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Examining Our Assumptions-

Have Oversimplifications Jeopardized Our Ability to Design Optimal Fracture Treatments?

Mike Vincent
mike@fracwell.com

Society of Petroleum Engineers
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Portions published in
SPE 119143 & 128612

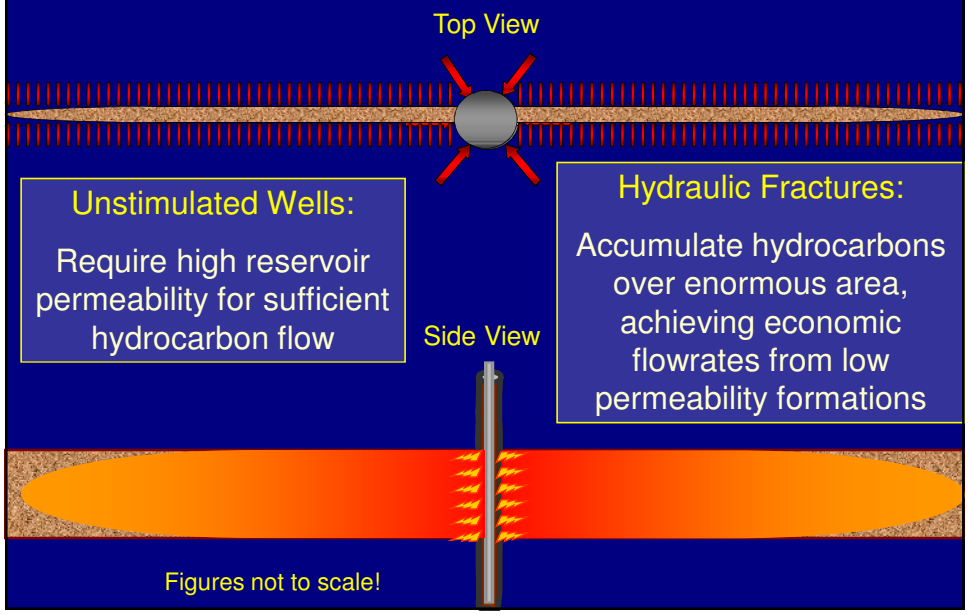
Outline

- Convenient Assumptions
  - Making frac design simple
- Models, Strategies resulting from those assumptions
- Actual Observations
  - Complex flow regimes
  - Complex frac geometry
- Field Results
  - 200 field studies where frac designs were altered
- Specific Challenges – Horizontal Well Fracs
- Opportunities for Improvement

Convenient Assumptions

- Fracs
  - Simple (bi-wing), planar, vertical, hydraulically continuous, highly conductive
- Reservoir
  - Homogenous reservoirs (or simplified layering)
- Fluid Flow
  - Simple fluid flow regimes
- Gel Cleanup
  - Consistent gel cleanup with all proppants, widths?
- More assumptions listed later

Why Fracture Stimulate?



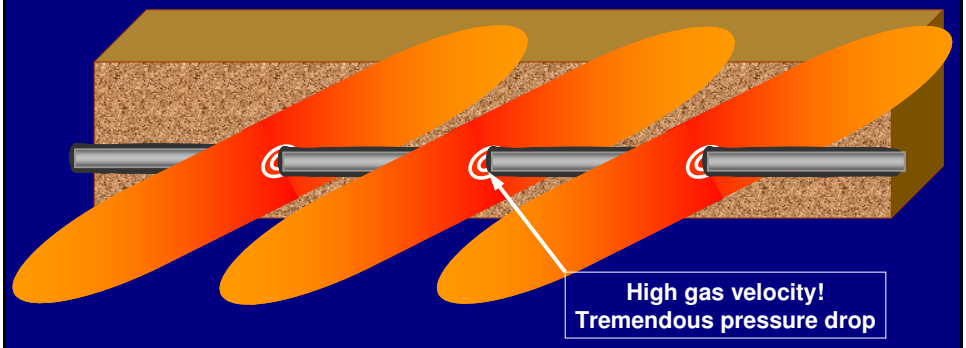
Unstimulated Wells:

Require high reservoir permeability for sufficient hydrocarbon flow

Hydraulic Fractures:

Accumulate hydrocarbons over enormous area, achieving economic flowrates from low permeability formations

Increased Reservoir Contact – Multiple Transverse Fracs



Some operators have placed 28 stages with 3 perf clusters per stage.
Initiate 80 transverse fracs?!

SPE 128612

Design Goals for Simple, Planar Fracture

- Adequate reservoir contact (frac length)
- Adequate flow capacity (conductivity)

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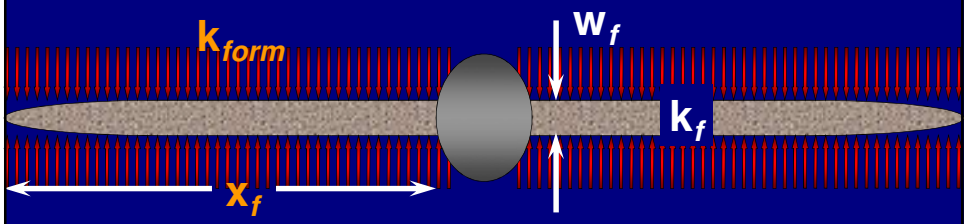
Simple approach to optimize length and conductivity



$$F_{CD} = \frac{k_f * w_f}{k_{form} * x_f}$$

Dimensionless Fracture Conductivity (F_{CD})
a ratio of the flow capacity of the fracture and the formation

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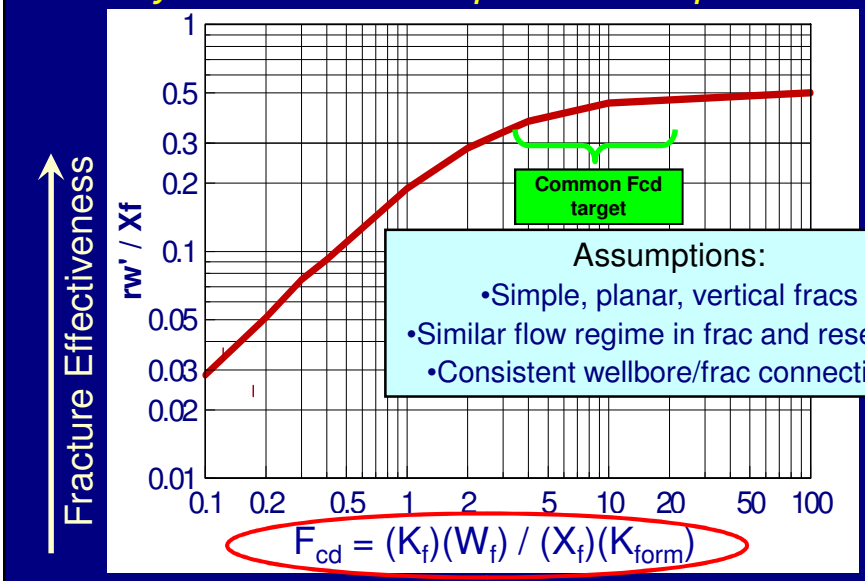
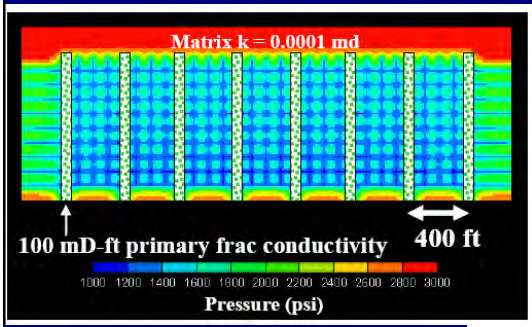
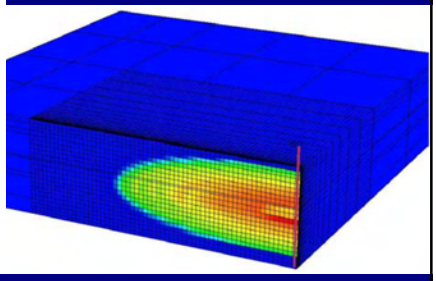
Analytic Solution to Optimize Simplistic Frac



Prats, M.: "Effect of Vertical Fractures on Reservoir Behavior-Incompressible Fluid Case," paper SPE 1575-G

Gridded Numerical Simulation





Even sophisticated 3d models frequently presume planar fracs with hydraulic continuity

SPE 124843

SPE 110093

Intuitive (but faulty) "proof" that fracs are infinitely conductive

If my formation looks like this...

Doesn't this provide infinite conductivity?

Proppant thin section courtesy of Stim-Lab

Common Assumptions

- Analytic Solutions, Numerical Models and Intuition
- Generally presume
  - simplistic flow,
  - simplistic geometry,
  - perfect wellbore-to-fracture communication,
  - hydraulic continuity throughout frac

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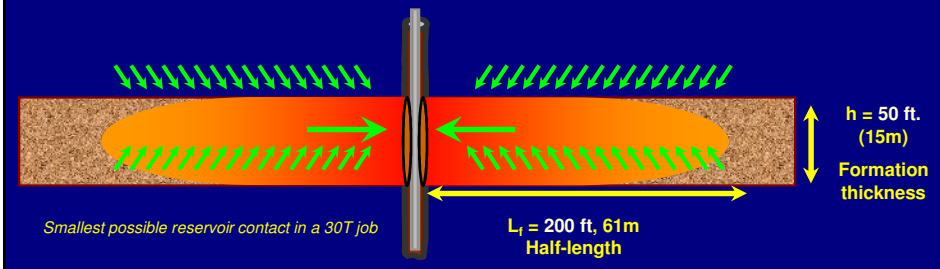
Flow Convergence – 30T "short, fat" frac



If we have contribution from the entire 40,000 ft² [3700m²] of reservoir rock which is in contact with the fracture, we may anticipate a "bottleneck" near wellbore

If we (optimistically) retain ¼ inch frac width 6mm (~3 lb/ft² or 15 kg/m²)

Our fracture cross section is merely = 2 ft² 0.18m²

40,000 ft² of reservoir rock is "feeding" 2 ft² of fracture cross section

Superficial velocity within the fracture is 20,000 times greater than in the formation!
Fracture conductivity frequently constrains production!

Navigation menu

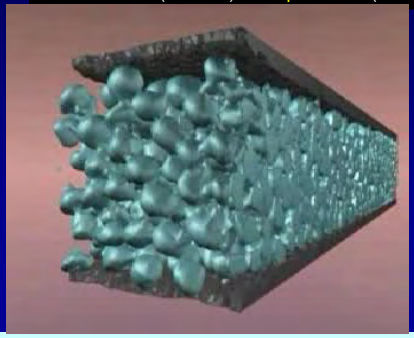
Velocity within Fracture – Vertical Well

This is only 6-8 grains/second.
Many *low* rate wells require 100x faster gas flow!
And this is pristine highly spherical proppant, zero crush, zero fines plugging, etc

The following animation depicts the flow through an actual proppant pack. The "landscape" was created using an X-ray CT scan of an actual sample of 16/20 LWC under 4000 psi stress.

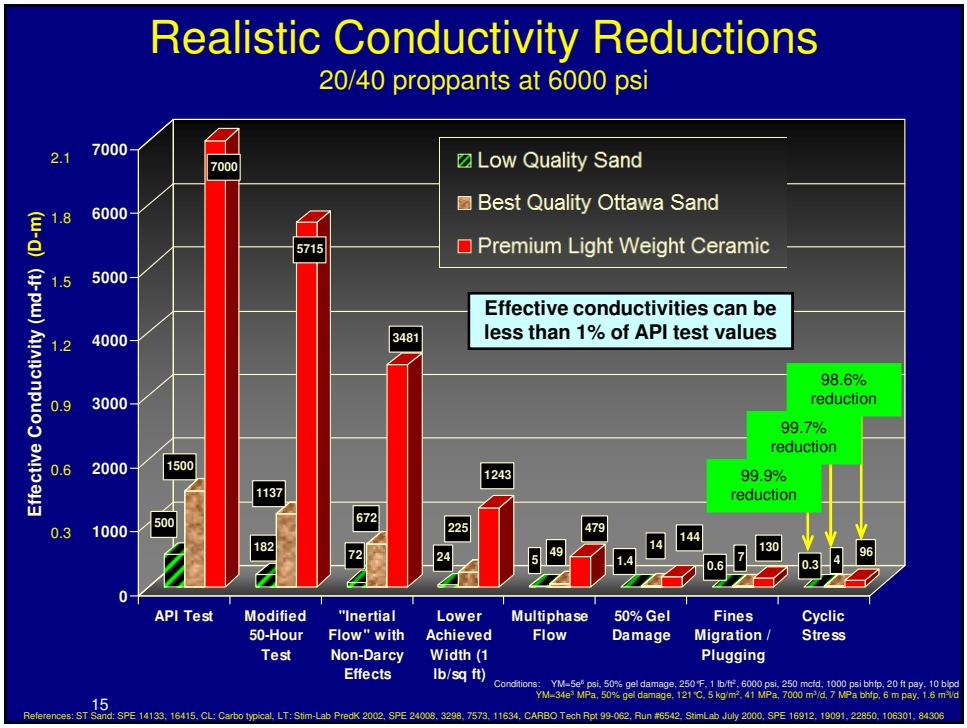
Approximate Velocity, API/ISO Test
2 ml/min through a 16/20 pack

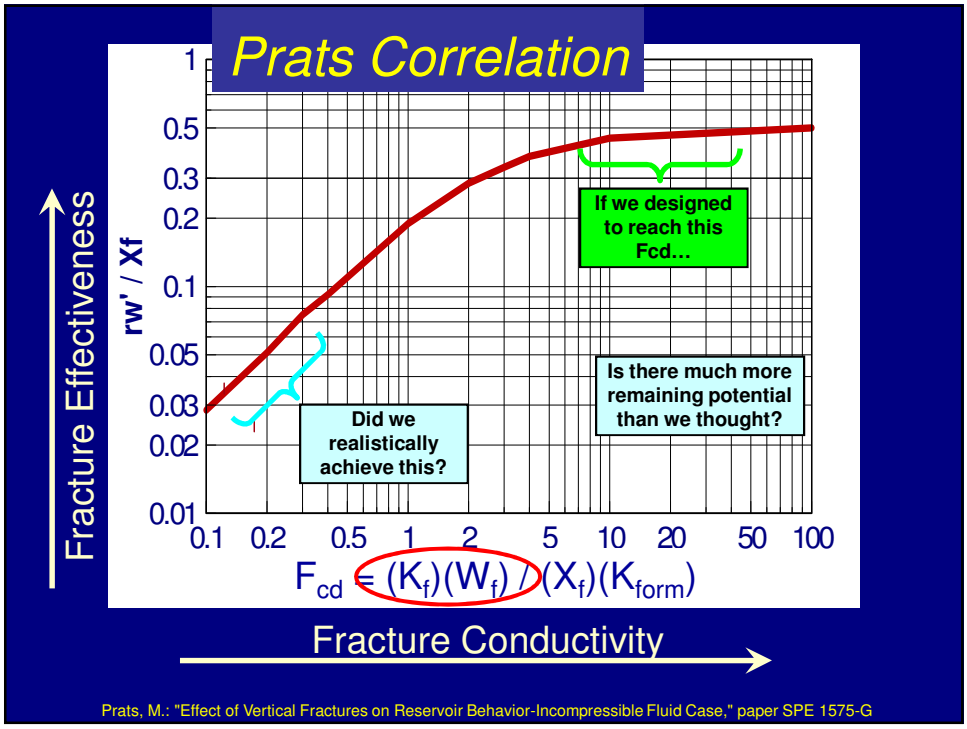
Approximate Velocity
35 MSCFD dry gas at 500 psi BHFP
Or 1 MSCFD (28 m³/d) at 15 psi BHFP (1 atm)



Conditions: 2 lb/ft² [10 kg/m²] 16/20 LWC at 4000 psi stress
50 ft fracture height, 2 frac wings, perfect wellbore-frac connection

CT Scan and mpg video courtesy of CARBO


Realistic Conductivity Reductions
20/40 proppants at 6000 psi
Effective Conductivity (md-ft) (D-m)
Low Quality Sand
Best Quality Ottawa Sand
Premium Light Weight Ceramic
Effective conductivities can be less than 1% of API test values
98.6% reduction
99.7% reduction
99.9% reduction
API Test
Modified 50-Hour Test
"Inertial Flow" with Non-Darcy Effects
Lower Achieved Width (1 lb/sq ft)
Multiphase Flow
50% Gel Damage
Fines Migration / Plugging
Cyclic Stress
Conditions: YM=5e6 psi, 50% gel damage, 250°F, 1 lb/ft², 6000 psi, 250 mcfd, 1000 psi bhfp, 20 ft pay, 10 blpd
YM=34e3 MPa, 50% gel damage, 121°C, 5 kg/m², 41 MPa, 7000 m³/d, 7 MPa bhfp, 6 m pay, 1.6 m³/d
15
References: ST Sand: SPE 14133, 16415, CL: Carbo typical, LT: Stim-Lab PredK 2002, SPE 24008, 3298, 7573, 11634, CARBO Tech Rpt 99-062, Run #6542, StimLab July 2000, SPE 16912, 19091, 22850, 106301, 84306


Prats Correlation
Fracture Effectiveness
rw' / Xf
If we designed to reach this Fcd…
Is there much more remaining potential than we thought?
Did we realistically achieve this?
Fcd = (Kf)(Wf) / (Xf)(Kform)
Fracture Conductivity
Prats, M.: "Effect of Vertical Fractures on Reservoir Behavior-Incompressible Fluid Case," paper SPE 1575-G

Off by 100-fold?!

- Even in simple, continuous, planar fracs
  - Even if we carefully arrange proppant with perfectly uniform distribution, with lab-grade fluids, perfect breakers, limit test to 50 hours, etc.
- Pressure losses are generally 50 to 1000 times higher than suggested by advertised data
- Concern #1

  Flow regimes are complex within propped fracs – oversimplifications may mislead us.

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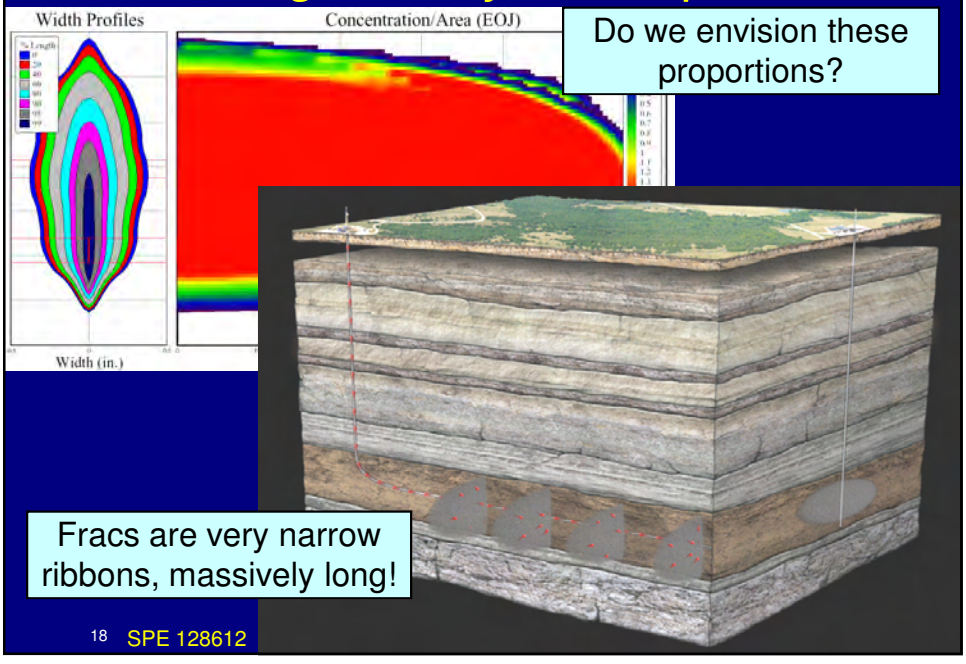
Is our frac geometry assumption valid?

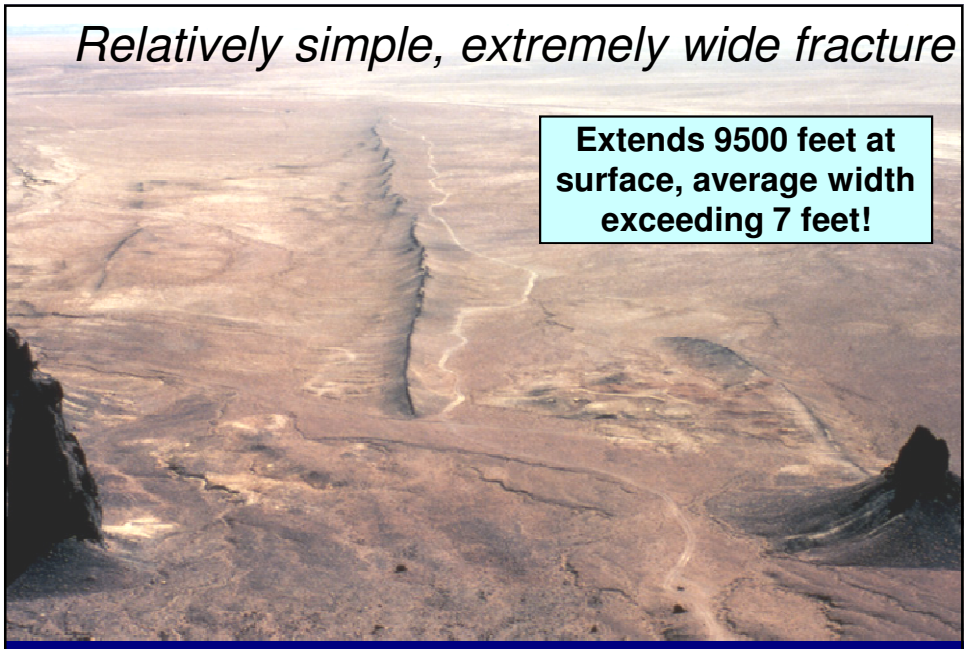


Do we envision these proportions?

Fracs are very narrow ribbons, massively long!

18 SPE 128612

Relatively simple, extremely wide fracture



Extends 9500 feet at surface, average width exceeding 7 feet!

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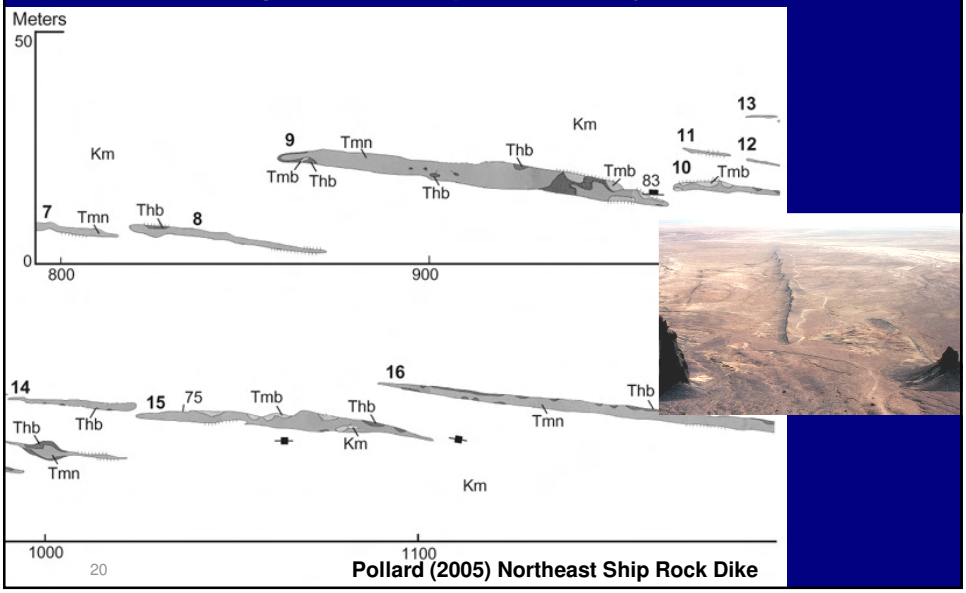
Pollard (2005) Northeast Ship Rock Dike, New Mexico

Outcrop actually comprised of >30 discrete echelon segments separated by intact host rock



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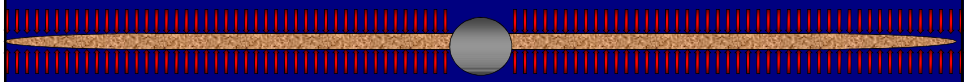
Pollard (2005) Northeast Ship Rock Dike

Are Hydraulic Fracs Simple Planes?

Top View



- Mineback studies
  - 22 CBM minebacks in 6 states; dozens in Australia
    - Surprising complexity, gel residue, discontinuous proppant
  - Less apparent conductivity than predicted by models

References: Bureau of Mines Rpt 9083, Diamond and Oyler, SPE 22395, Diamond CBM Symposium 11/87, Lambert OGJ 10/9/89, SPE 15258. Dozens in Australia (Jeffrey 124919, 28079, 119351, 63031)

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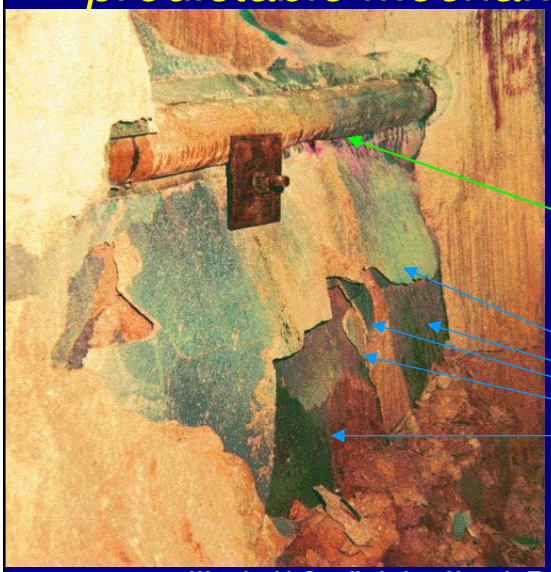
Even in competent rock selected for predictable mechanical properties…



- 6 perforations on lower side of hole (plus 6 on top)
- 5 separate fractures initiated from the 6 lower perforations

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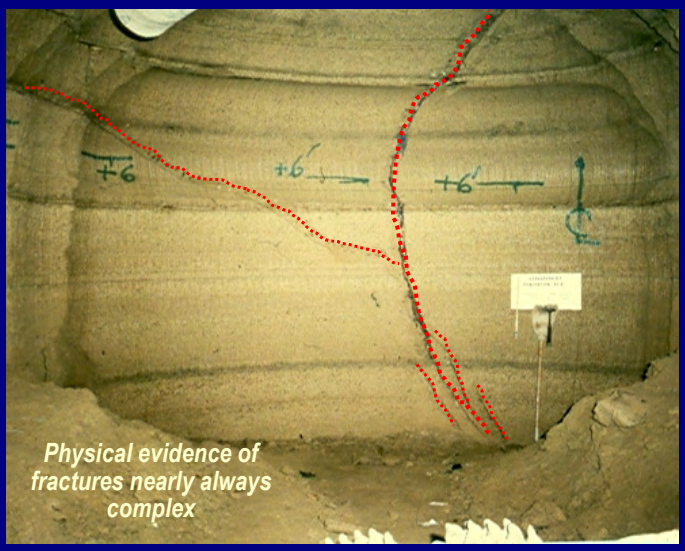
Warpinski, Sandia Labs. Nevada Test Site, Hydraulic Fracture Mineback

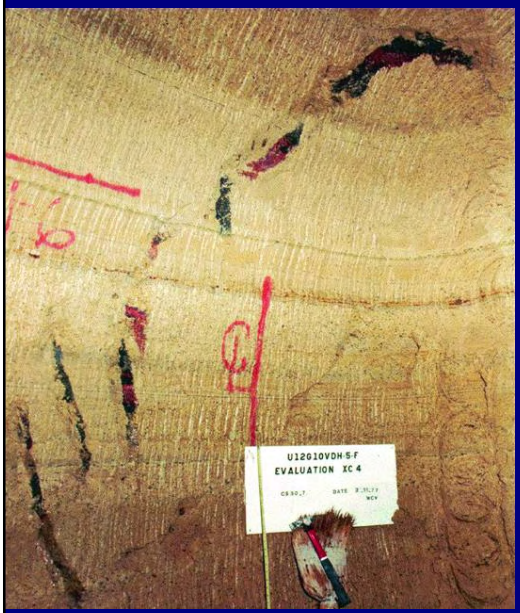
Observations of Fracture Complexity



Physical evidence of fractures nearly always complex

23 **Warpinski, Sandia Labs. Nevada Test Site, Hydraulic Fracture Mineback**

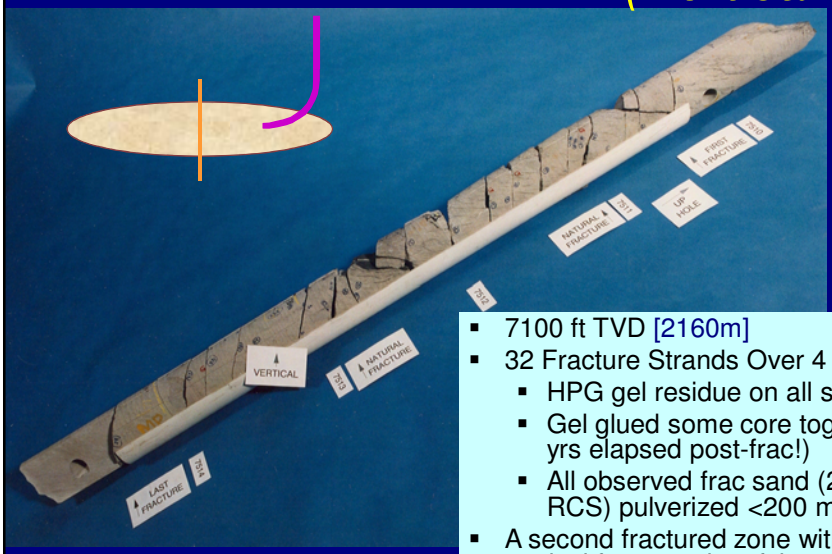
Multiple Strands in a Propped Fracture (Vertical Well)



Physical evidence of fractures nearly always complex

24 **Warpinski, Sandia Labs. Nevada Test Site, Hydraulic Fracture Mineback**

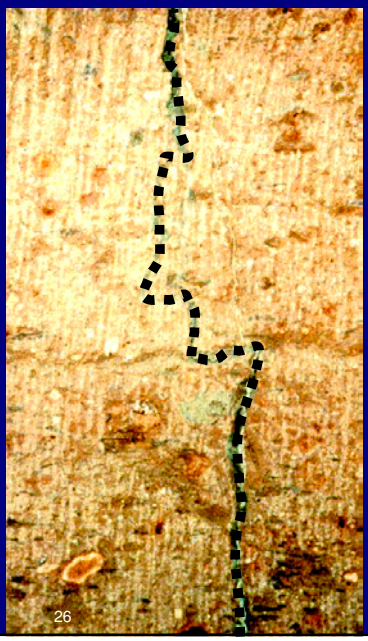
Multiple Strands in a Propped Fracture (Vertical Well)



- 7100 ft TVD [2160m]
- 32 Fracture Strands Over 4 Ft Interval
  - HPG gel residue on all surfaces
  - Gel glued some core together (>6 yrs elapsed post-frac!)
  - All observed frac sand (20/40 RCS) pulverized <200 mesh
- A second fractured zone with 8 vertical fractures in 3 ft interval observed 60 feet away (horizontally)

Mesaverde MWX test, SPE 22876

Vertical Complexity Due To Joints



Physical evidence of fractures nearly always complex

NEVADA TEST SITE HYDRAULIC FRACTURE MINEBACK

Woodford Shale Outcrop

Some reservoirs pose challenges to effectively breach and prop through all laminations

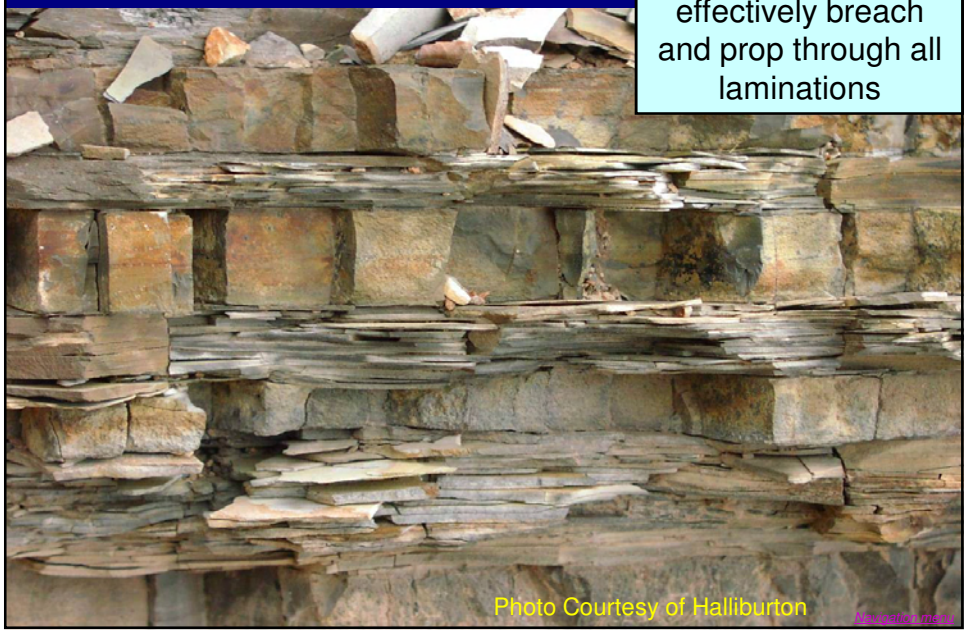
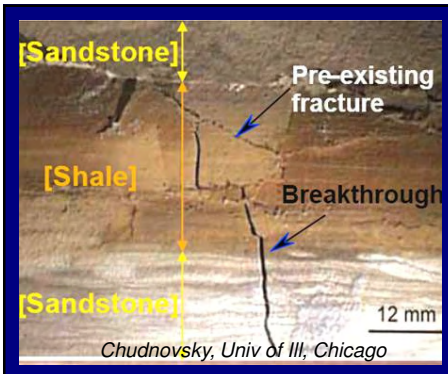


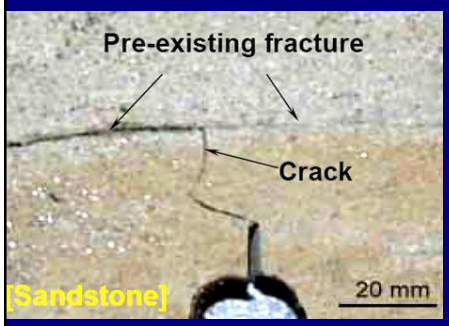
Photo Courtesy of Halliburton

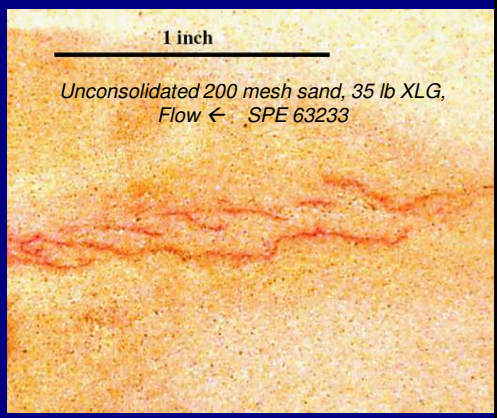
Navigation menu

Is complexity solely attributed to "rock fabric"?



Chudnovsky, Univ of Ill, Chicago





Unconsolidated 200 mesh sand, 35 lb XLG, Flow ← SPE 63233

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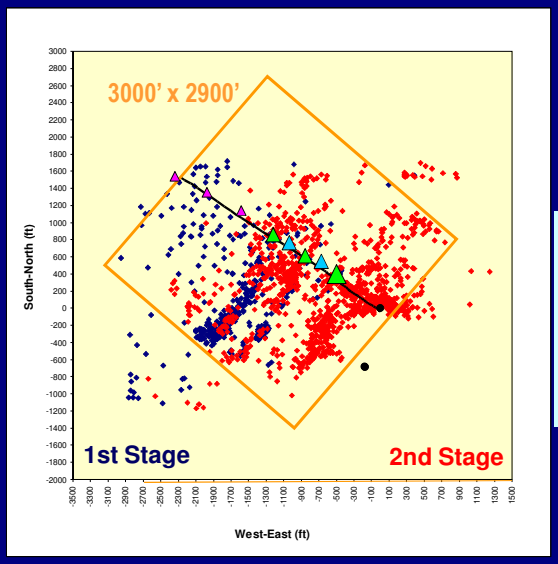
Many other examples! [TerraTek, Baker, Weijers, CSM FAST consortium]

Fractures Can be Enormous Features



▲ = First Stage Perf Clusters
▲ = 2nd Stage Initial Perf Clusters
▲ = Revised 2nd Stage Perf Clusters

- Box covers 9 million ft^2 [~200 acre land area]
- Arguably
  - 10 to 100 million ft^2 of fracture surface area! [reservoir contact]

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Complexity?

- Concern #2

  On every scale that we investigate, fractures are more complex than the simplified frac geometry we presume in our models

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Does this degree of complexity matter?

- Interesting industry dialogue
  - Are these examples anomalous or "worst case"?
  - Do we need any more precise info for fracture propagation theory?
- The concern evaluated here is *not* propagation modeling, it is fluid flow and production optimization

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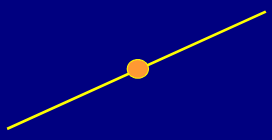
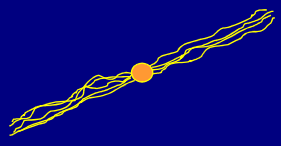
Range of Fracture Complexity

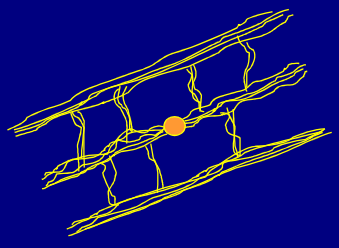
Simple Fracture



Complex Fracture



Very Complex Fracture Network



Pro:

Complex fracs increase the reservoir contact (beneficial in nano-Darcy shales?)

Con:

Complex fracs complicate the flow path, and provide less cumulative conductivity than simple, wider fractures [SPE 115769]

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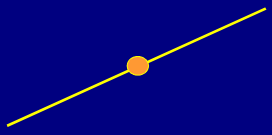
SPE 77441

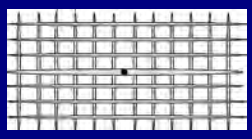
Frac Optimization Implications

Simple Fracture



Optimal Frac Conductivity proportional to reservoir perm

Large Network



Reducing Reservoir Perm by 10,000 only reduces conductivity requirement by 10

($k^{1/4}$)

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SPE 115769

Fractures Intersecting Offset Wellbores

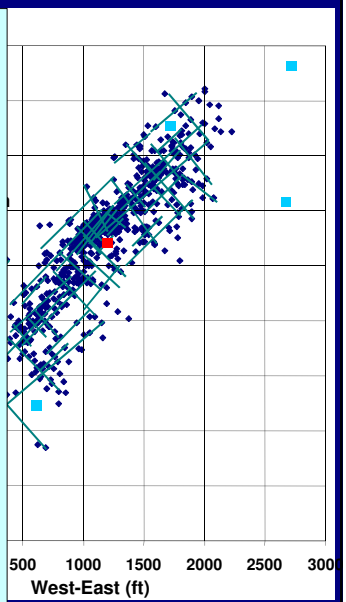
<u>Evidence frac'ed into offset wells</u>

Microseismic mapping
Slurry to surface
Increased watercut
Solid radioactive tracer (logging)
Noise in offset monitor well

<u>Observed in</u>

Tight sandstone (Piceance, Jonah, Cotton Valley, Codell)
High perm sandstone (Prudhoe)
Shale (Barnett)
Dolomite (Middle Bakken)
Chalk (Dan)

Often EUR, "pulse tests" "interference tests" fail to indicate sustained hydraulic connectivity!



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SPE 77441

Lack of Hydraulic Connection?

- Possible Explanations
  - Poor gel cleanup – gel plugged regions
    - But does not satisfactorily explain slickwater results
  - Extremely low frac conductivity
    - Probable
  - Discontinuous frac – lack of hydraulic continuity
    - Probable

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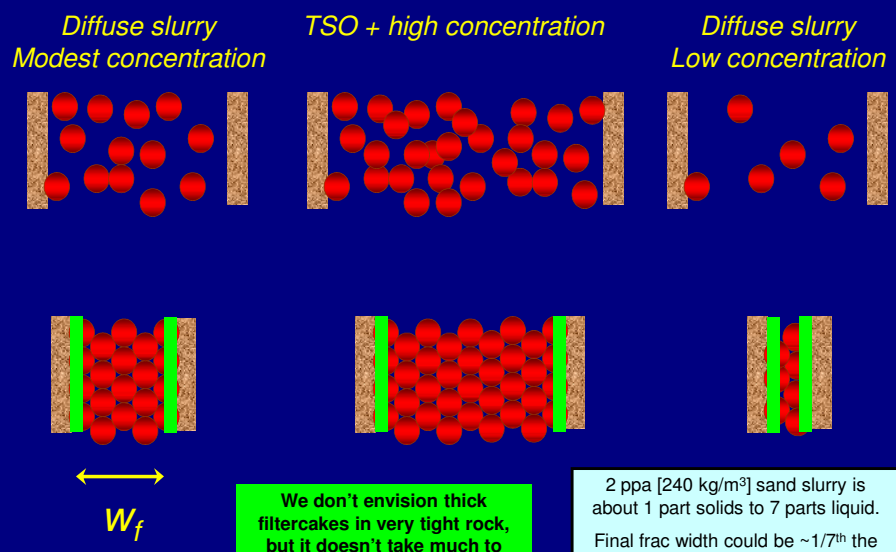
Frac Width – with CrossLinked Gel



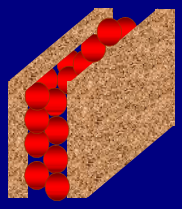
We don't envision thick filtercakes in very tight rock, but it doesn't take much to damage a narrow frac!

2 ppa [240 kg/m^3] sand slurry is about 1 part solids to 7 parts liquid.

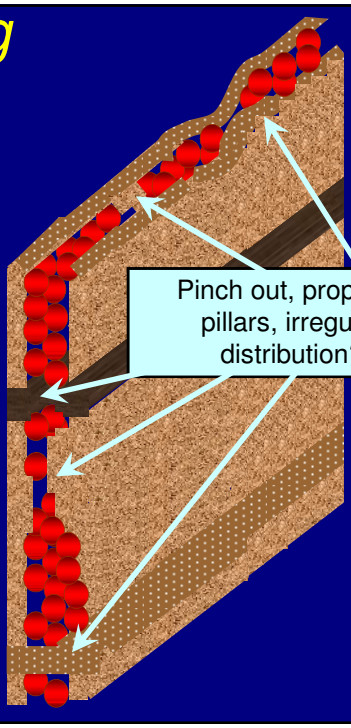
Final frac width could be ~1/7th the pumping width!

Navigation menu

Uniform Packing Arrangement?



Is this ribbon laterally extensive and continuous for hundreds or thousands of feet?



Pinch out, proppant pillars, irregular distribution?

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Concern #3

- Fracs may provide imperfect hydraulic continuity
  - Vertical
  - Lateral

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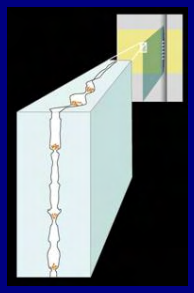
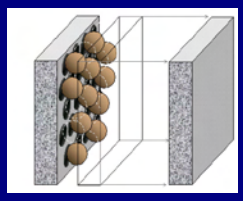
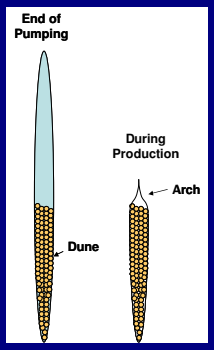
Potential Proppant Arrangements







- 100,000 lbs of 20/40 proppant contains ~125 billion particles
- Most every arrangement we can envision likely exists somewhere in a frac
- All arrangements cause higher stress concentration on proppant than our "idealized" testing on uniform wide packs
- In series, the flow capacity limited by poorest arrangement, not the average

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SPE 115769, 114173, 115766, 90698

Flow Capacity of Narrow Fractures – Split Core

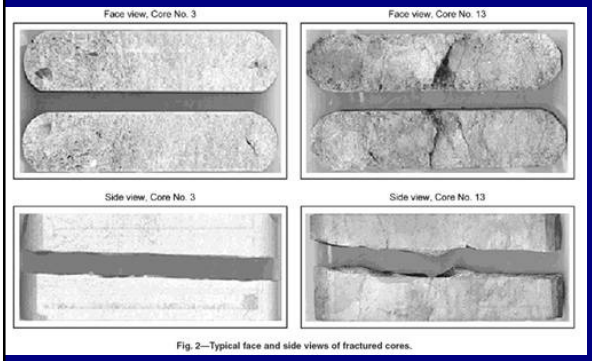


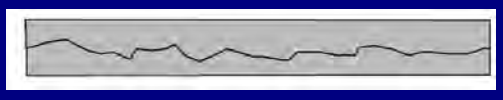
Fig. 2—Typical face and side views of fractured cores.

Cotton Valley Sandstone core

YM 3.6 to 7.0 e6 psi

12% porosity

0.05 mD



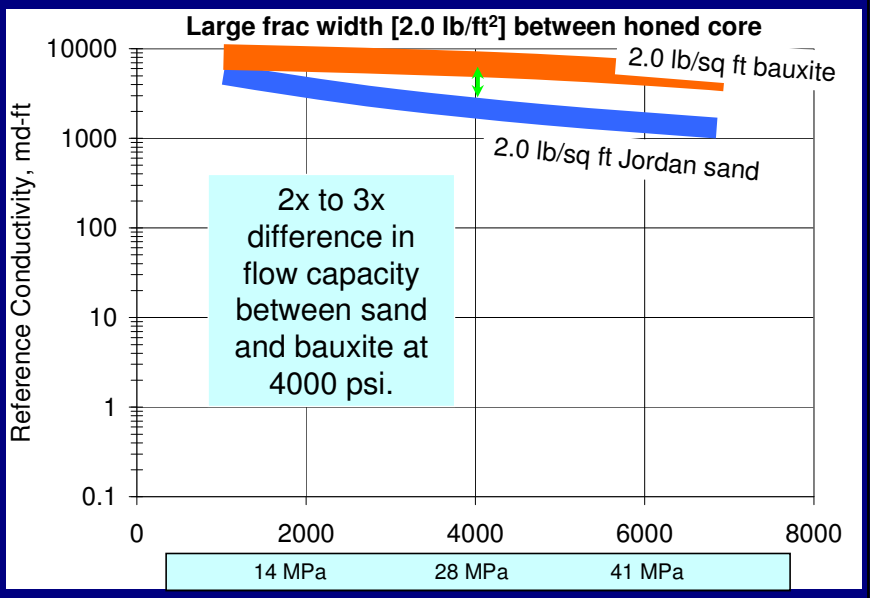
Split Core – No Proppant

Split Core – 0.1 lb/ft^2 Proppant

40

SPE 60326, 74138

Behavior of Proppant In Various Concentrations



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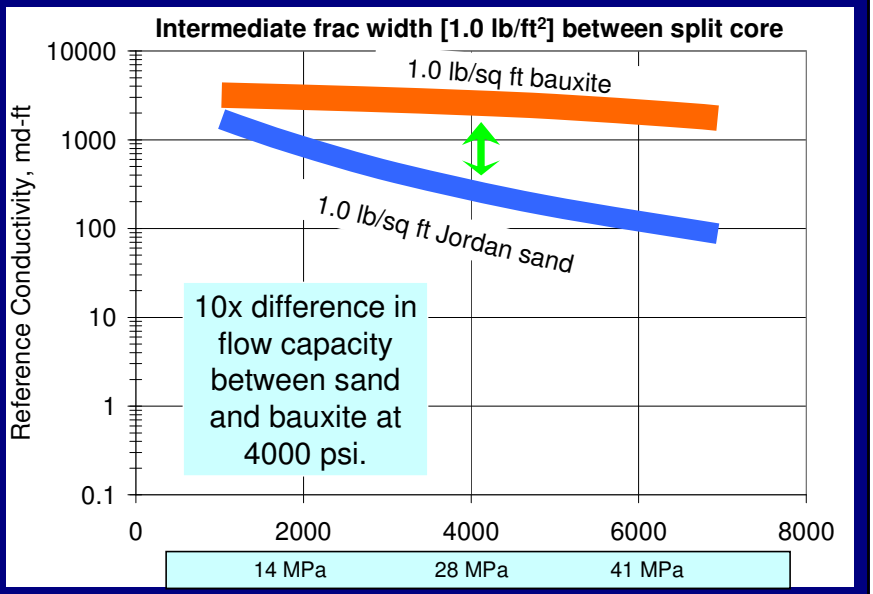
Adapted from SPE 60326, 74138, 119143

Behavior of Proppant In Various Concentrations



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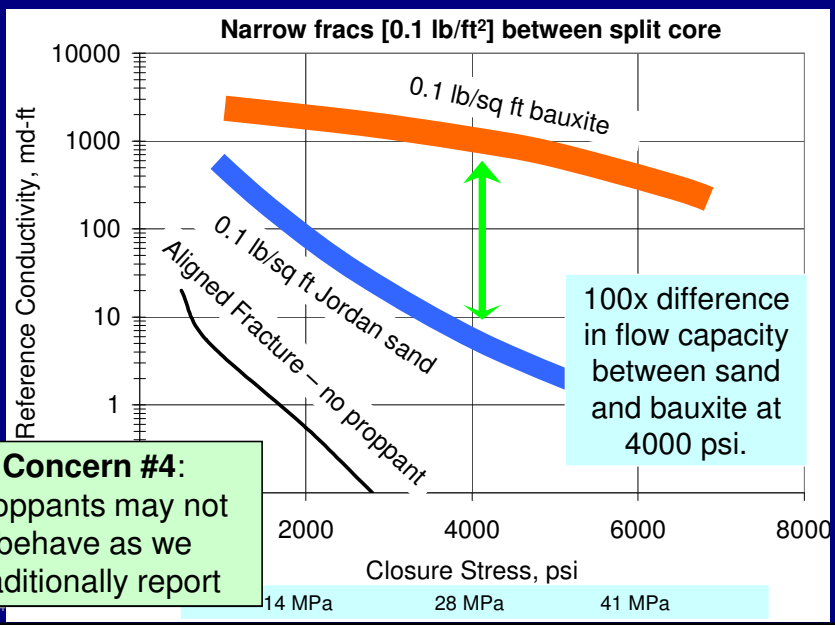
Adapted from SPE 60326, 74138, 119143

Behavior of Proppant In Various Concentrations



100x difference in flow capacity between sand and bauxite at 4000 psi.

Concern #4: Proppants may not behave as we traditionally report

Assumptions

- Flow Complexity, Frac Geometry, etc
  - All challenge ability to provide adequate conductivity
- Other Omissions:
  - Stress concentration on irregularly distributed proppant
  - Gel cleanup is more thorough in high conductivity fracs
  - Wider fracs are less damaged by
    - Filtercake, cyclic stress, fines plugging
  - Higher porosity fracs less damaged by
    - Filtercake, fines plugging
  - All proppants degrade over time – but at different rates
  - Not all proppants are thermally stable

Hypothesis: Conductivity may be more important than our traditional models and conventional wisdom predict

Field Evidence of Inefficient Fracs

- Lack of competition in wells connected by frac
- Steep production declines
  - Surprisingly limited drainage areas often don't correspond to mapped fracture extent
- Infill Drilling
  - Often successful on surprisingly close spacing
- Well Testing
  - Disappointing frac lengths and/or low apparent conductivity
- Field trials
  - Refrac results
  - Where operators experimented with increased frac conductivity

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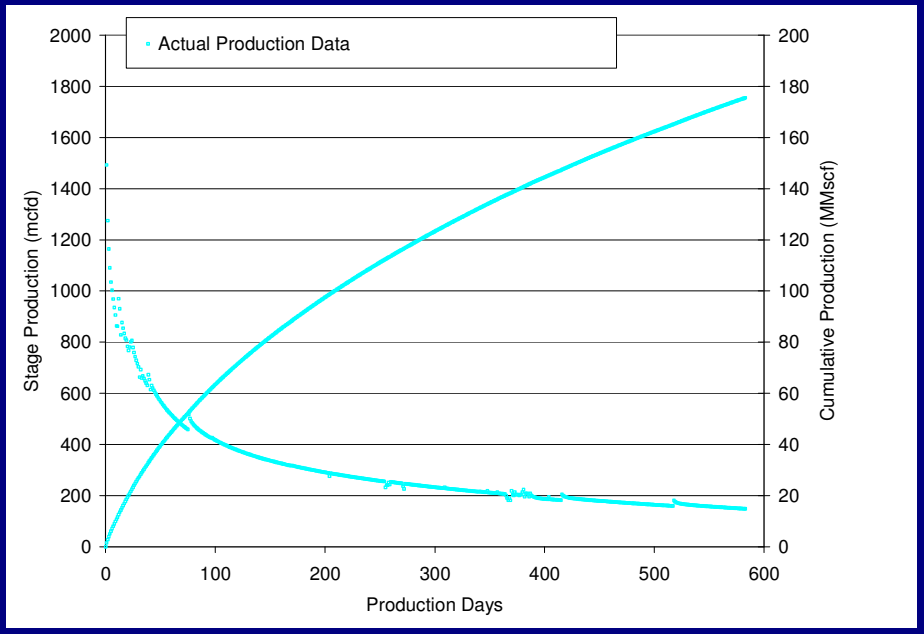
Shouldn't complexities be obvious from production data?



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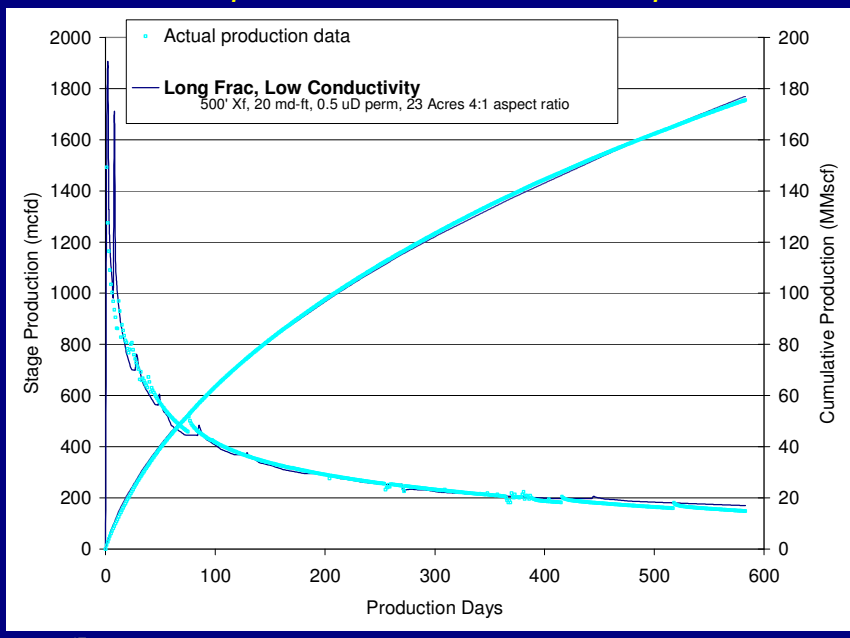
SPE 106151 Fig 13 – Production can be matched with a variety of fracture and reservoir parameters

Shouldn't complexities be obvious from production data?



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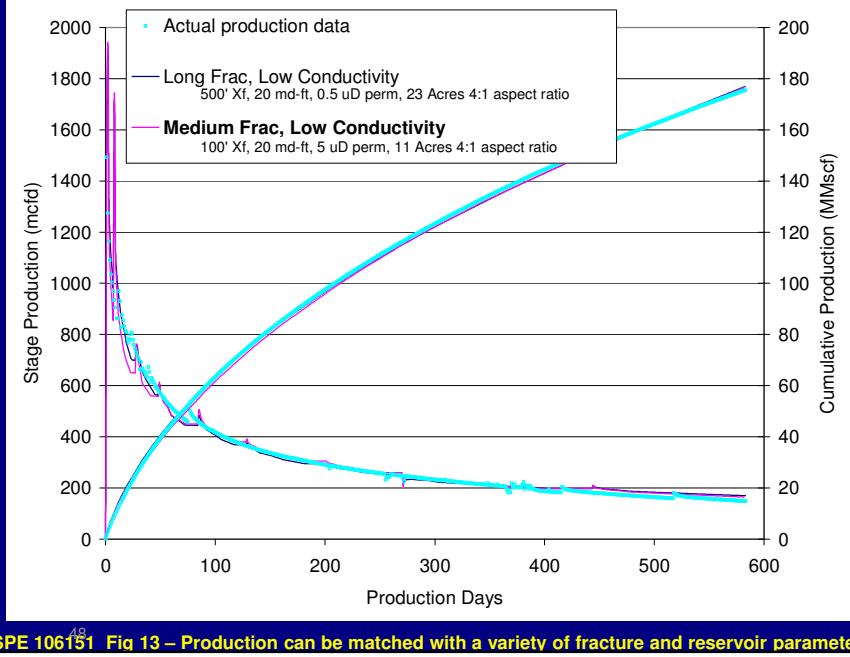
SPE 106151 Fig 13 – Production can be matched with a variety of fracture and reservoir parameters

Shouldn't complexities be obvious from production data?



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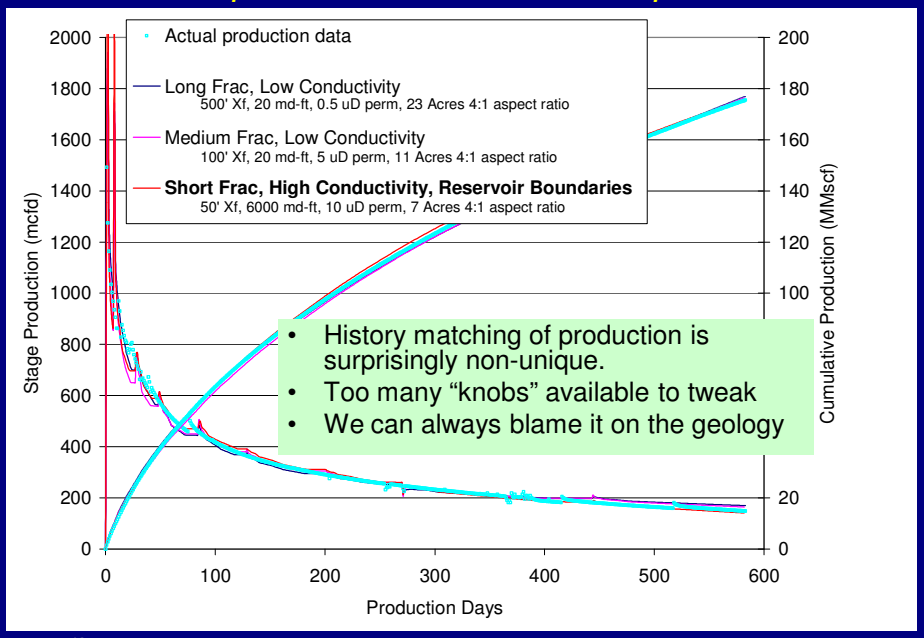
SPE 106151 Fig 13 – Production can be matched with a variety of fracture and reservoir parameters

Shouldn't complexities be obvious from production data?



SPE 106151 Fig 13 – Production can be matched with a variety of fracture and reservoir parameters

Removing the Uncertainty

- If we require a production match of two different frac designs, we remove many degrees of freedom
  - lock in *all* the "reservoir knobs"!
  - Attempt to explain the production results from initial frac *AND* refrac [~100 published trials]
  - Require simultaneous match of two different frac designs in same reservoir! [200+ trials]

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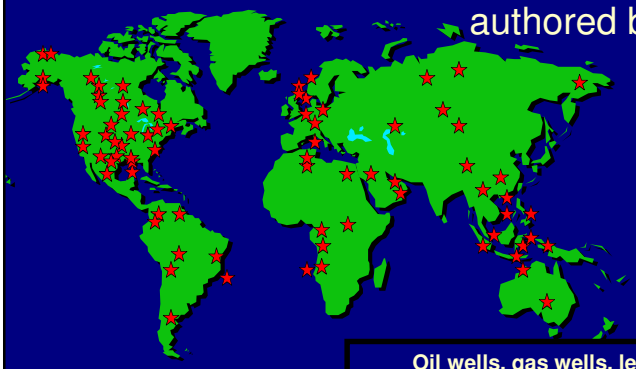
Field Studies Documenting Production Impact with Increased Fracture Conductivity

>200 published studies identified, authored by >150 companies



Oil wells, gas wells, lean and rich condensate
Carbonate, Sandstone, Shale, and Coal

Well Rates	**Well Depths**
1 to 25,000 bopd	100 to 20,000 feet
0.25-100 MMSCFD	

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SPE 119143 tabulates over 200 field studies

Dataset Limitations

- Intentional
  - Eliminated most field examples with dramatic fluid rheology changes
  - Are production gains attributed to proppant transport (frac length), differing gel cleanup, differing frac heights?
- Unintentional
  - It's just my literature review. Certainly I missed some excellent papers
- Publication Bias
  - Industry rarely publishes failures
  - Nonetheless I summarize 10 examples of "exceptions to the rule"

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A tabulation of 200 papers in SPE 119143

Production Benefit

- In >200 published studies and hundreds of unpublished proppant selection studies,
- Operators frequently report greater benefit than expected using:
  - Higher proppant concentrations
  - More aggressive ramps, smaller pads
  - Screen outs
  - Larger diameter proppant
  - Stronger proppant
  - Higher quality proppant
  - More uniformly shaped & sized proppant
- Frac conductivity appears to be much more important than our models or intuition predict!

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A tabulation of 200 papers in SPE 119143

Statistically Compelling Example

- 0.002 mD
- 446 fracs in carefully conducted trial
  - Reference F_{cd} > 400 with modest sand concentrations; >2000 with ceramics
  - Using published conductivity data and simplistic models, frac conductivity should not matter
  - However, field results prove with 99.9% certainty that proppant selection does matter
  - 70% increase in productivity with better ceramic!
    - <5% benefit predicted with laminar model
  - 200 other examples in SPE 119143

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SPE 106151

W TX, NM, Permian Examples (1 of 3)

- SPE 4677, Smith: High prop concentrations and screenouts beneficial:
  - New Mexico: Lea County
  - Texas: Crane, Howard, Midland, Gaines, Yoakum Counties
  - Colorado, Arizona, Utah
- SPE 24307, Hower: recompleting nitroglycerin fracs in Mesaverde in San Juan Basin, NM
- SPE 77675, Vincent: Refrac SJB CBM wells with better proppant
- SPE 67206, Logan: Morrow formation, SE NM. High conductivity fracs increased well #1 80->600 mcfd; well #2 400->3500 mcfd
- SPE 20708, Ely: high proppant concentrations, larger volumes, forced closure
  - SE New Mexico
  - Several Texas fields including Ector County
- World Oil, Mar, 1990, Smith: Rio Arriba County, NM Mesaverde: sand to 12 ppg, "very favorable" production response
- SPE 27933, Hailey: Granite Wash, Mendota: isolation and restim of individual layers

Field examples customized for each audience

W TX, NM, Permian Examples (2 of 3)

- SPE 6440, Cooke: 17 field tests, TX and Miss with bauxite instead of sand or acidized completions. Significant gains in all wells
- SPE 13817, Pauls: Olmos. Refracs at 12 ppg gave 13-fold increase
- SPE 7912, Logan: SW TX (Webb Cty). Refracs with larger diameter proppant and high proppant concentration yielded 620% increases
- SPE 3298, Coulter: Crockett Cty TX. Canyon Sand gas production more sustained with higher proppant concentrations
- SPE 117538, Blackwood: Sutton Cty, TX, Canyon Sand: ELWC provided 60% higher IP and ~40% superior cumulative production in 1st 3 years compared to Brady sand.
- SPE 14371, Britt: Andrews and Ector Counties, TX: Increasing sand concentration from 2 ppg to 6 ppg improved production 160%
- SPE 11930, Illseng: Anton Clearfork (near Lubbock) Initial wells stimulated with low sand concentrations resulted in steep decline. 100 wells treated near 14 ppg gave sustained rates and 100-day payouts

Field examples customized for each audience

W TX, NM, Permian Examples (3 of 3)

- SPE 24011, Fleming: Mitchell County TX, Middle Clearfork dolomite: more aggressive concentrations, larger diameter sand (up to 8/16!) 32 refracs >200% ROR
- SPE 4118, Holditch: Devonian, Wilcox, Hosston including Pecos Cty TX. High viscosity gels and increased prop concentration
- SPE 20134, Kolb: Crane, Upton Counties, dolomite. Acid jobs failed to provide long term stimulation. Refracs with sand, then up to 10 ppg refracs
- SPE 22834, Olson: Devonian, Crane County TX: 2 ppg sand refractured with 5 ppg ceramics. 2x to 8x increase in oil rates
- SPE 23995, Blauer: Midland Basin, Spraberry/Dean. Larger, more aggressive fractures showed greater long-term production and greater EUR

Field examples customized for each audience

Maybe conductivity matters even in this part of the world?

But what about Horizontal Wells?

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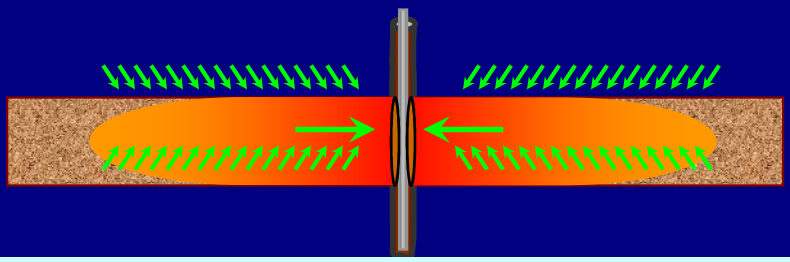
Intersection of Wellbore and Fracture

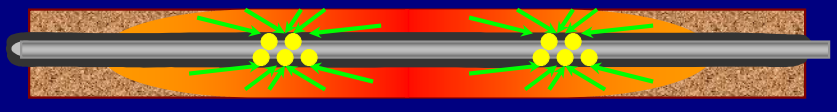


Vertical Wells: Typically benefit greatly from improved conductivity
200 field studies - SPE 119143

Horizontal Well with Longitudinal Frac:
Uncemented or fully perforated liner
Good connection, fluid only needs to travel ½ the pay height within the frac.
proppant conductivity requirements are trivial – almost anything will be fine

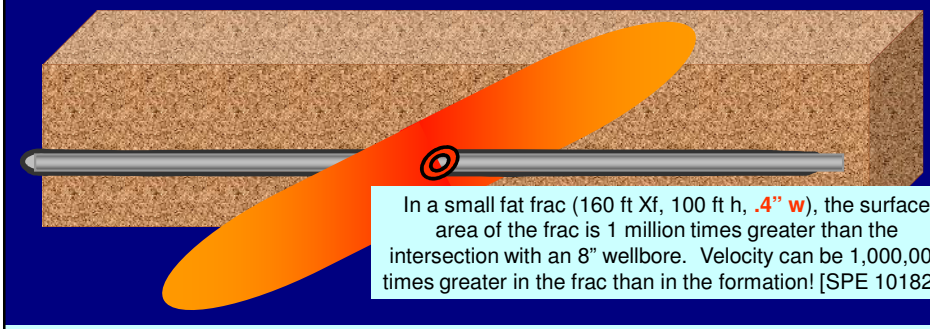
Intersection of Wellbore and Fracture
Cemented Liner

Horizontal Well
Cemented liner with limited perforations
Fluid travels shorter distances within the frac, but there is significant flow convergence around perfs.
Proppant conductivity requirements are a consideration
Lyco selected RCS for this completion style (SPE 90697)



Intersection of Wellbore and Fracture

What if the fracs are NOT longitudinal?



In a small fat frac (160 ft Xf, 100 ft h, **.4" w**), the surface area of the frac is 1 million times greater than the intersection with an 8" wellbore. Velocity can be 1,000,000 times greater in the frac than in the formation! [SPE 101821]

Horizontal Well with Transversely Intersecting Frac:
(Orthogonal, perpendicular, transverse, imperfectly aligned)

Oil/gas must travel hundreds/thousands of feet within fracture, and converge around a very small wellbore – high velocity within frac!

Horrible Connection; Enormous fluid velocity and near-wellbore **proppant characteristics are key!**

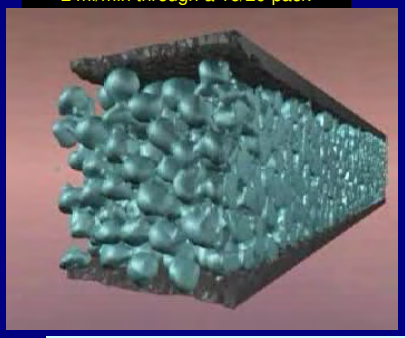
Velocity within Transverse Fracture

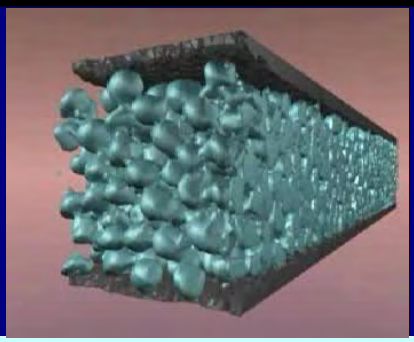
This is only 6-8 grains/second.
Many wells require 100-10,000x faster gas flow!
And this is pristine highly spherical proppant, zero crush, zero fines plugging, single phase, etc

The following animation depicts the flow through an actual proppant pack. The "landscape" was created using an X-ray CT scan of an actual sample of 16/20 LWC under 4000 psi stress.

Approximate Velocity, API/ISO Test
2 ml/min through a 16/20 pack

Approximate Velocity
20 SCFD (0.5m^3/d) at 15 psi BHFP (1 atm)
Or 600 SCFD dry gas at 500 psi BHFP
Or 6 mcfd at 5000 psi BHFP





Conditions: 2 lb/ft^2 [10 kg/m^2] 16/20 LWC at 4000 psi stress
1 transverse frac

mpg video format courtesy of CARBO

More Stages?

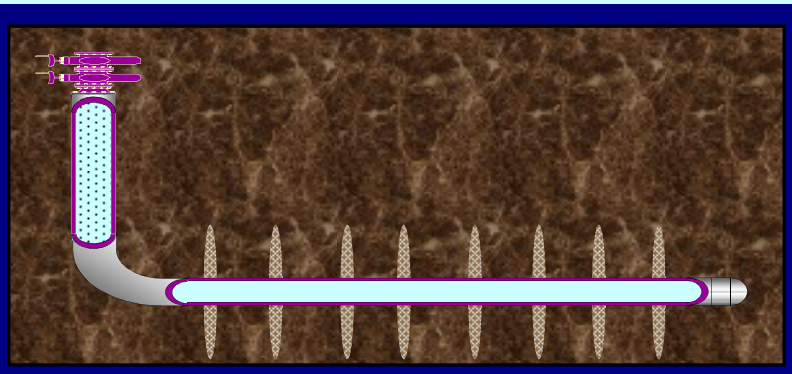
In some reservoirs, operators have pumped 28 stages, with 3 perf clusters per stage.

84 entry points!

Question: Are we convinced we "touch more rock" with more stages, or are we simply redistributing our investment, placing it nearer the wellbore with more entry points?

If you increase intersection by 84-fold, you decrease velocity by 84 fold and reduce pressure losses by 84^2 or >7000 fold!

However, operators are understandably reluctant to be aggressive on toe stages!



Courtesy Karen Olson, BP

Summary (1 of 3)

- The world is complex. We must make simplifying assumptions:
  - Mathematically convenient to describe fractures as simple, vertical features with uniform proppant distribution and continuity
  - Published "reference conductivity" data are often presumed to provide reasonable estimates of flow capacity
  - Simplified reservoir descriptions (minimal layering, predictable drainage boundaries) simplifies modeling efforts
  - Handy to assume same flow regime in reservoir and in fracture
- These assumptions are demonstrably false (at least imperfect)

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Summary (2 of 3)

- Pressure losses within uniformly propped fractures are ~100-times higher than predicted by simplistic models
- Reservoirs contain heterogeneities (boundaries, laminations, anisotropy, lenticular bodies, etc) that increase the need for laterally and vertically continuous fractures
- Frac geometry is often complex
- Not all fracs demonstrate sustained hydraulic continuity
- Introducing any degree of fracture complexity increases our need to design more conductive fractures
- We are not making offsetting errors!! All our assumptions are erring the same direction!!

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Summary (3 of 3)

- 200 field studies
  - tremendous opportunities to improve the productive potential of hydraulically fractured wells
  - simplistic models fail to recognize that potential
- *It will be much easier to double well productivity than to cut well costs by another 50%!*

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Recommendations

- Recognize that tools are imperfect
  - Improve them where easy
  - Compensate for their shortcomings
- Frac Complexity
  - Touches more rock (good!)
  - Challenges our ability to provide adequately conductive frac (bad)
- Conductivity
  - You need more than you think!
- Be willing to listen to the production data
  - Especially when the results violate your intuition!
- There is always a better frac design!
  - Don't be limited by your tools or imagination!

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SPE 119143
Examining Our Assumptions-

Have Oversimplifications Jeopardized Our Ability to Design Optimal Fracture Treatments?

Mike Vincent
mike@fracwell.com