Propped Fracs Are Collapsing – What Are the Causes and Ramifications?*

Mike Vincent[1]

Search and Discovery Article #41621 (2015)**
Posted May 18, 2015

*Adapted from oral presentation given at AAPG/STGS Geoscience Technology Workshop, Fourth Annual Eagle Ford Shale, San Antonio, Texas, March 9-11, 2015

[1]Independent Frac Consultant, Denver, CO, USA (mike@fracwell.com)

Abstract

Although most engineers have historically presumed that propped fracs are highly conductive and durable, the evidence is overwhelming that fractures are collapsing and losing connection with the reservoir over time. This presentation will refer to newly available examples in the Eagle Ford, Marcellus, Bakken, and Niobrara that demonstrate progressive collapse of fractures during the first weeks and years of production.

While the data are compelling that our fractures as currently designed are not durable, what is less clear is the mechanism. This presentation will list approximately 20 different mechanisms that have been postulated that may contribute to fracture degradation. Fractures likely collapse due to a combination of proppant embedment, insufficient proppant concentration, salt or scale deposition, proppant crush, fluid damage and a host of other causes. Likely, the severity of each damage mechanisms will vary in different formations and with different fracture designs.

The ramifications of fracture collapse are many. The most obvious are that to harvest the recoverable reserves, we will be forced to either a) drill closely spaced (adjacent) wells, stack laterals (vertical downspacing), refrac wells, or learn to improve our initial fracture designs. However, another more subtle ramification is our basic failure to understand the resource potential. When engineers presume that a highly conductive, durable fracture has been created, a steep decline curve is commonly attributed to low reservoir quality or insufficient reservoir contact area. After we recognize that our fractures are collapsing

and only draining limited portions of the available reserves, we discover the formation is capable of much greater productivity and longevity.

References Cited

Edwards, K.L., S. Weissert, J.B. Jackson, and D. Marcotte, 2011, Marcellus Shale Hydraulic Fracturing And Optimal Well Spacing To Maximize Recovery And Control Costs: SPE Hydraulic Fracturing Technology Conference, 24-26 January, The Woodlands, Texas, USA, SPE 140463.

Huckabee, P.T., M.C. Vincent, J.M. Foreman, and J.P. Spivey, 2005, Field Results: Effect of Proppant Strength and Sieve Distribution Upon Well Productivity: SPE Annual Technical Conference and Exhibition, 9-12 October, Dallas, Texas, SPE 96559.

Mayerhofer, M.J., N.A. Stegent, J.O. Barth, and K.M. Ryan, 2011, Integrating Fracture Diagnostics and Engineering Data in the Marcellus Shale: SPE Annual Technical Conference and Exhibition, 30 October-2 November 2011, Denver, Colorado, USA, SPE 145463.

Portis, D.H., H. Bello, M. Murray, G. Barzola, P. Clarke, and K. Canan, 2013, Searching for the Optimal Well Spacing in the Eagle Ford Shale: A Practical Tool-Kit: Unconventional Resources Technology Conference, 12-14 August, Denver, Colorado, USA, URTeC 1581750.

Potapenko, D.I., S.K. Tinkham, B. Lecerf, C.N. Fredd, M.L. Samuelson, M.R. Gillard, J.H. Le Calvez, and J.L. Daniels, 2009, Barnett Shale Refracture Stimulations Using a Novel Diversion Technique: SPE Hydraulic Fracturing Technology Conference, 19-21 January, The Woodlands, Texas, SPE-119636.

Vincent, M.C., P.T. Huckabee, 2007, Field Results to Guide Proppant Selection in the Pinedale Anticline: Rocky Mountain Oil & Gas Technology Symposium, 16-18 April, Denver, Colorado, U.S.A., SPE 108991.

Vincent, M.C., P. Huckabee, and M. Conway, 2007, Field Trial Design and Analyses of Production Data From a Tight Gas Reservoir: Detailed Production Comparisons From the Pinedale Anticline: SPE Hydraulic Fracturing Technology Conference, 29-31 January, College Station, Texas, U.S.A., SPE 106151.

Vincent, M.C., 2010, Refracs: Why Do They Work, and Why Do They Fail in 100 Published Field Studies? SPE Annual Technical Conference and Exhibition, 19-22 September, Florence, Italy, SPE 134330.

Vincent, M.C., 2011, Restimulation of Unconventional Reservoirs: When Are Refracs Beneficial? Journal of Canadian Petroleum Technology, v. 50/5, p. 36-52.

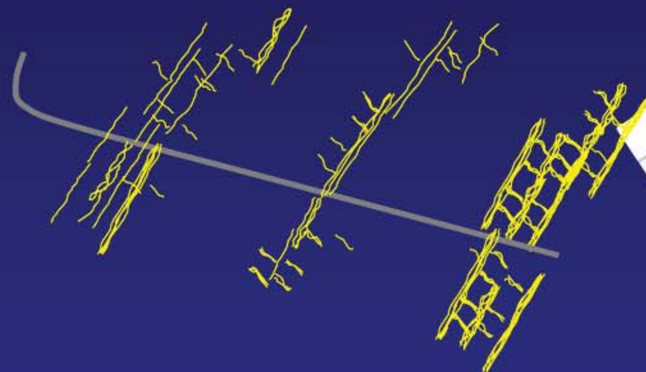
Vincent, M.C., 2011, Optimizing Transverse Fractures in Liquid-Rich Formations: SPE Annual Technical Conference and Exhibition, 30 October-2 November, Denver, Colorado, USA, SPE 146376.

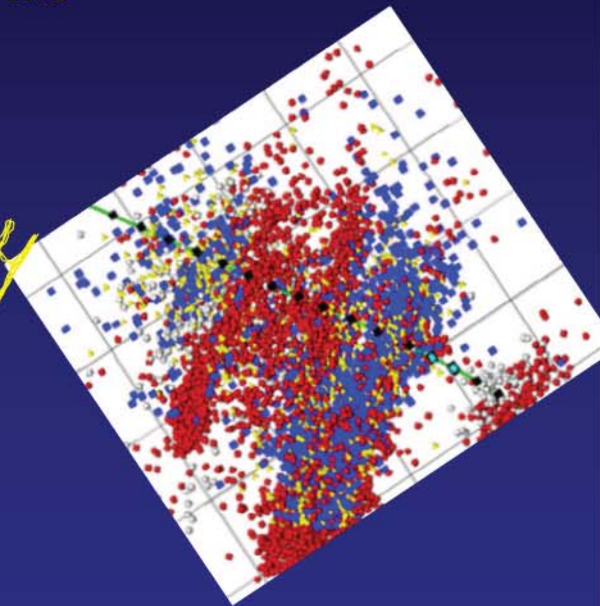
Vincent, M.C., and M.R. Besler, 2013, Declining Frac Effectiveness - Evidence that propped fractures lose conductivity, surface area and hydraulic continuity: Unconventional Resources Technology Conference, 12-14 August, Denver, Colorado, USA, URTeC 1579008.

Propped Fracs are Collapsing

What are the causes and ramifications?

AAPG GTW Mar 9-11, 2015 San Antonio





Fracwell LLC Insight Petroleum Consulting

Mike Vincent
mike@fracwell.com
303 568 0695

Microseismic image: SPE 119636

Outline

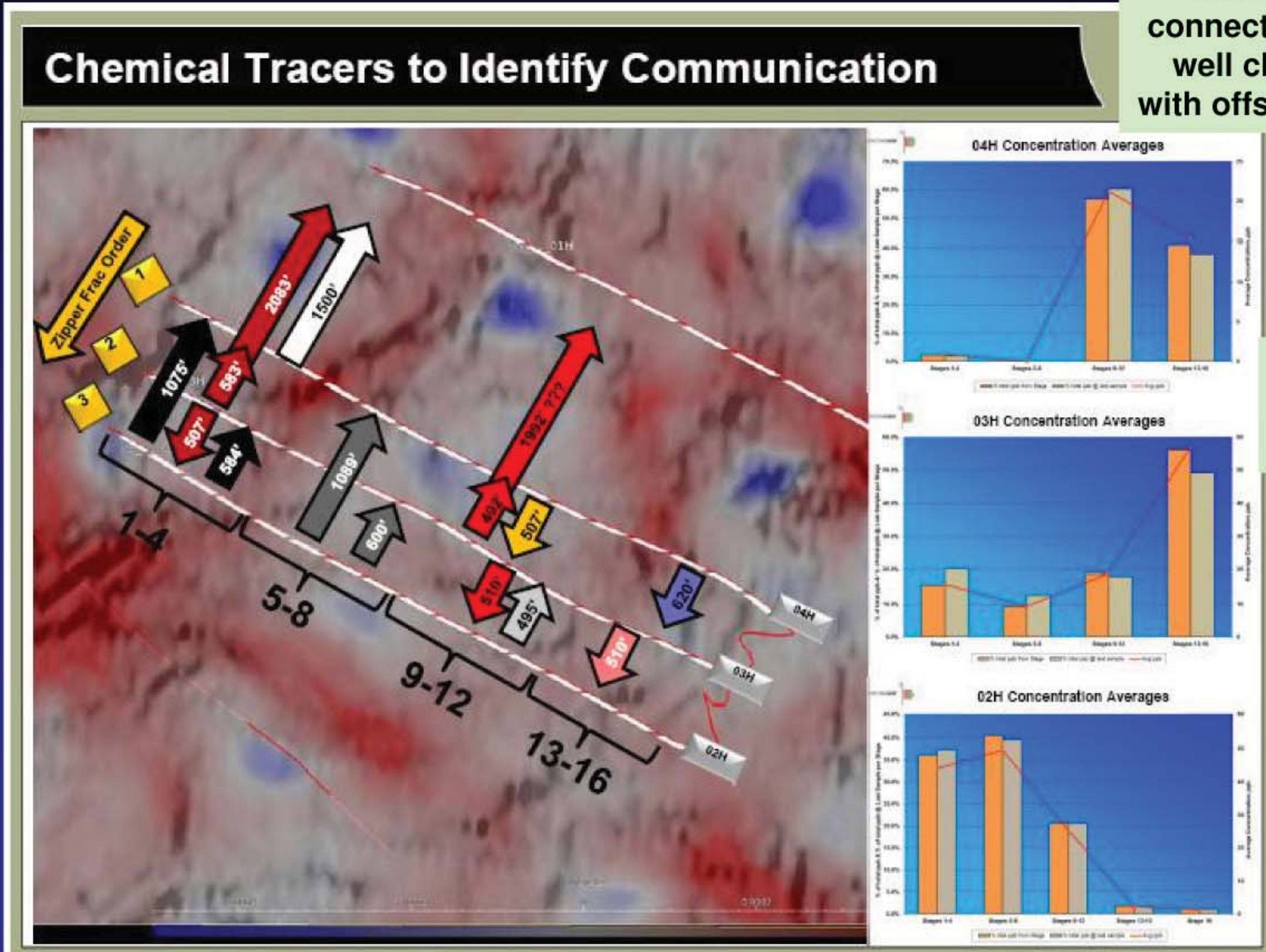
- Some evidence propped fracs are collapsing
  - Eagle Ford
  - Marcellus, Bakken, Niobrara

- Why? What are the mechanisms?

- Ramifications
  - Infill drill (both adjacent and vertical downspacing)
  - Refrac
  - Failure to understand resource potential
  - Or, we need to learn to design more durable initial fracs

Eagle Ford: Fractures Intersecting Offset Laterals

The intent of zipper fracs was to divert/deflect and not connect fracs. Yet center 03H well clearly communicated with offsets during stimulation.



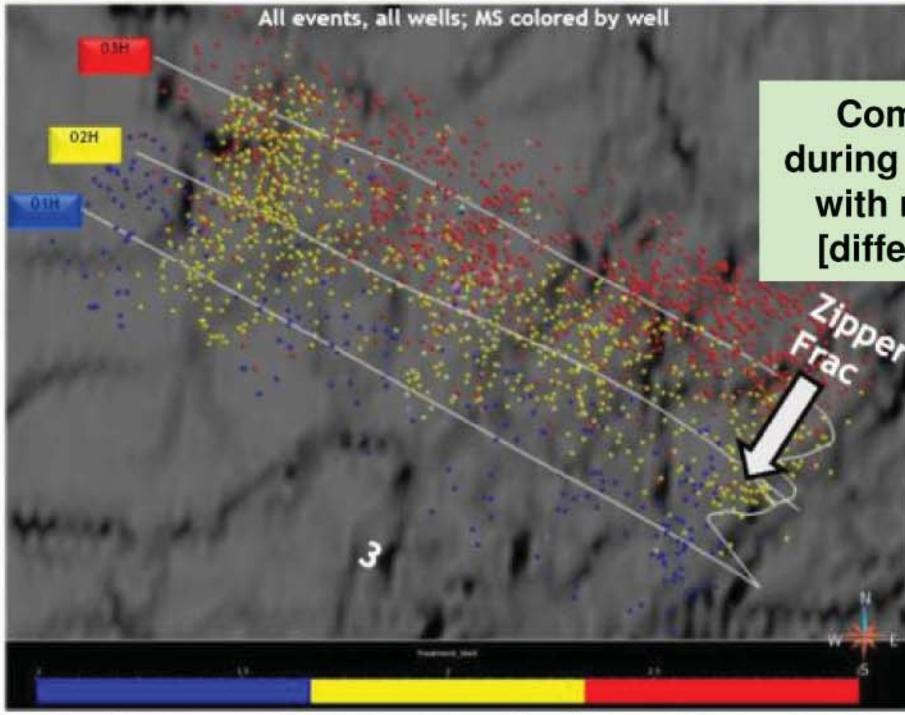
Communication during frac confirmed with chemical tracers

Murray, Santa Fe ATW, Mar 2013, and URTeC 1581750

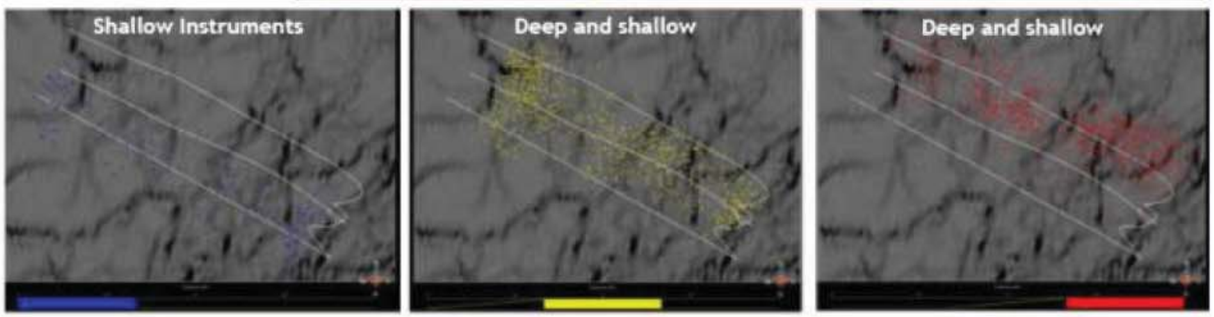
Eagle Ford: Fractures Intersecting Offset Laterals

Micro Seismic Data Collection

- Well 01H used for deep monitoring for wells 02H and 03H zipper fracs.
- Well 01H frac'd after zipper frac of wells 02H and 03H.
- Limited micro seismic data collected on well 01H because no deep instruments.
- Zipper frac order
  - 03H
  - 02H



Communication during frac confirmed with microseismic [different well set]

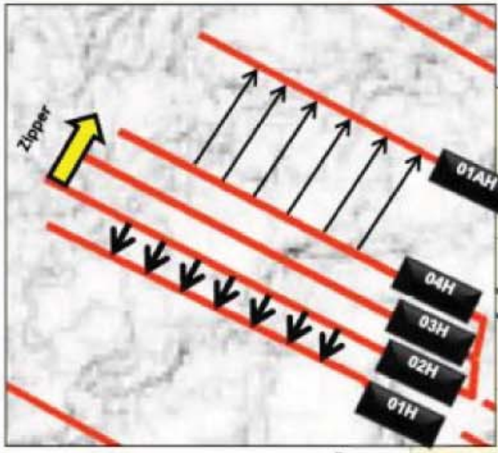


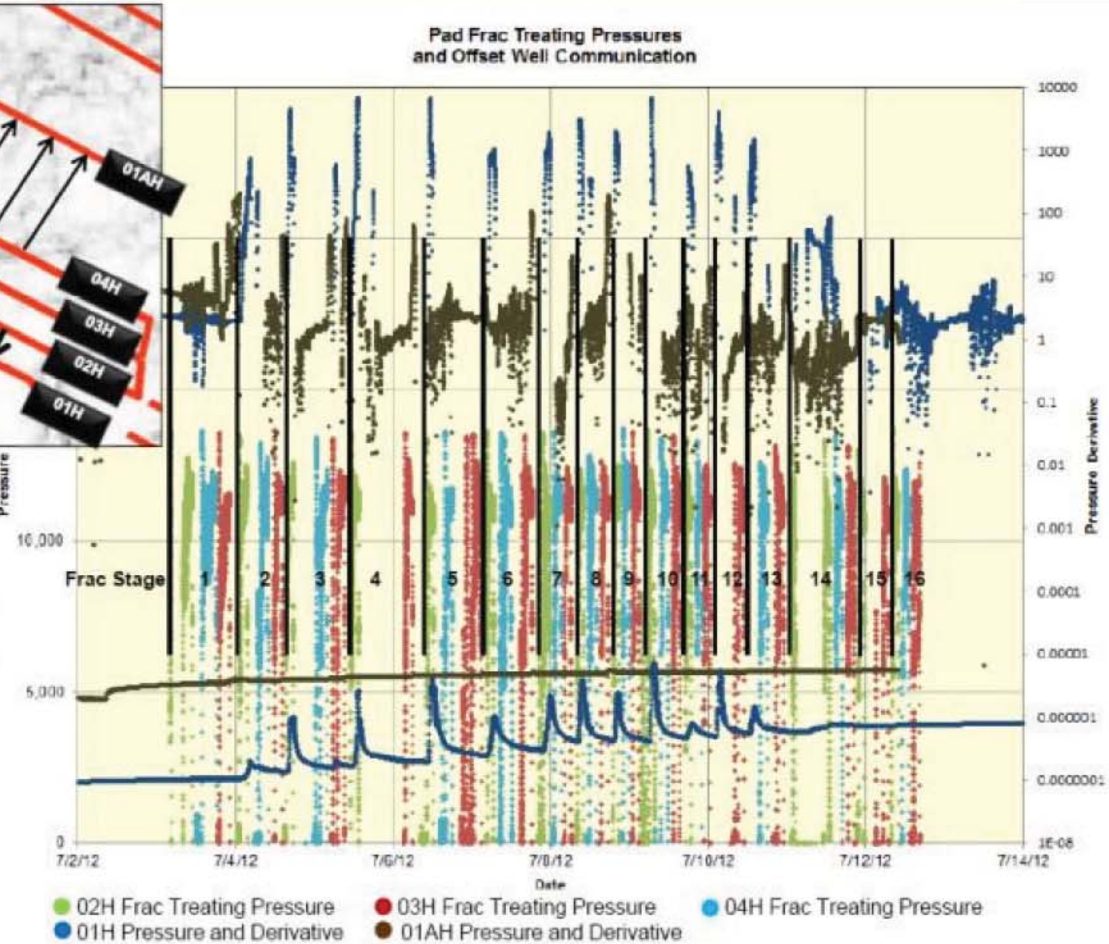
Murray, Santa Fe ATW, Mar 2013

Eagle Ford: Fractures Intersecting Offset Laterals

Communication during frac evident from treating pressures

Frac Treatment Pressure Response





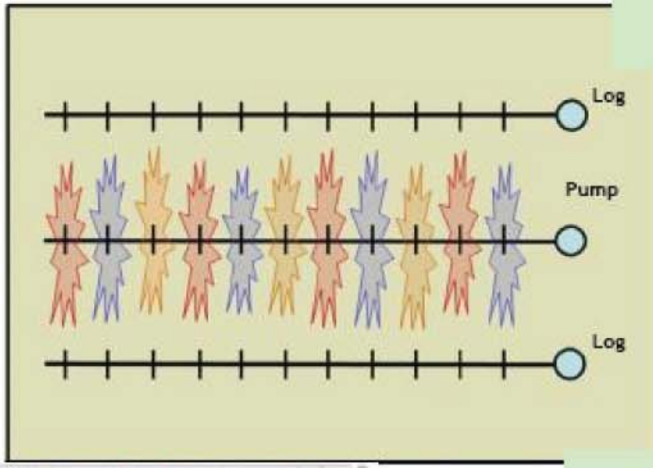
- 02H frac increased pressure in 01H more than 1,500 psi (500 ft).
- Slight pressure response in 01AH due to 04H frac (1,700 ft).

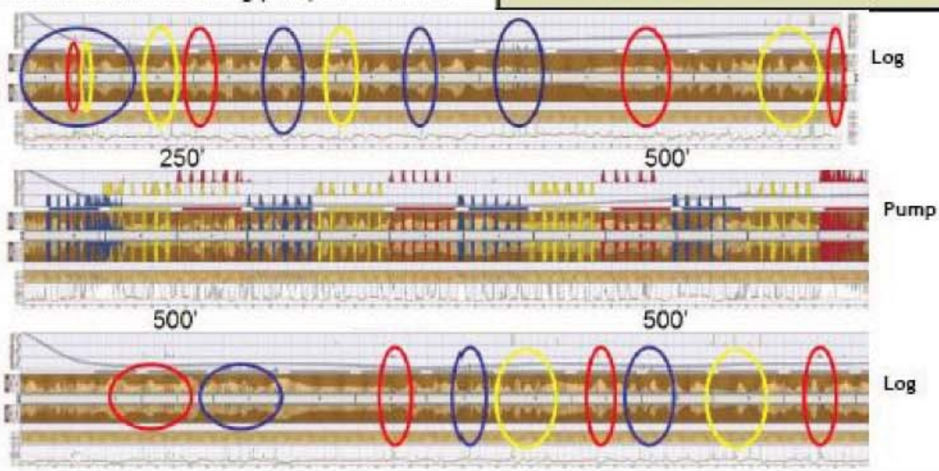
Murray, Santa Fe ATW, Mar 2013, and URTeC 1581750

Eagle Ford: Fractures Intersecting Offset Laterals

Radioactive Tracers (RA Tracers)

- **Basics:**
  - Tracer material is a resin coated grain of ceramic proppant that is irradiated in a reactor
  - 3 isotopes
    - Iridium
    - Scandium
    - Antimony
  - RA usually last ~12 months
- **Work flow:**
  - Pump Radioactive Tracer in one or more wellbores.
  - Ran GR log in all wells to analyze proppant transport between laterals as well as along pumped wellbore.





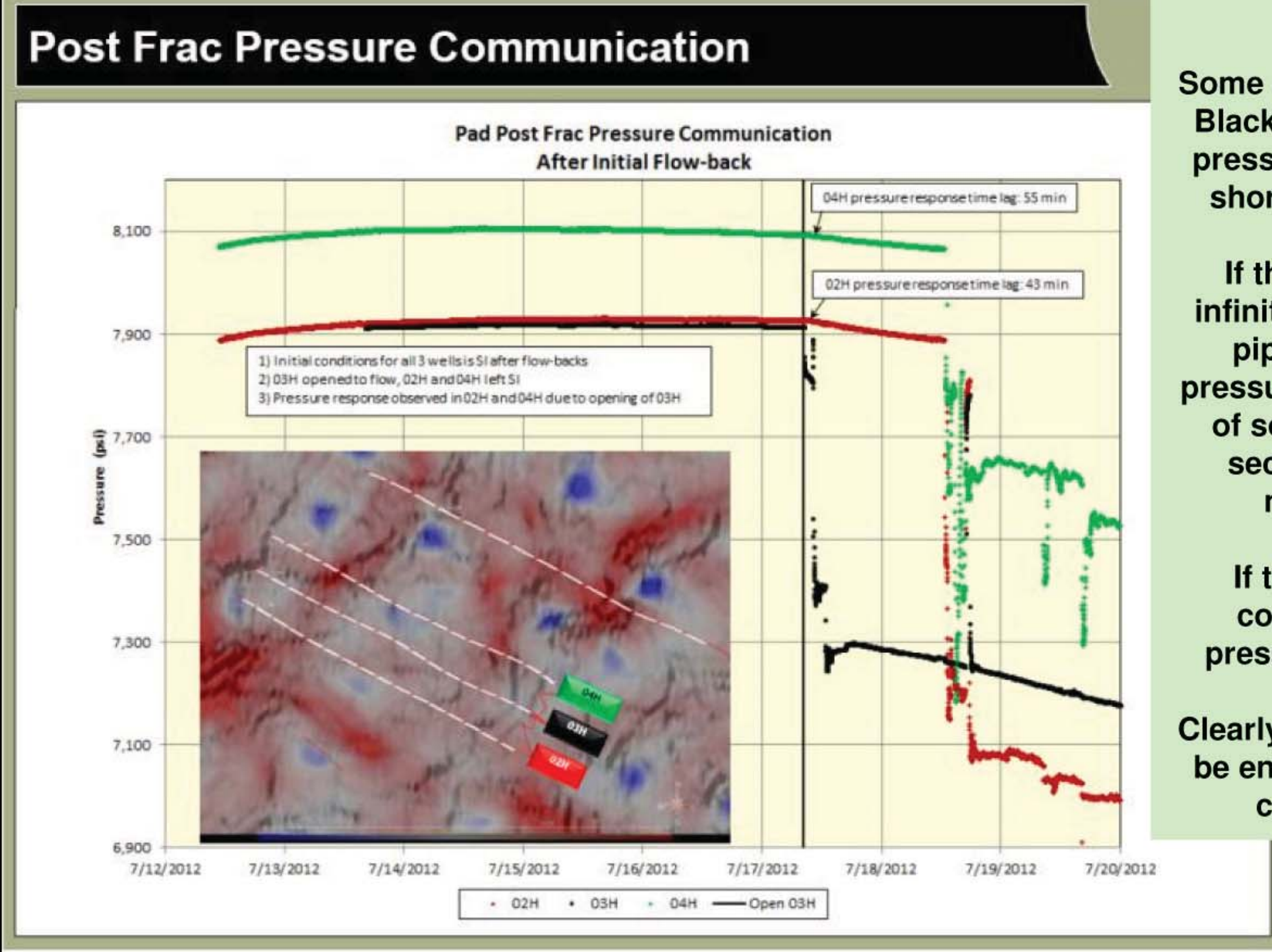
Eagle Ford

Communication during frac confirmed with solid RA tracers in most stages

**Cool.
All diagnostics showed we "communicated" during the treatment.
Can we measure the effectiveness and durability of the connecting fractures?**

Murray, Santa Fe ATW, Mar 2013, and URTeC 1581750

Eagle Ford: Fractures Intersecting Offset Laterals



Eagle Ford

Some degree of connection. Black well is able to lower pressure in adjacent wells shortly after stimulation

If the fracture were an infinitely conductive open pipe, we would see a pressure pulse at the speed of sound (less than one second) instead of 50 minutes lag time

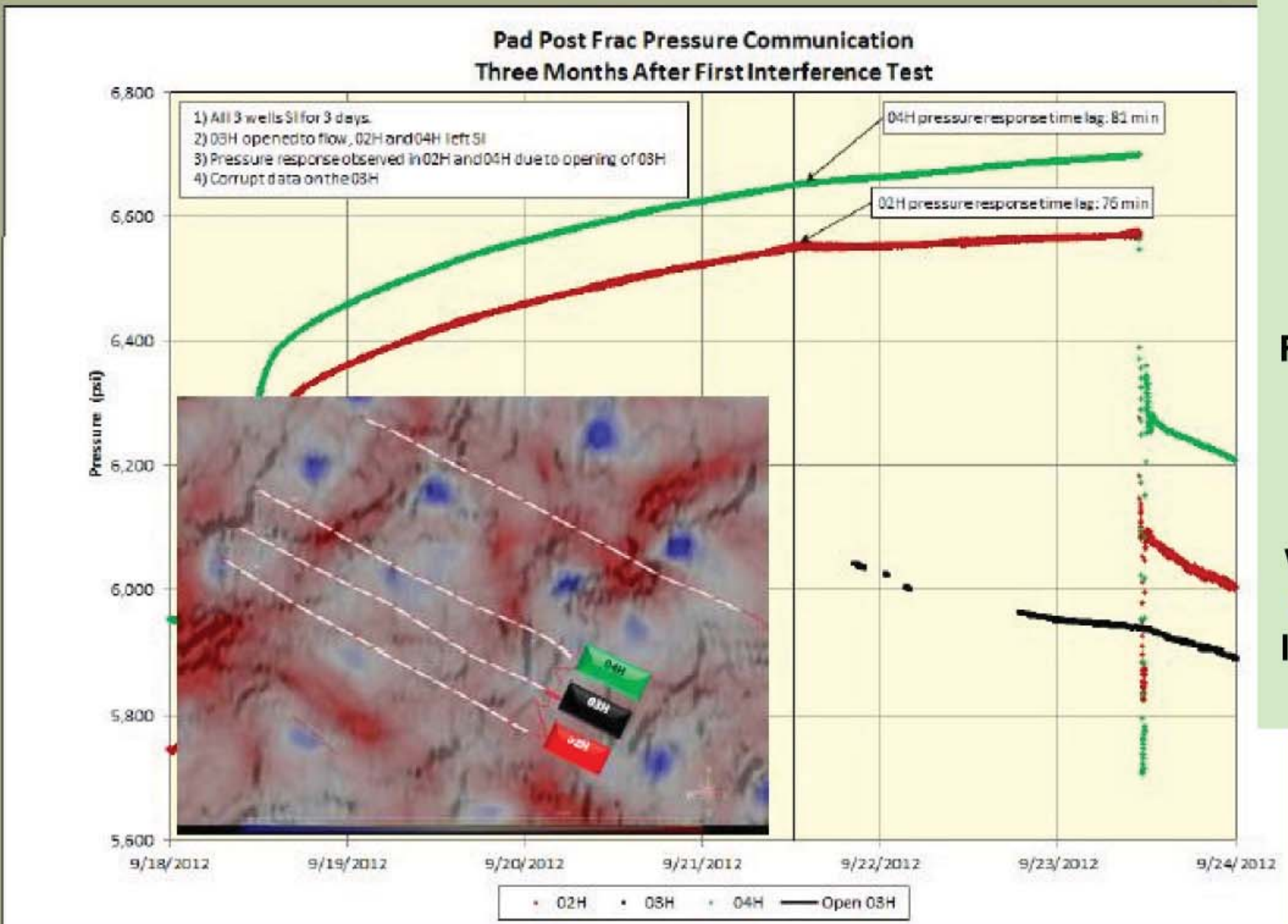
If they were infinitely conductive fracs, all pressures would overlay

Clearly, the fracs should not be envisioned as infinitely conductive pipes.

Murray, Santa Fe ATW, Mar 2013, and URTeC 1581750

Eagle Ford: Fractures Intersecting Offset Laterals

Post Frac Pressure Communication



3 months later, the black well is incapable of draining gas from offsets as fast as the reservoir can deliver hydrocarbons!

Lag time increased.

The wells are not redundant.

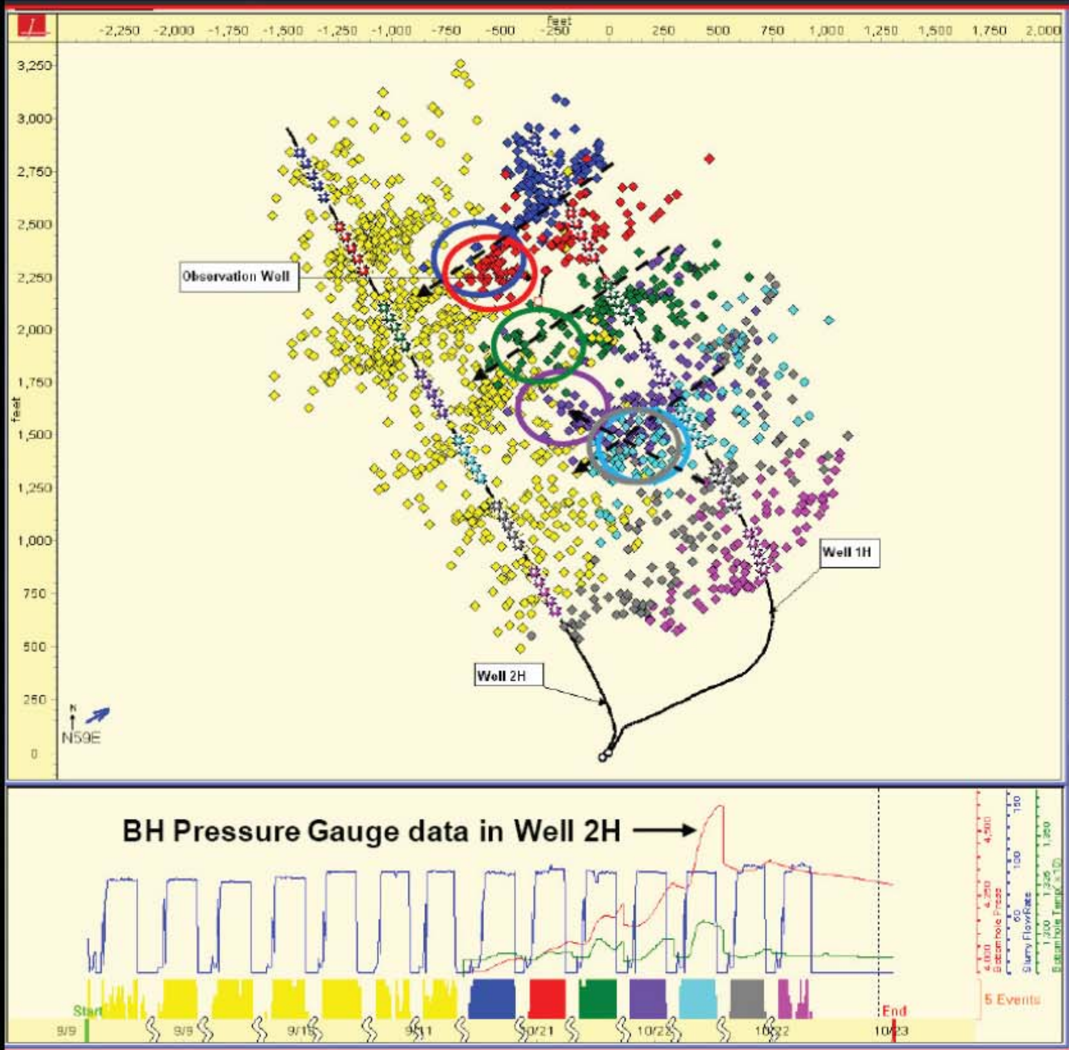
Frac connection between wells is constraining productivity, clearly not behaving like an infinitely conductive frac.

Where did the created fracture heal? Near wellbore void? At laminations? At some distance between wells?

Similar evidence of fracture collapse in Niobrara, Bakken, Marcellus…

Murray, Santa Fe ATW, Mar 2013, and URTeC 1581750

Marcellus Fractures Intersecting Offset Laterals



Marcellus - Slickwater

950 ft spacing. 1H treated 5 weeks after 2H

Cemented, 7 stage PnP
Slickwater 100 mesh, 40/70 and 30/50 sand
~6000 ft TVD

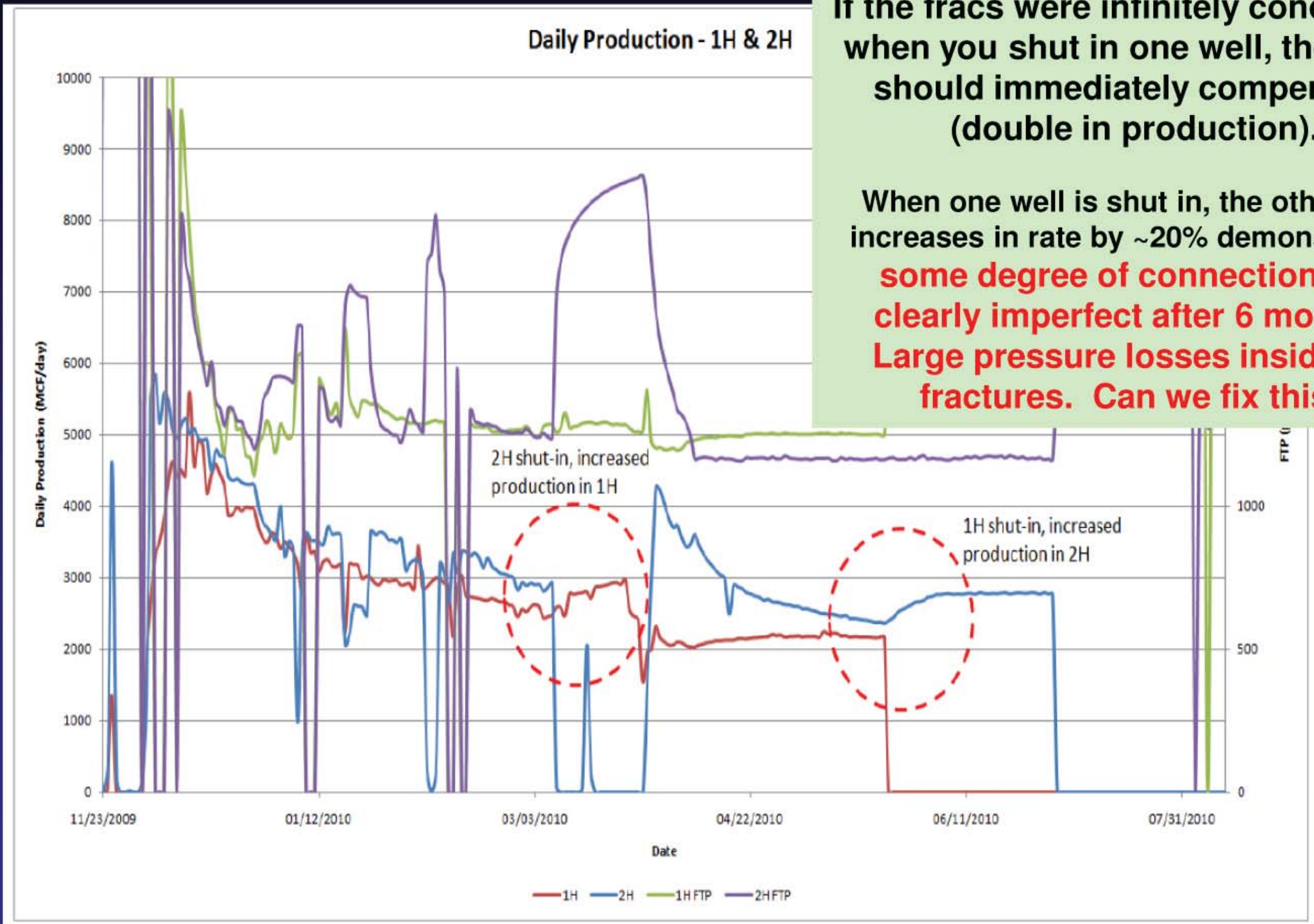
Microseismic, DFITS, downhole pressure gauges, PTA, chemical tracers, production interference

Pressure communication in 6 of 7 stages
Chem tracers from 2,3,5,6,7 recovered in 2H

So how much conductivity would you expect in the fractures connecting the wells?

Mayerhofer SPE 145463 – Nov 2011
Pinnacle and Seneca

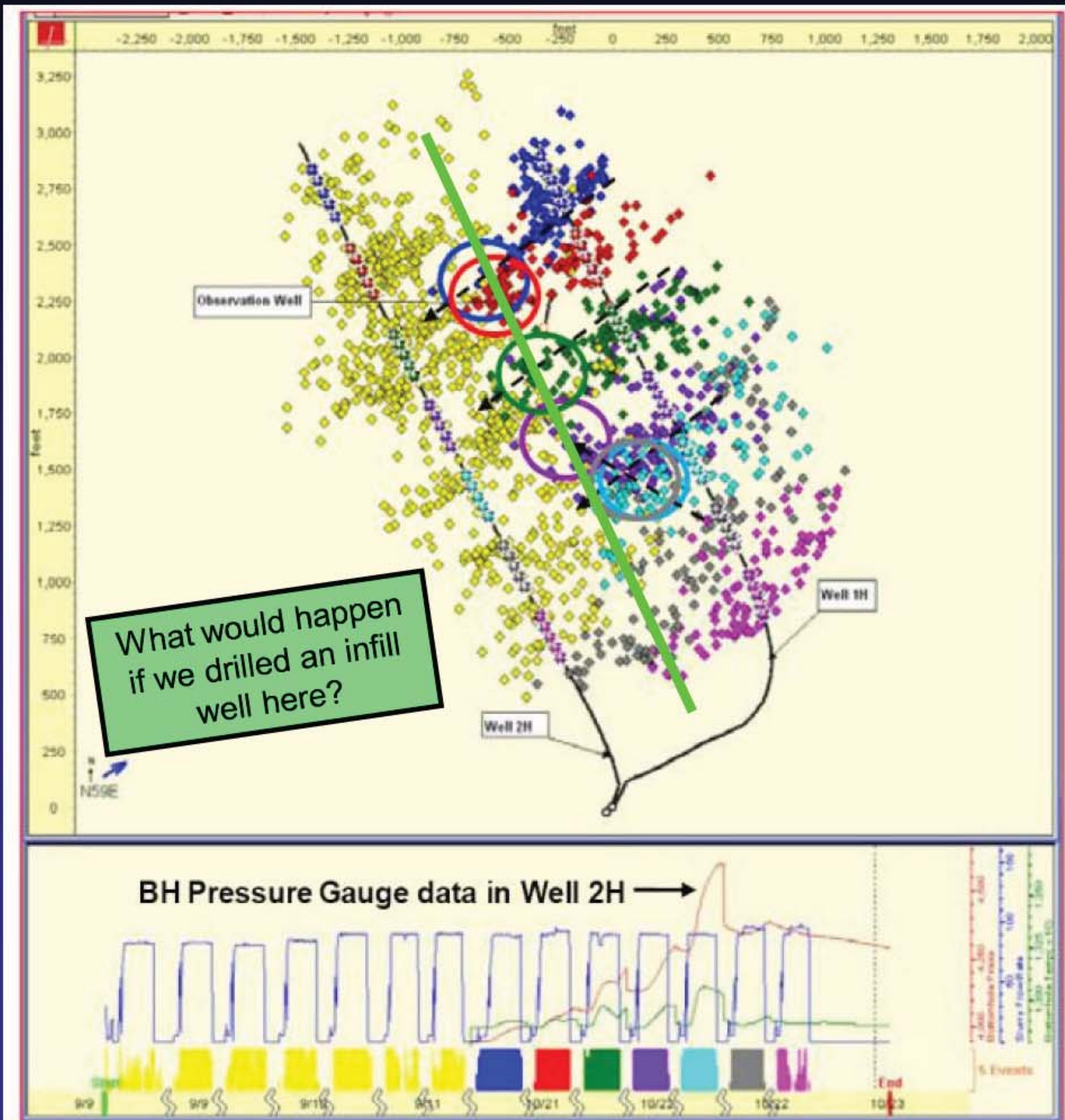
Marcellus Fractures Intersecting Offset Laterals



If the fracs were infinitely conductive, when you shut in one well, the other should immediately compensate (double in production).

When one well is shut in, the other well increases in rate by ~20% demonstrating some degree of connection, but clearly imperfect after 6 months. Large pressure losses inside the fractures. Can we fix this?

Marcellus Fractures Intersecting Offset Laterals



Mayerhofer SPE 145463 – Nov 2011
Pinnacle and Seneca

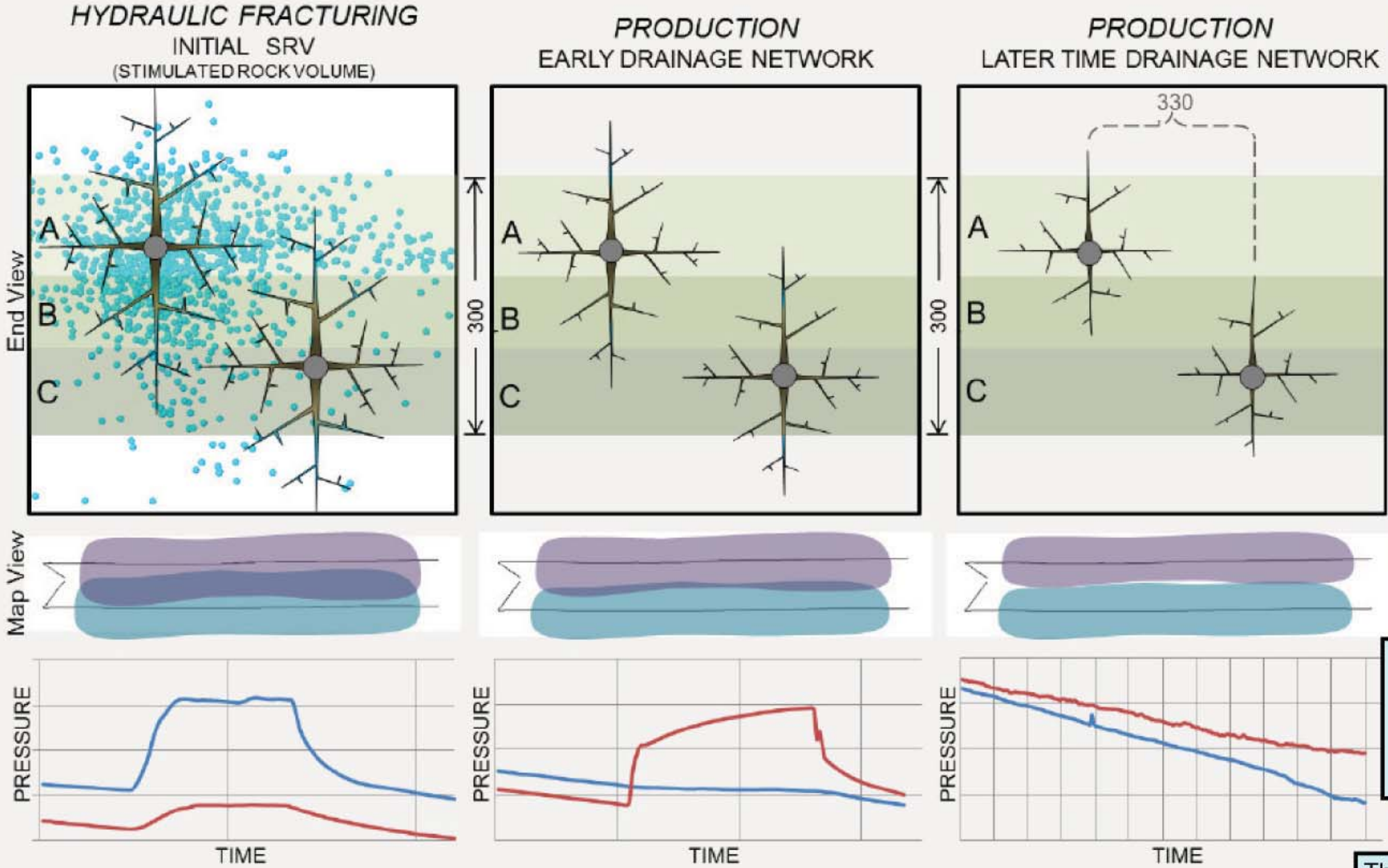
Marcellus – Wells on 500 ft spacing do not appear to share reserves

- SPE 140463 – Edwards, Weisser, Jackson, Marcotte [EQT&CHK]
  - All diagnostics (microseismic, chemical tracers, surface pressure gauges, etc) indicate fracturing treatments interact.
  - Well-to-well connection while the reservoir is dilated with frac fluid.
  - Microseismic suggests lengths >1000 ft
  - Production analysis estimates ~150 ft effective half length after 6 months
  - However, wells drilled on 500 ft spacing are similar in productivity to those on 1000 ft spacing, suggesting they are not competing for reserves

Similar findings in Niobrara, Eagle Ford, Barnett, Bakken, many Permian Wolfcamp, Spraberry, etc.

We can infill drill on much closer spacing than anticipated.
We are leaving reserves behind!

Frac Collapse over Time - Niobrara



- *Constructive interference*
- Calibrated with: Microseismic, pressure gauges, proppant tracers & DTS

- Reducing interference
- Calibrated with: Pressure gauges & geochemistry

- Low interference
- Calibrated with: Pressure gauges & geochemistry

The pressure plots are REAL data

Third figure is ~2 yrs post frac. Diverging BHFP

Link: Noble Underground Lab, Dave Koskella Jan 2015

What do these results demonstrate?

1. We know we have pumped proppant from one wellbore into another.
2. We can directly interrogate the conductivity and durability of the fracs.
3. The results are not pretty. We are pursuing enormous investments in downspacing.

So what are some of the culprits that cause fracs to not perform as we modeled?

Portions of the following list are discussed in URTeC 1579008

Potential Mechanisms – Frac Collapse (2 of 3)

All of these are multi-disciplinary issues

Plausible "Geology" Problems:

- Embedment of proppant. Spalling of frac face. Continued rock creep.
- Fluid sensitivity – evidence that some frac fluids "soften" the formation allowing more significant embedment and/or spalling – Clay swelling, etc.
- Failure to land lateral in strata that will accommodate our stupid completion practices
- Precipitation of salt, asphaltenes, barium sulfate and calcium carbonate scales or migration of fines (formation fines). Bio-slime or corrosion. H_2S, CO_2 damage
- Potential for chemical diagenesis of proppant (controversial and conflicting laboratory studies). To date, proppant samples recovered from wells do not appear to indicate formation of zeolites
- Continued slippage of frac faces after closure impacting continuity
- Pore pressure depletion/subsidence/compaction "stranding" thin proppant ribbons
- Others?

Potential Mechanisms – Frac Collapse (3 of 3)

All of these are multi-disciplinary issues

"Whose Responsibility?" Problems:

- Failure to recover water from liquid-submerged portions of the fracture below the wellbore elevation
- Aggressive production techniques to report high IPs (some fracs vulnerable to drawdown)
- Industry rush to secure acreage as "held by production" without adequate attention to completion effectiveness or optimization. Frenetic development pace has reduced many completion engineers' primary responsibility to be scheduling and assuring materials are available, with less time devoted to optimization of well productivity
- Rel perm/condensate banking/capillary pressure/water block   Emulsions
- Stress shadowing causing unanticipated issues
  - Next stage "compresses" existing frac. Might move slurry in existing fracs containing XL gel
- Complex frac geometry requiring stronger or more conductive proppant in the turns and "pinch points". Inability to push proppant through tortuous network.
- Wellbores plugged with frac sand somehow providing complete isolation [doubtful]. Salt, scale, or fines maybe?…

No single discipline is expert in all these mechanisms… We need the right team!

Potential Mechanisms – Frac Collapse (3 of 3)

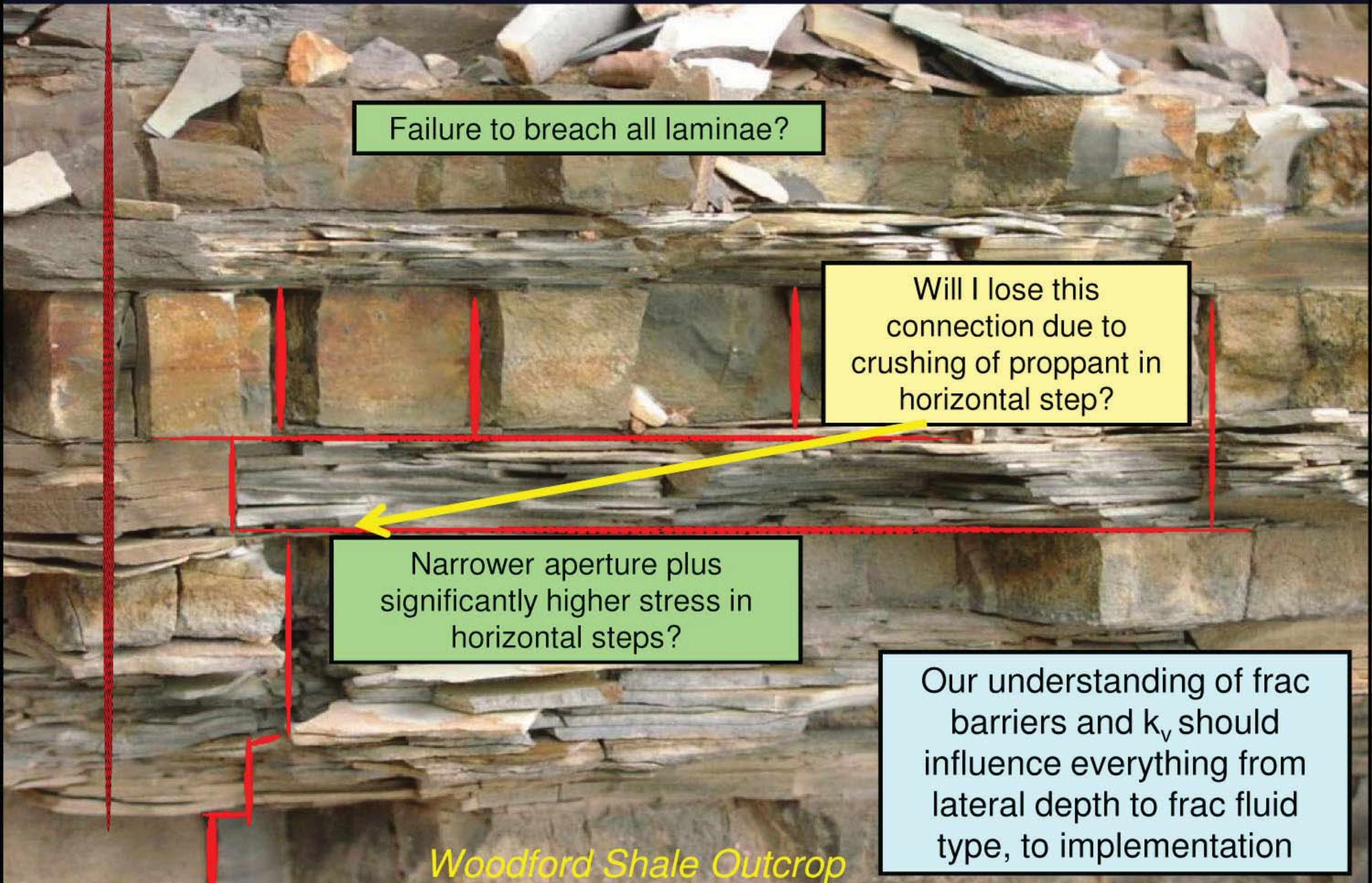
All of these are multi-disciplinary issues

"Whose Responsibility?" Problems:

- Failure to recover water from liquid-submerged portions of the fracture below the wellbore elevation
- Aggressive production techniques to report high IPs (some fracs vulnerable to drawdown)
- Industry rush to secure acreage as "held by production" without adequate attention to completion effectiveness or optimization. Frenetic development pace has reduced many completion engineers' primary responsibility to be scheduling and assuring materials are available, with less time devoted to optimization of well productivity
- Rel perm/condensate banking/capillary pressure/water block   Emulsions
- Stress shadowing causing unanticipated issues
  - Next stage "compresses" existing frac. Might move slurry in existing fracs containing XL gel
- Complex frac geometry requiring stronger or more conductive proppant in the turns and "pinch points". Inability to push proppant through tortuous network.
- Wellbores plugged with frac sand somehow providing complete isolation [doubtful]. Salt, scale, or fines maybe?…

No single discipline is expert in all these mechanisms… We need the right team!

If I cannot sustain lateral continuity with conventional frac designs, what about VERTICAL continuity?



Thought Experiment:
Can I be creating highly conductive vertical fracs?

If I created this infinitely conductive vertical frac,

lateral placement (depth) wouldn't significantly affect productivity in Eagle Ford.

But it does!

[Marathon, EF Energy, SLB, EP Energy in Aug 2013 ATW]

Eagle Ford Shale Outcrop
Peschler, AAPG

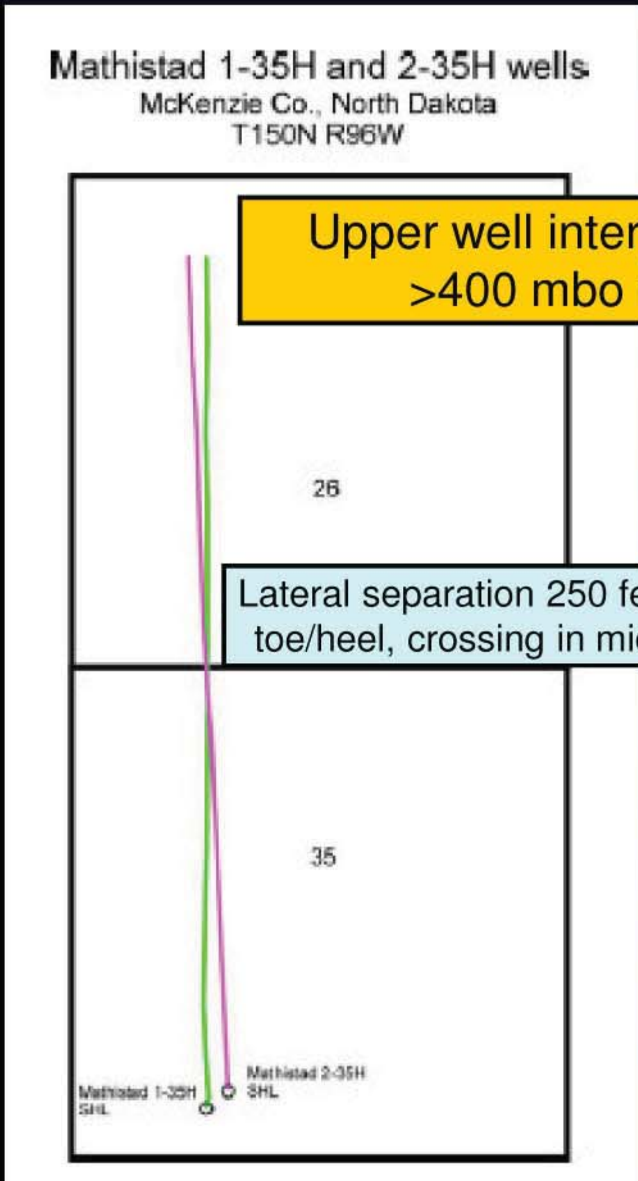
Laminated on every scale?

Figure 2 – On every scale, formations may have laminations that hinder vertical permeability and fracture penetration. Shown are thin laminations in the Middle Bakken [LeFever 2005], layering in the Woodford [outcrop photo courtesy of Halliburton], and large scale laminations in the Niobrara [outcrop and seismic images courtesy of Noble]

Outline

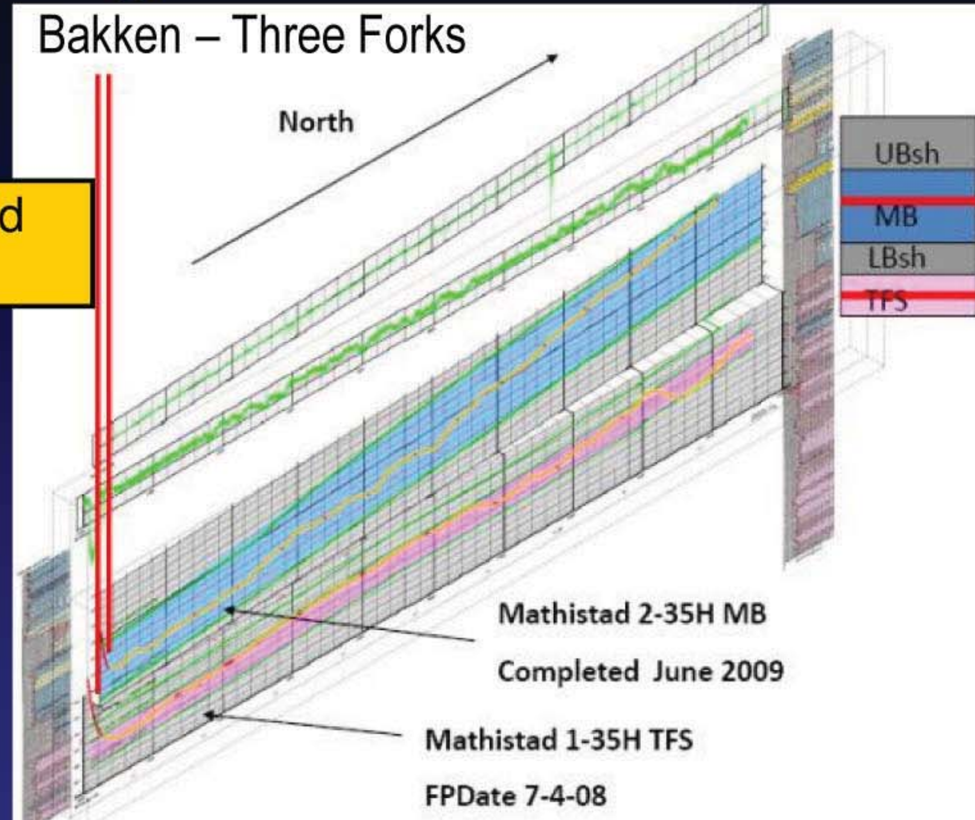
- Some evidence propped fracs are collapsing
  - Eagle Ford
  - Marcellus, Bakken, Niobrara
- Why? What are the mechanisms?
- Ramifications
  - Infill drill (both adjacent and vertical downspacing)
  - Refrac
  - Failure to understand resource potential
  - Or, we need to learn to design more durable initial fracs

Fractures Intersecting Stacked Laterals



Upper well interpreted to add >400 mbo reserves

Lateral separation 250 feet at toe/heel, crossing in middle



23 ft thick Lower Bakken Shale

Frac'ed Three Forks well ~1MM lb proppant in 10 stages

1 yr later drilled overlying well in Middle Bakken; K_v<0.000,000,01D (<0.01 µD)

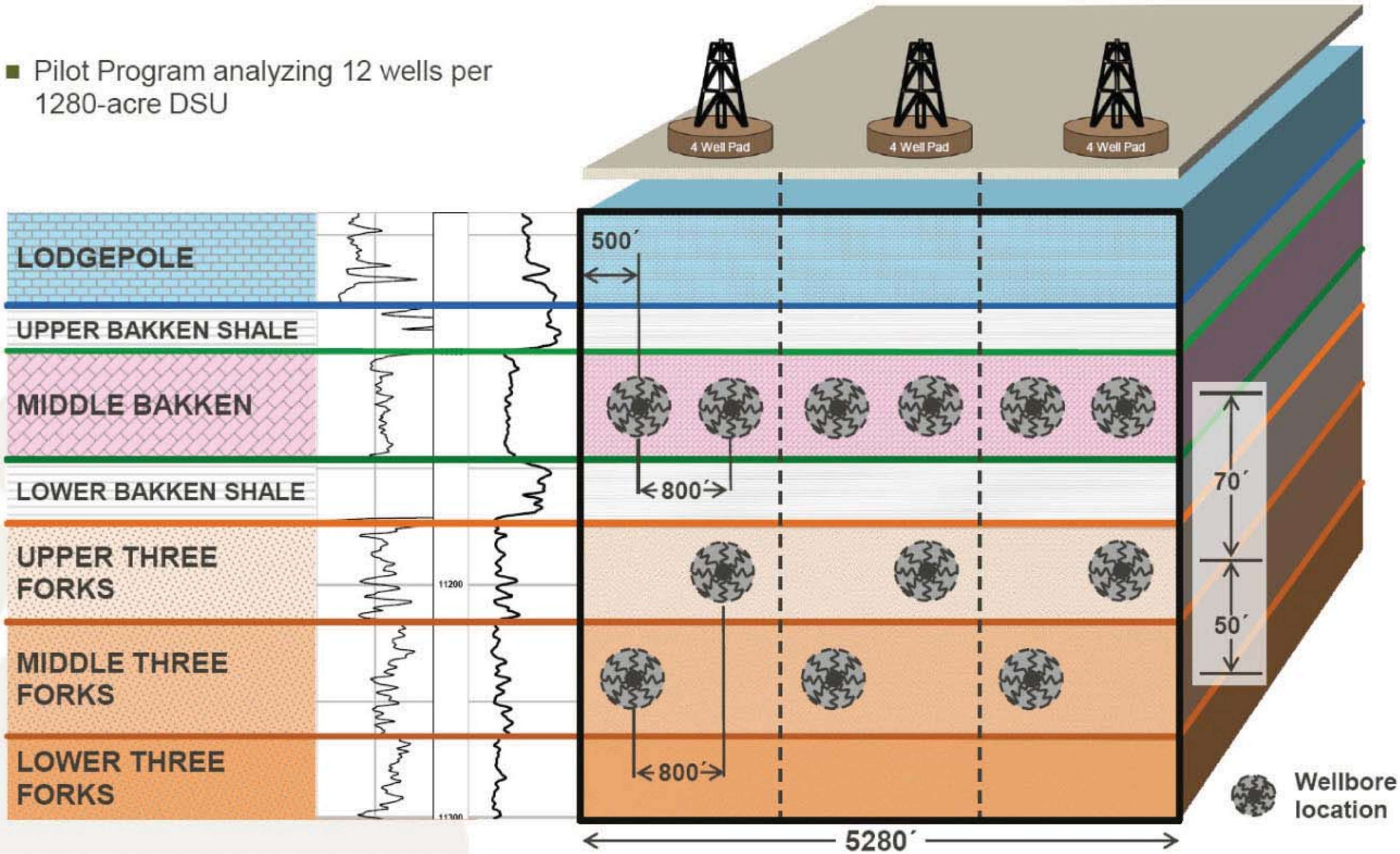
k_v/k_h~0.00025

Modified from Archie Taylor SPE ATW – Aug 4 2010

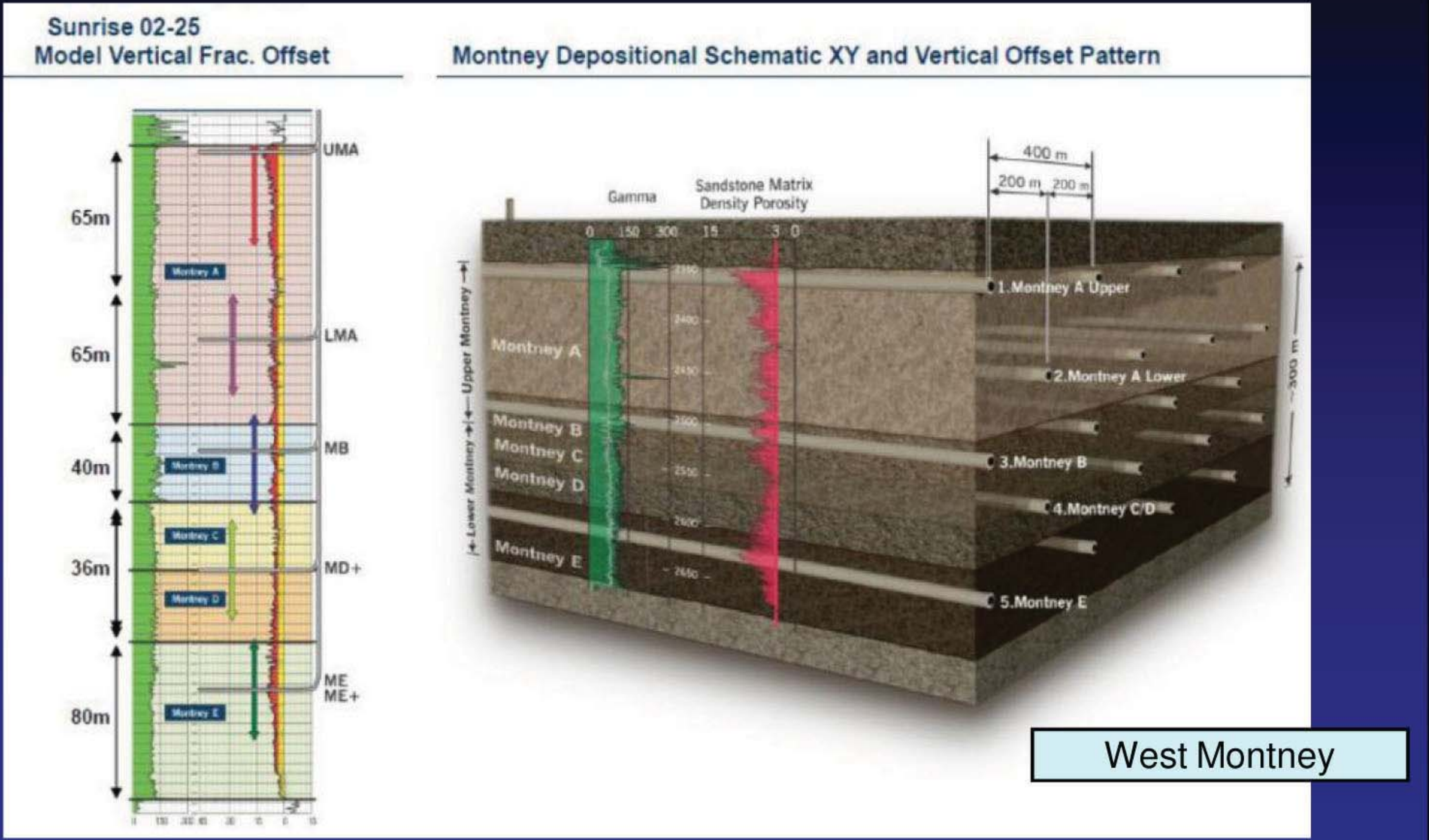
Bakken Operators – Well Spacing Pilots

Polar & Smokey Pilot Projects:
Reservoir Well Spacing Pattern

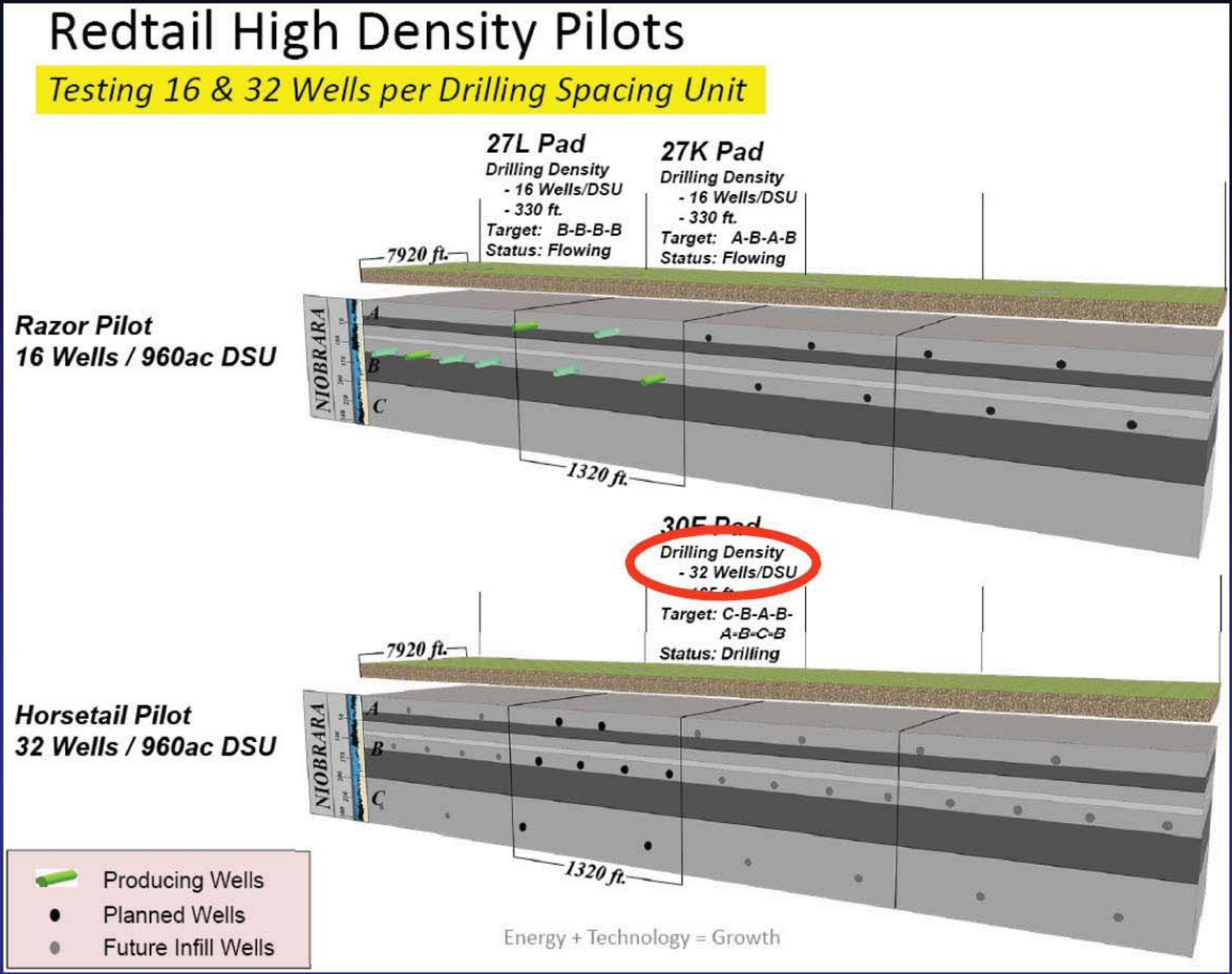
- Pilot Program analyzing 12 wells per 1280-acre DSU



Same Challenge in Montney?



Same Challenge in Niobrara?

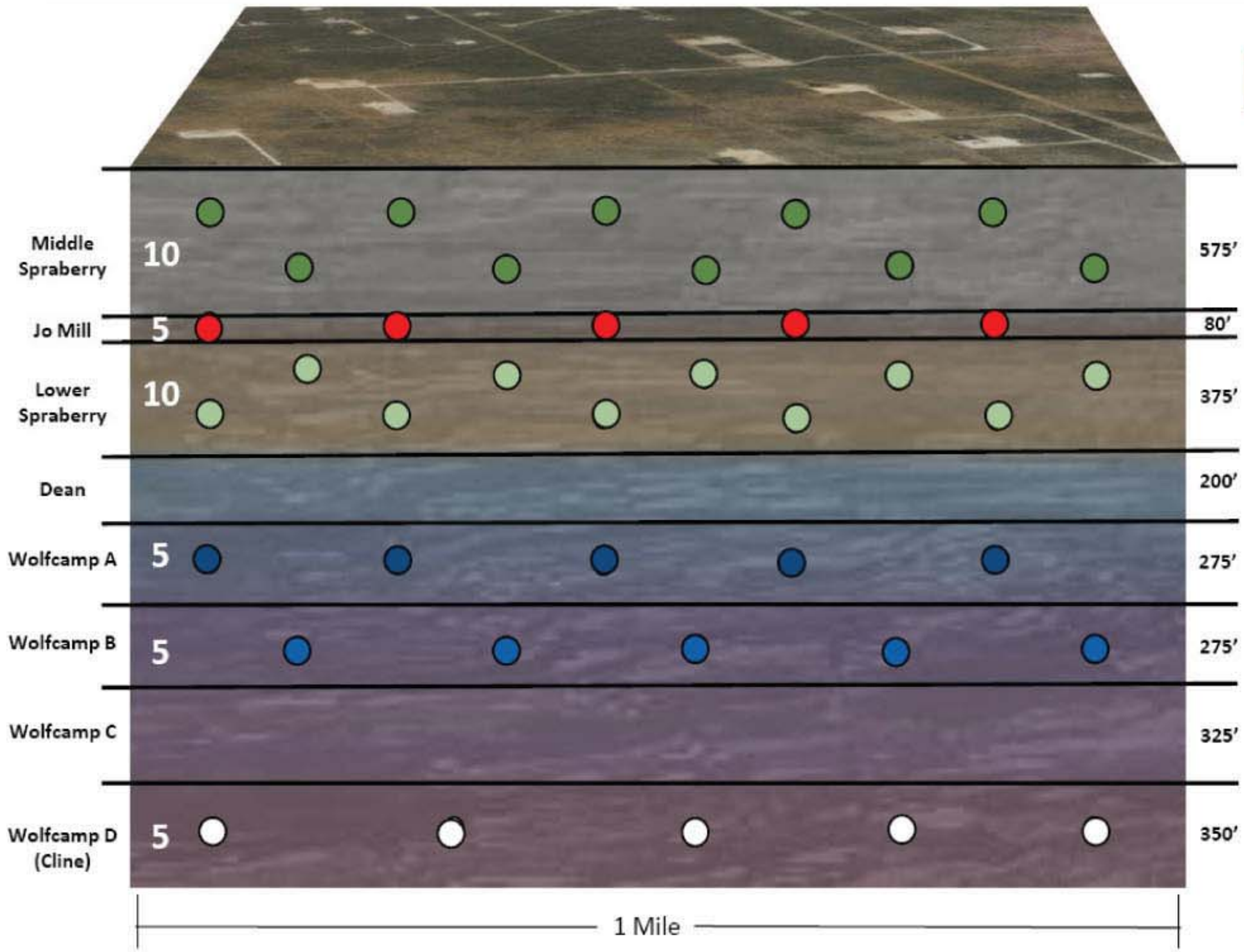


Source: Whiting Corp Presentation, Mar 2014

How about the entire Wolfberry?

Cross Bar Microseismic – Conclusions and Implications

Hypothetical Development Scheme Implied by Cross Bar Ranch Microseismic Study



Preliminary Microseismic Conclusions:

<u>Middle Spraberry</u> – Micro Seismic indicates 10 wells across one mile

<u>Jo Mill</u> – Micro Seismic indicates undeveloped gap between MS and LS

<u>Lower Spraberry</u> – Micro Seismic indicates 10 wells across one mile

<u>Dean</u> – Micro Seismic indicates Dean is covered by LS and WA stimulation

<u>Wolfcamp A</u> – Micro Seismic indicates correct spacing of 5 wells across one mile

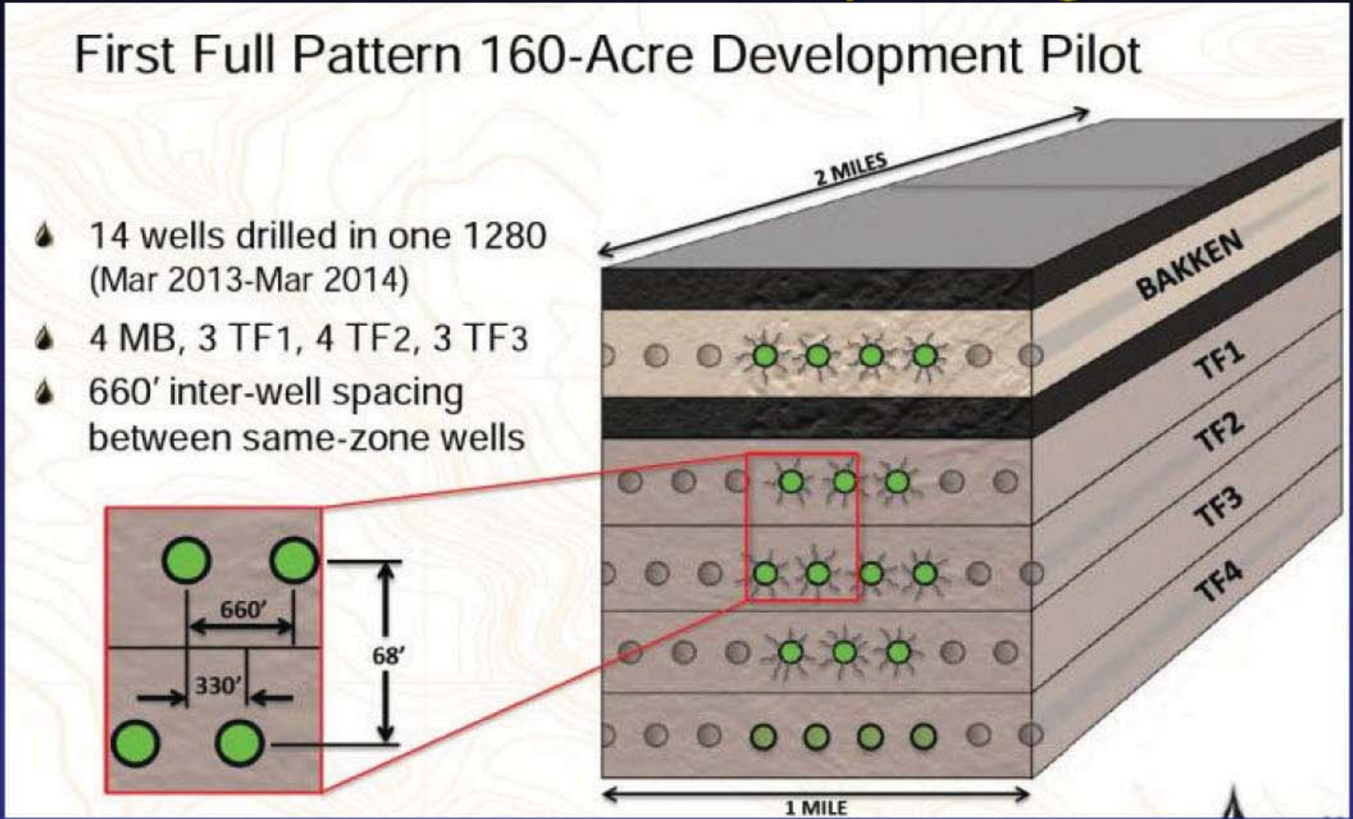
<u>Wolfcamp B</u> – Micro Seismic indicates correct spacing of 5 wells across one mile

<u>Wolfcamp D (Cline)</u> – No data available for verification of spacing

Potential for 40 horizontal wells across 1 mile section

Data Sources: RSP Permian based on surface microseismic

Continuity Loss
Necessitates vertical downspacing?



A number of operators are investigating "vertical downspacing" in the Bakken petroleum system. Similar efforts underway in Niobrara, Woodford, Montney and Permian formations.

Is it ***possible*** that some number of these expensive wells could be unnecessary if fractures were redesigned?

"Array Fracturing" or "Vertical Downspacing" Image from CLR Investor Presentation, Continental, 2012

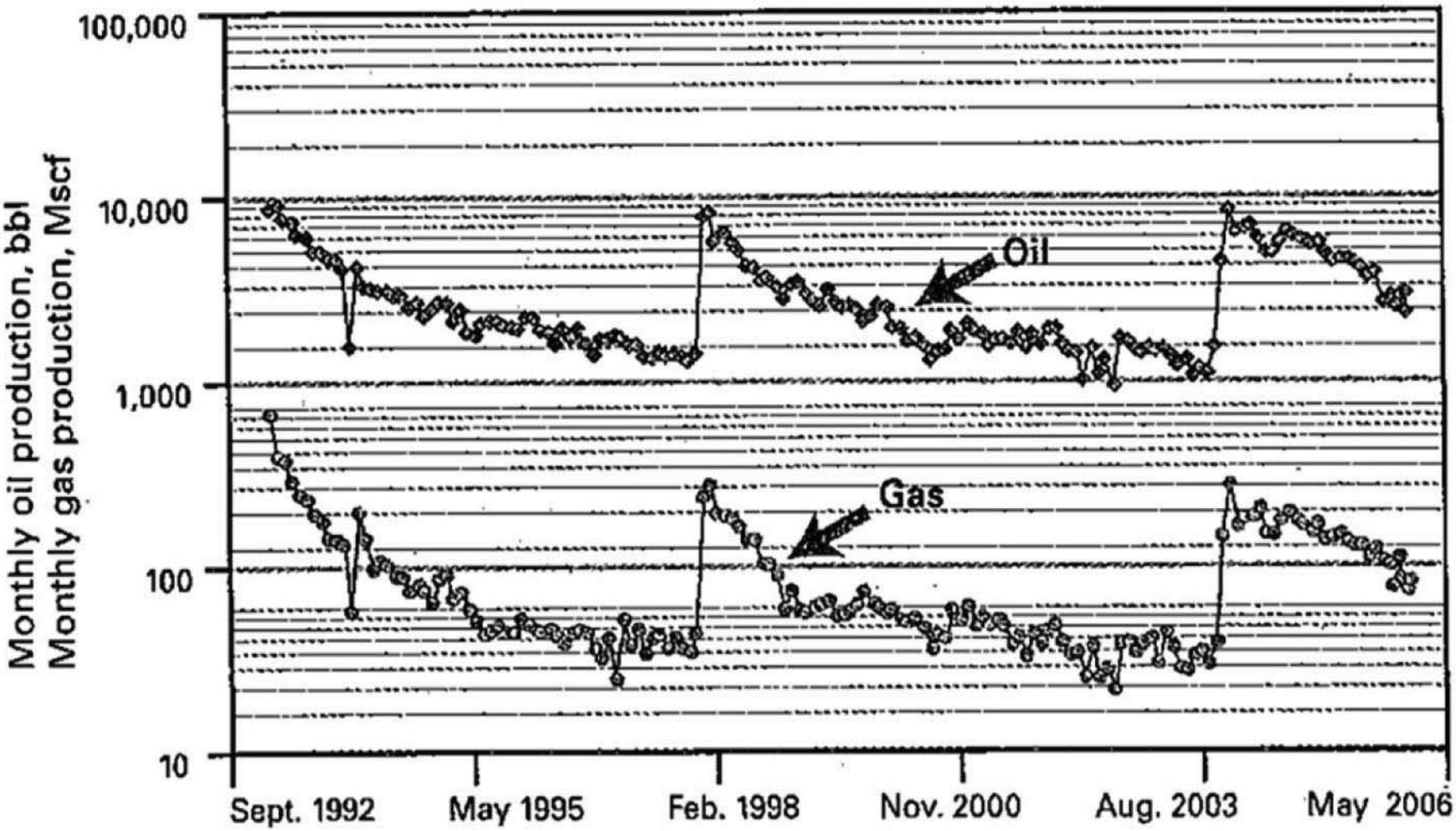
Outline

- Some evidence propped fracs are collapsing
  - Eagle Ford
  - Marcellus, Bakken, Niobrara

- Why? What are the mechanisms?

- Ramifications
  - Infill drill (both adjacent and vertical downspacing)
  - Refrac
  - Failure to understand resource potential
  - Or, we need to learn to design more durable initial fracs

Why do Refracs work so often?



Codell - Pagano, 2006 – discussed in 134330 and 136757

Successful refracs have been performed in Barnett, Eagle Ford, Bakken, Marcellus, Haynesville, Niobrara, Spraberry, Wolfcamp…

Does this demonstrate that our initial well was not optimized?

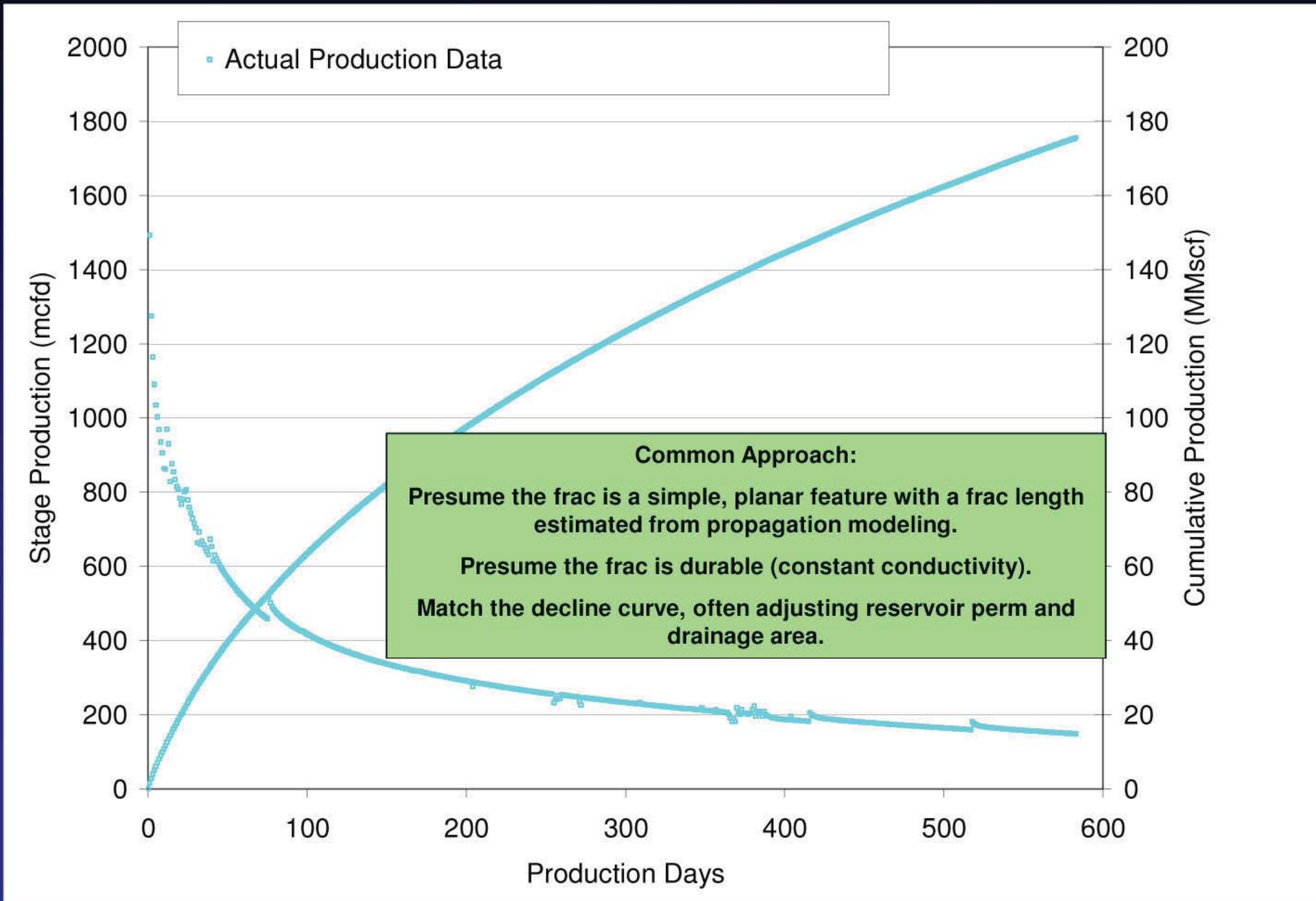
Outline

- Some evidence propped fracs are collapsing
  - Eagle Ford
  - Marcellus, Bakken, Niobrara

- Why? What are the mechanisms?

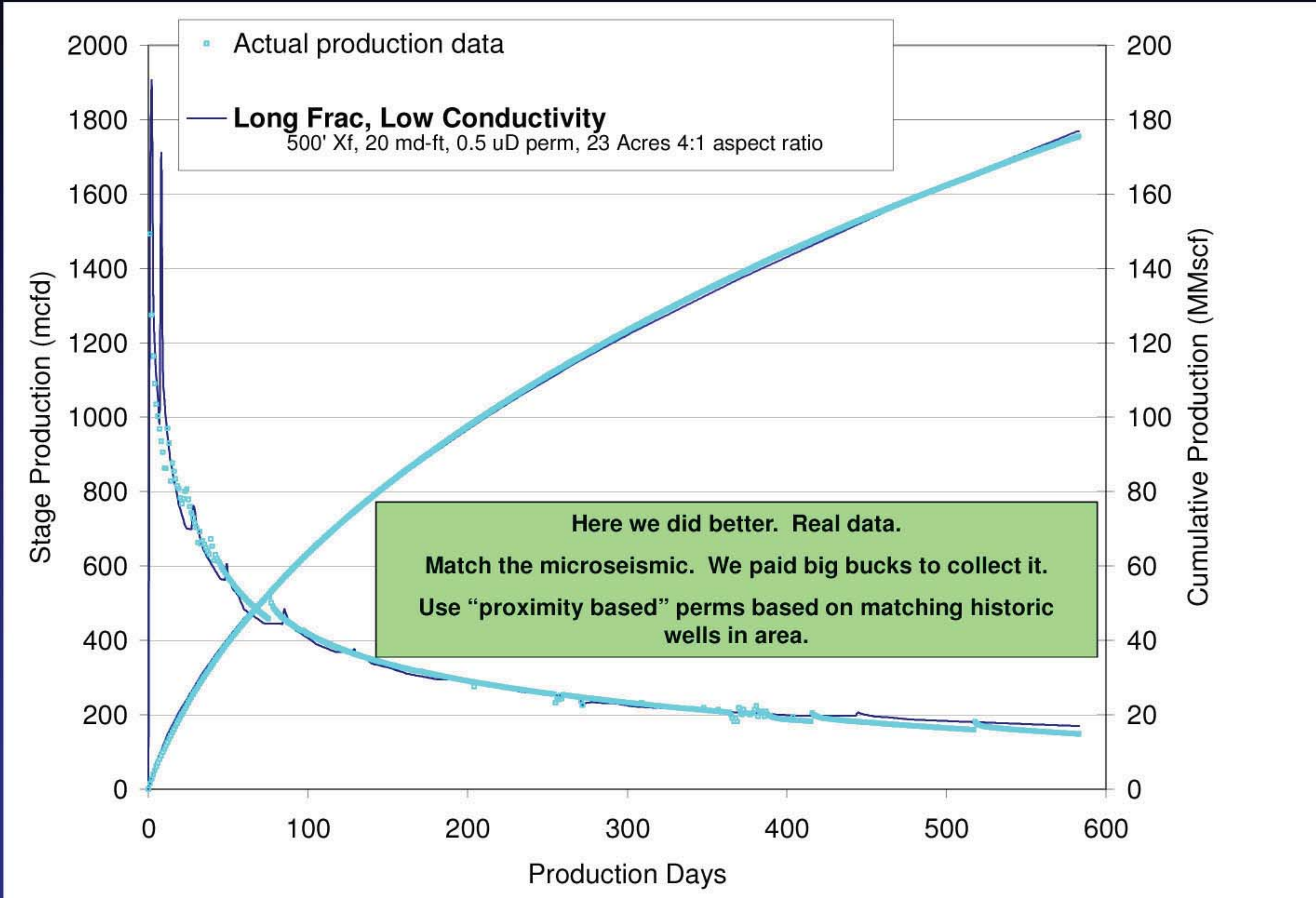
- Ramifications
  - Infill drill (both adjacent and vertical downspacing)
  - Refrac
  - Failure to understand resource potential
  - Or, we need to learn to design more durable initial fracs

With what certainty can we explain this production?



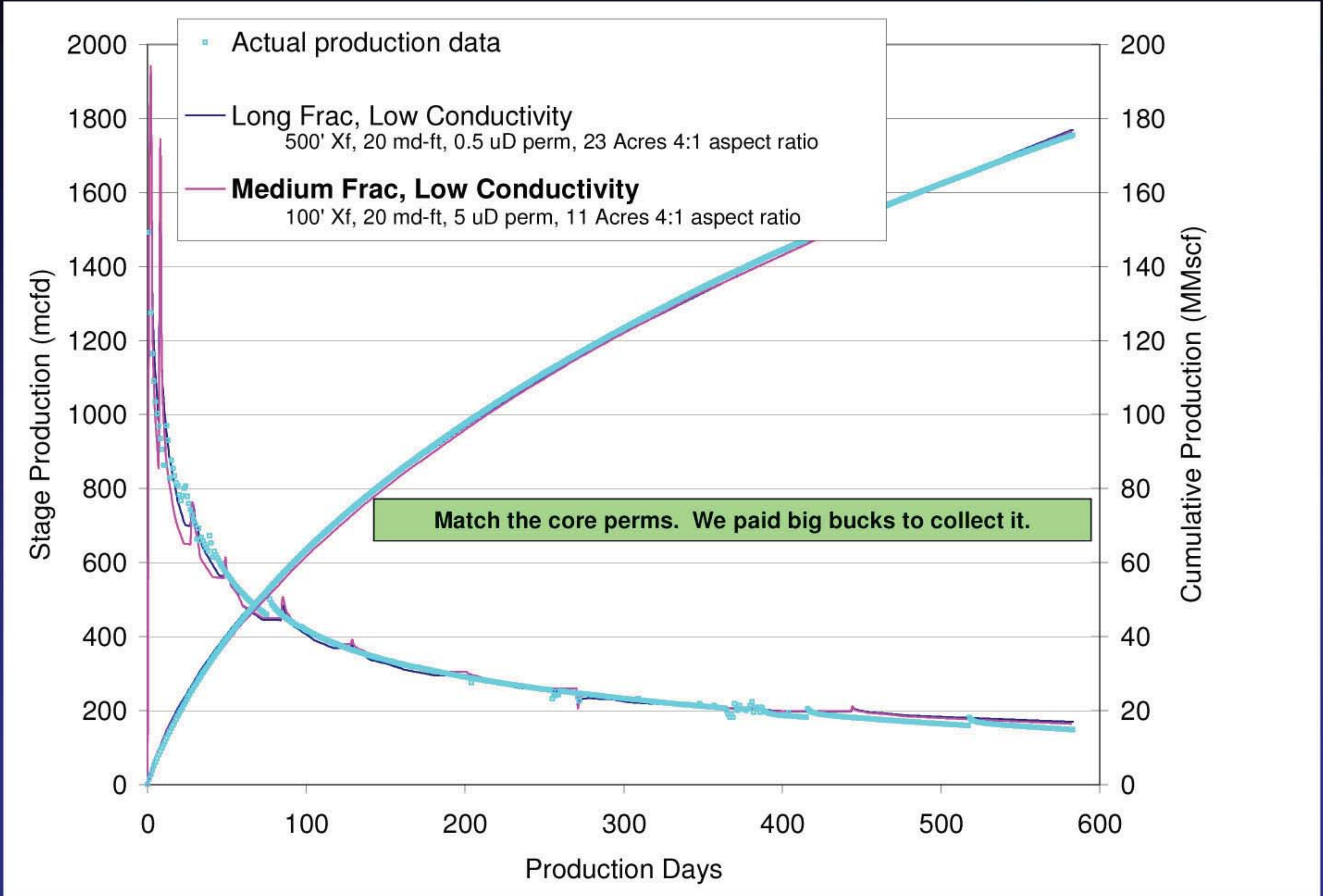
SPE 106151 Fig 13 – Production can be matched with a variety of fracture and reservoir parameters

Nice match to measured microseismic, eh?



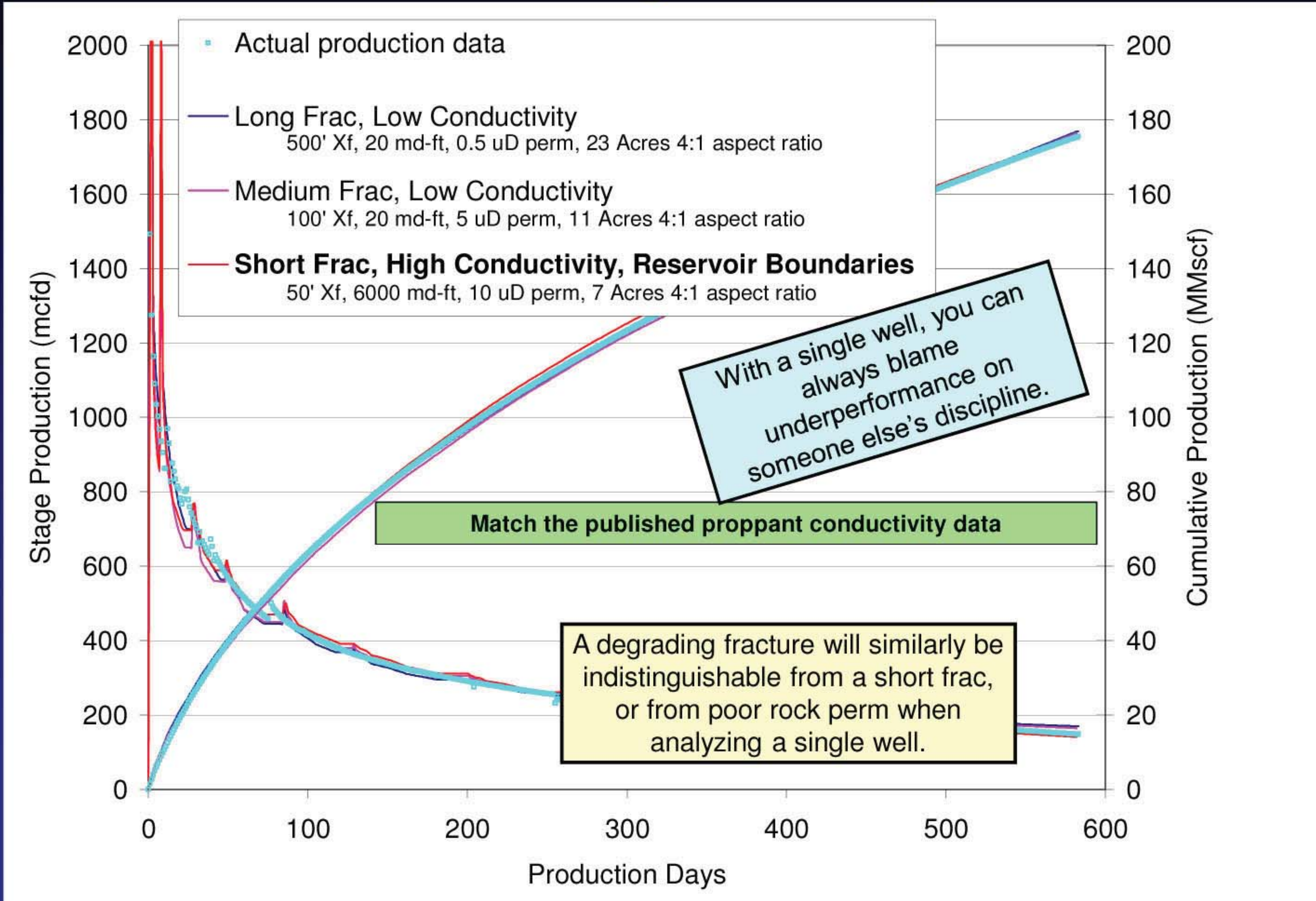
SPE 106151 Fig 13 – Production can be matched with a variety of fracture and reservoir parameters

Is this more accurate? Tied to core perm



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

Can I reinforce my misconceptions?

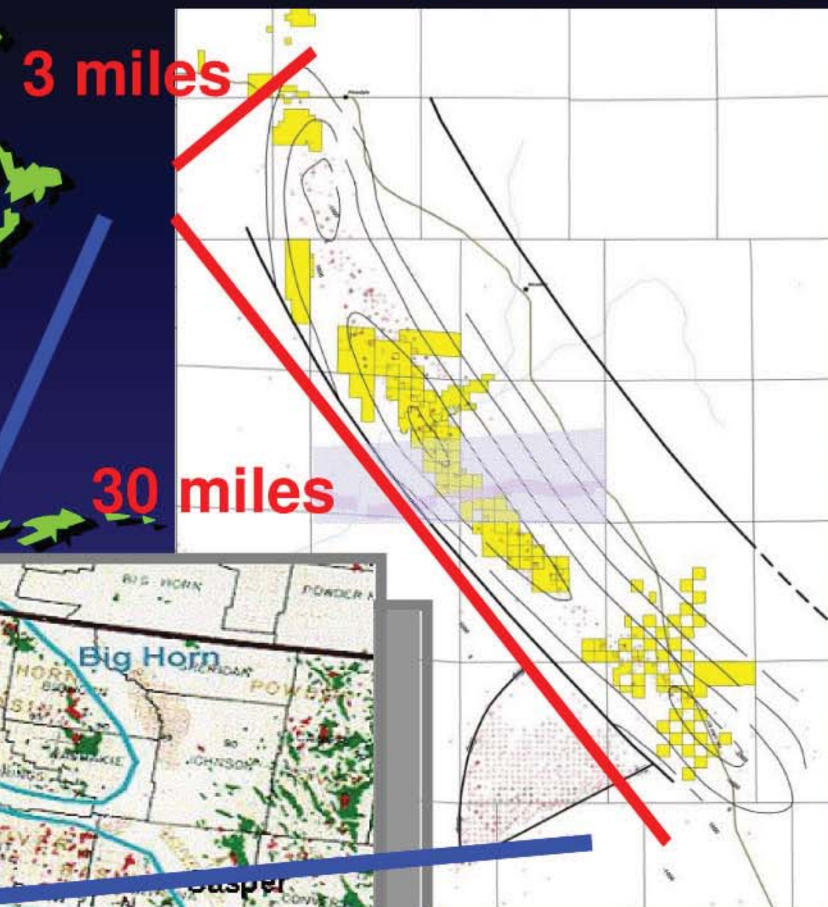


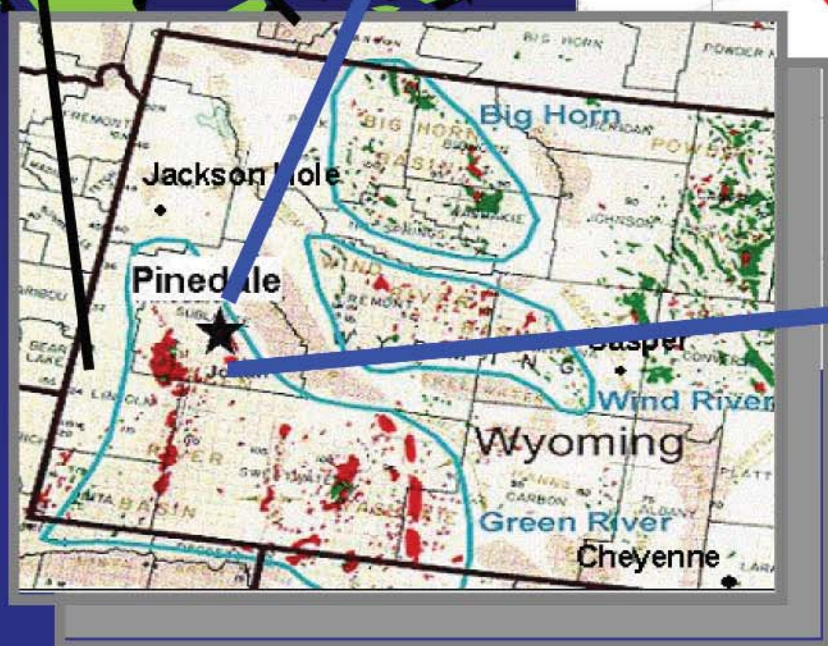
SPE 106151 Fig 13 – Production can be matched with a variety of fracture and reservoir parameters

Example of
Multi-Disciplinary Trial

to determine a more unique solution

Tight Gas Wells
Pinedale Anticline, Wyoming





Reservoir permeability 0.0006 - 0.015 md

Motivation for Study

During last 5 years:

- 200 wells
- 500 million lbs proppant
- No consensus on optimal stimulation design

SPE 96559, 106151, and 108991

Design the trial to answer specific questions

- Does *frac conductivity* matter in microdarcy formations?

- Does proppant *sieve distribution* matter in microdarcy formations?

- With variation in reservoir quality, is it even possible to conduct a field trial that give *statistically reliable answers*?

Some Answers

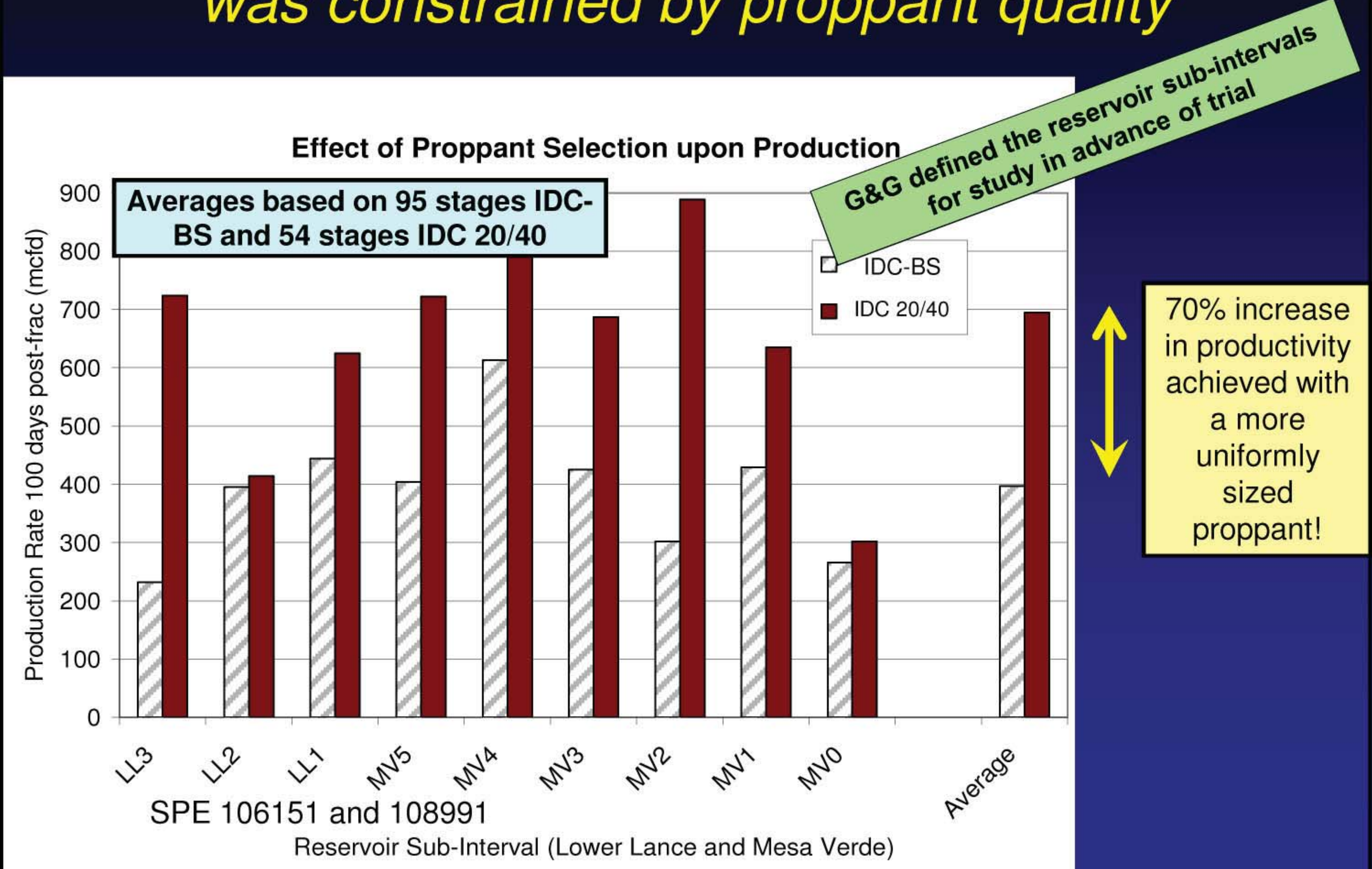
- We can conclude with over 99.99% certainty that proppant selection affected gas production in the Pinedale Anticline (median perm = 2 µD).

- Stages receiving 20/40 sieved IDC provided 70% higher Q_{100} gas rates (298 mcfd) than similar stages receiving a broadly sieved IDC.
  - 20/40 IDC   695 mcfd
  - BS IDC   397 mcfd
  - 95% confidence interval (107 and 399 mcfd)

- High statistical confidence achieved with:
  - Careful design of trial, honoring geological variation
  - Minimize variables – modify only the proppant selection
  - Use of 13 techniques to analyze production, honoring petrophysics
  - Statistical analyses of full dataset and subgroups giving consistent conclusions. (4 study areas and 22 geologic subintervals)

SPE 96559, 106151, and 108991

We are 99.99% certain the Pinedale Anticline was constrained by proppant quality



What are the results after normalization from log-derived petrophysical properties?

Honor the petrophysics!

	ISP-BS	ISP
GRMRKR		
UL5		
UL4		
UL3		
UL2		
UL1		
ML5		
ML4		
ML3		
ML2		
ML1		
LL5	128	
LL4	269	
LL3	232	724
LL2	395	414
LL1	444	625
MV5	404	722
MV4	613	791
MV3	425	687
MV2	302	889
MV1	429	635
MV0	266	302
Average	397	695

Percent Production/Productivity of IDC compared to BS-IDC

Interval	Q_{100}	Q_{100}/h	Q_{100}/k	Q_{100}/kh	$Q_{100}/kh\Delta P$	$Q_{100}/kh(P_r^2-P_w^2)$	$Q_{100}/\Phi h$
All	175%	149%	196%	160 %	176%	160%	140%
Common	172%	146%	194%	157 %	174%	158%	137%
L. Lance	173%	166%	182%	170 %	190%	172%	164%
M. Verde	172%	139%	201%	152 %	167%	153%	129%

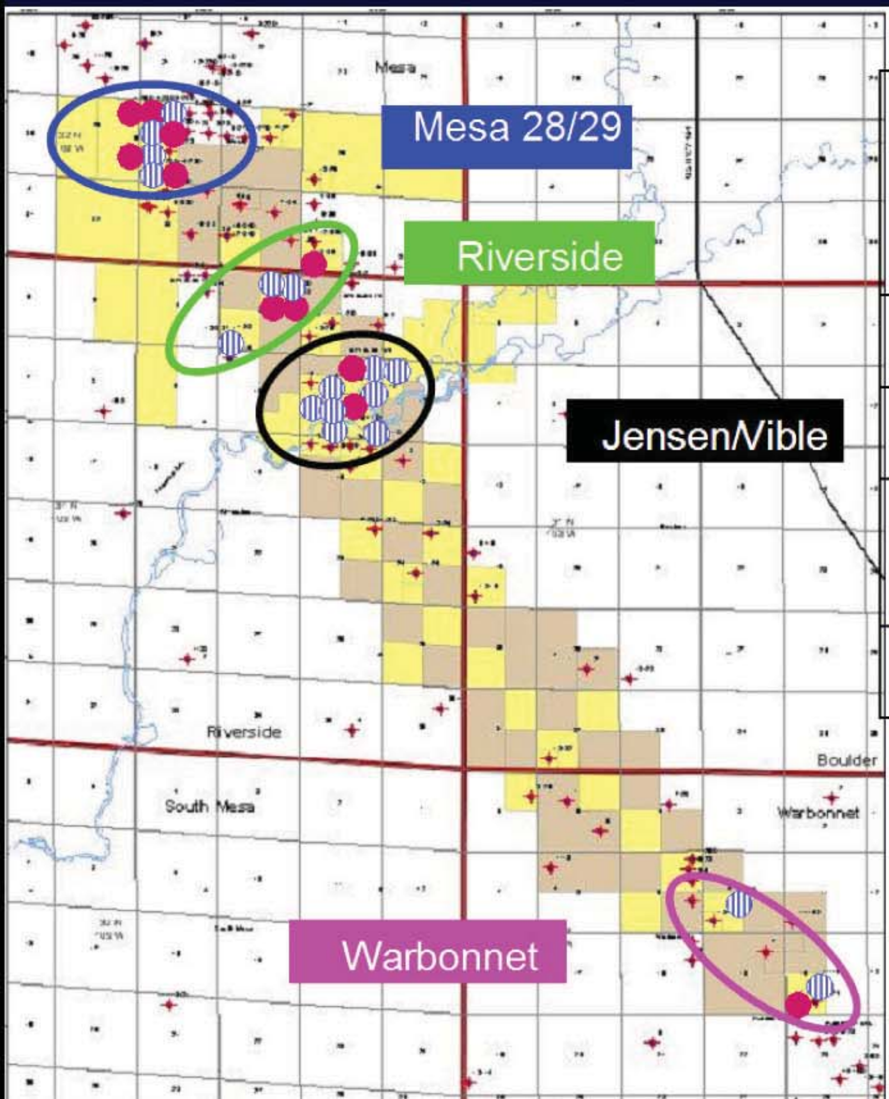
Regardless of which technique you use, the API-spec IDC dramatically outperformed BS-IDC.

The minimum benefit in the tables above is 29%. In the Mesaverde, this equates to 125 mcfd incremental, which pays out the incremental proppant cost in less than 20 days.

Other Analyses

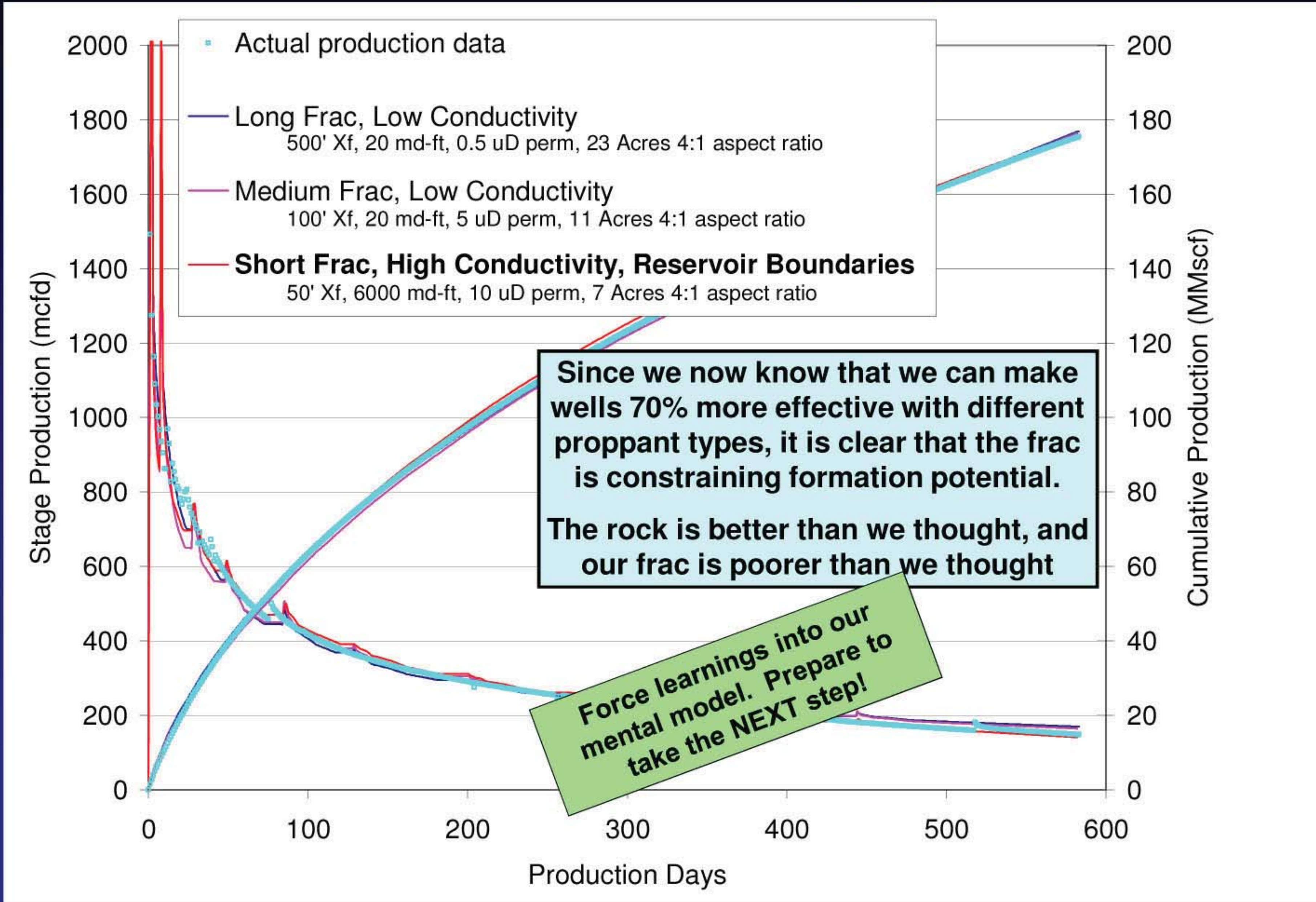
- IDC outperformed BS-IDC in all 4 stud

Confirm results give same answers in different parts of the field



Study Area	**Number of Sub-Intervals in which IDC outperformed**	**Q_{100} of IDC divided by Q_{100} of IDC-BS**
Mesa 28/29	7 of 7	257%
Riverside	3 of 5	140%
Jensen/Vible	3 of 7	106%
Warbonnet	2 of 2	323%

Remember this ambiguity?



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

Summary

- Despite our success, we are not optimized
- There is overwhelming evidence that conventionally designed fracs are not durable
- There are enormous economic implications at stake
    - Either: Infill drill adjacent wells
    - Vertical downspacing (stack laterals)
    - Refrac

    - Or…
    - Assemble the correct multidisciplinary teams to find better ways to more efficiently harvest the reserves with fewer wellbores