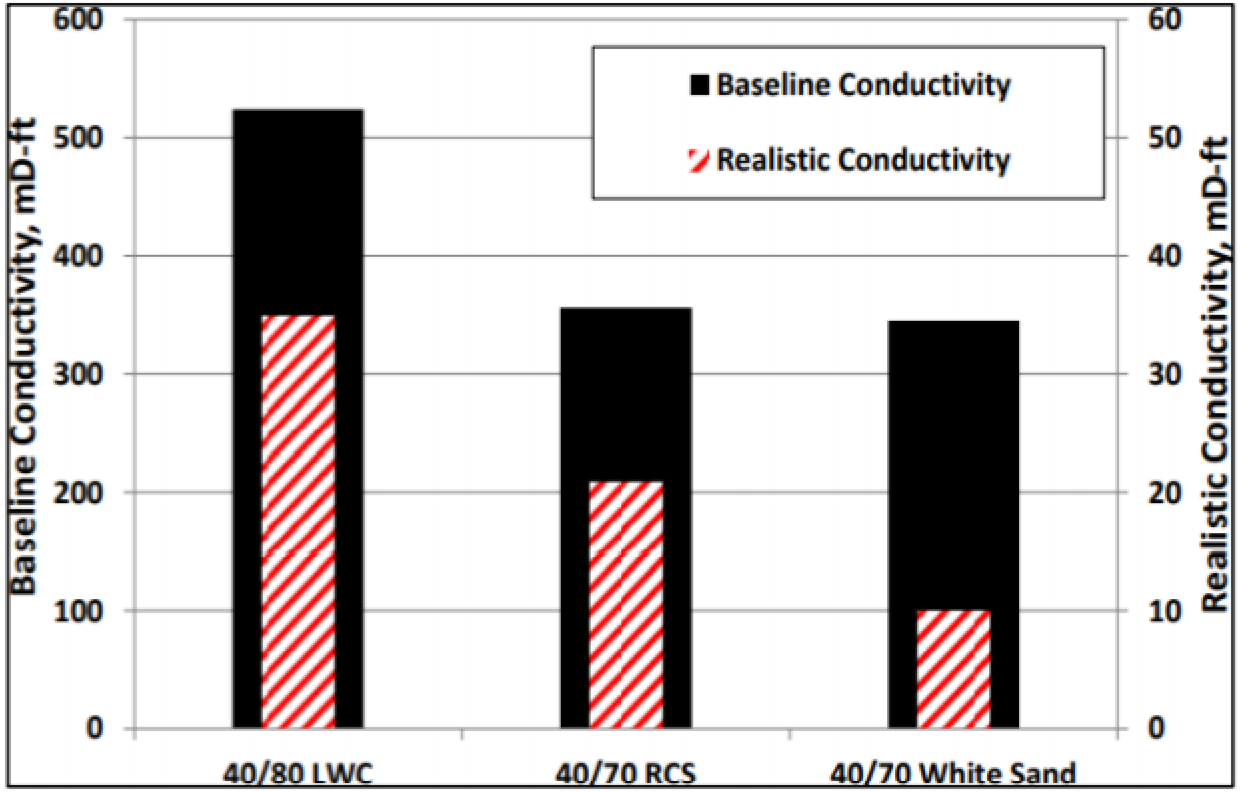


Fig. 11 – Concentration per area profiles at closure for Well A, loss of conductivity because of overflush (connected-cluster DFN).

Bazan, L. W., Larkin, S. D., Lattibeaudiere, M. G., & Palisch, T. T. (2010, January 1). Improving Production in the Eagle Ford Shale With Fracture Modeling, Increased Fracture Conductivity, and Optimized Stage and Cluster Spacing Along the Horizontal Wellbore. Society of Petroleum Engineers. doi:10.2118/138425-MS

Proppant Conductivity – Not What We Think



Comparison between proppant baseline conductivity and "downhole" conductivity for 40/80 LWC, 40/70 RCS and 40/70 white sand proppants at Eagleford shale reservoir conditions (Bazan 2012)

Bazan, L. W., Larkin, S. D., Lattibeaudiere, M. G., & Palisch, T. T. (2010, January 1). Improving Production in the Eagle Ford Shale With Fracture Modeling, Increased Fracture Conductivity, and Optimized Stage and Cluster Spacing Along the Horizontal Wellbore. Society of Petroleum Engineers. doi:10.2118/138425-MS

Elsarawy, A. M., & Nasr-El-Din, H. A. (2018, August 16). Propped Fracture Conductivity in Shale Reservoirs: A Review of Its Importance and Roles in Fracturing Fluid Engineering. Society of Petroleum Engineers. doi:10.2118/192451-MS

Effect of More Proppant – best 3 months and best 12 months – Eagle Ford – Gas Window

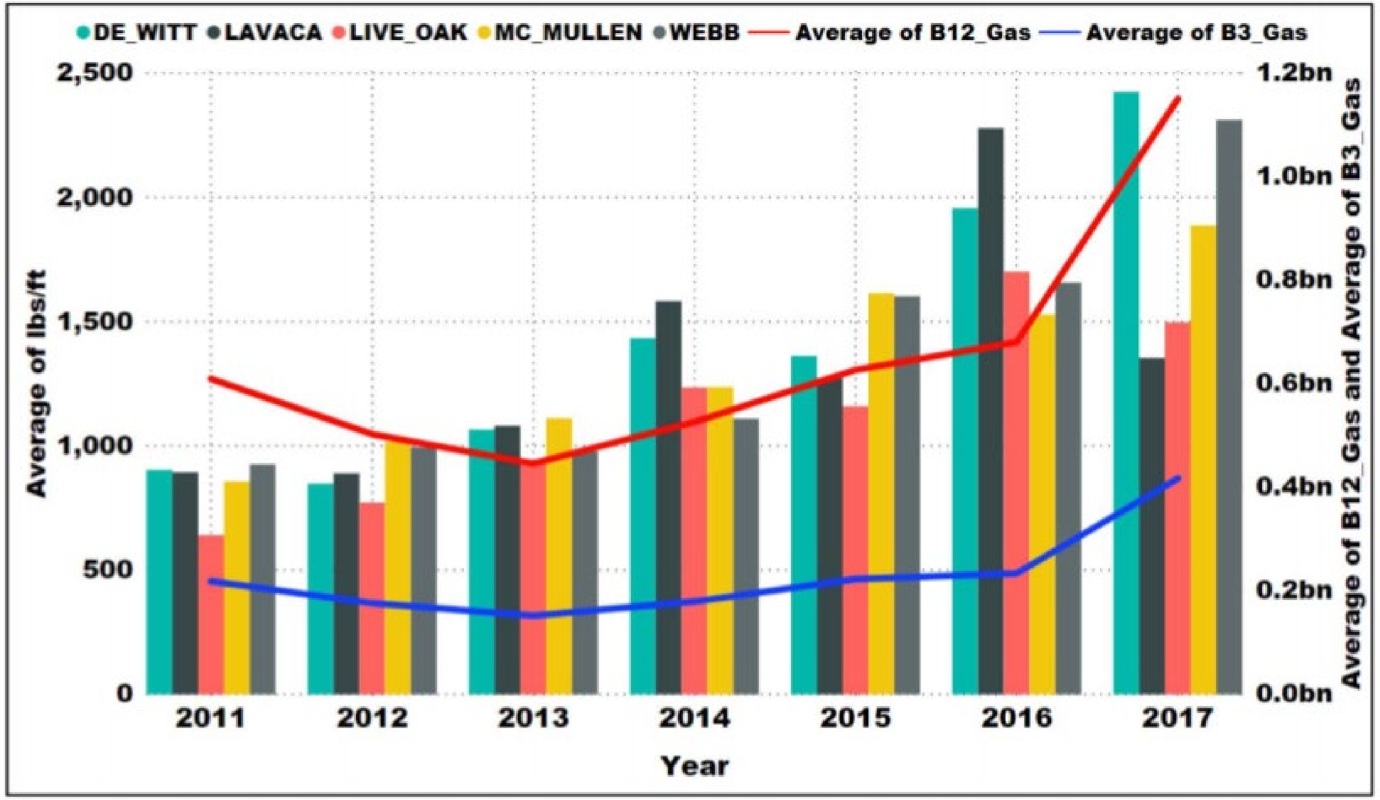


Figure 16—Average of the best 3 months and 12 months of gas production and volume of sand per lateral foot in the Eagle Ford formation, Texas (Gas window).

Srinivasan, K., Ajisafe, F., Alimahomed, F., Panjaitan, M., Makarychev-Mikhailov, S., & Mackay, B. (2018, August 28). Is There Anything Called Too Much Proppant? Society of Petroleum Engineers. doi:10.2118/191800-MS

Proppant – Eagle Ford - Oil Window Results

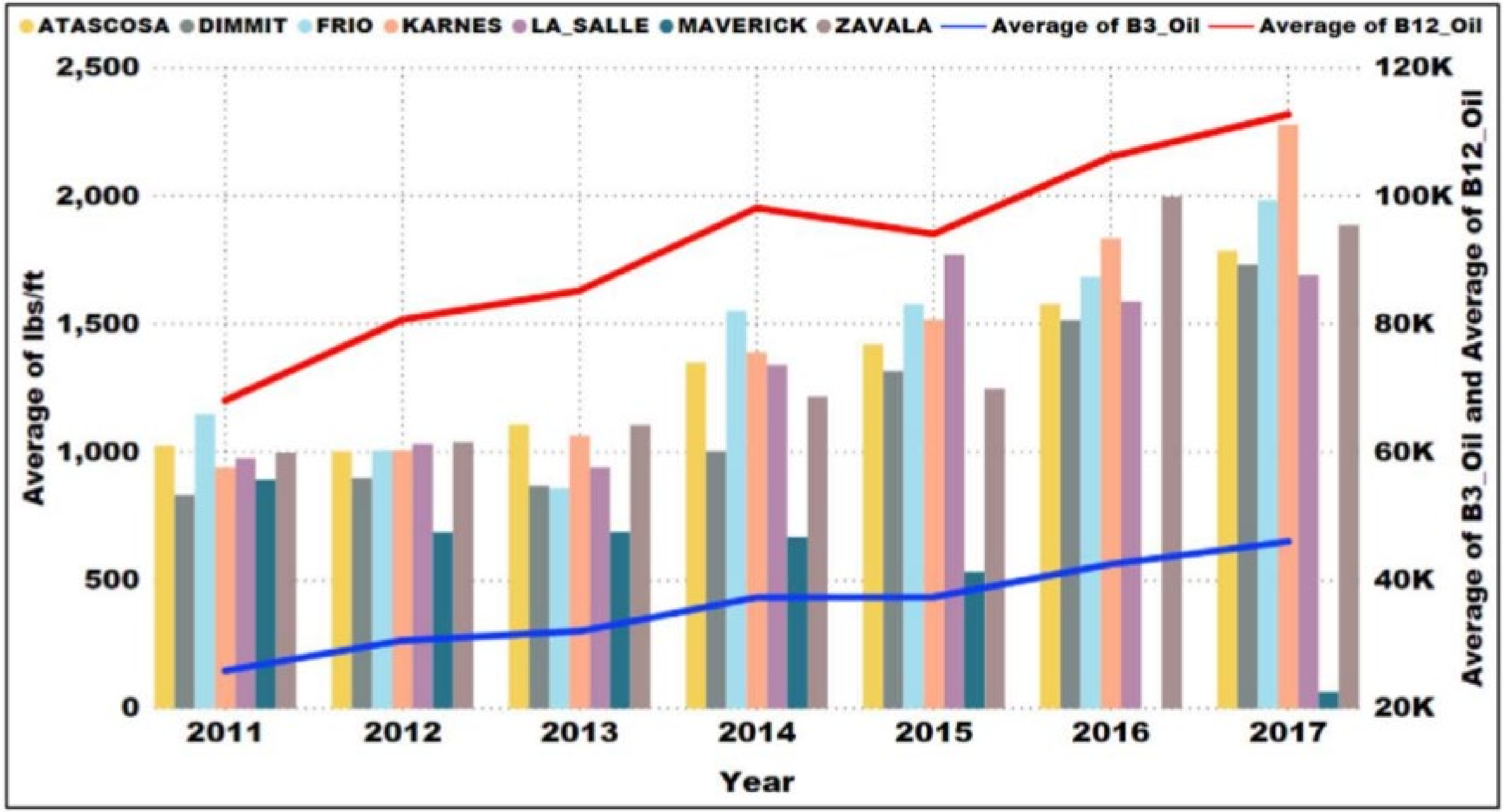


Figure 17—Average of the best 3 months and 12 months gas production and volume of sand per lateral foot in the Eagle Ford formation, Texas (Oil window).

Srinivasan, K., Ajisafe, F., Alimahomed, F., Panjaitan, M., Makarychev-Mikhailov, S., & Mackay, B. (2018, August 28). Is There Anything Called Too Much Proppant? Society of Petroleum Engineers. doi:10.2118/191800-MS

Haynesville – More Prop – More Gas

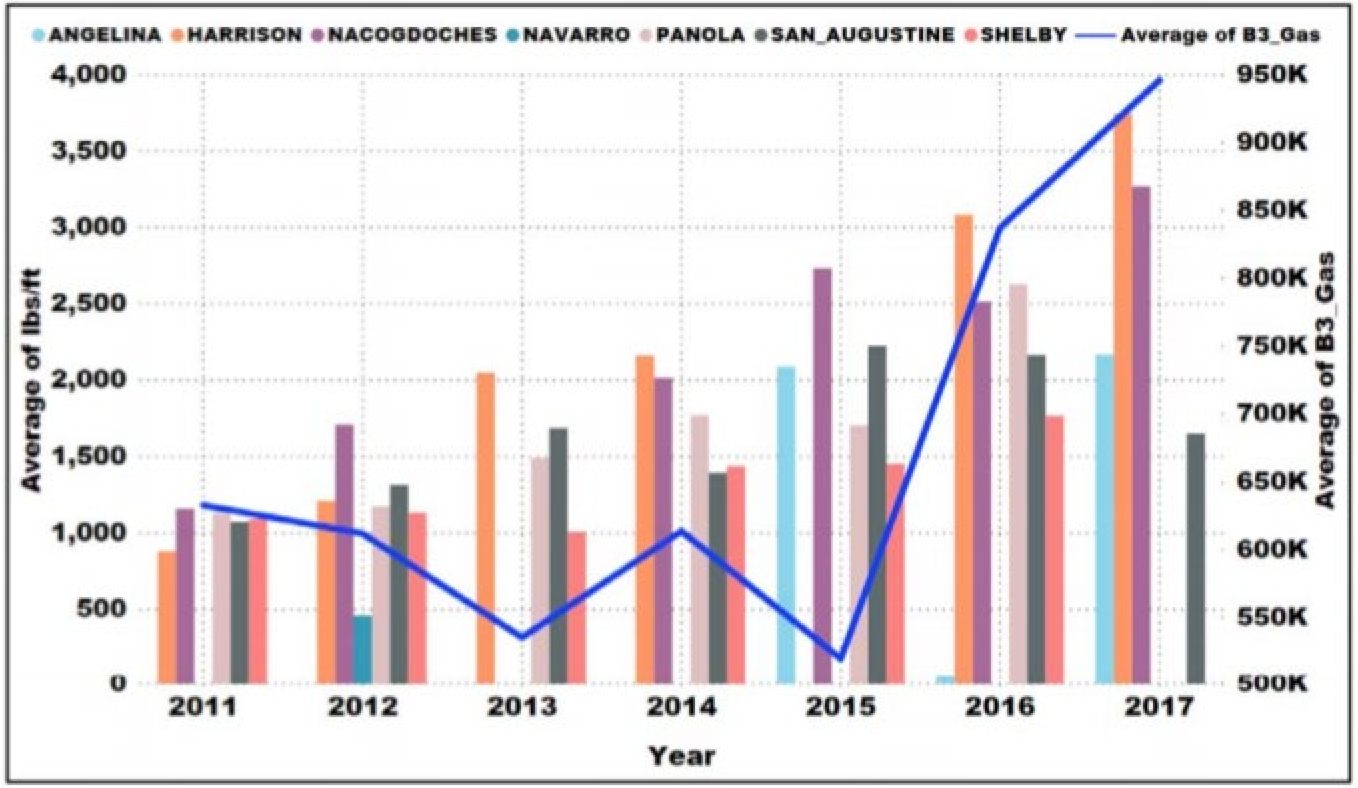


Figure 20—Average of the best 3-month gas production and volume of sand per lateral foot in the Haynesville formation, Texas.

Srinivasan, K., Ajisafe, F., Alimahomed, F., Panjaitan, M., Makarychev-Mikhailov, S., & Mackay, B. (2018, August 28). Is There Anything Called Too Much Proppant? Society of Petroleum Engineers. doi:10.2118/191800-MS

Frac Fluid Change

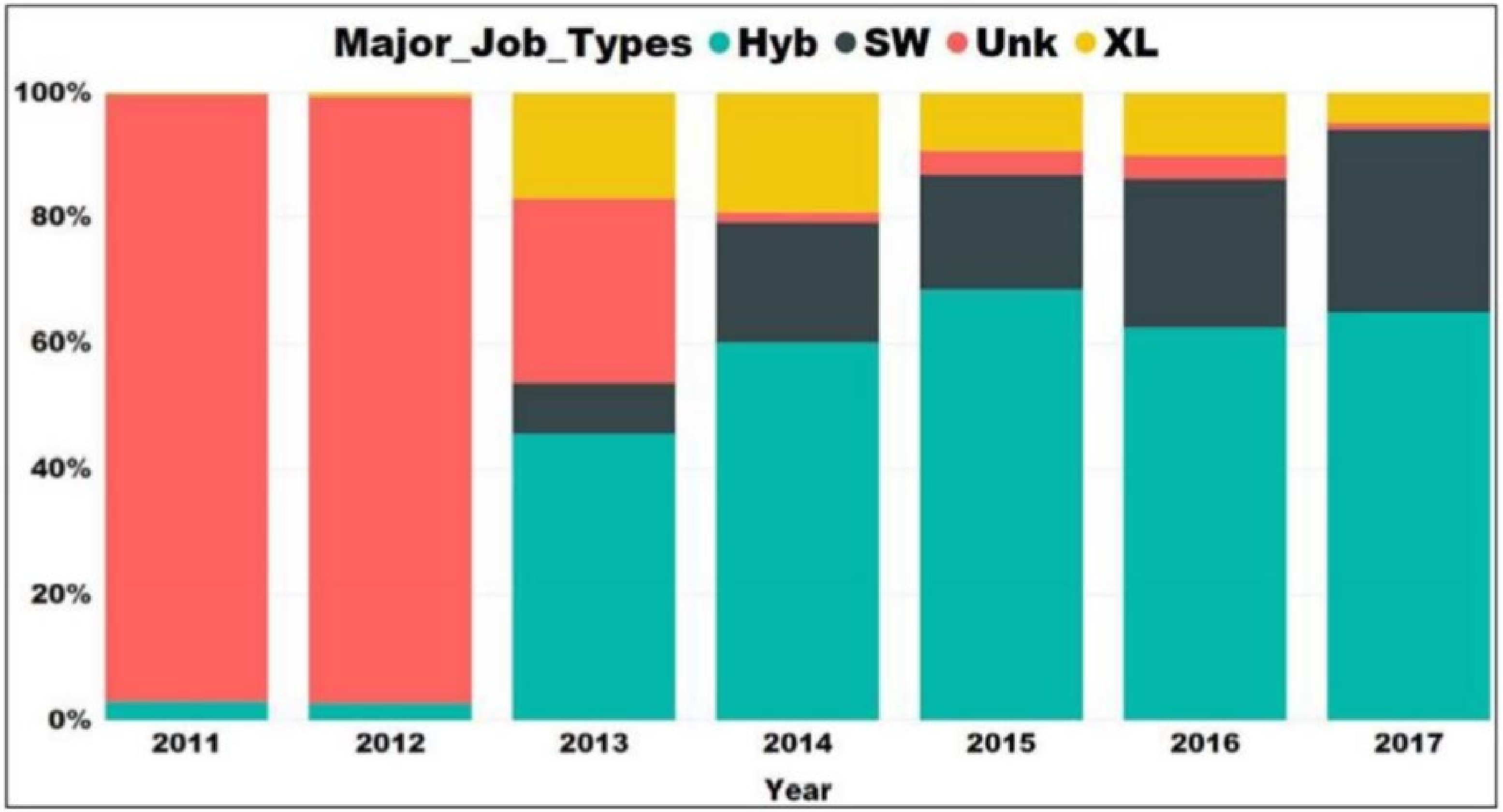


Figure 19—Evolution of hydraulic fracturing fluid type pumped in the Eagle Ford Formation.

Srinivasan, K., Ajisafe, F., Alimahomed, F., Panjaitan, M., Makarychev-Mikhailov, S., & Mackay, B. (2018, August 28). Is There Anything Called Too Much Proppant? Society of Petroleum Engineers. doi:10.2118/191800-MS

Is the fracture half empty or half full? Yes. And that is the problem.

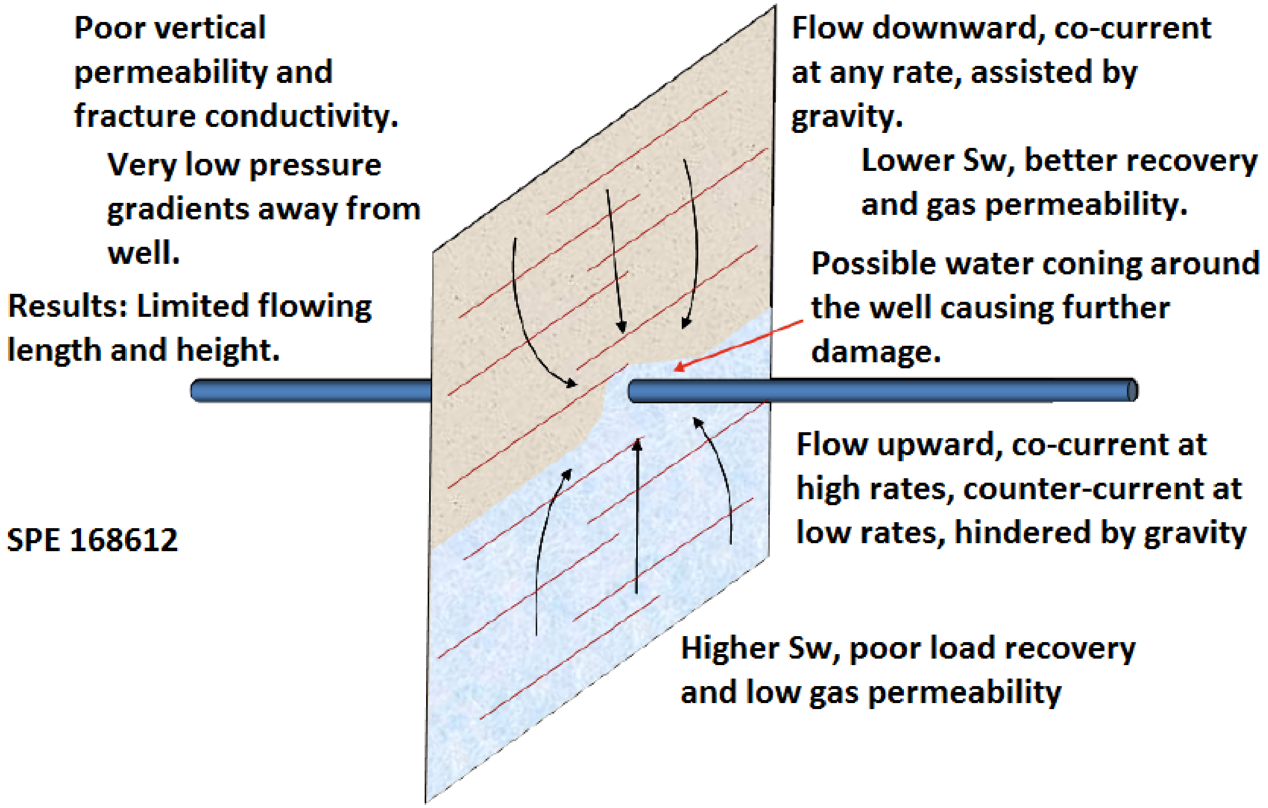


Diagram of a vertical fracture in a horizontal well showing effects of convergent flow and gravity driven fluid segregation.

“Because of the combination of near-well saturation and inertial flow, the pressure gradient increases to more than 2 psi/ft at the wellbore, but is less than 0.02 psi/ft ten feet beyond the well, where velocity and inertial effects are very low.” (Barree, et.al., 2014)

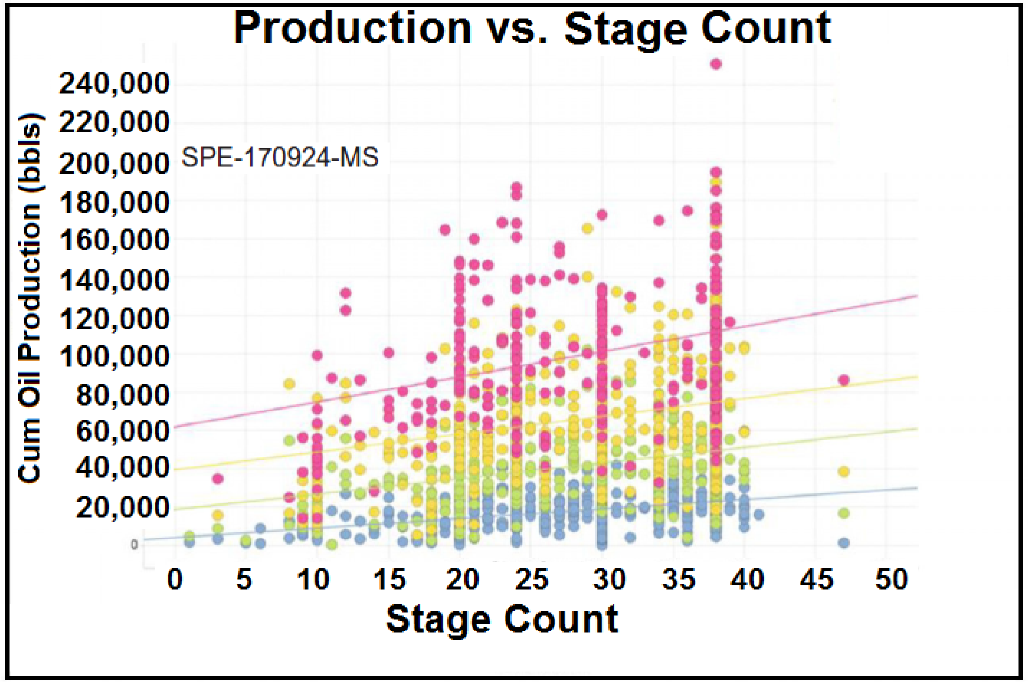
Does adding more frac stages really help?

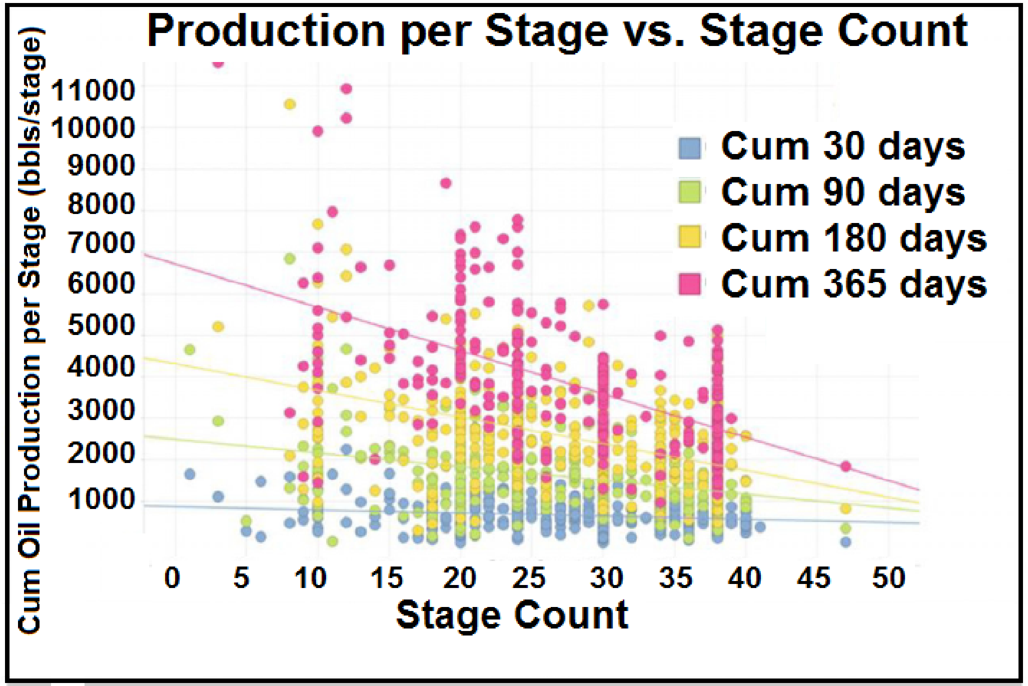
Is it a case of diminishing returns?

Production vs. stage count

and

Production per stage vs stage count.





Bakken Production per well after 30, 90, 180 & 365 days vs. stage count (above) and production per stage vs. stage count (below).

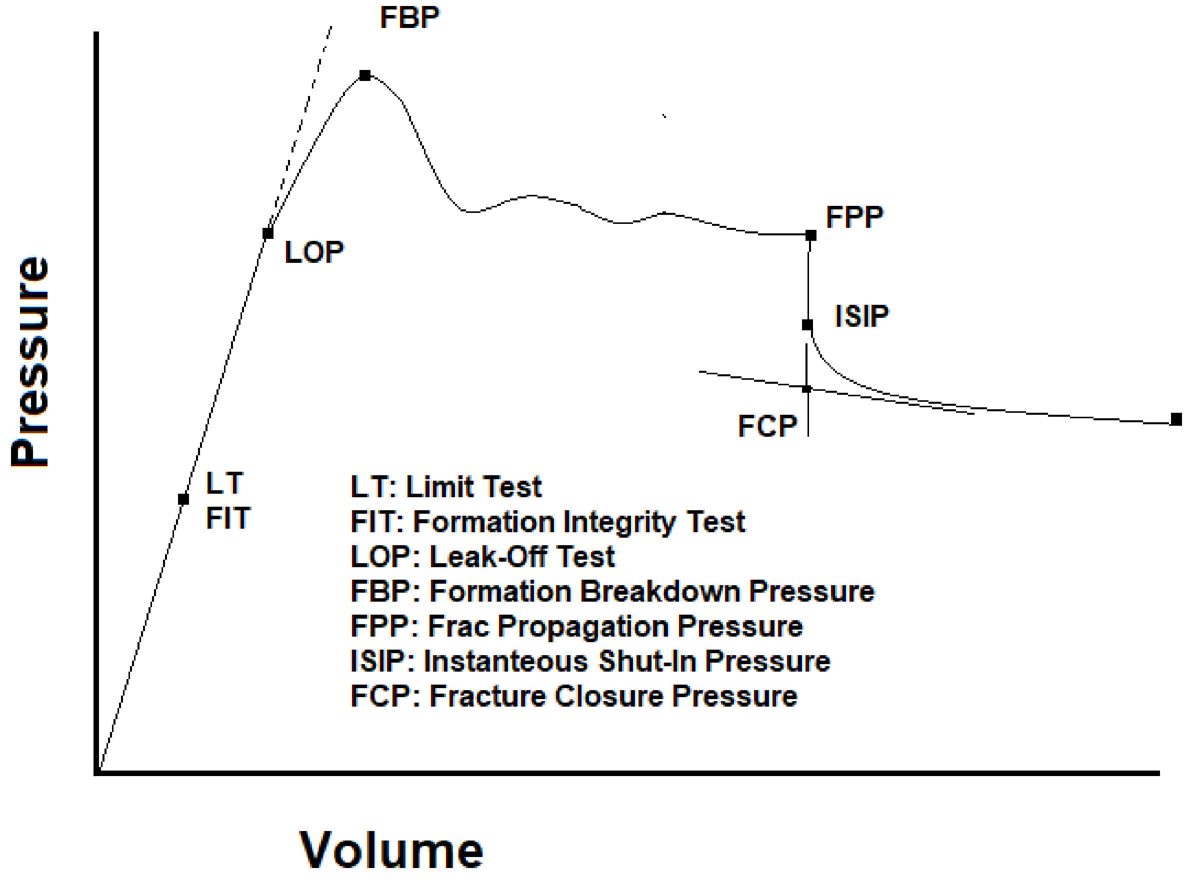
Data from NDIC public database & graphs courtesy of Neil Decker, Hess Bakken Team.

Production performance does not scale up in simple increments when adding closely spaced fractures.

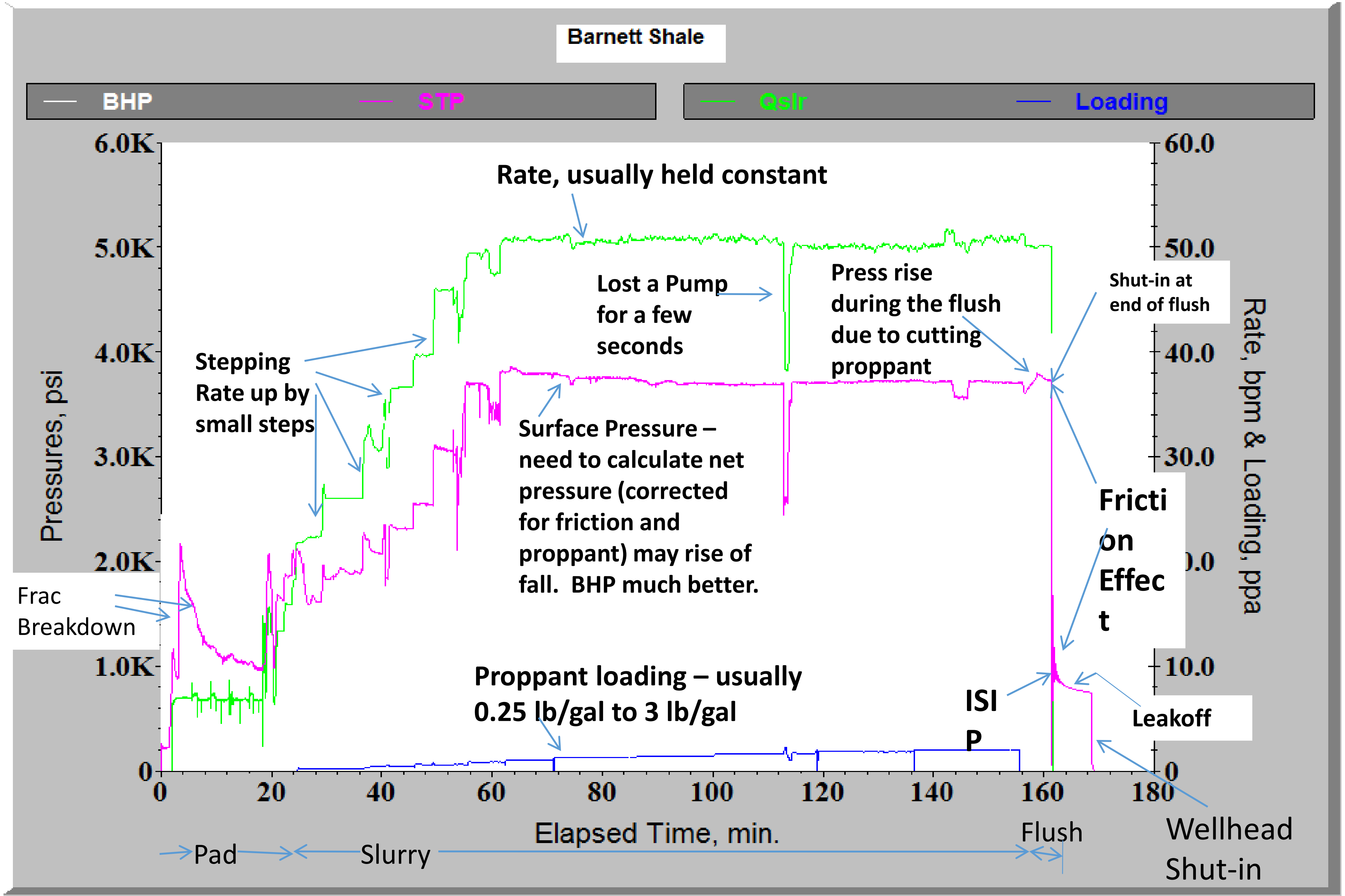
Choices of Frac Fluids

- The choice of frac fluid is set by the formation.
- Considerations:
  - Formation Sensitivity
  - Ability to breakdown & initiate a fracture,
  - Need to penetrate & open natural fracture system,
  - Ability to place the proppant,
  - Need to build a very large frac contact area,
  - Efficiency of load fluid recovery & minimum damage,
  - Fluid recycling and disposal where necessary,
  - Economics

Pumping the Frac



Parts of the Frac



Conclusions from Literature & Experience

- Knowledge of Rock Fabric and Stresses are critical Information.
- Even Ductile rocks have a high variance.
- Land the lateral in the highest quality formation.
- Variance in mineralogy & stress along the laterals must set frac points.
- Use the best frac technology for the stimulation (Fluids and Proppant)
- Control the drawdown on cleanup and production.

Questions?