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Examining Our Assumptions-

Have Oversimplifications Jeopardized Our Ability to Design Optimal Fracture Treatments?

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Portions published in
SPE 119143 & 128612

Outline

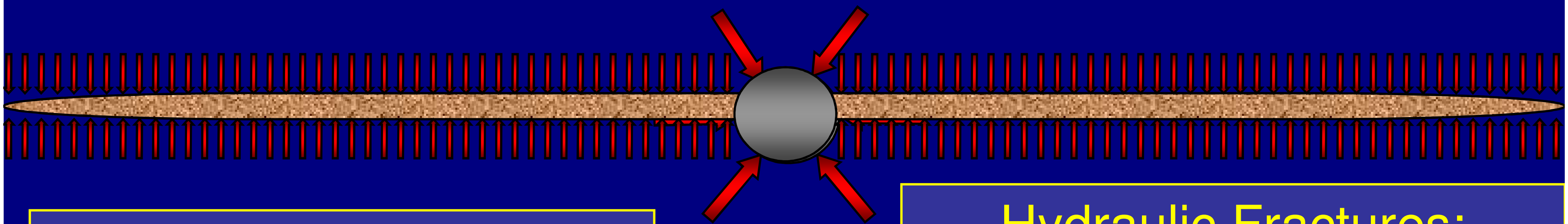
- Convenient Assumptions
  - Making frac design simple
- Models, Strategies resulting from those assumptions
- Actual Observations
  - Complex flow regimes
  - Complex frac geometry
- Field Results
  - 200 field studies where frac designs were altered
- Specific Challenges – Horizontal Well Fracs
- Opportunities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

Top View



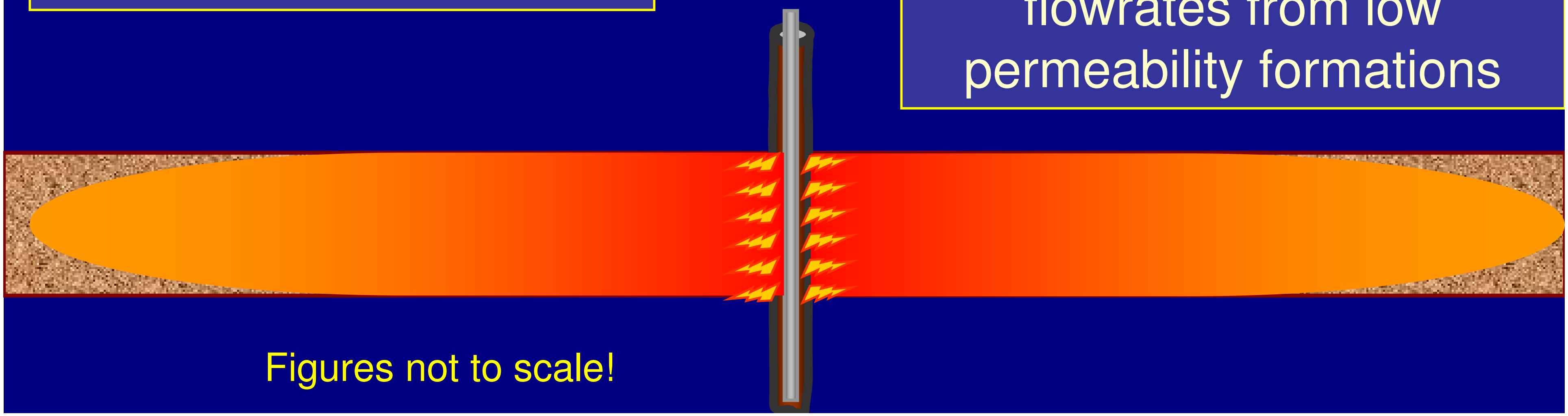
Unstimulated Wells:

Require high reservoir permeability for sufficient hydrocarbon flow

Hydraulic Fractures:

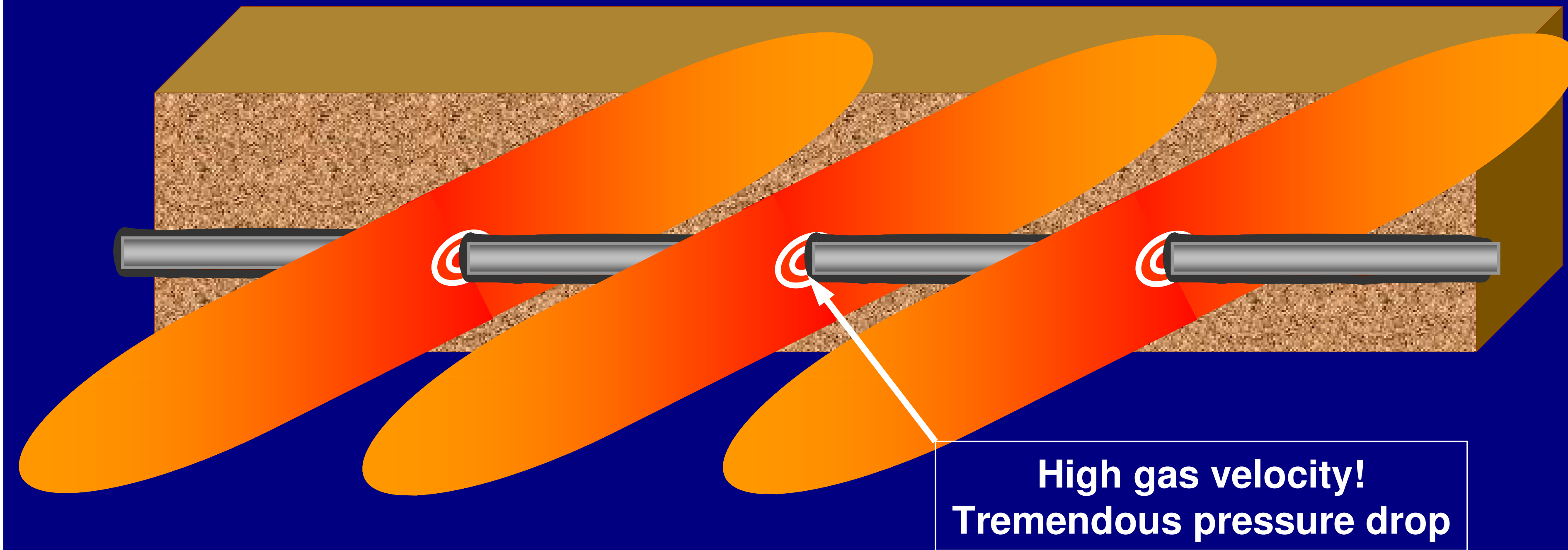
Accumulate hydrocarbons over enormous area, achieving economic flowrates from low permeability formations

Side View



Figures not to scale!

Increased Reservoir Contact – Multiple Transverse Fracs



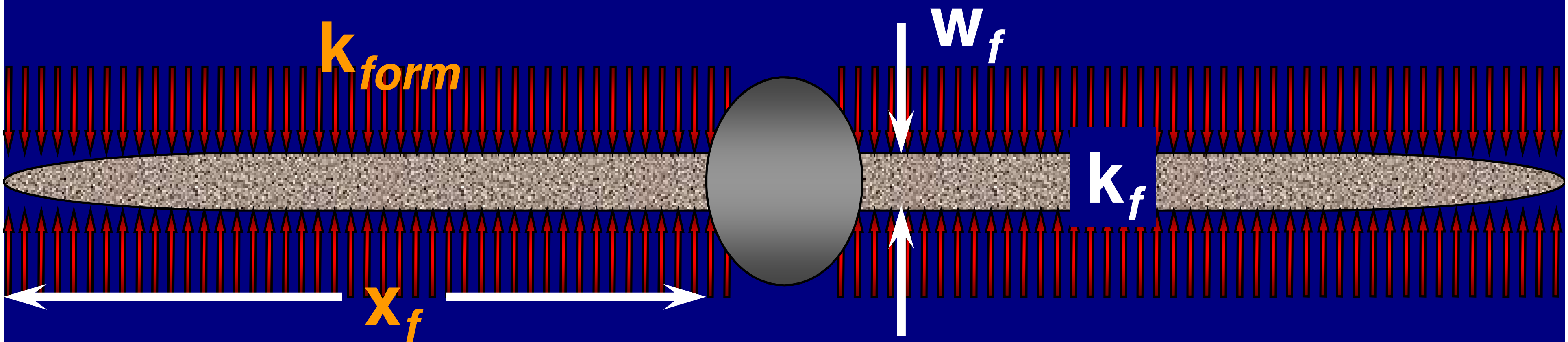
Some operators have placed 28 stages with 3 perf clusters per stage.
Initiate 80 transverse fracs?!

SPE 128612

Design Goals
for Simple, Planar Fracture

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

Simple approach to optimize length and conductivity

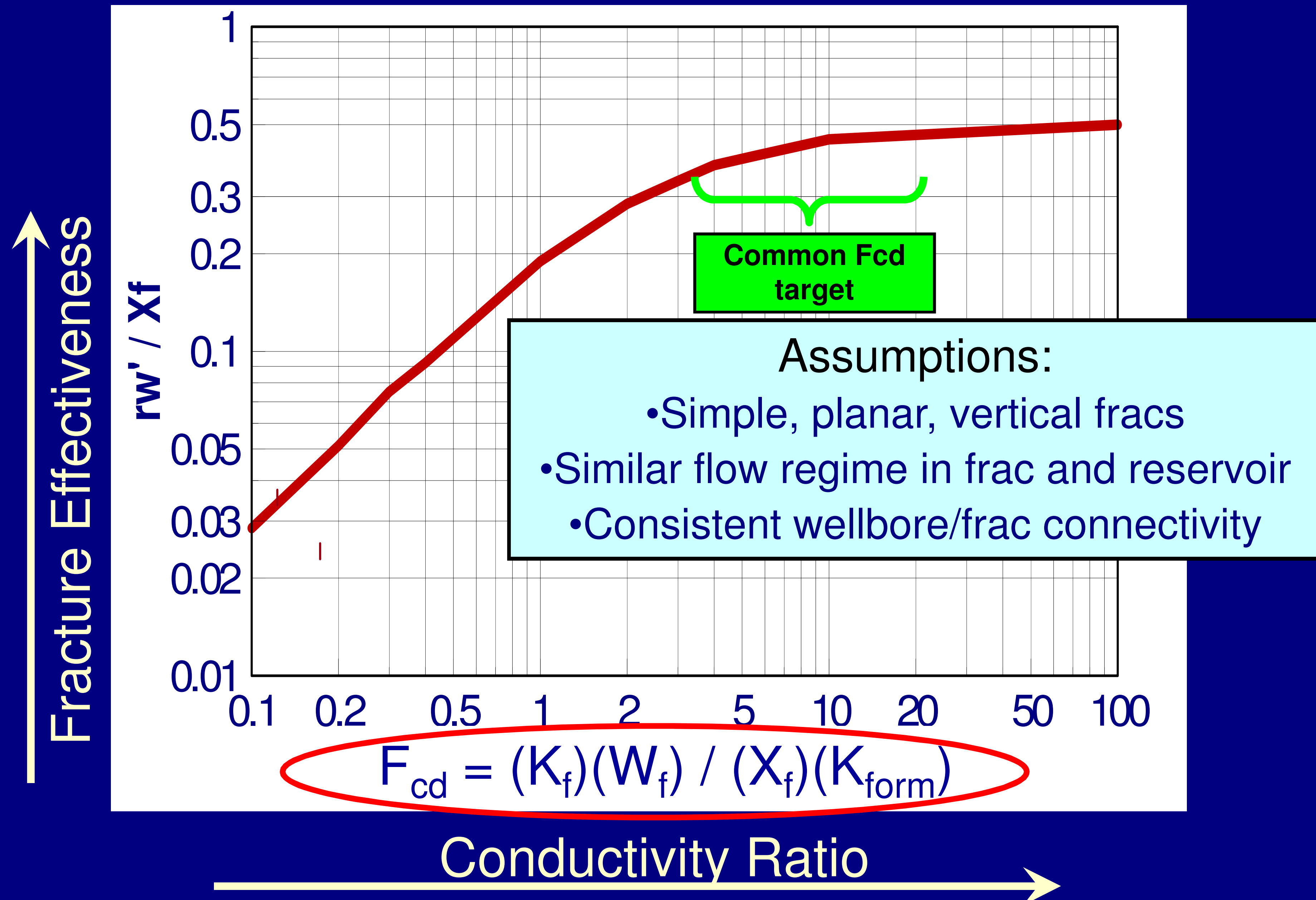


$$F_{CD} = \frac{k_f * w_f}{k_{form} * x_f}$$

Dimensionless Fracture Conductivity (F_{CD})

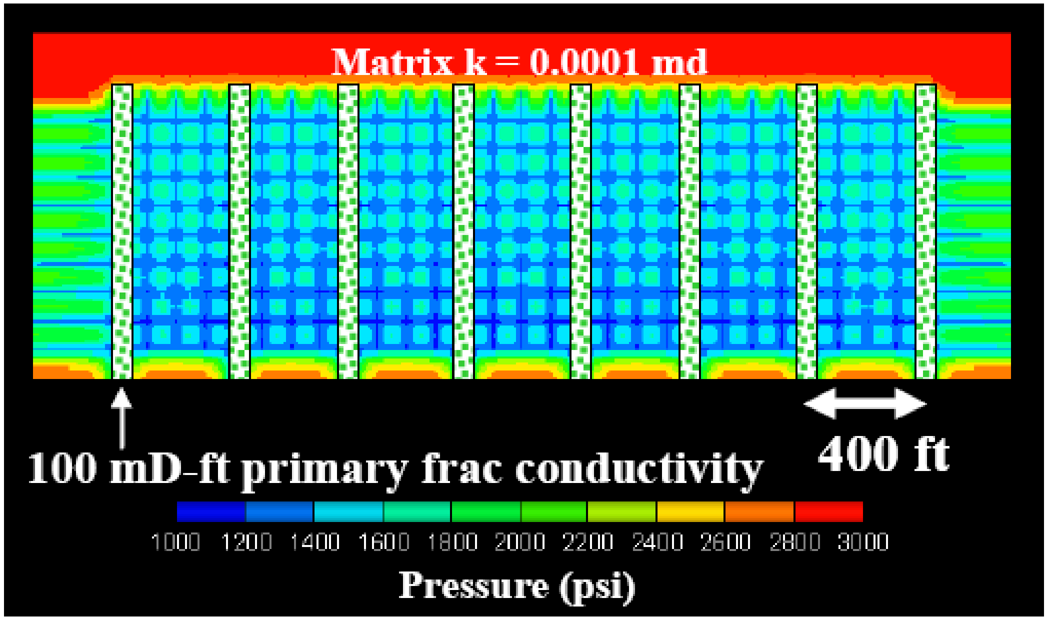
a ratio of the flow capacity of the fracture and the formation

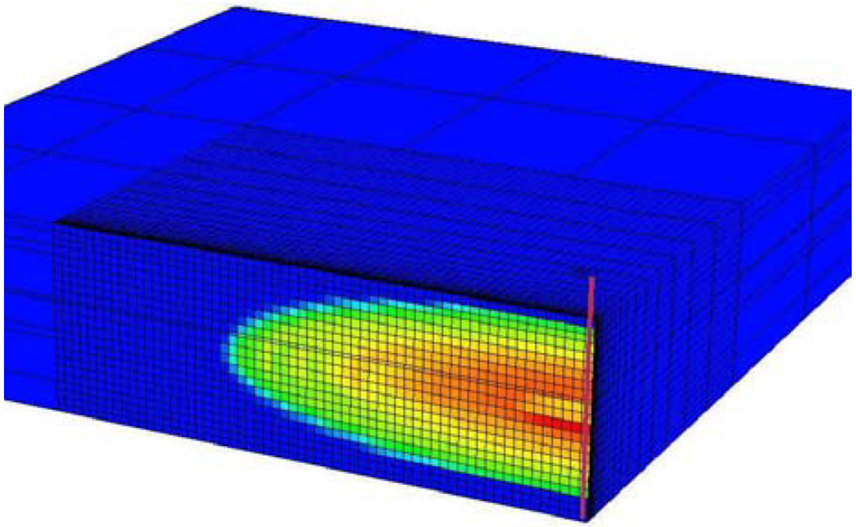
Analytic Solution to Optimize Simplistic Frac



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

Proppant thin section courtesy of Stim-Lab

If my formation looks like this...

Doesn't this provide infinite conductivity?

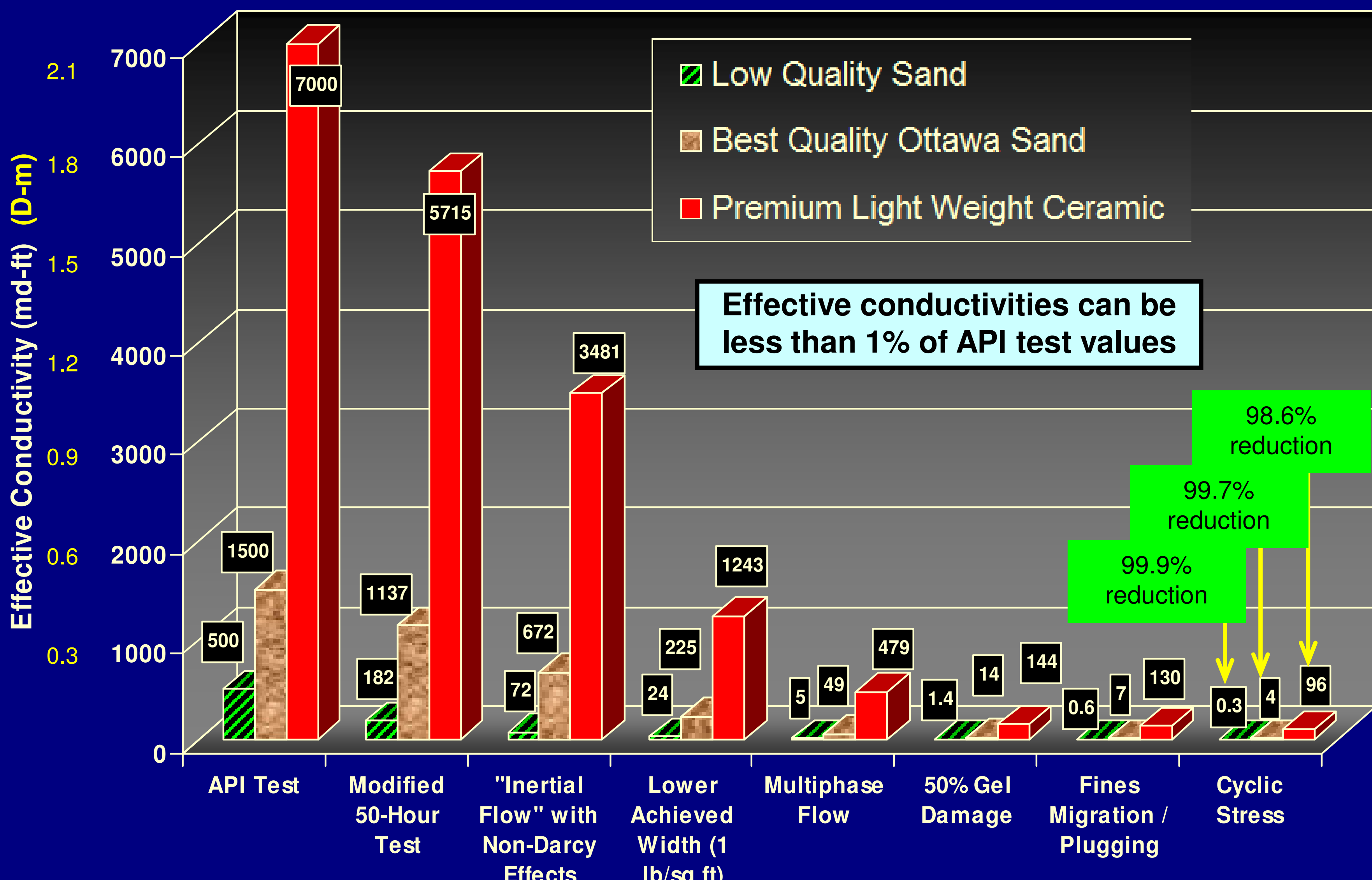
Common Assumptions

- Analytic Solutions, Numerical Models and Intuition

- Generally presume
  - simplistic flow,
  - simplistic geometry,
  - perfect wellbore-to-fracture communication,
  - hydraulic continuity throughout frac

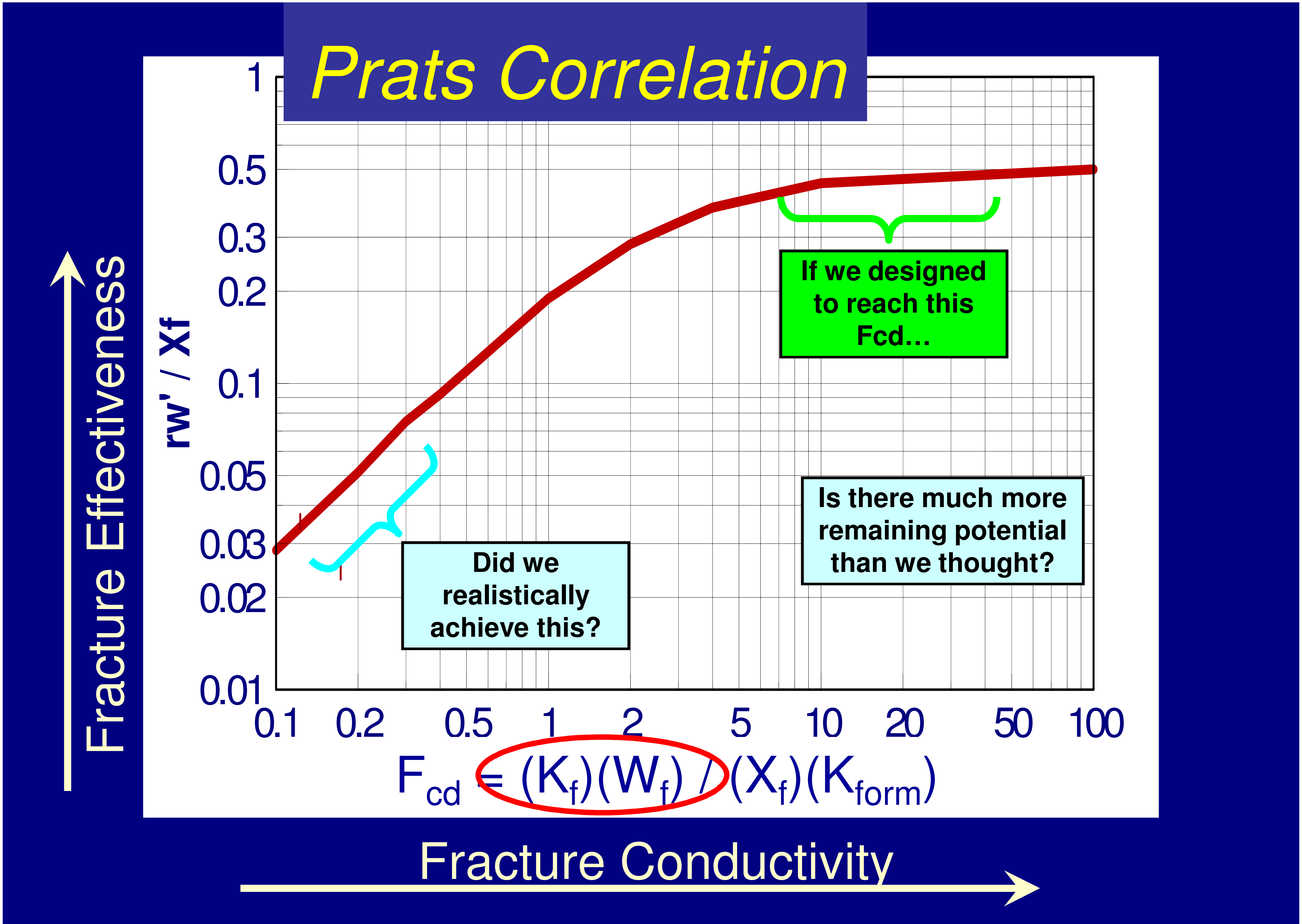
Realistic Conductivity Reductions

20/40 proppants at 6000 psi



Conditions: YM=5e6 psi, 50% gel damage, 250°F, 1 lb/ft^2, 6000 psi, 250 mcfd, 1000 psi bhfp, 20 ft pay, 10 blpd
YM=34e3 MPa, 50% gel damage, 121°C, 5 kg/m^2, 41 MPa, 7000 m^3/d, 7 MPa bhfp, 6 m pay, 1.6 m^{3}l/d

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

Off by 100-fold?!

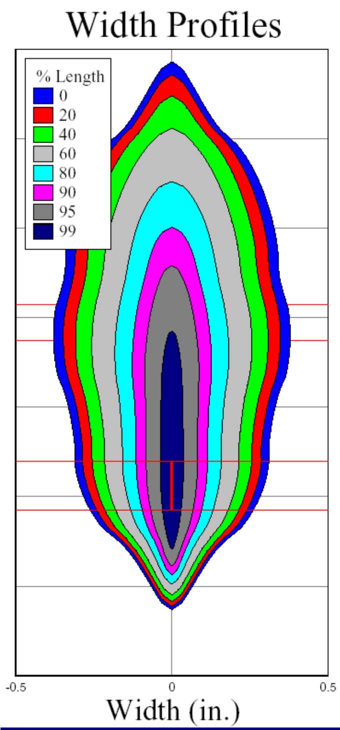
- Even in simple, continuous, planar fracs
  - Even if we carefully arrange proppant with perfectly uniform distribution, with lab-grade fluids, perfect breakers, limit test to 50 hours, etc.

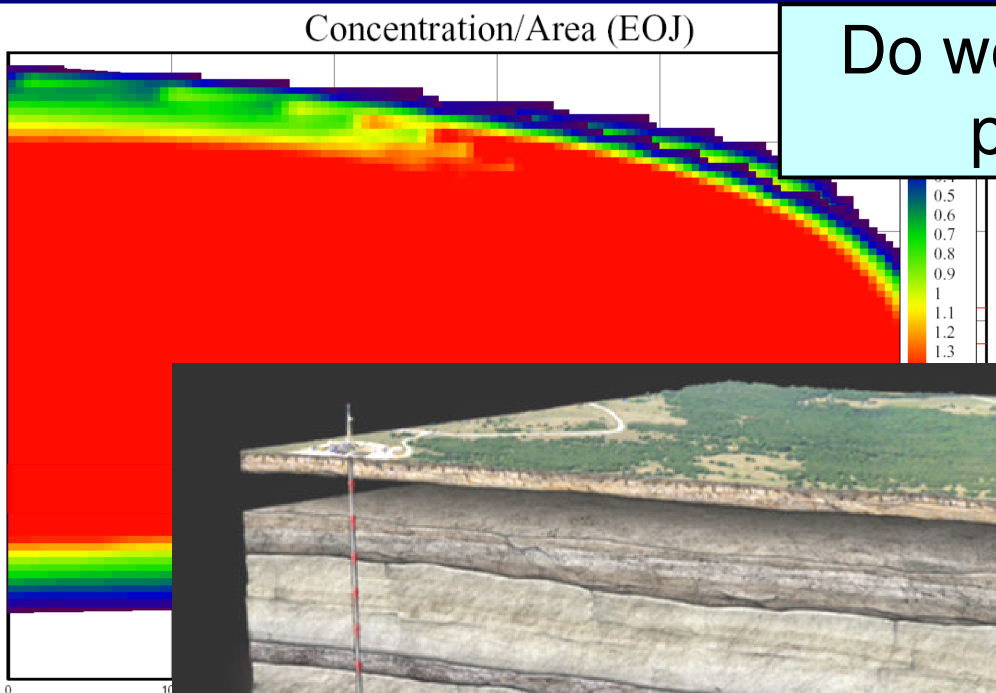
- Pressure losses are generally 50 to 1000 times higher than suggested by advertised data

- Concern #1

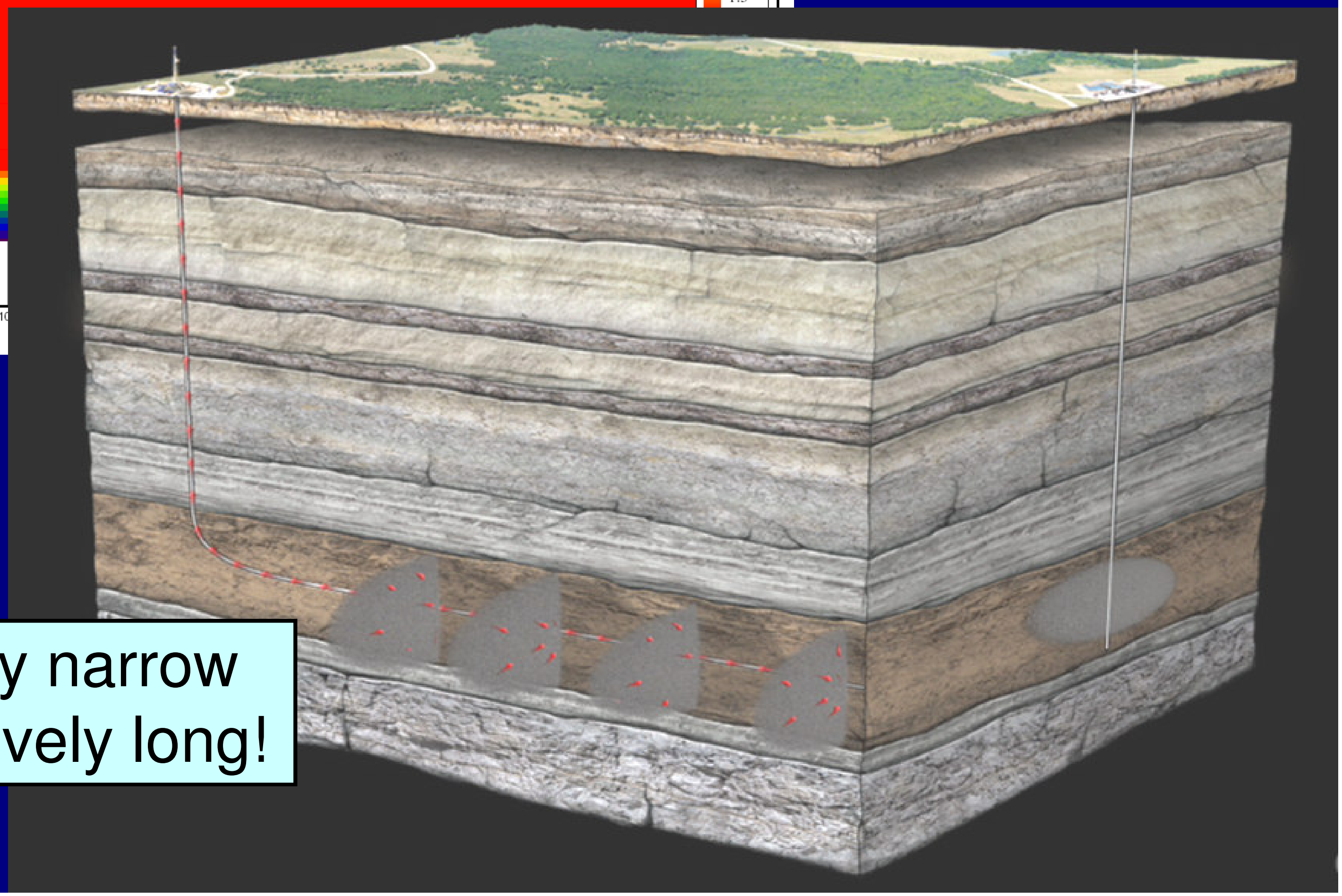
  Flow regimes are complex within propped fracs – oversimplifications may mislead us.

Is our frac geometry assumption valid?



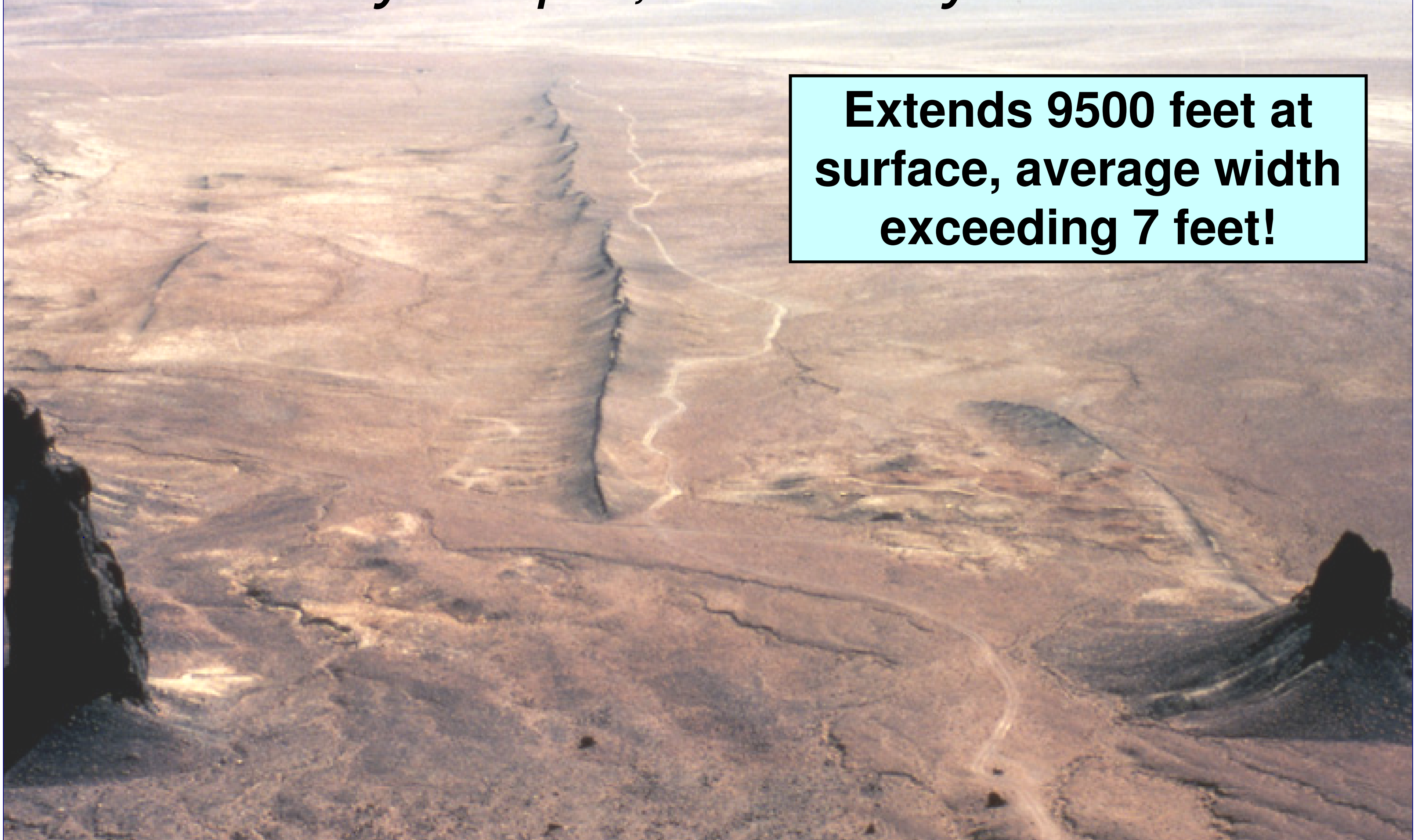


Do we envision these proportions?



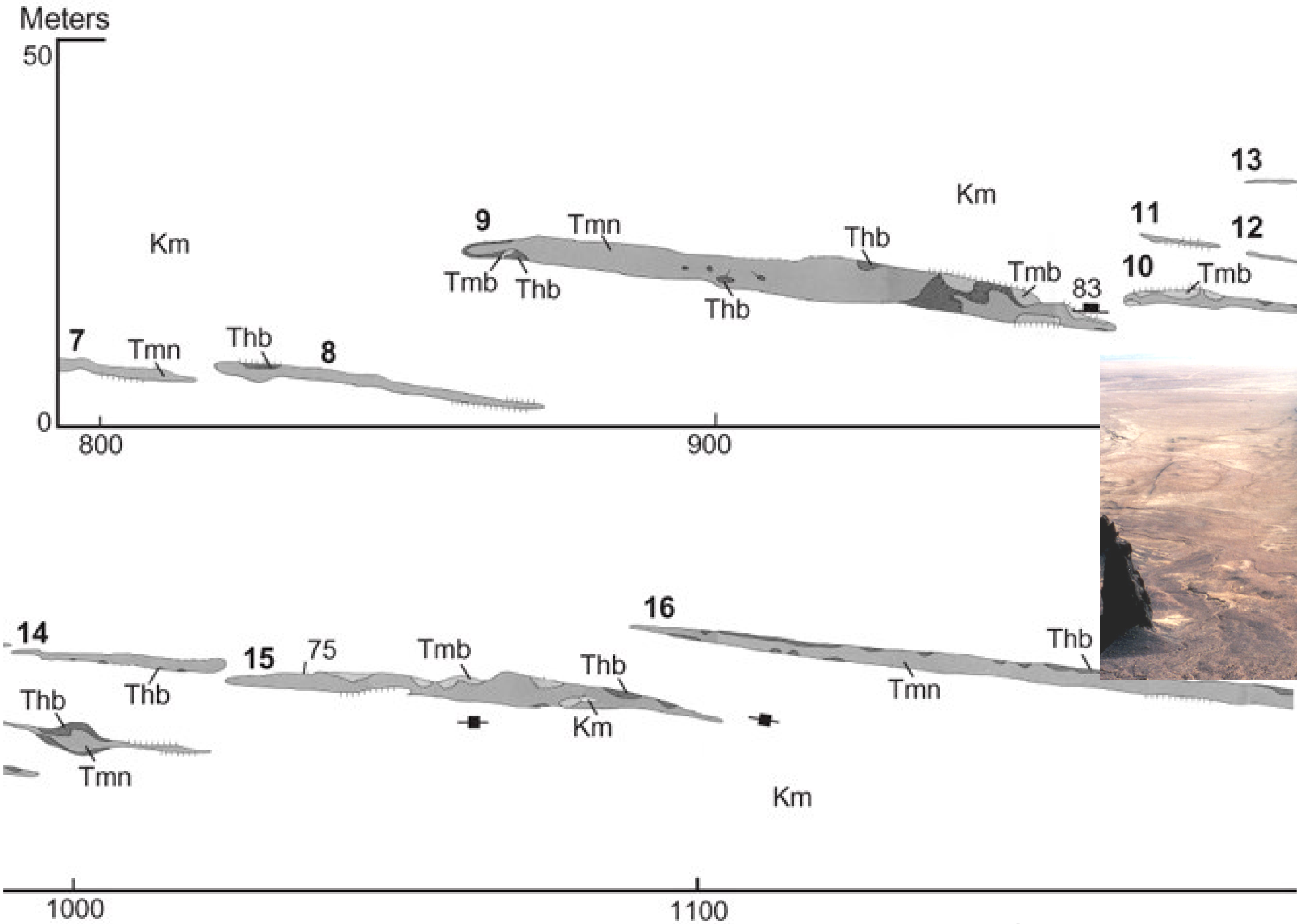
Fracs are very narrow ribbons, massively long!

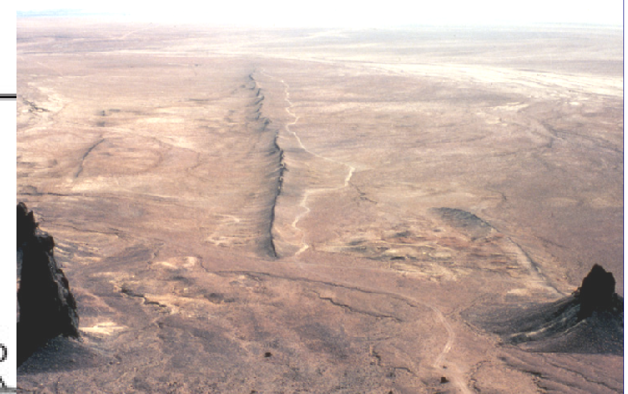
Relatively simple, extremely wide fracture



Pollard (2005) Northeast Ship Rock Dike, New Mexico

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

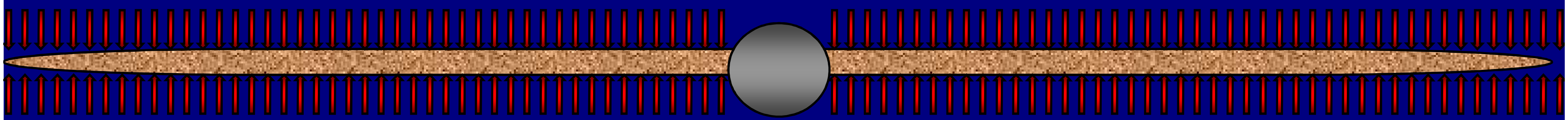




Pollard (2005) Northeast Ship Rock Dike

Are Hydraulic Fracs Simple Planes?

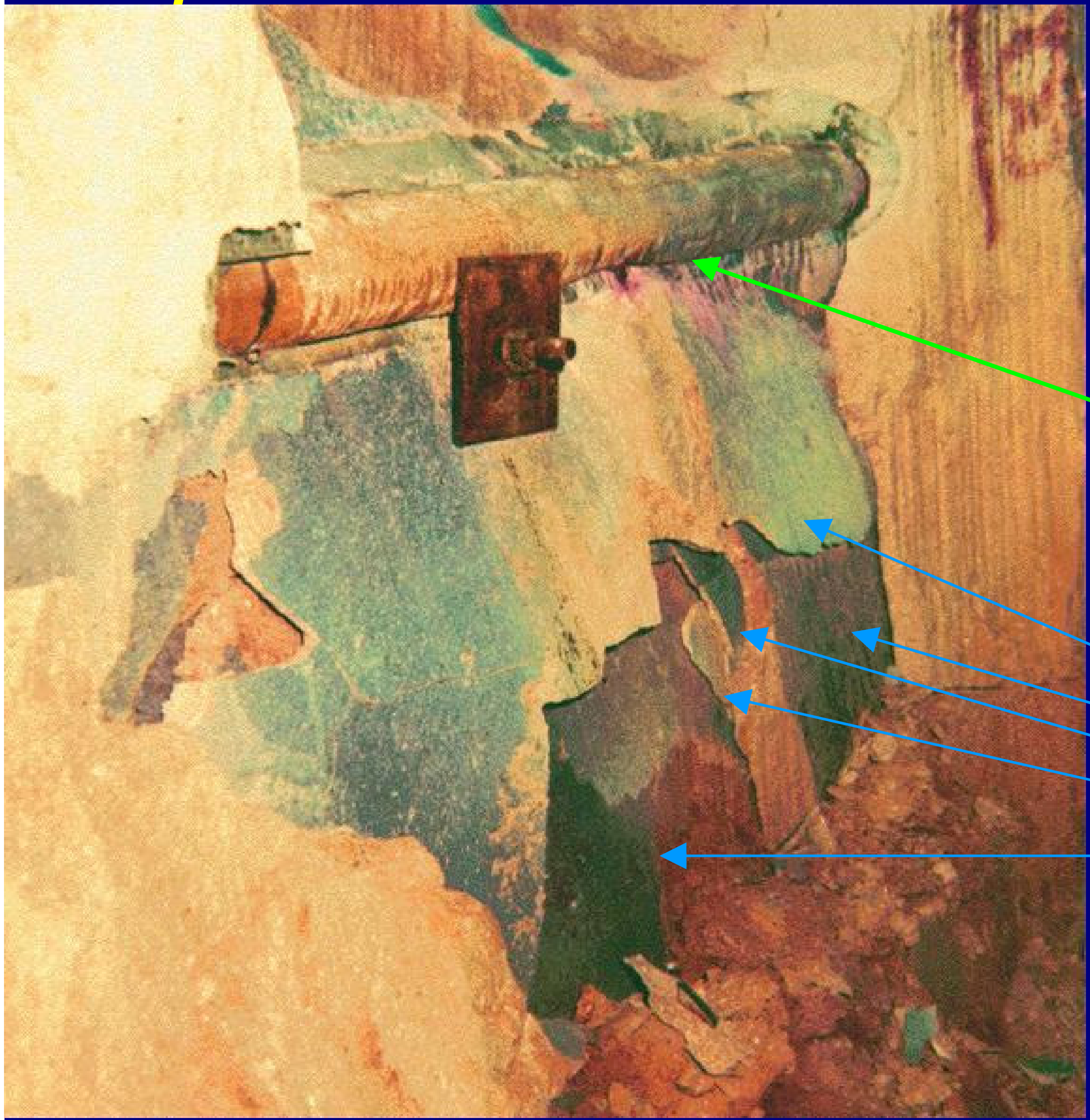
Top View



- 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)

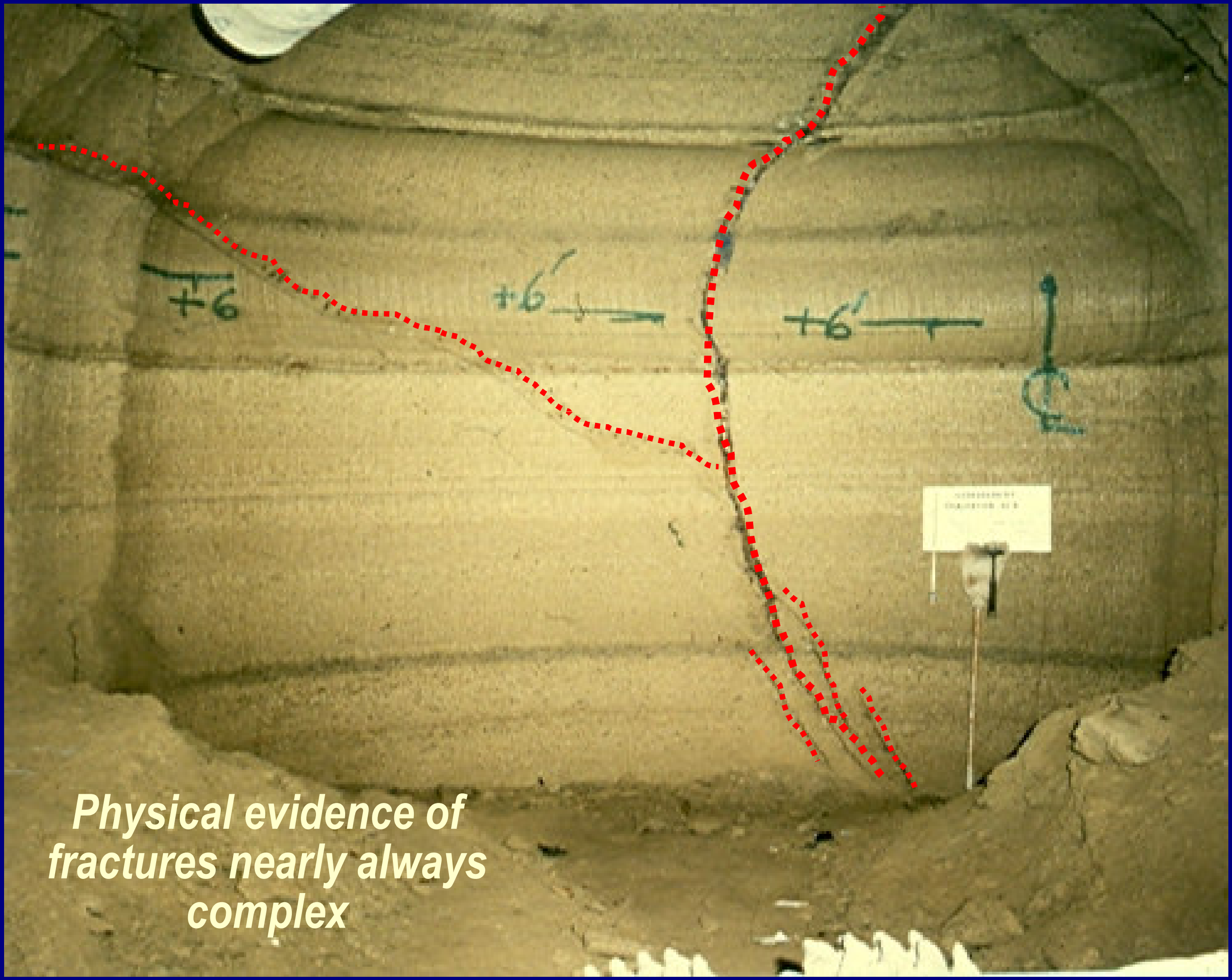
Even in competent rock selected for predictable mechanical properties…



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

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

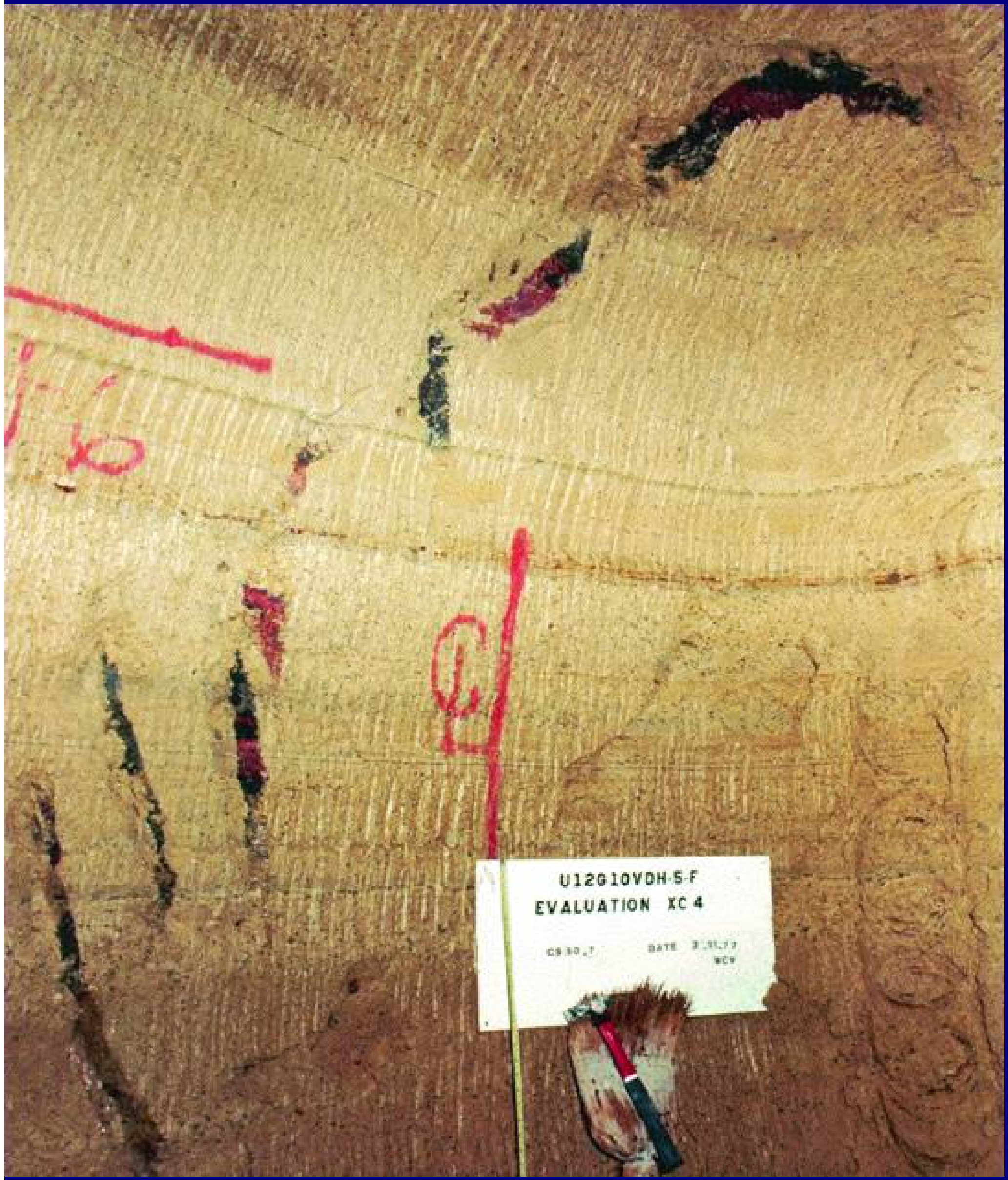
Observations of Fracture Complexity



Physical evidence of fractures nearly always complex

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

Multiple Strands in a Propped Fracture (Vertical Well)



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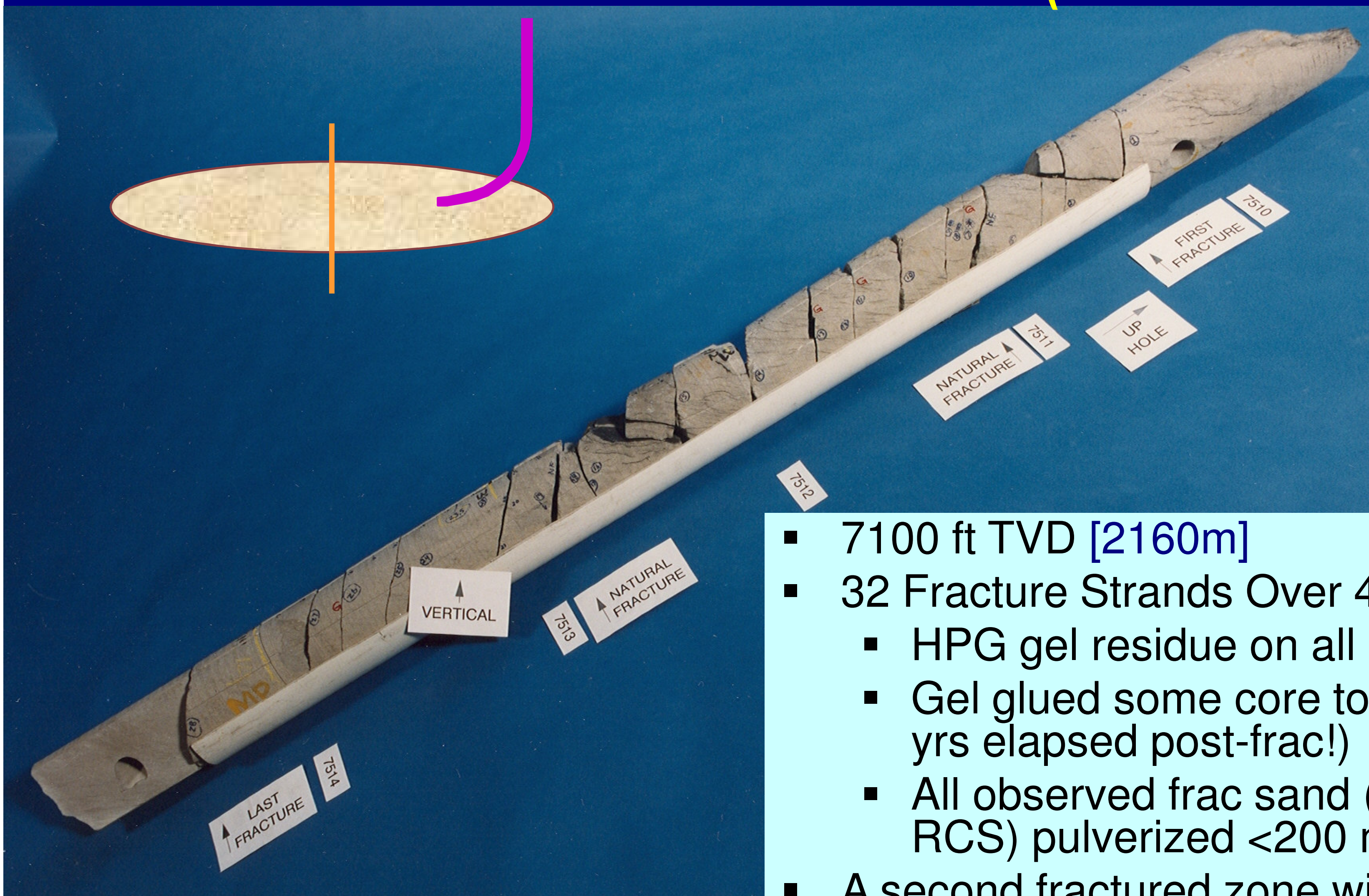
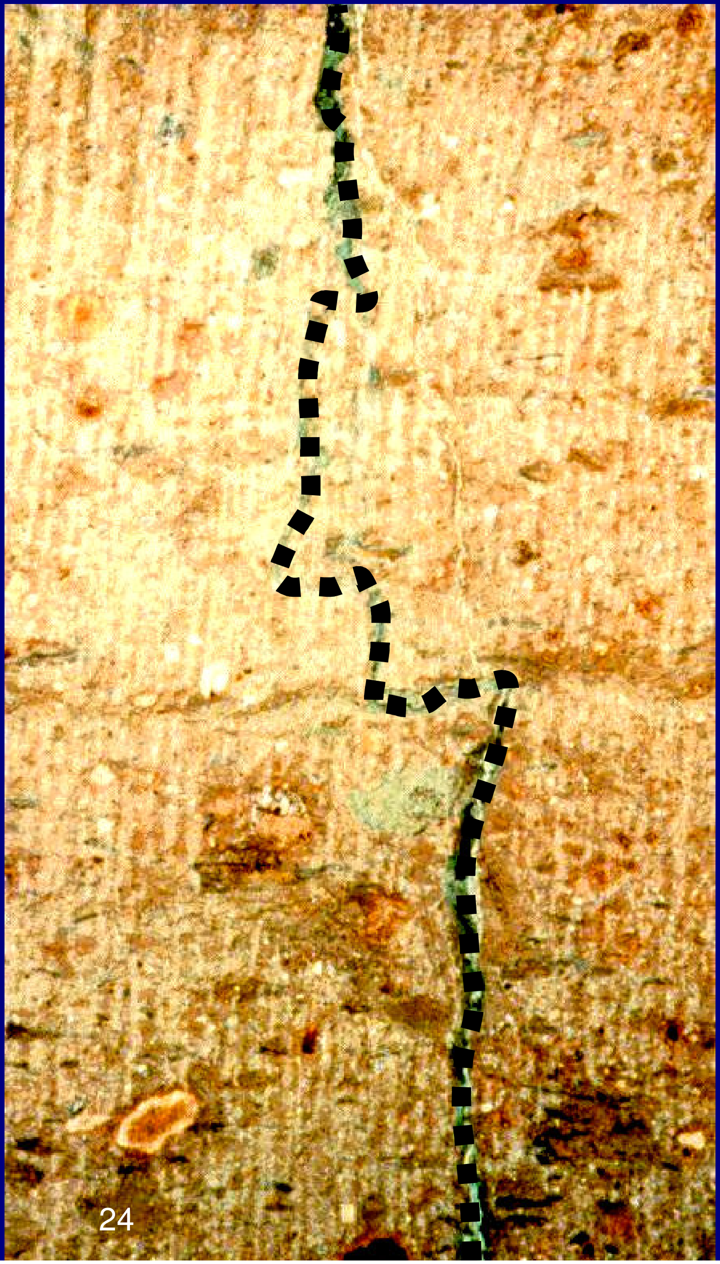


- 7100 ft TVD [2160m]
- 32 Fracture Strands Over 4 Ft Interval
  - HPG gel residue on all surfaces
  - Gel glued some core together (>6 yrs elapsed post-frac!)
  - All observed frac sand (20/40 RCS) pulverized <200 mesh
- A second fractured zone with 8 vertical fractures in 3 ft interval observed 60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

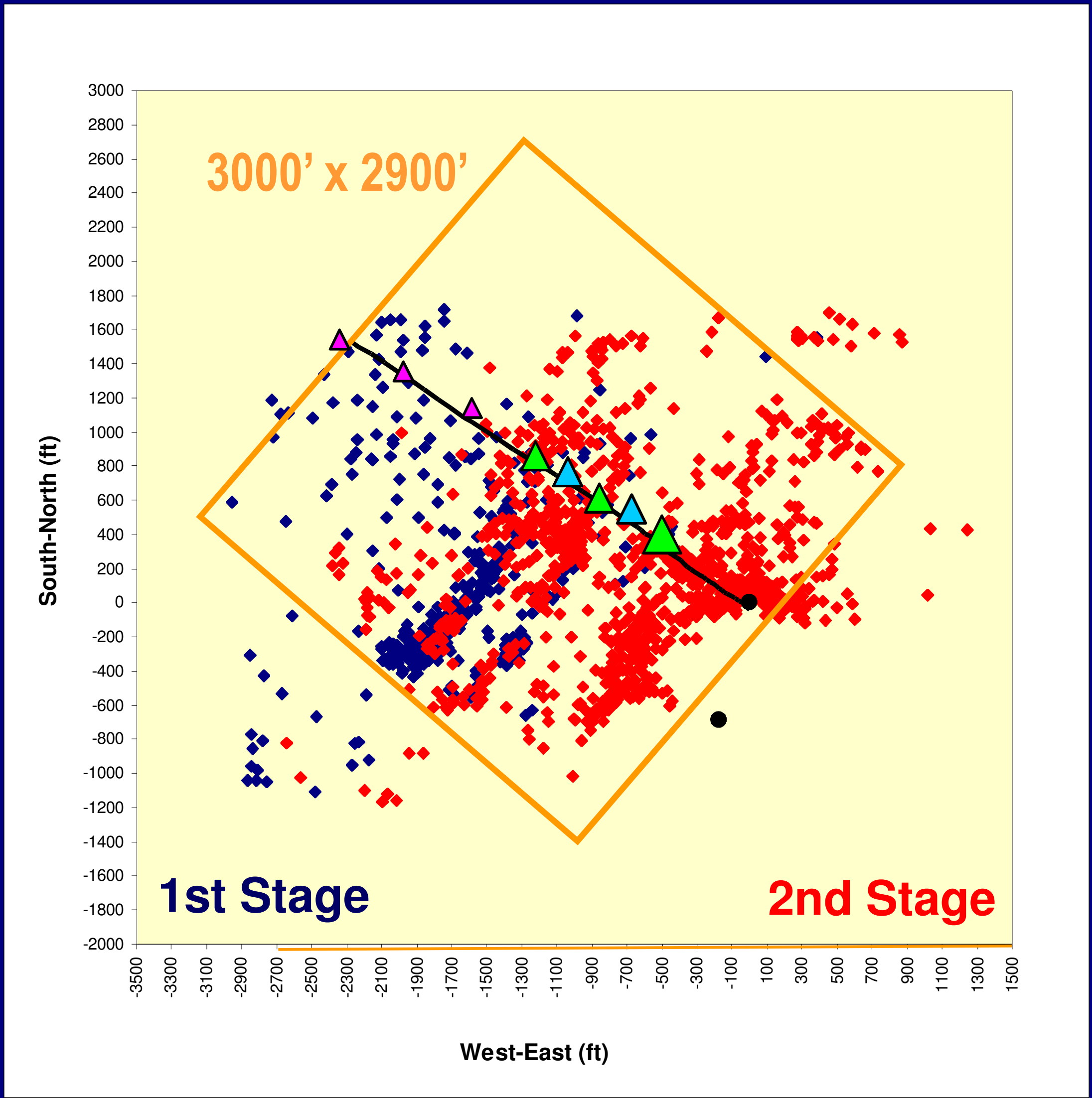
Woodford Shale Outcrop

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

Photo Courtesy of Halliburton

Navigation menu

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]

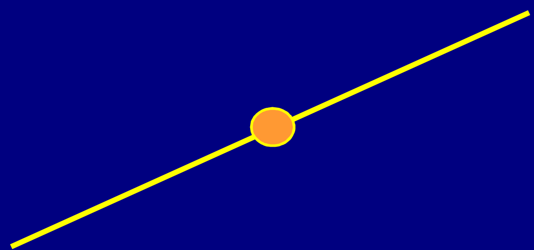
Complexity?

- Concern #2

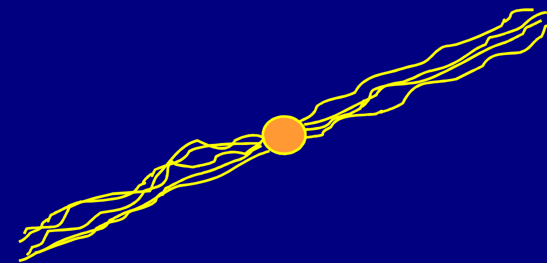
  On every scale that we investigate, fractures are more complex than the simplified frac geometry we presume in our models

Range of Fracture Complexity

Simple Fracture



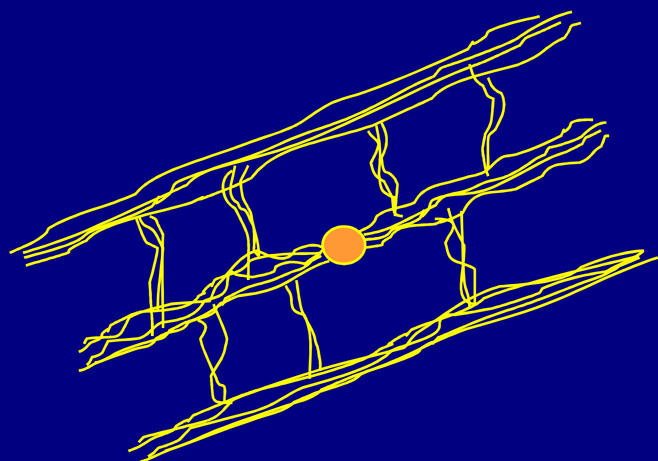
Complex Fracture



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]

SPE 77441

Fractures Intersecting Offset Wellbores

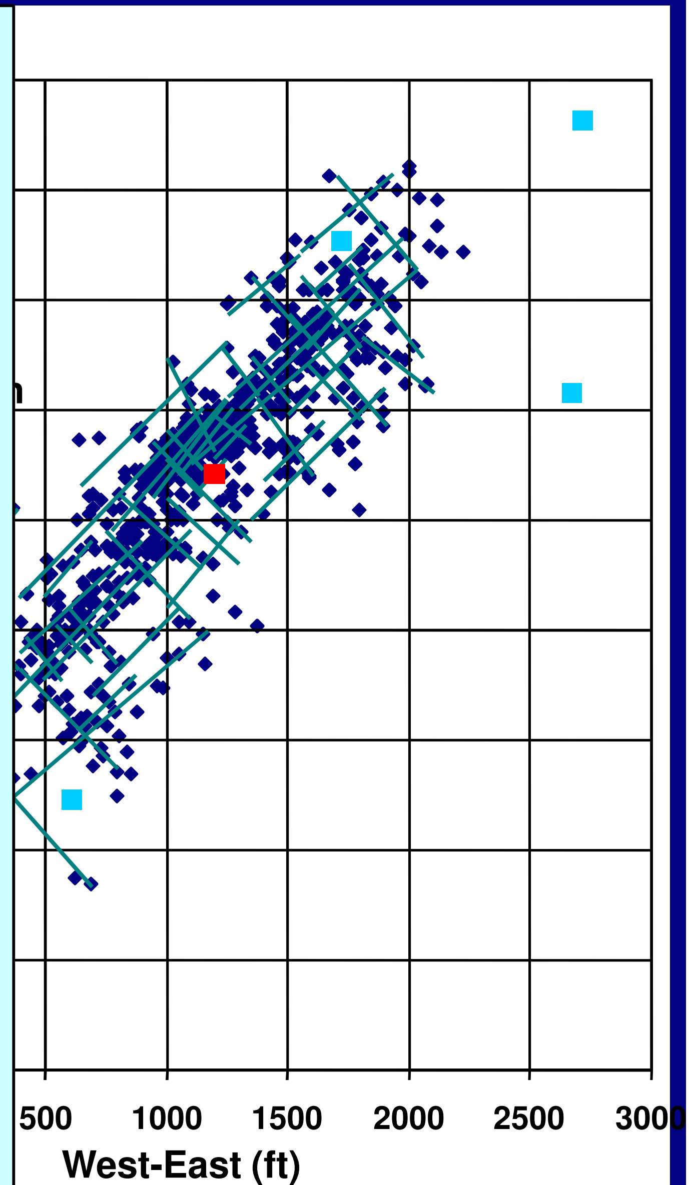
<u>Evidence frac'ed into offset wells</u>

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!



SPE 77441

Concern #3

- Fracs may provide imperfect hydraulic continuity
  - Vertical
  - Lateral

Assumptions

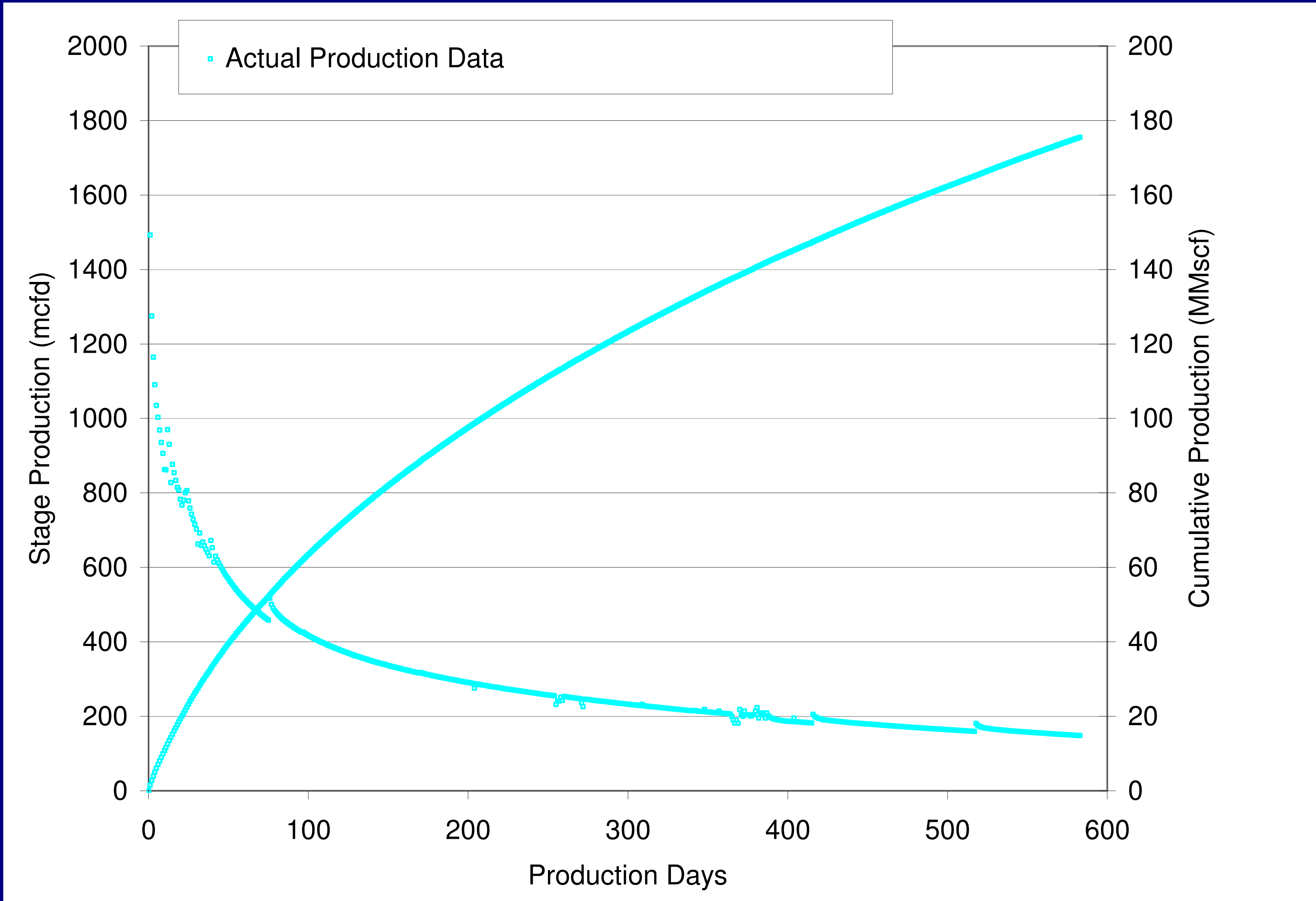
- Flow Complexity, Frac Geometry, etc
  - All challenge ability to provide adequate conductivity
- Other Omissions:
  - Stress concentration on irregularly distributed proppant
  - Gel cleanup is more thorough in high conductivity fracs
  - Wider fracs are less damaged by
    - Filtercake, cyclic stress, 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

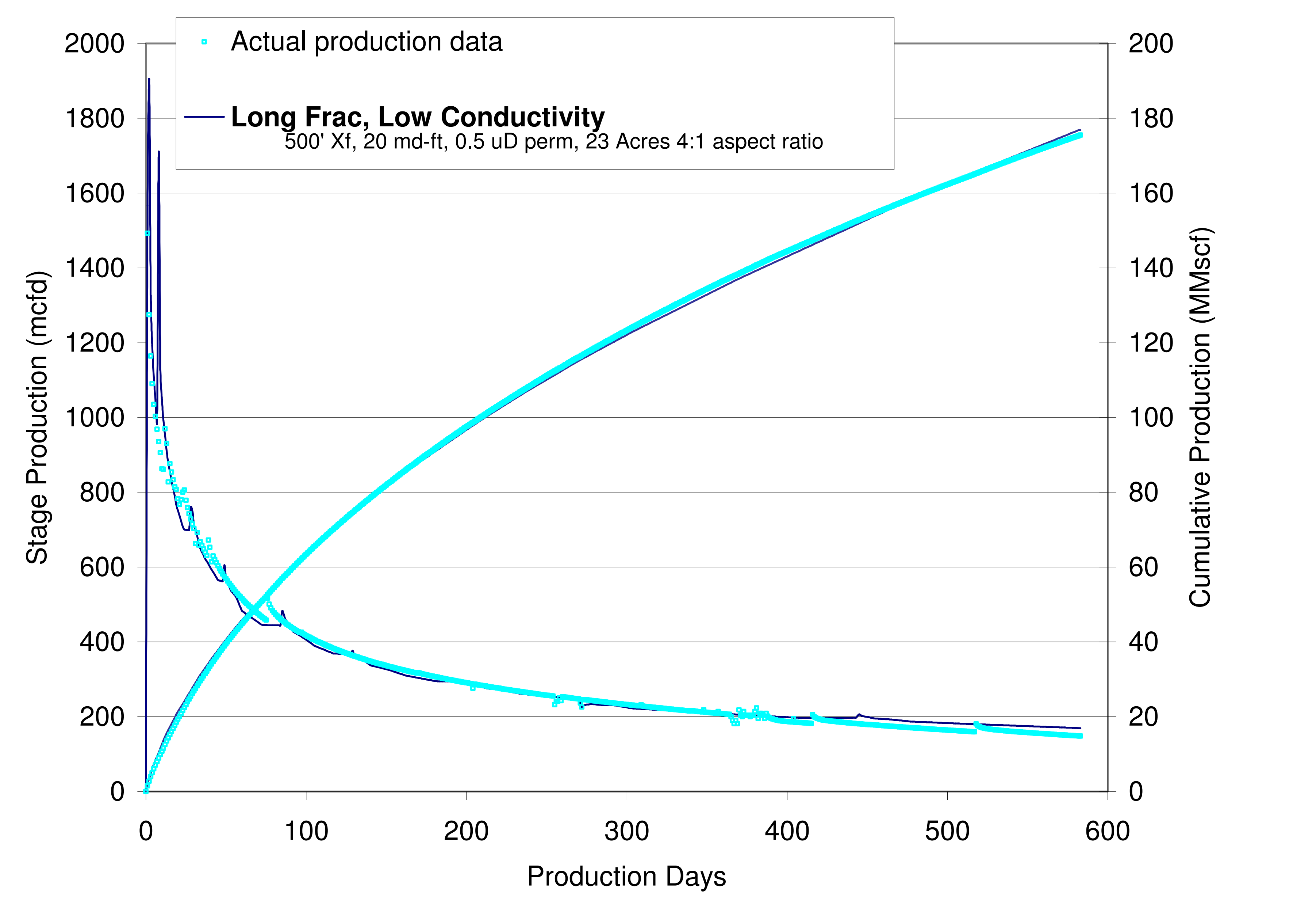
- Lack of competition in wells connected by frac
- Steep production declines
  - Surprisingly limited drainage areas often don't correspond to mapped fracture extent
- Infill Drilling
  - Often successful on surprisingly close spacing
- Well Testing
  - Disappointing frac lengths and/or low apparent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

Shouldn't complexities be obvious from production data?



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

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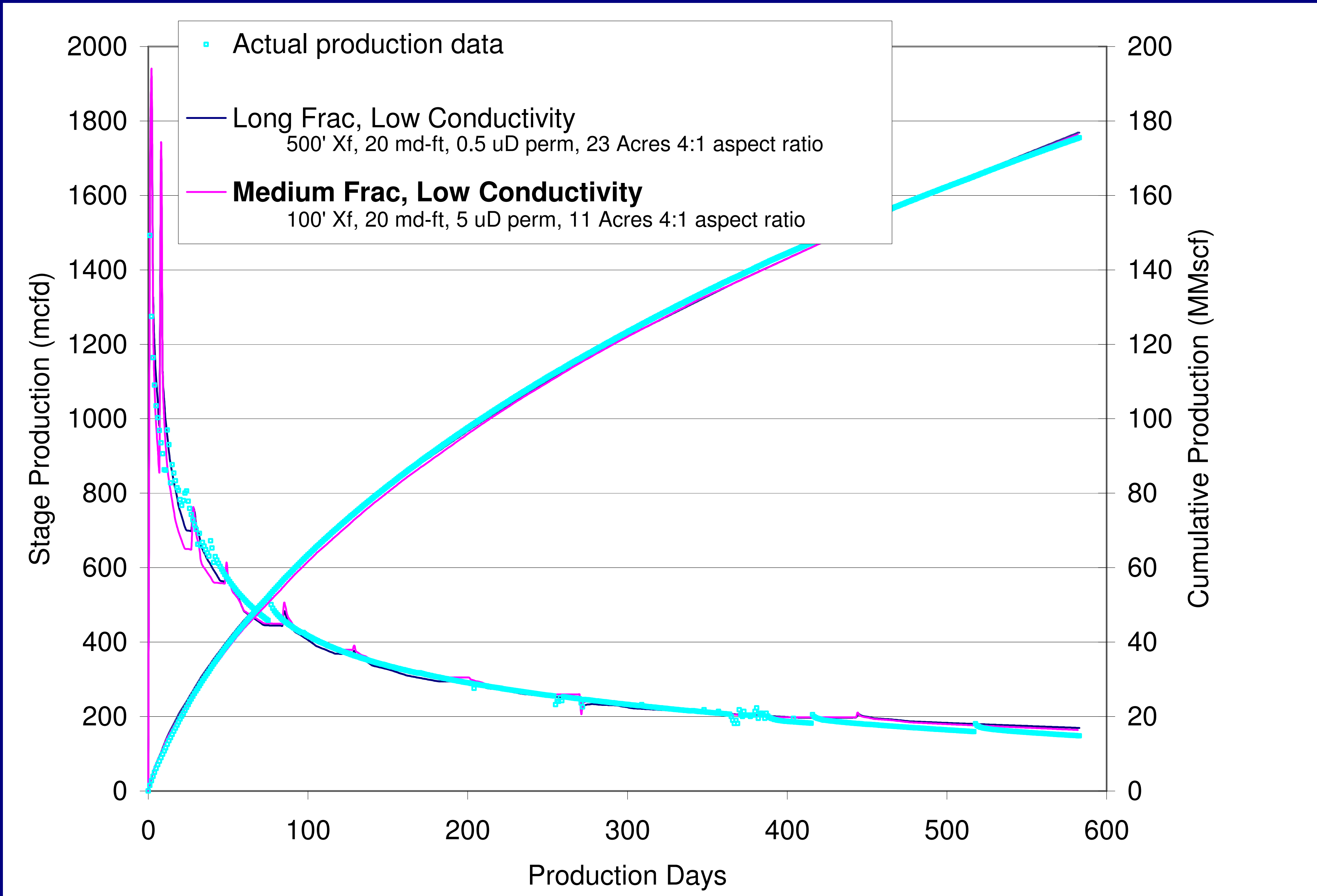

SPE 106151 Fig 13 – Production can be matched with a variety of fracture and reservoir parameters

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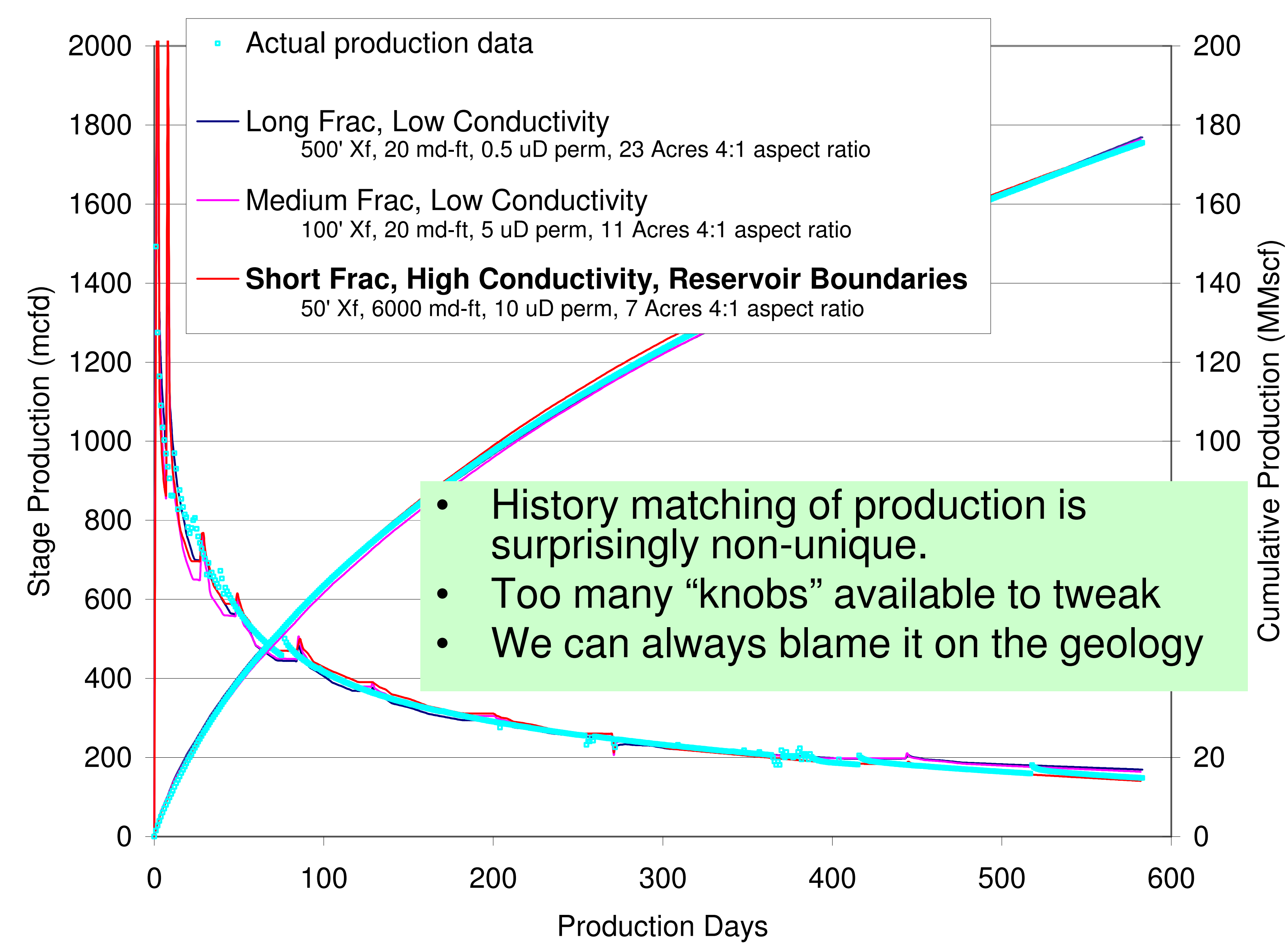


- History matching of production is surprisingly non-unique.
- Too many "knobs" available to tweak
- We can always blame it on the geology

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]

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	

SPE 119143 tabulates over 200 field studies

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!

A tabulation of 200 papers in SPE 119143

Statistically Compelling Example

- 0.002 mD gas wells
- 446 fracs in carefully conducted trial
  - Reference F_{cd} > 400 with modest sand concentrations; F_{cd} >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

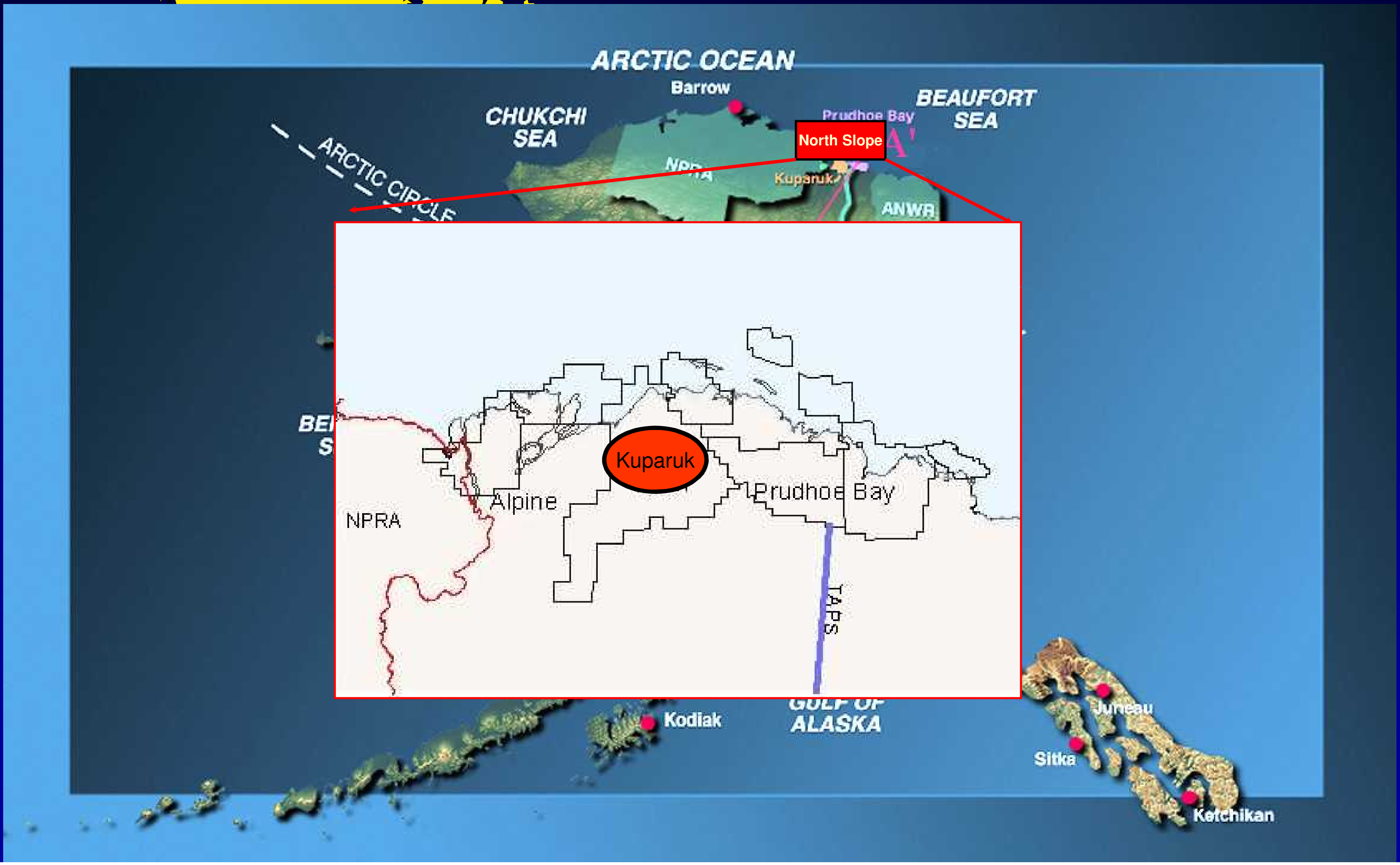
SPE 106151

Case Study

Modest Rate Oil Wells

SPE 15507, 20707 & 24857

Kuparuk River Field, Alaska



Kuparuk River Field, Alaska

SPE 15507, 20707 & 24857

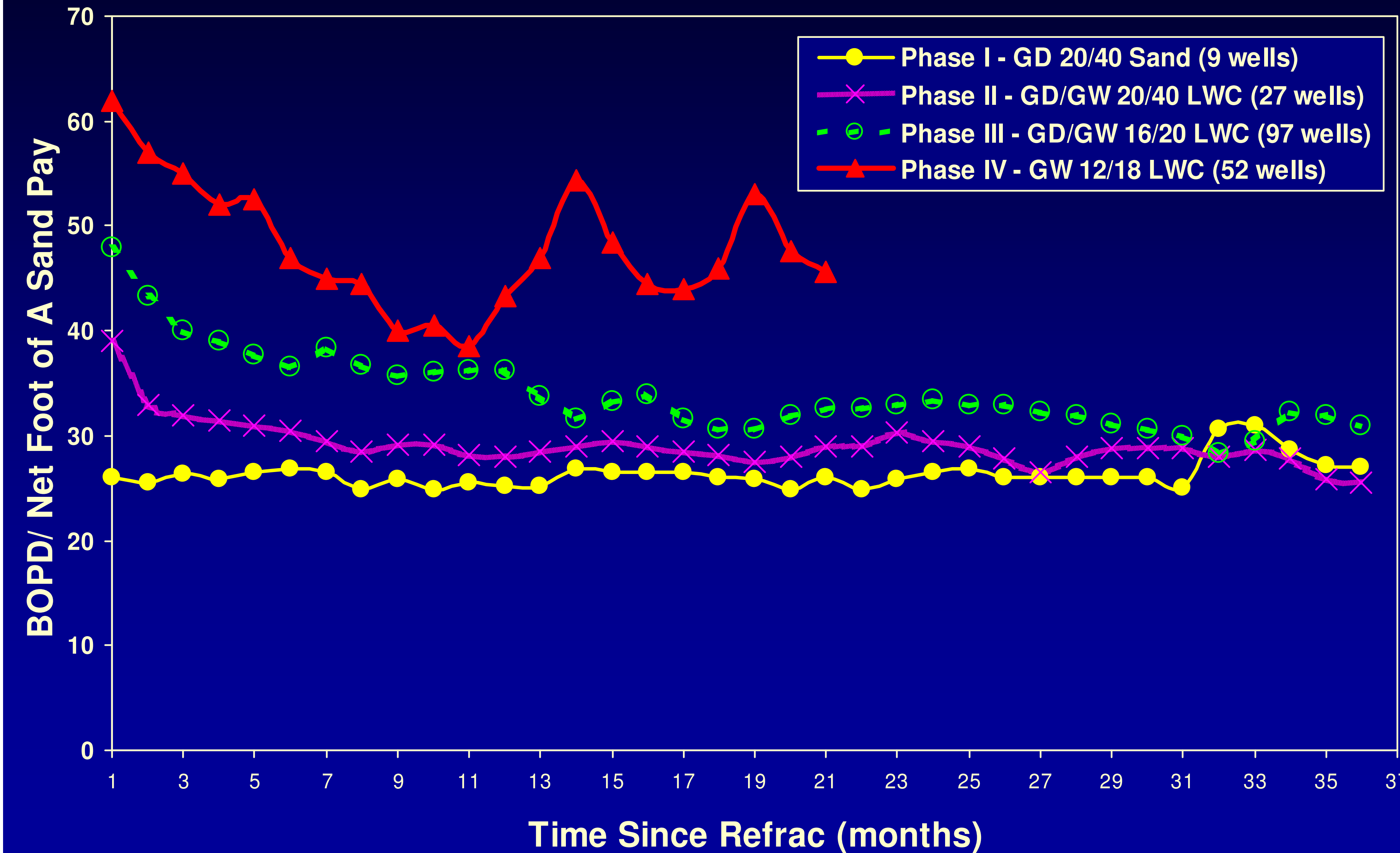
- 20 to 100 md
- ~6000 ft TVD
- Stress on proppant = 3400 psi
- ~30 feet of pay
- Slant / High Angle wells drilled from pad

Traditional thought was that these wells should not be fracture stimulated.

Unique data quality and quantity. Over 880 fracs, and over 200 refracs with multiple build up tests.

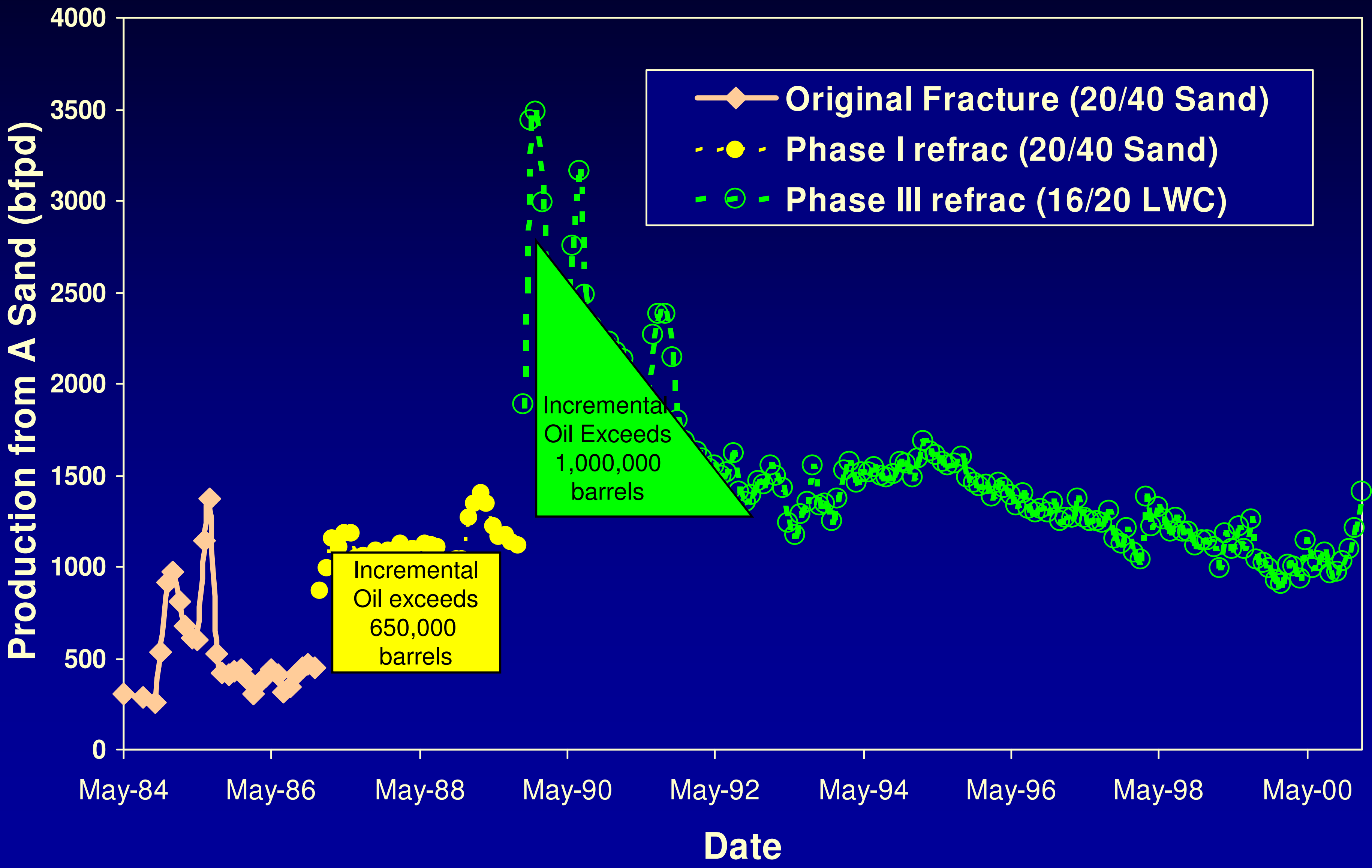
Kuparuk Refrac Rates

SPE 24857, Pospisil, *et al*, ARCO



Kuparuk Well 2F-08

SPE 24857 with updated data



Some "Local" Examples (Page 1 of 2)

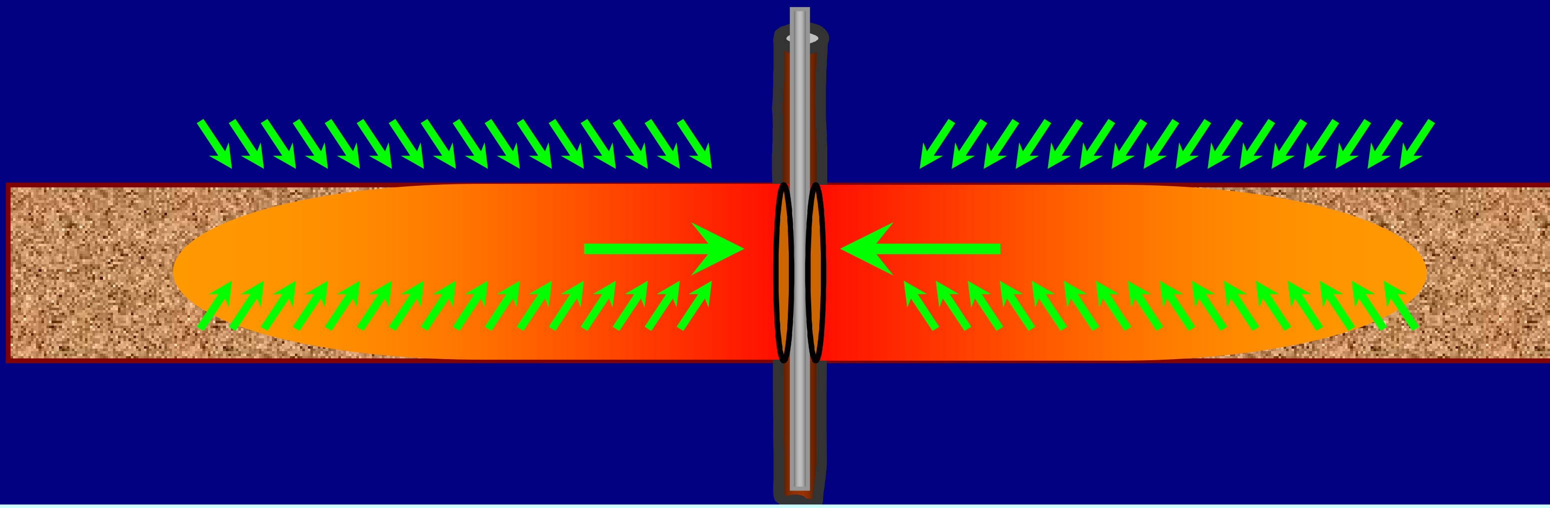
- SPE 39954, Kondratoff: Kalchinskoye Oilfield. 3- to 7-fold increases in production with superior conductivity and implementation
- SPE 84916, Nor-Azlan: Vyngayakhinskoe Field. Refrac with 16/30 ceramic, large net pressure increase (wide frac). Oil production increased from 60 to 150 tonne/day.
- SPE 90357, Economides: Priobskoye. Transition from small diameter proppant to 16/30 and 12/20. "Tremendous increases" in oil rate.
- SPE 94727, Butula: Yamburgskoe Field. Wide, conductive fractures with larger proppant provided 4-fold increases
- SPE 91760, Rueda: Siberia turbidite. Doubling proppant per meter of pay increased production by 82%.
- SPE 98259, Guglielmo: Priobskoye. Use of 12/18 and 8/14 proppant has increased production 7-fold.

Some "Local" Examples (Page 2 of 2)

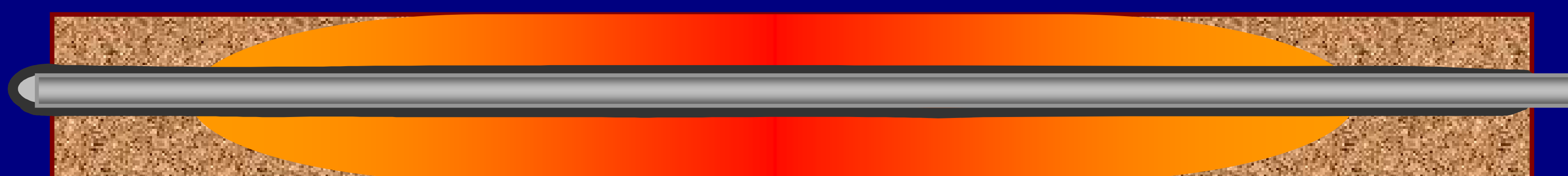
- SPE 75146, Shaoul: Kazakhstan, 3500 ft depth Arman Field. Ceramic up to 18 ppg; increased production 2- to 5-fold, increased reserves
- ATW, 2006, Brovchuck: Western Siberia. Romanovskoye and Sugmutskoye Fields. Aggressive proppant concentrations of 8/14 ceramic resulted in 3.3-fold increase in production
- TEK, 2005, Маньер: Western Siberia. Yamburgskoye Field. High conductivity fractures resulted in 2.75-fold of increase
- SPE 101821, Dedurin: Several Russian Fields [Priobskoye, Orenburg, Yamburgskoye, Sugmutskoye, Romanovskoye, Kalchinskoye, Vyngayakhinskoe]. Superior production with increased fracture conductivity.
- SPE 94643, Demarchos: W. Siberia, Sugmutskoye Field. Doubling the volume of proppant and increasing proppant quality can increase rates by 50%.
- SPE 103987, Ruiz: Pribskoye. Use of higher conductivity proppant is yielding higher productivity indices.

But what about Horizontal Wells?

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

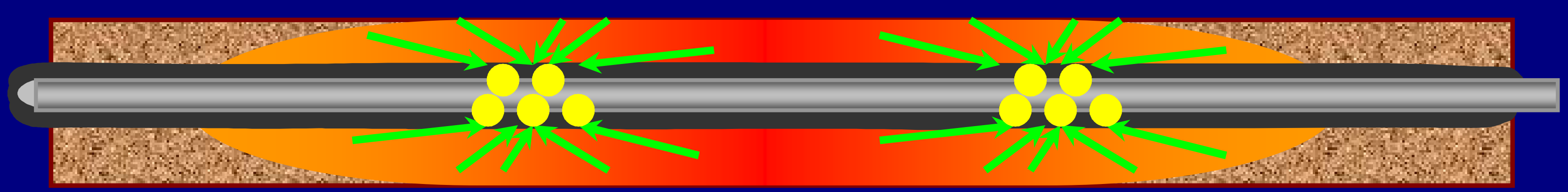
Horizontal Well

Cemented liner with limited perforations

Fluid travels shorter distances within the frac, but there is significant flow convergence around perfs.

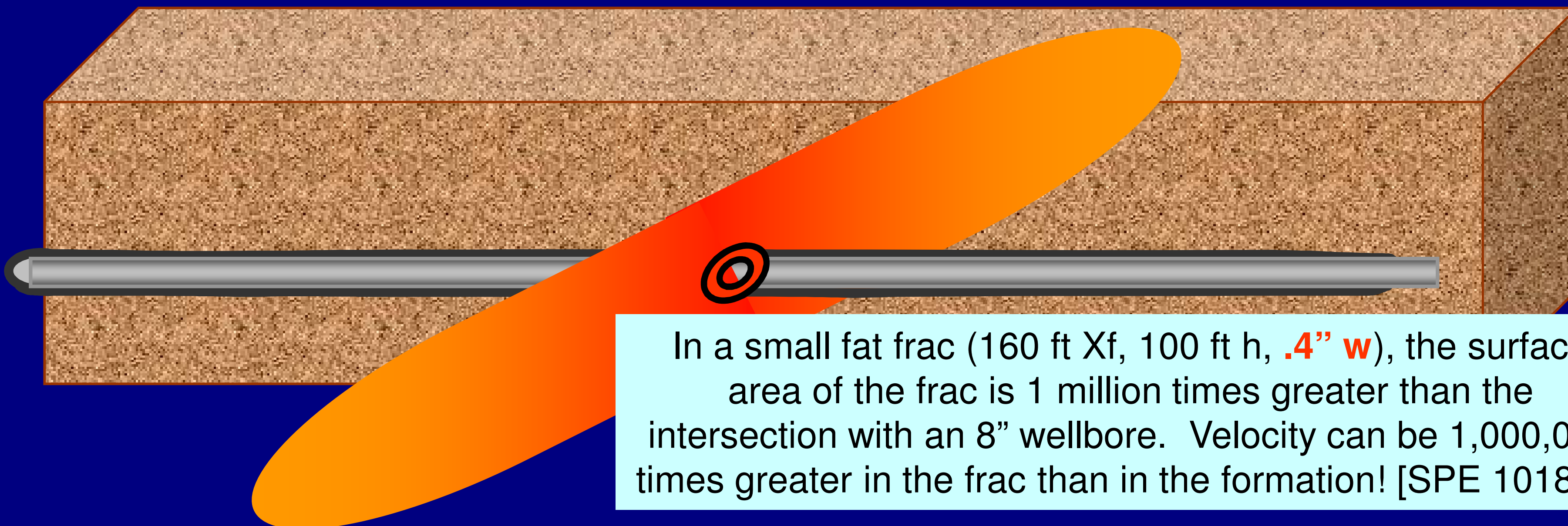
Proppant conductivity requirements are a consideration

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!**

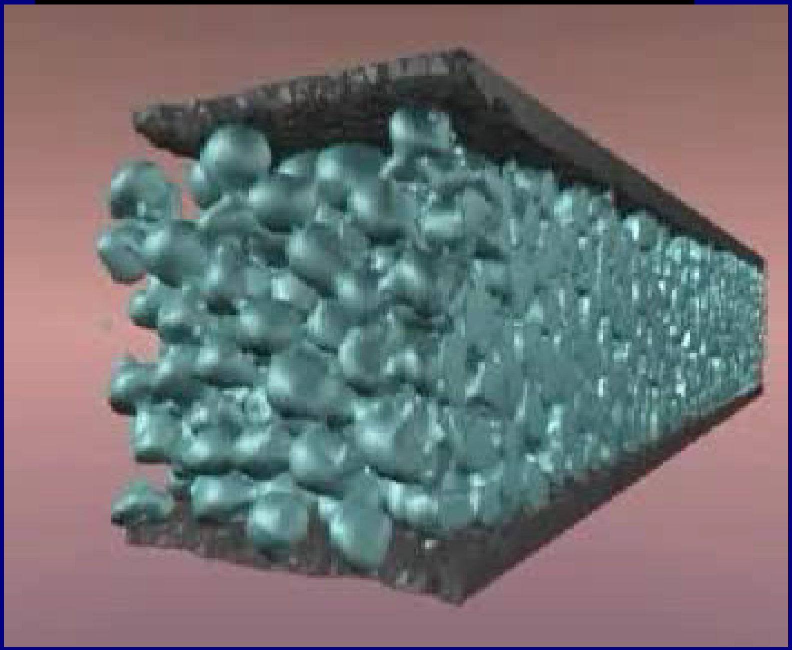
Velocity within Transverse Fracture

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.

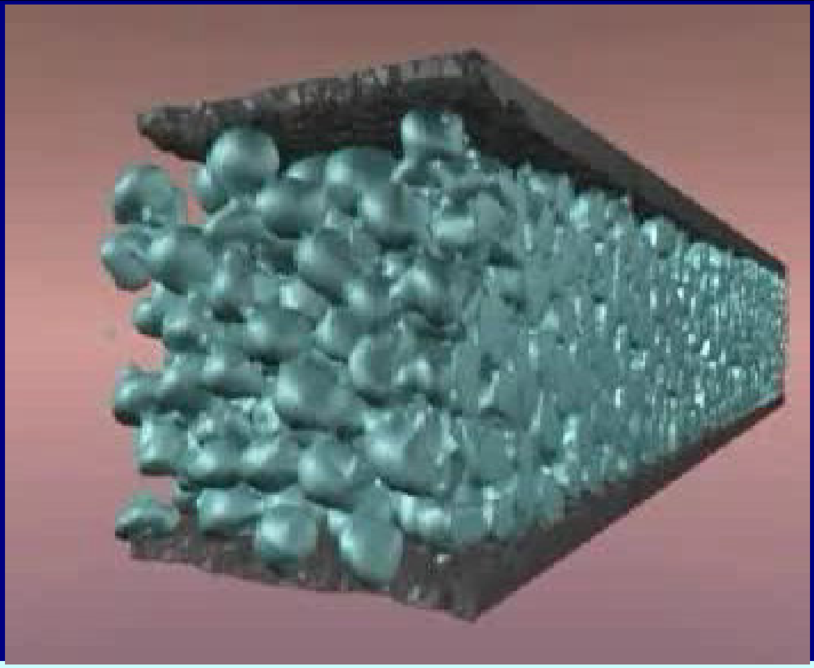
Approximate Velocity, API/ISO Test

2 ml/min through a 16/20 pack



Approximate Velocity
20 SCFD ($0.5 m^3/d$) 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?

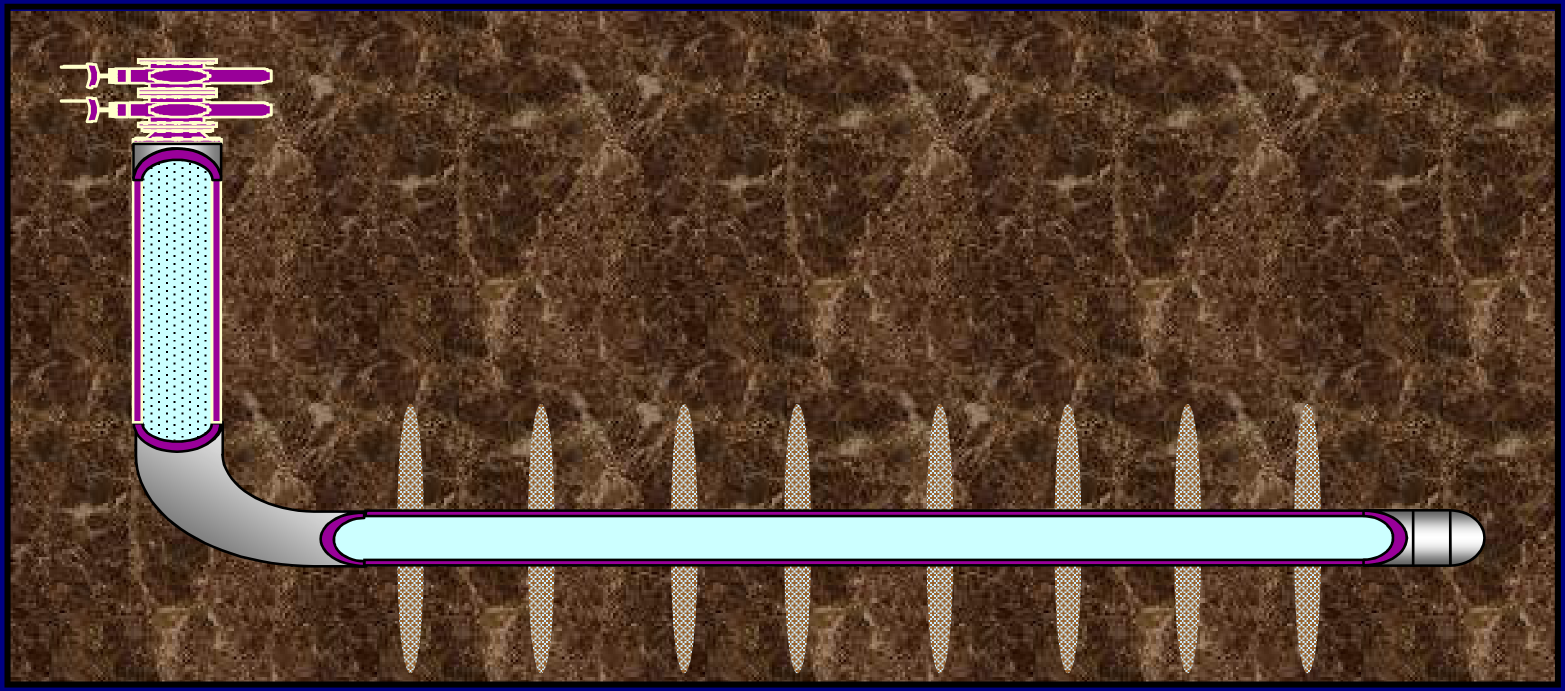
In some reservoirs, operators have pumped 28 stages, with 3 perf clusters per stage.

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)

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!!

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%!*

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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