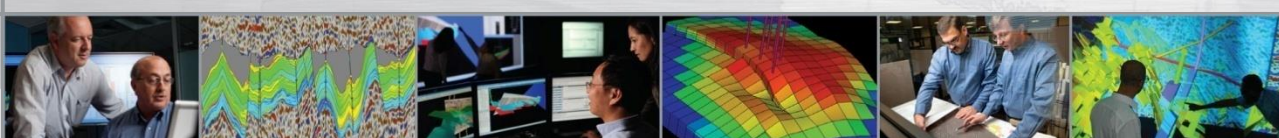
Considerations for Infill Well Development in Low Permeability Reservoirs

George Waters

Technical Manager – Unconventional Completions

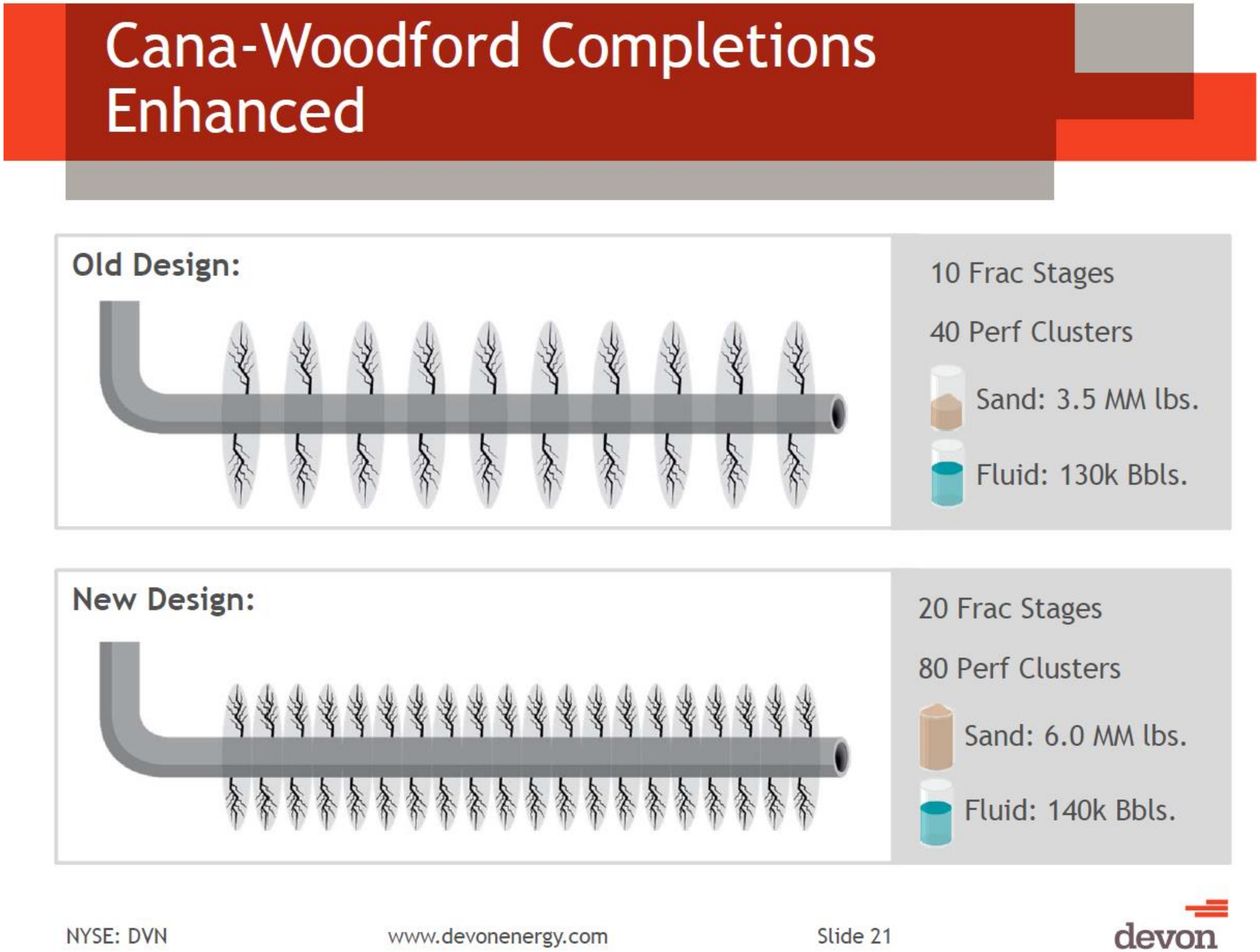
September 9, 2014



Topics

- Continuous Improvement in Field Development
- What Drives Frac / Well Spacing?
- Field Development Workflow
  - Bakken Shale Example
  - Cana Woodford Shale Example

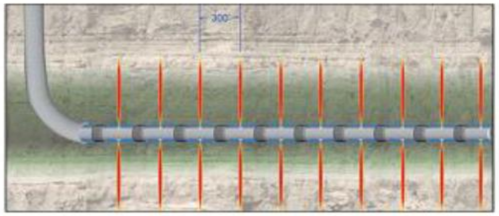
The Quest For The Optimized Completion



The Quest For The Optimized Completion

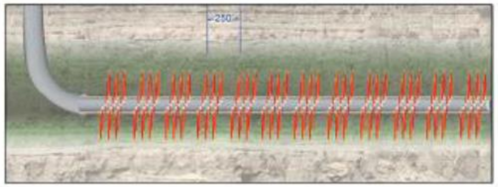
Maximizing Recovery Efficiency

Improving Frac Design



Sliding Sleeve Completion

Annulus	Stages	Frac Ports per Stage	Potential Entry Points
Free fluid between packers	30	1	30



Cemented Liner Completion

Annulus	Stages	Perforation Clusters per Stage	Potential Entry Points
Cemented	40	3	120

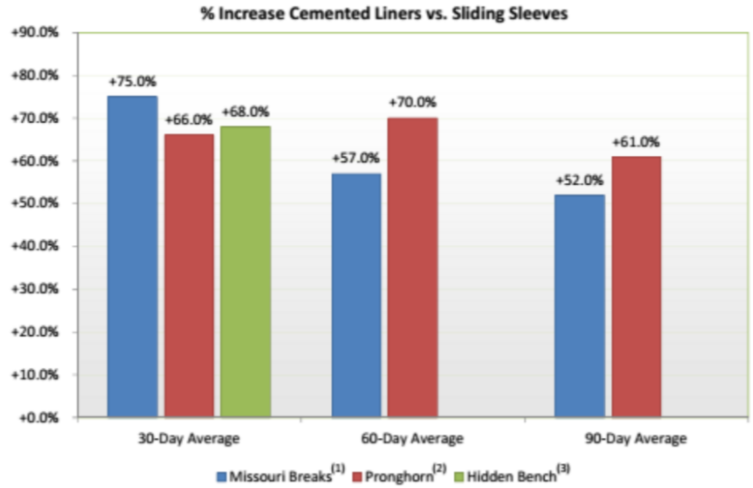
NYSE: WLL

Energy + Technology = Growth

6

New Completion Design Delivers Superior Results

50% to 75% Increases in 30, 60, 90 Day Rates



(1) Missouri Breaks includes 9 wells completed with cemented liners in 2013 and 31 wells with sliding sleeves. All wells have at least 90 days of production history.
(2) Pronghorn includes 5 wells completed with cemented liners in 2013 and 44 wells with sliding sleeves. All wells have at least 90 days of production history.
(3) Hidden Bench includes 6 wells completed with cemented liners in 2013 and 62 wells with sliding sleeves. All wells have at least 30 days of production history.

NYSE: WLL

Energy + Technology = Growth

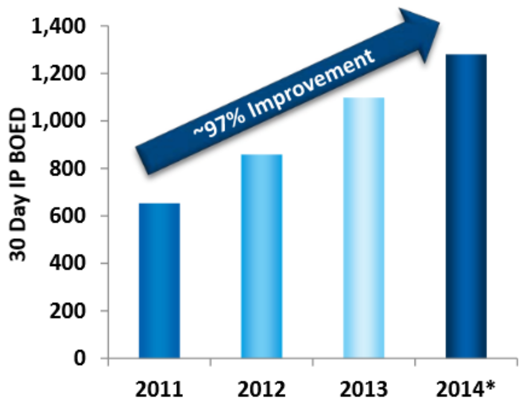
WHITING Whiting Petroleum Corporation

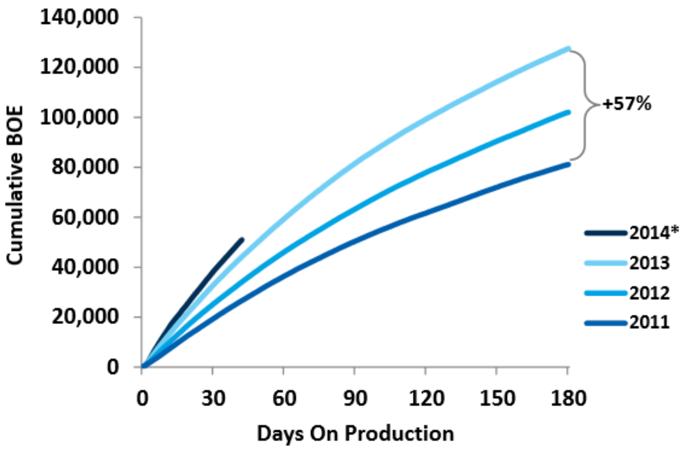
The Quest For The Optimized Completion

Eagle Ford

Completion design enhancements driving improved well performance

- **Improvements in stimulation design outpacing impacts from downspacing**
  - **2013 wells at 40 & 60 acre spacing exhibit higher IP than 2011 wells at 80 - 160 acre spacing**
  - **Early 2014 wells at 40 acre spacing exhibiting further improvements**
- **Ongoing testing of stimulation design to continually improve well performance**
  - **Zipper stimulations from pads materially impacting complexity & improving recovery**
  - **Fluids, volumes, rates, cluster spacing and proppant loading evolving with spacing**
  - **Geologic completions, proppant size, gel loading, sleeve technology, perforation clusters being tested**





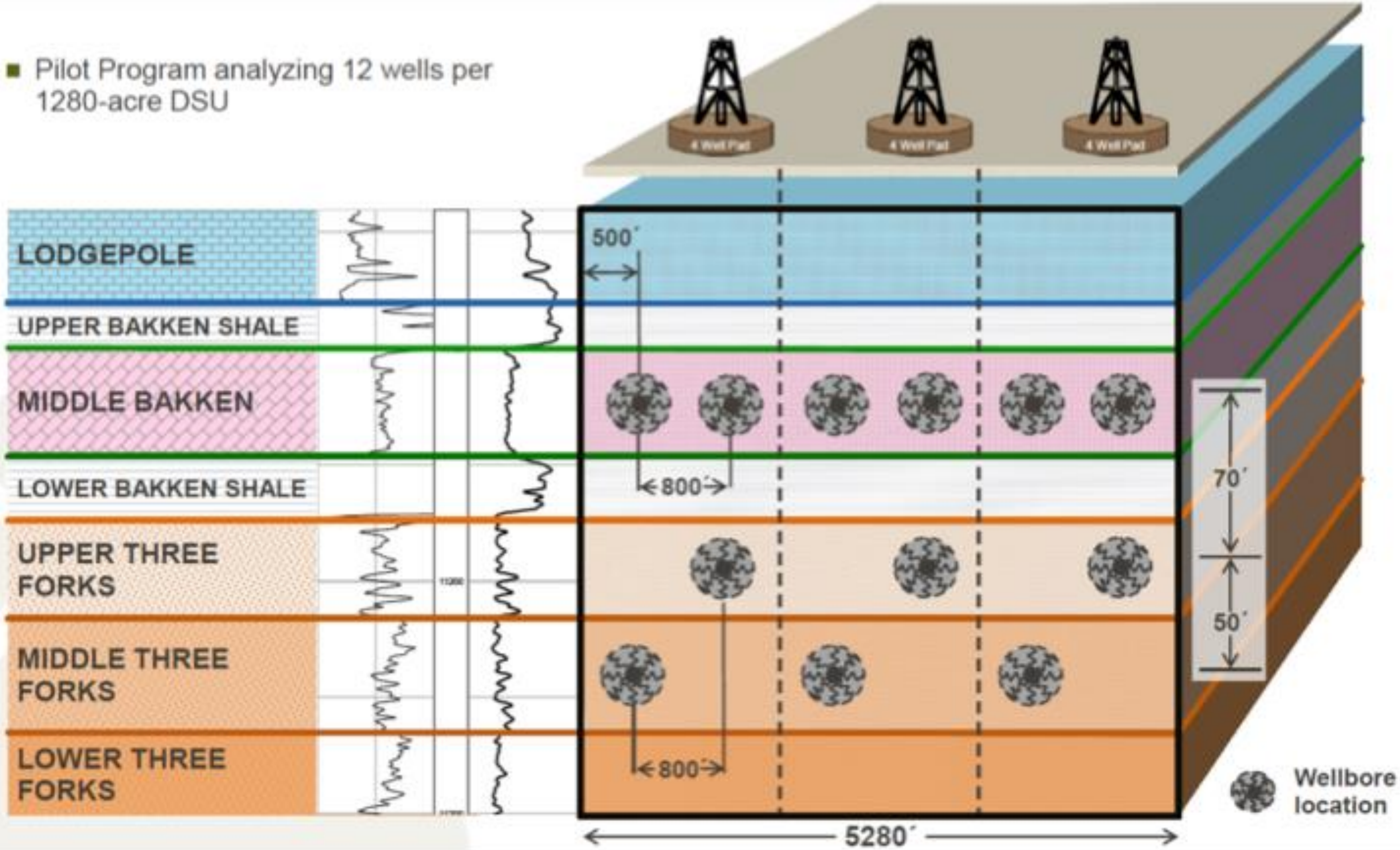
MRO-operated wells, gross basis
2013 includes wells with 180d of production excluding lease retention wells and ≥400 ft stage spacing wells
**2014 wells to date (15) using updated completion design*

Marathon Oil Corporation

Schlumberger

The Quest For Optimized Field Development

- Pilot Program analyzing 12 wells per 1280-acre DSU



Unconventional Resources

KODIAK OIL & GAS CORP.

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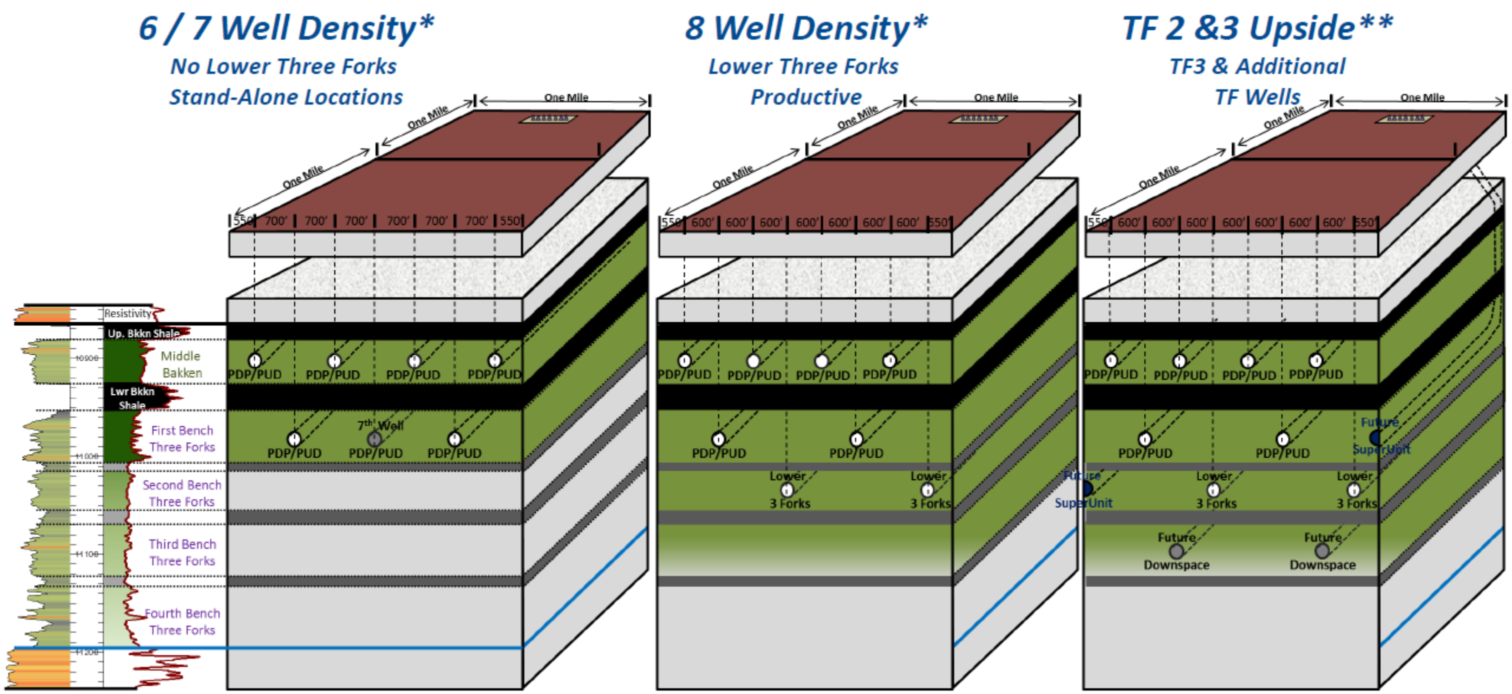
The Quest For Optimized Field Development

Well Density Schematic



enerPLUS

* Assumes 15% recovery factor.
** "Super unit" equivalent to lease line drilling.

enerPLUS

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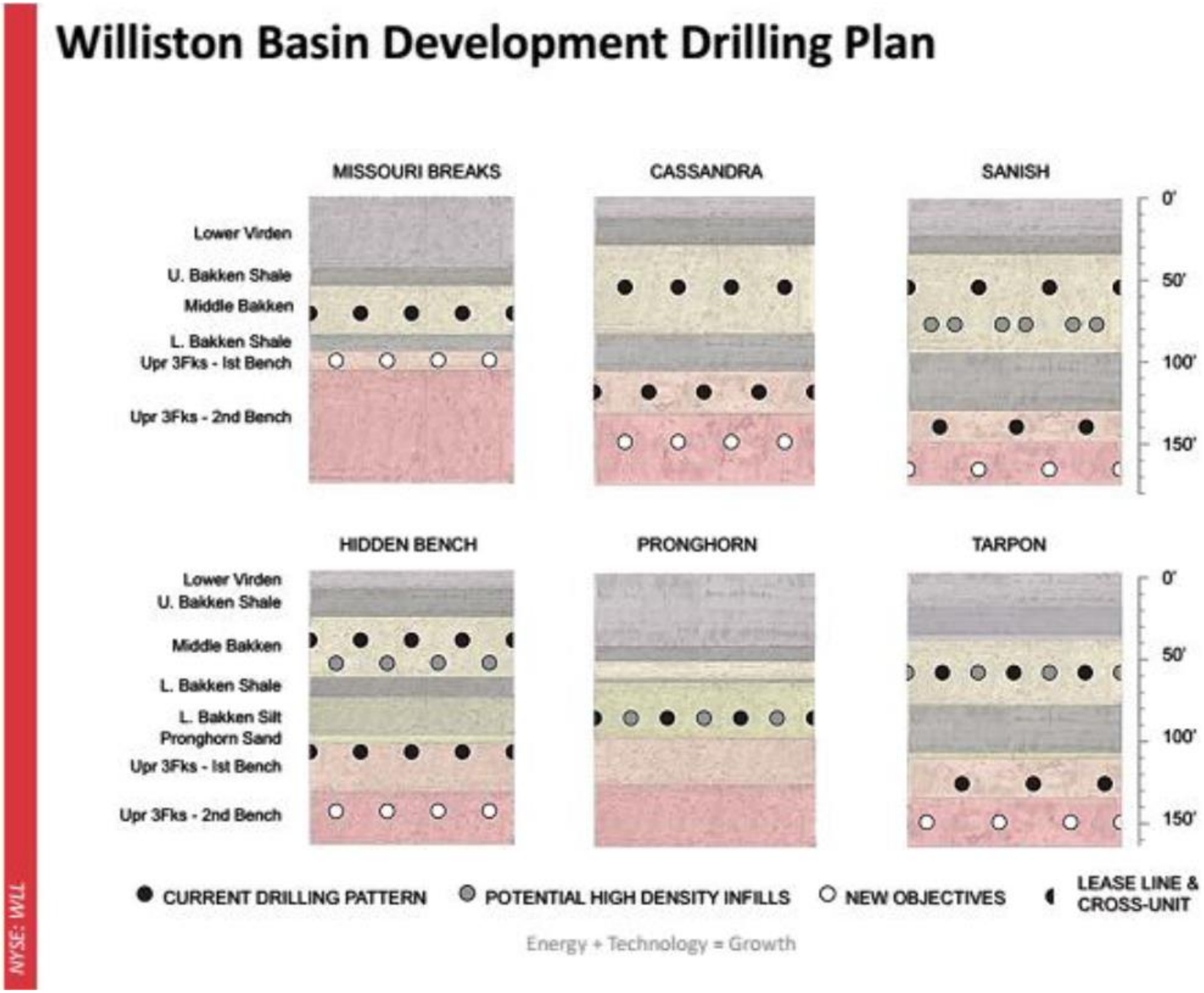
The Quest For Optimized Field Development



Unconventional Resources

WHITING Whiting Petroleum Corporation

Schlumberger

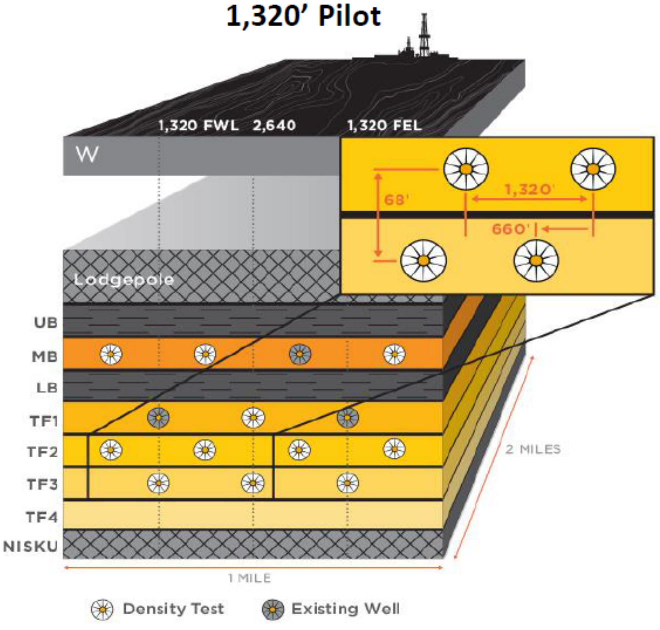
The Quest For Optimized Field Development

Continued Robust Hawkinson Performance

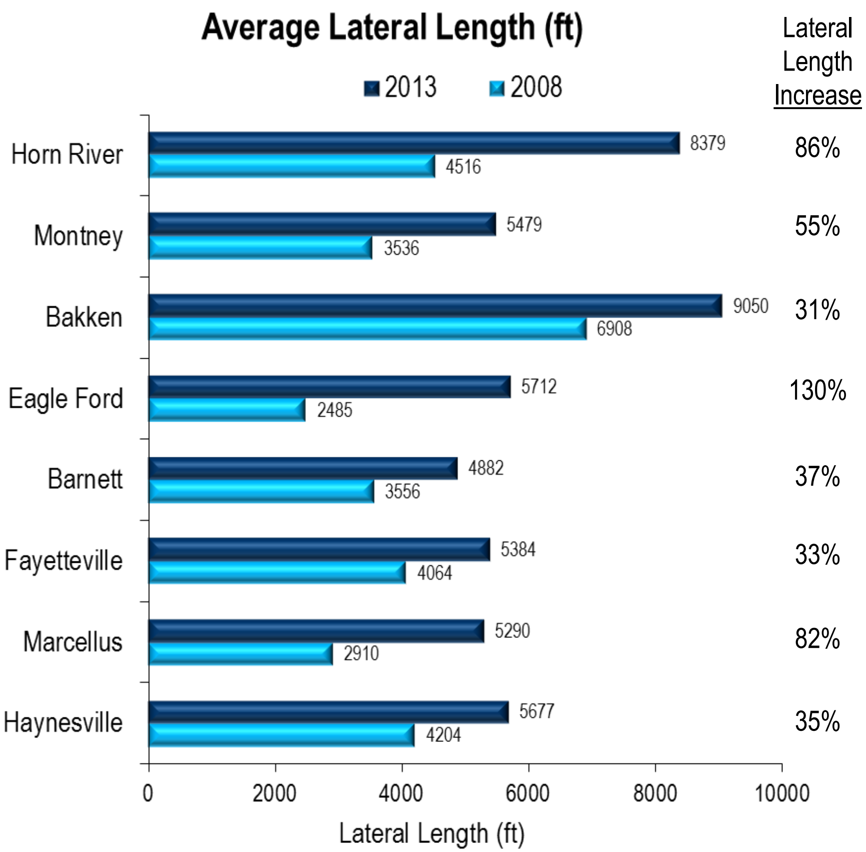
- Continued strong production after 150+ days
- 13 of 14 wells trending on average 50% above 603 MBoe model EUR
  - Completed using standard design with ~100,000 pounds of proppant per stage (30 total stages)
- To date the original existing 3 wells continue to produce on average at or better than prior to drilling and completing the additional 11 wells
- Validates full-field development & demonstrates vast resource potential

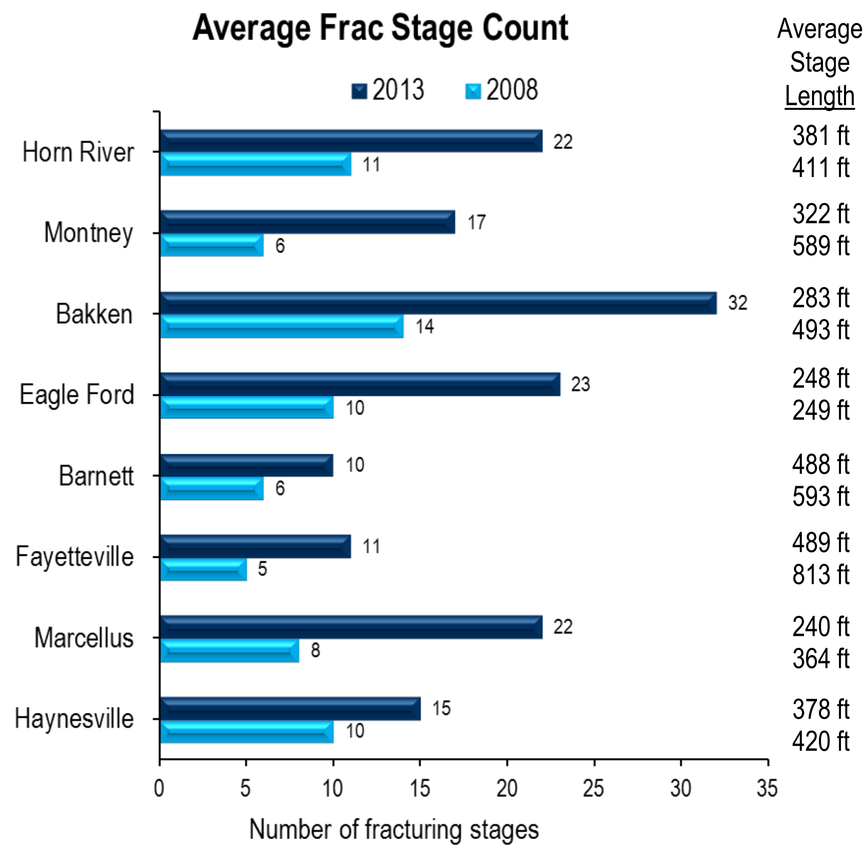
Hawkinson Unit

1,320' Pilot



North American Horizontal Evolution

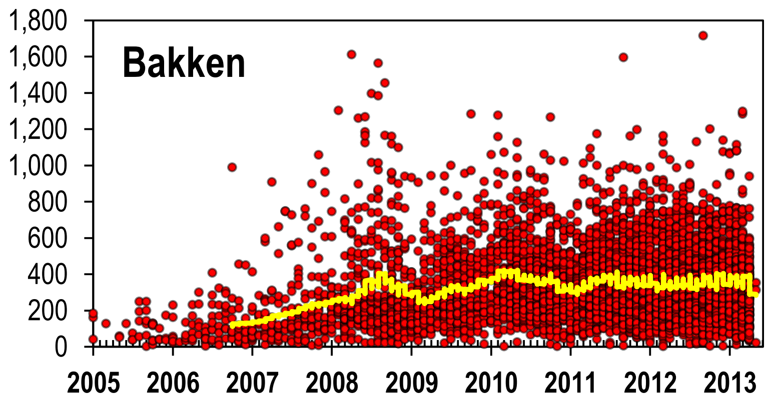




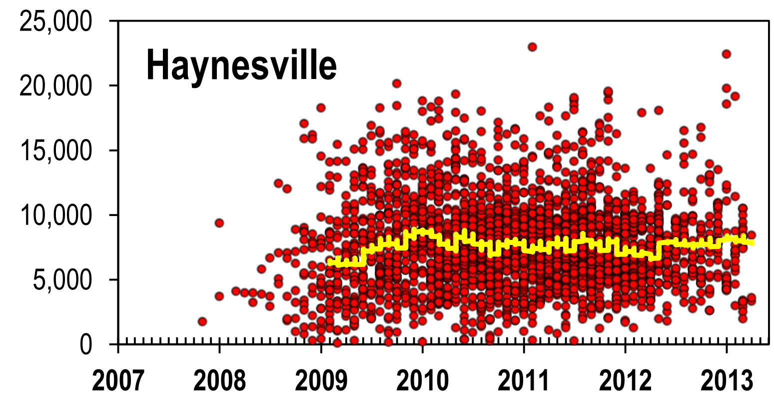
US Unconventional Production

Unconventional Liquid Plays
(best 3 months production bpd)

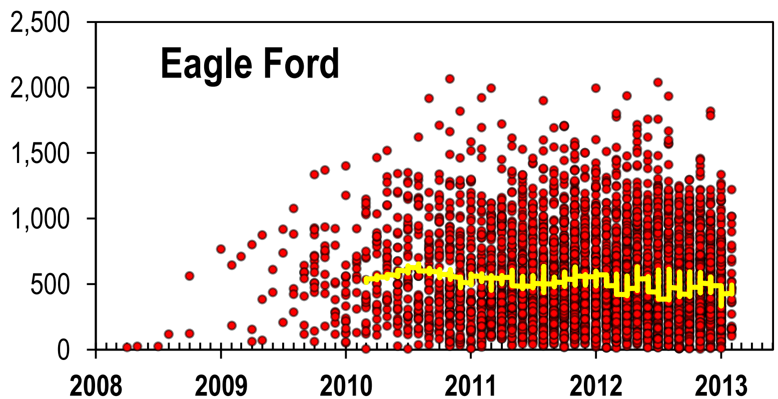
Unconventional Gas Plays
(best 3 months production mcfd)



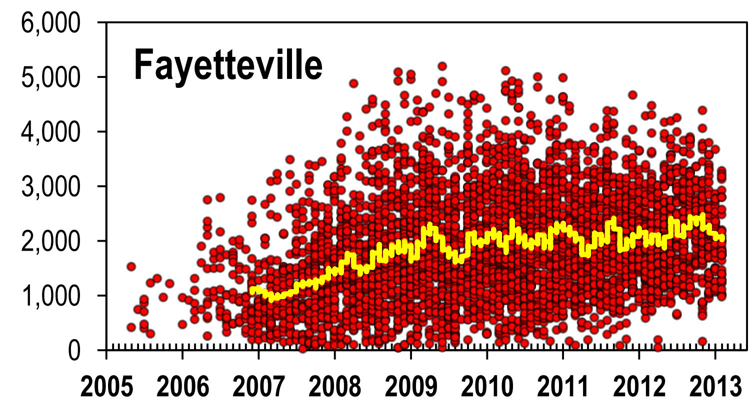
Best 3-month average ~ 340 bbl/d



Best 3-month avg ~ 7,650 Mscf/d



Best 3-month average ~ 518 bbl/d



Best 3-month avg ~ 1,900 Mscf/d

Unconventional Resources

IHS Public Production Data

Schlumberger

Topics

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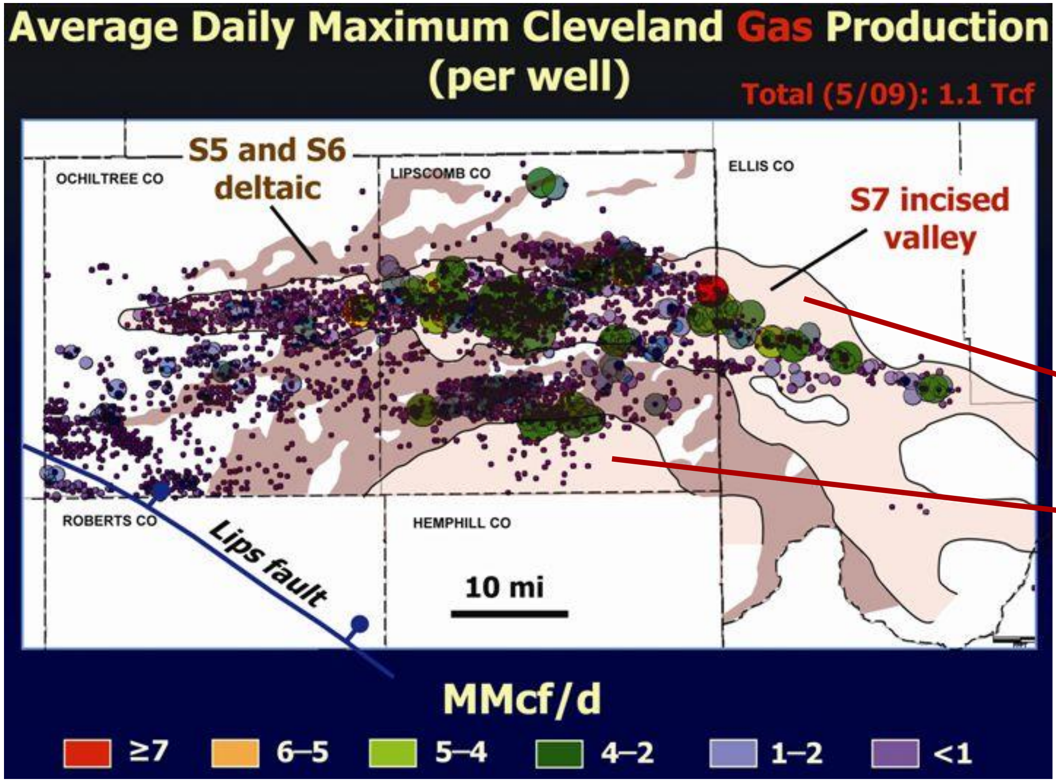
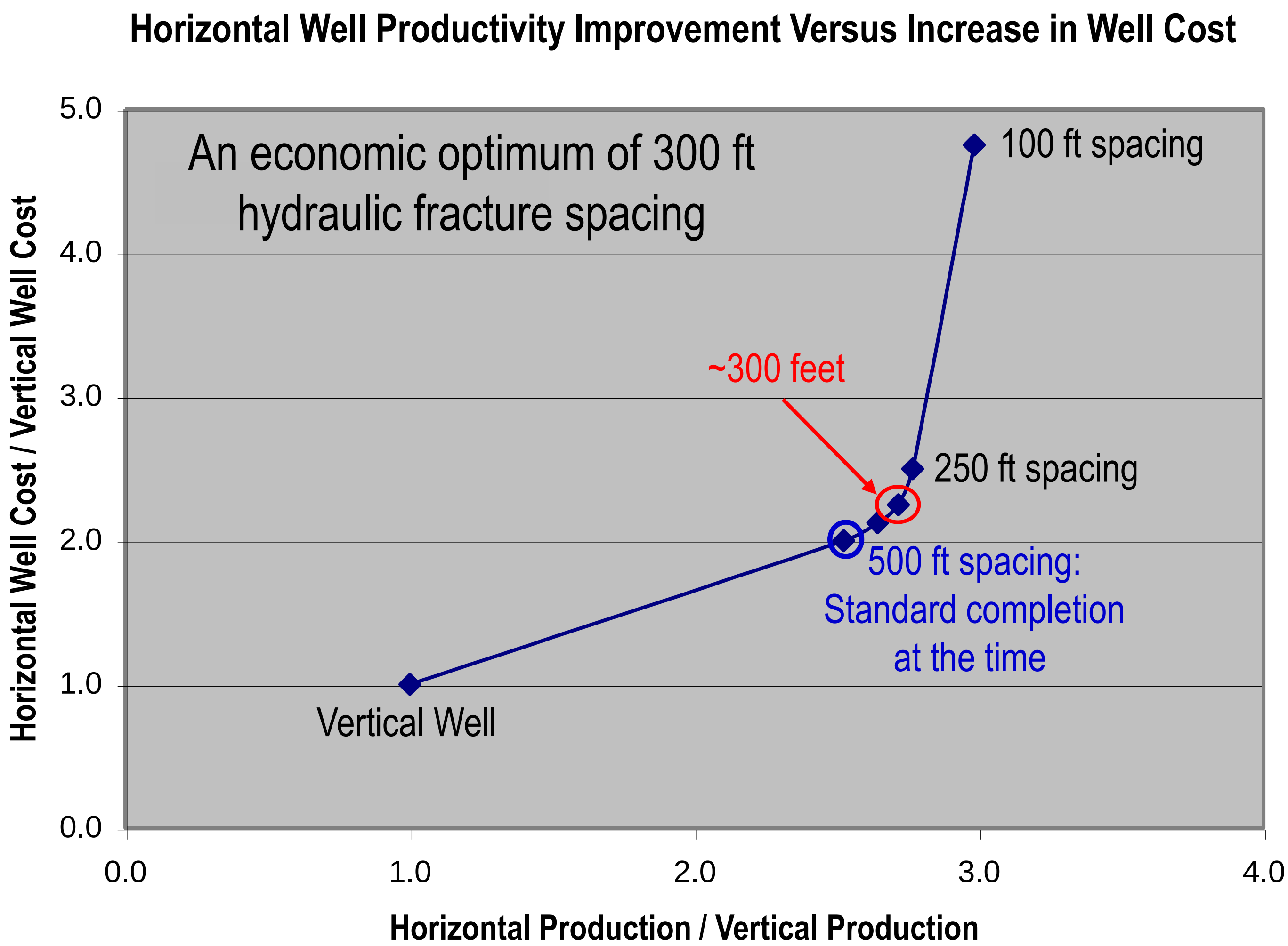
- What Drives Frac / Well Spacing?
- Field Development Workflow
  - Bakken Shale Example
  - Cana Woodford Shale Example

Cleveland Sand Horizontal Well Development



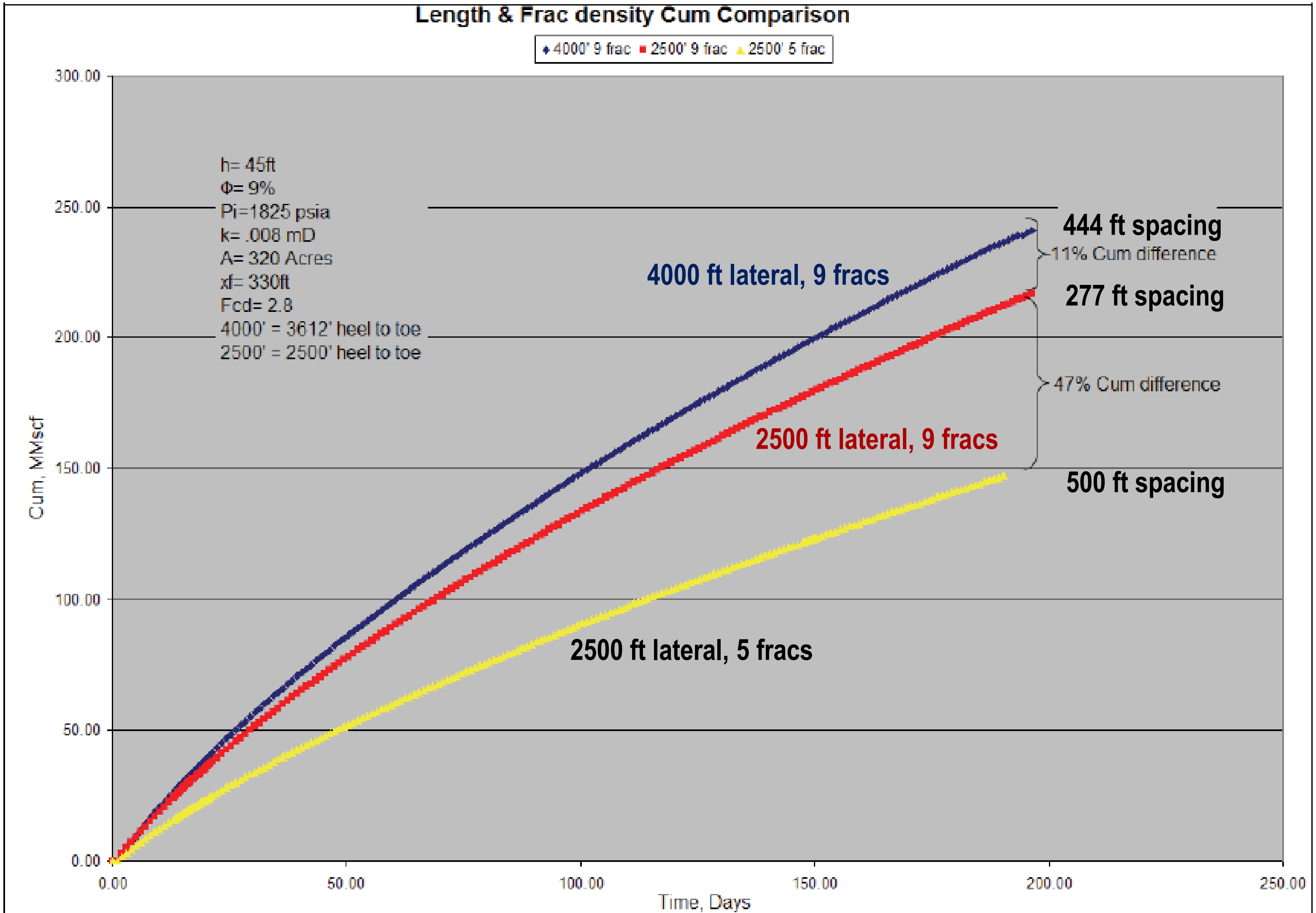
- Vertical well development since 1980s
- Produces both oil and gas
- Revitalized with horizontal wells in 2000s
- Completion Techniques:
  - One large frac with ball diversion
  - Packers / Port Collars

Cleveland Sand Frac Spacing Optimization: 2005

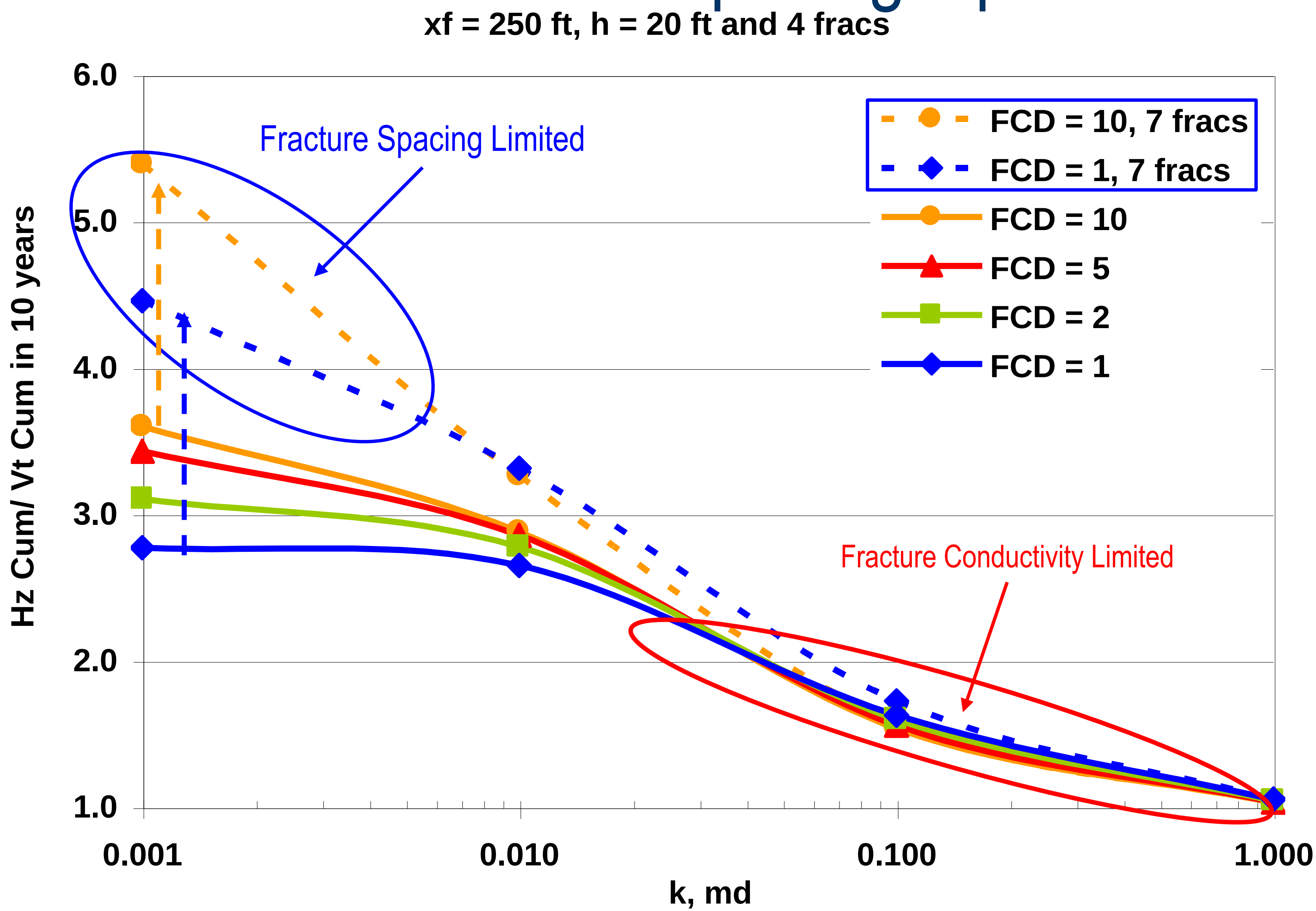


Schlumberger Internal Study: October, 2005

BP Results After Increasing Frac Stages: 2011



Cleveland Sand Fracture Spacing Optimization



Schlumberger Internal Study: October, 2005

Parameters That Control Well / Frac Spacing

- Matrix Perm
  - Frac spacing and conductivity needs
- Natural Fractures
  - Enhanced permeability, stimulation difficulty, stimulated geometry
- Faults
  - Inefficient fracturing and unwanted fluid migration potential
- Reservoir Fluids
  - Fluid viscosity impacts pressure transient
- Variability Along the Horizontal Well
  - Quality of the reservoir will vary along the well
  - Well may not stay within the reservoir
- Orientation of Well Relative to Stress Field
  - Frac orientation and spacing

Topics

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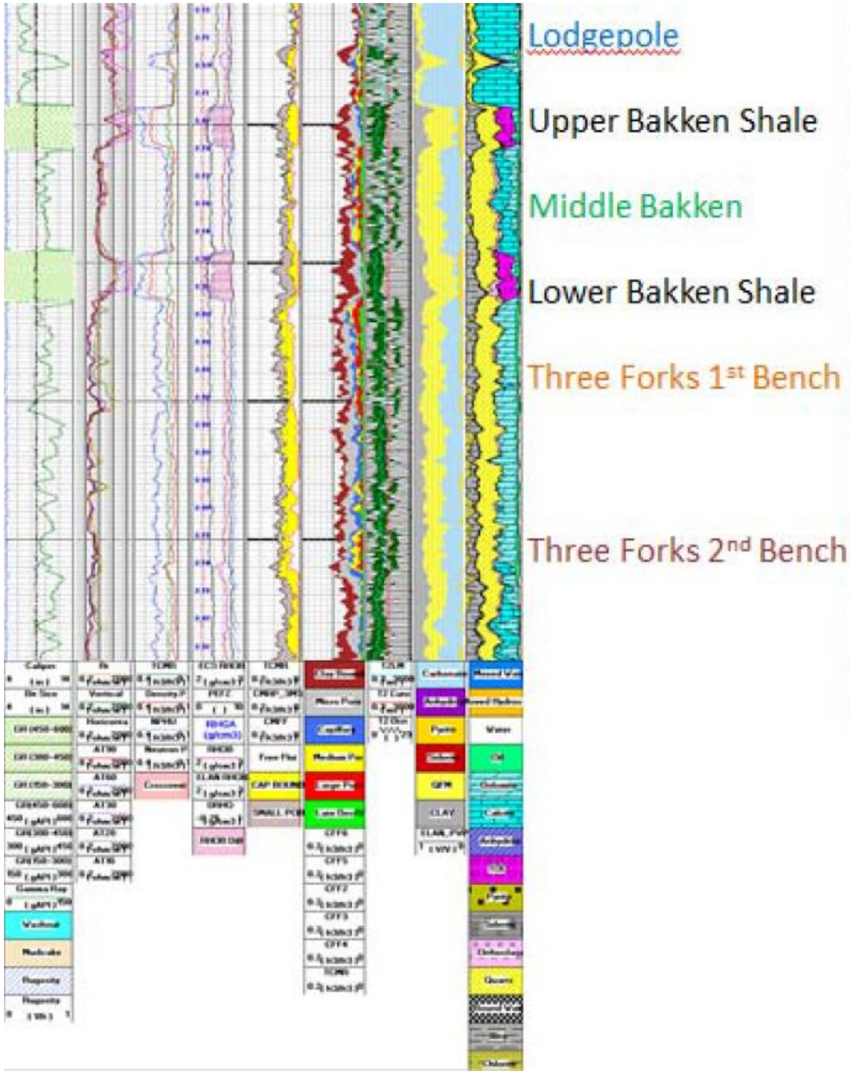
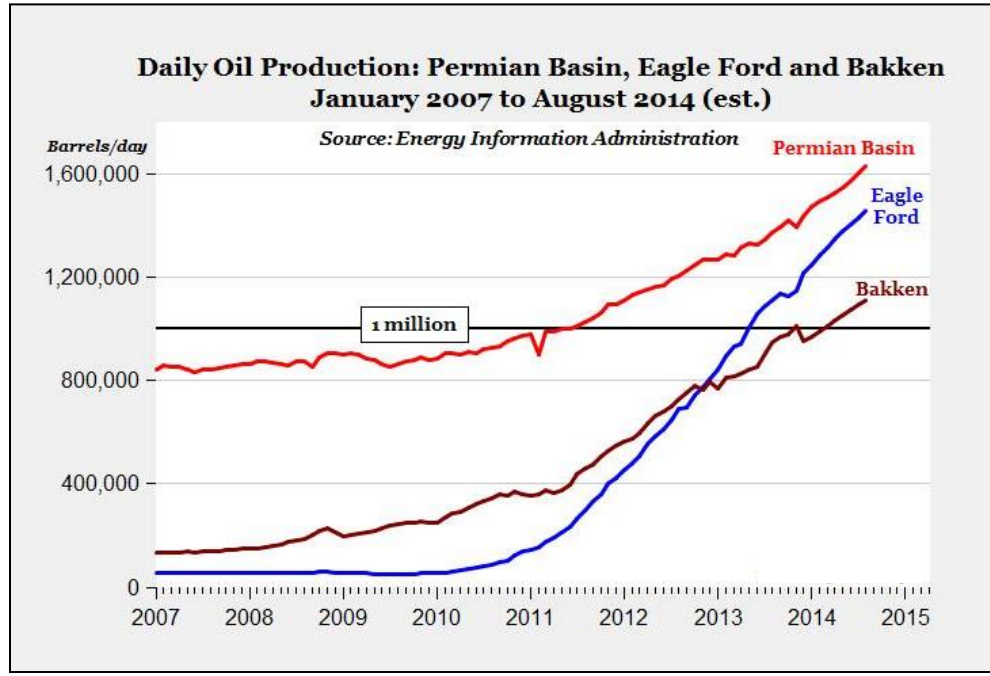
Bakken Shale Field Development Strategy



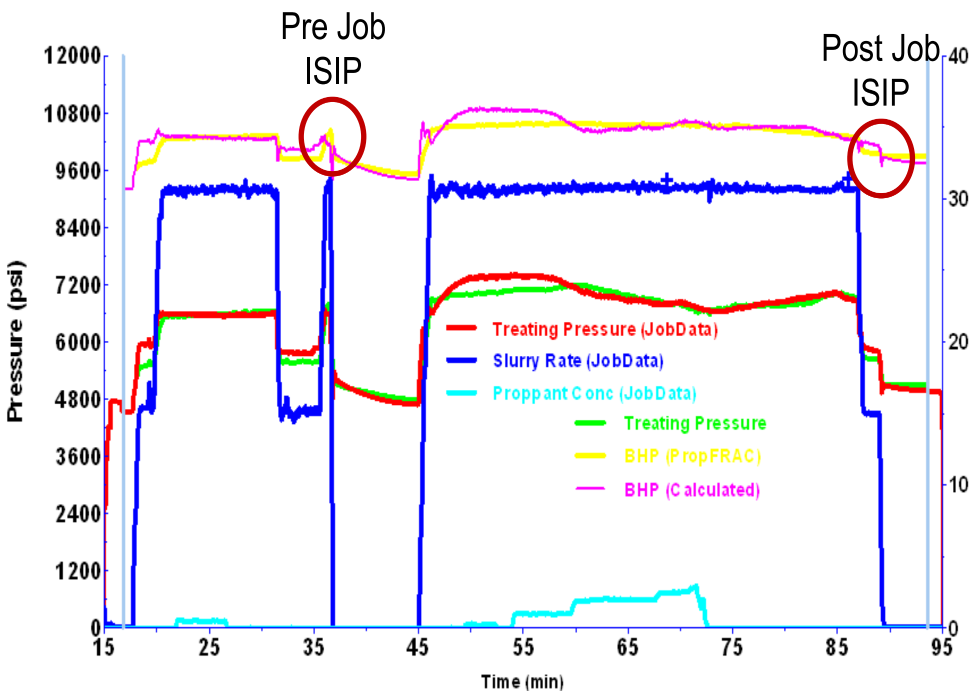


Field Development Challenges:

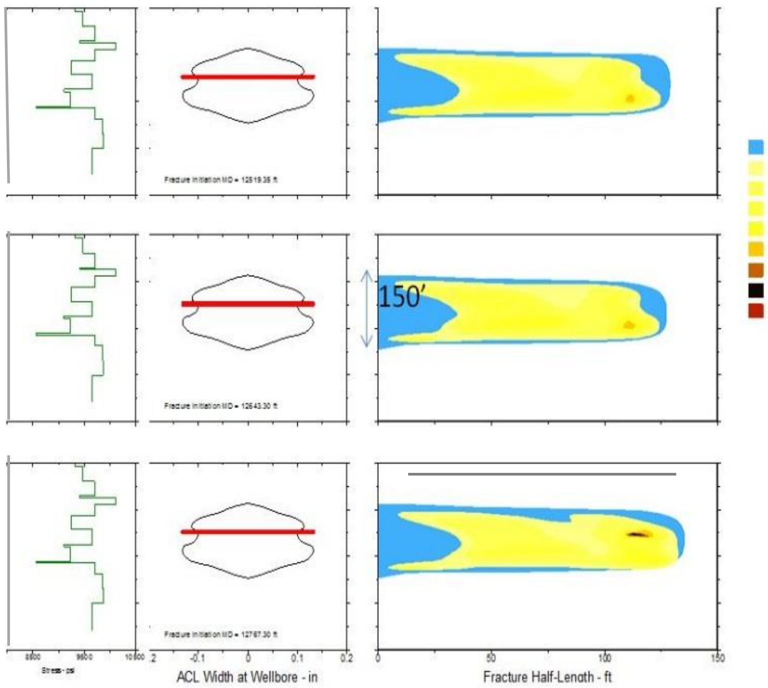
- Hydraulic fracture spacing
- Offset well placement
- Bakken / Three Forks development
- Well placement between Bakken and Three Forks

Single Well Optimization: How Many Fracs/Stages?

Pressure History Match



Multiple Fractures

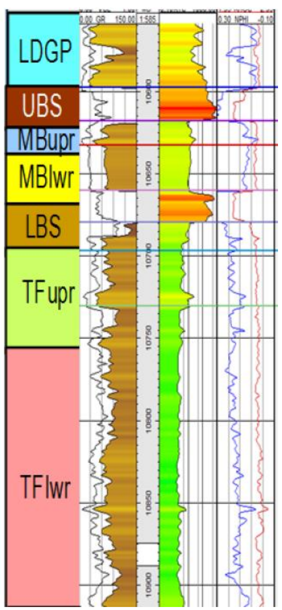


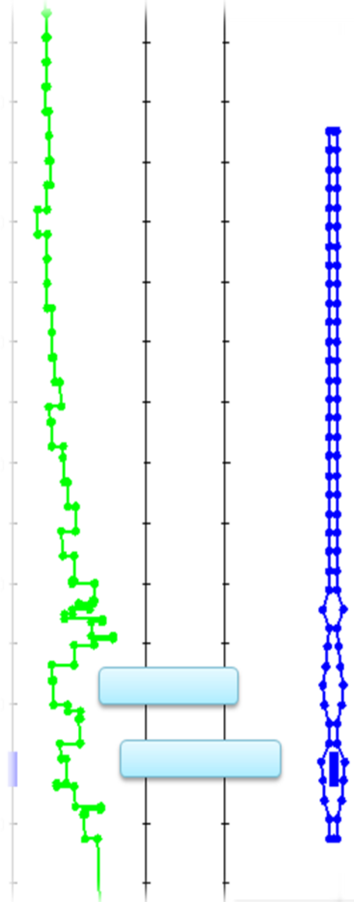
Fracturing pressure responses indicate that the number of fractures varies from one to three, with one dominant frac most common

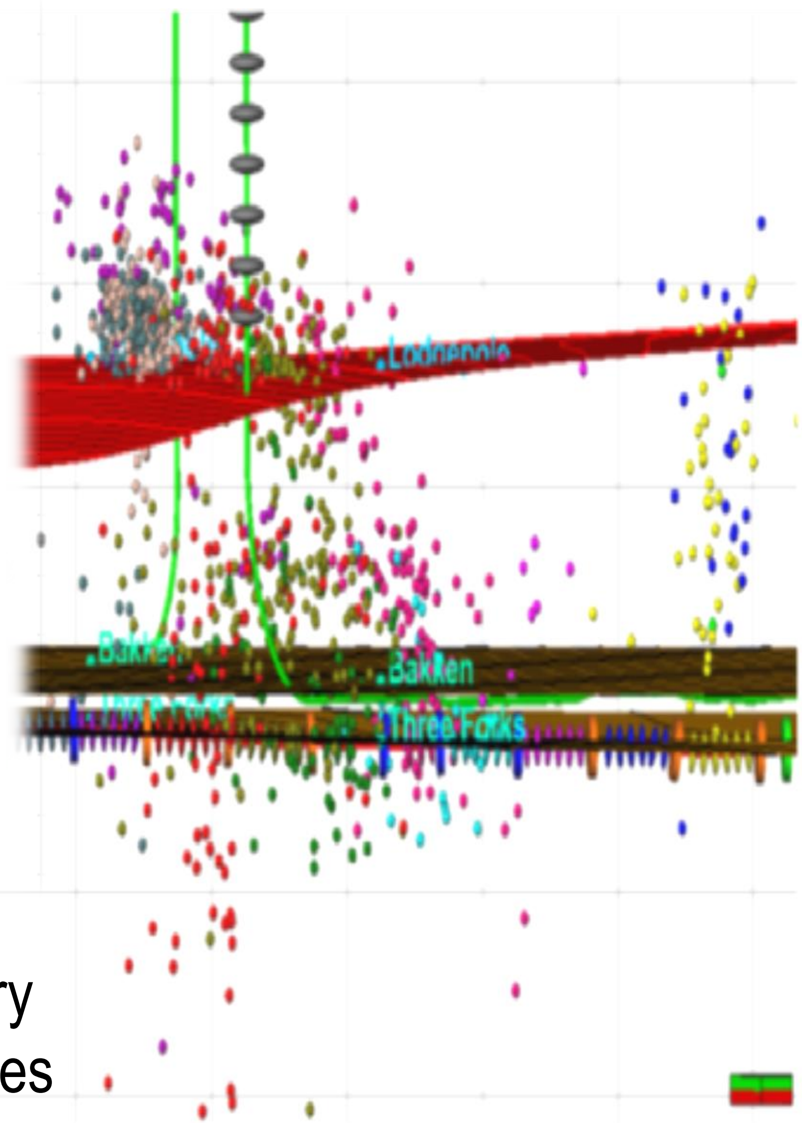
(Uncemented Port Collar / Perforated Completions)

Single Well Optimization: Frac Geometries

Height growth and vertical communication between Bakken and Three Forks



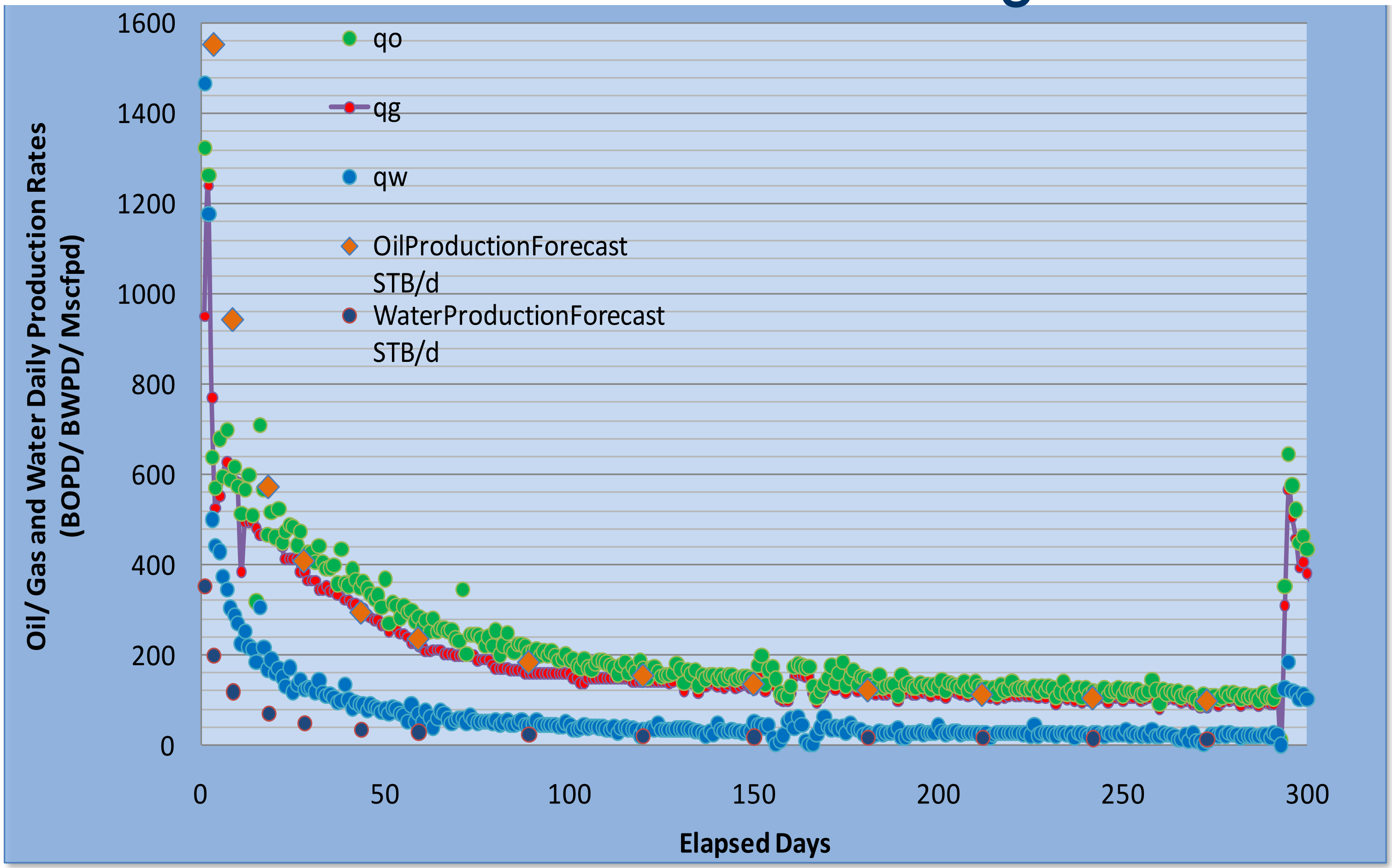




Large frac geometry infers fewer fractures

SPE142388, SPE 163855

Number of Fractures and Height Growth Validated via Production Matching

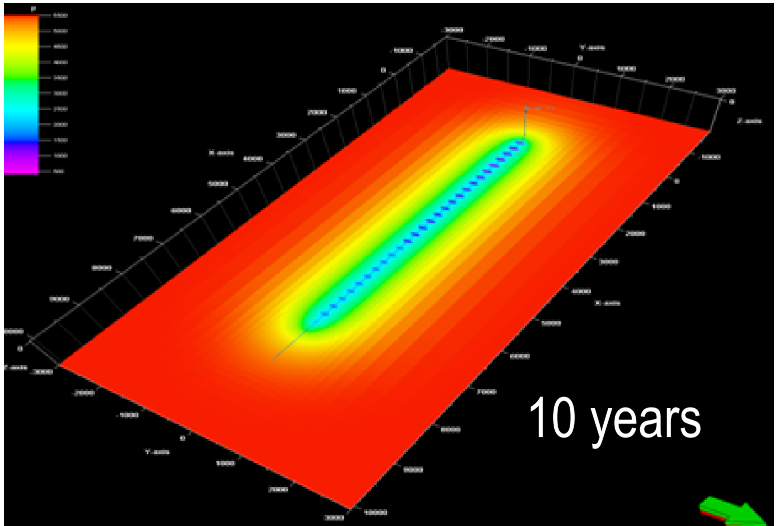


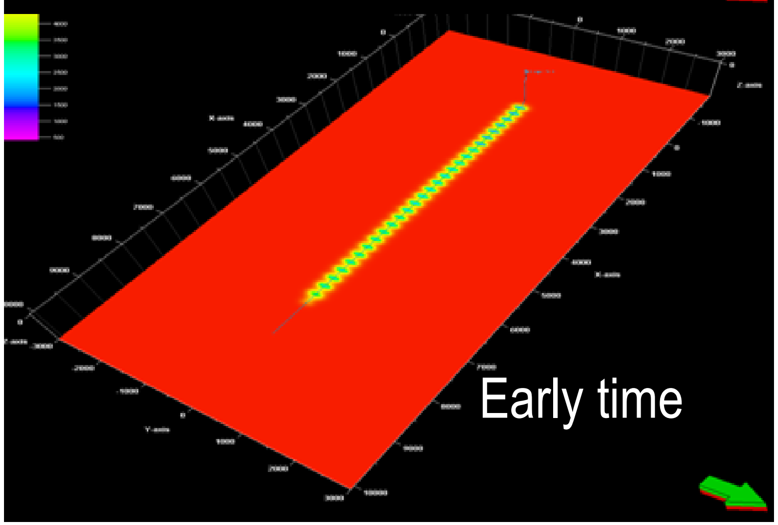
History match early production

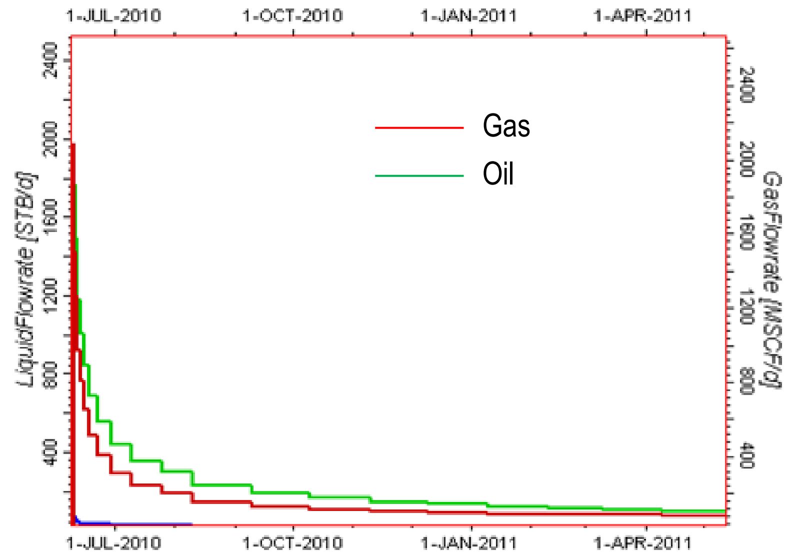
Reconcile number of fractures (producing area) and fracture conductivity

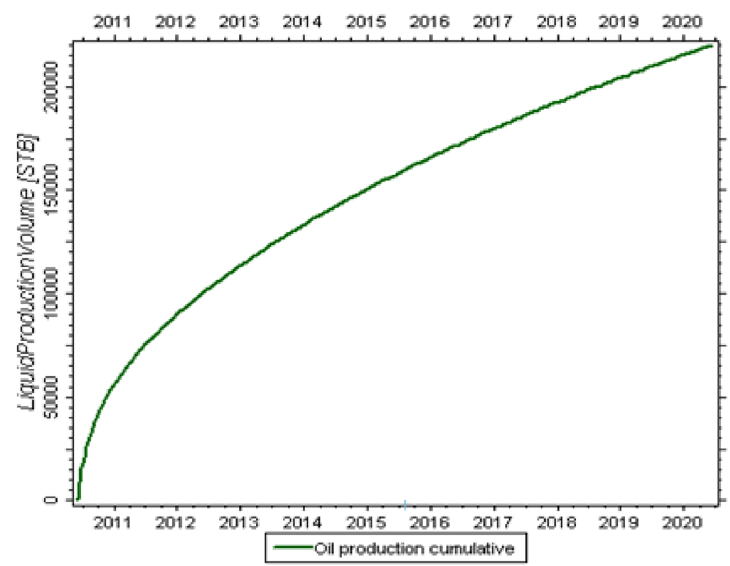
Calibrated Model used to Forecast Recovery

Forecast EUR

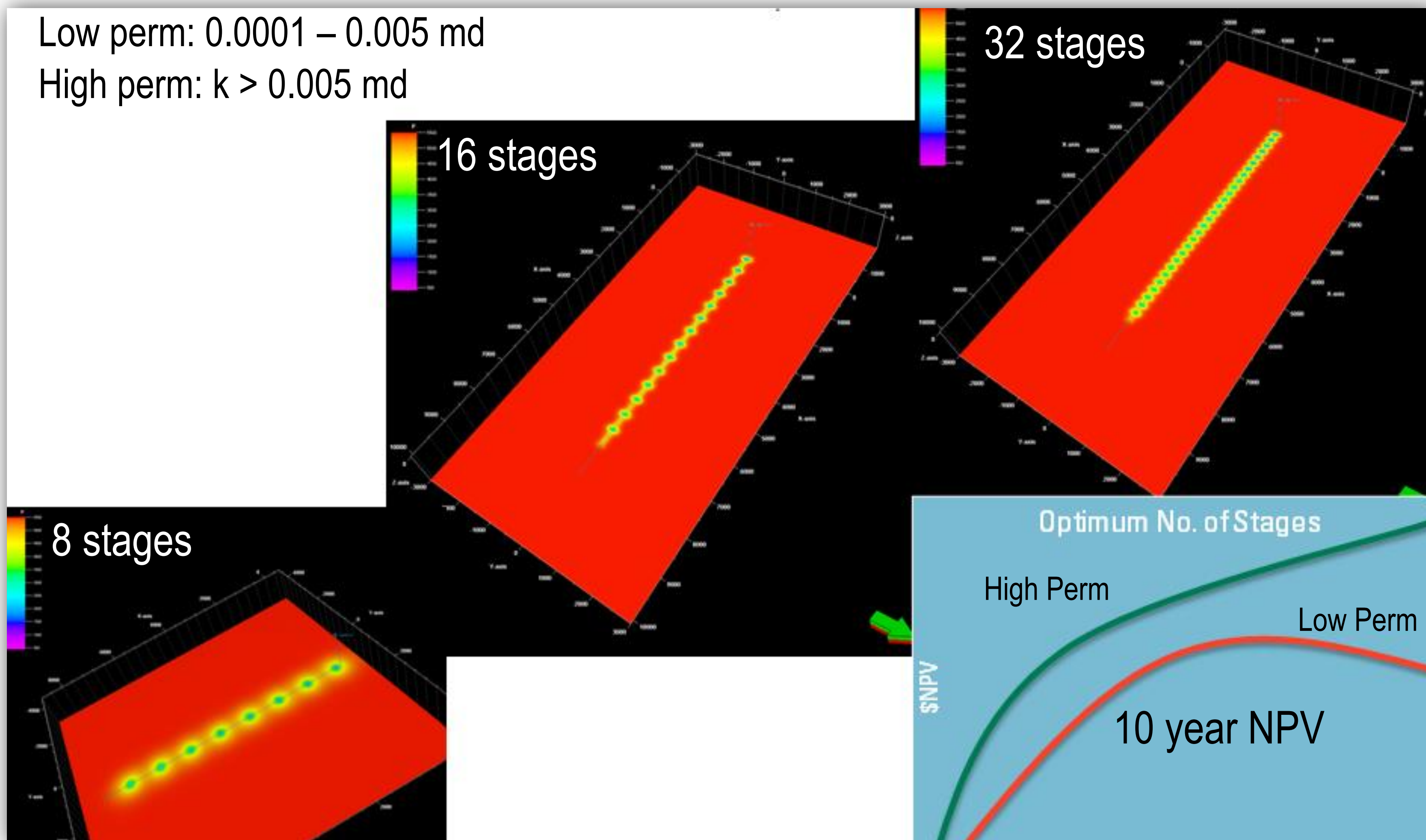






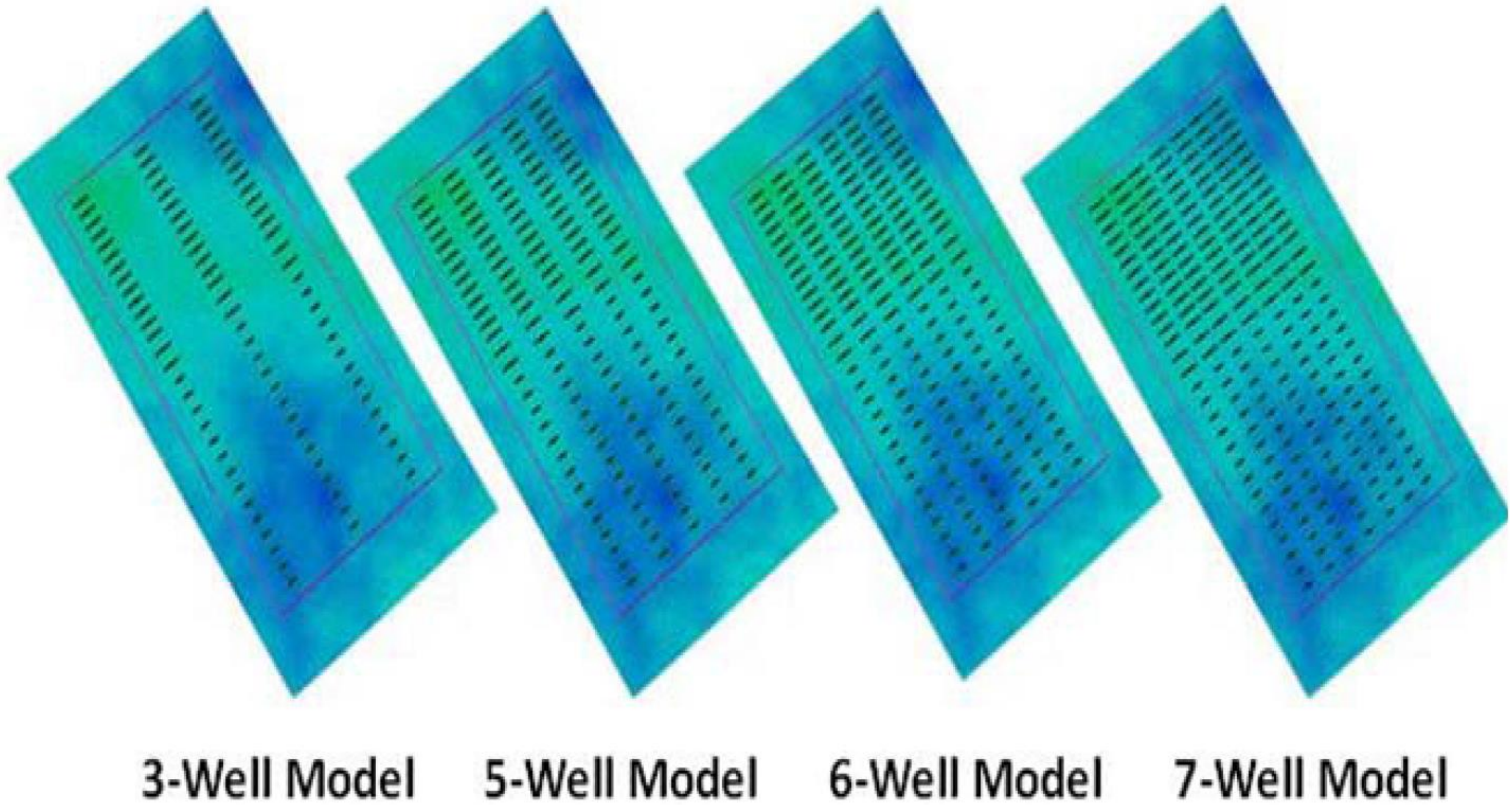


Calibrated Model Optimize Completions

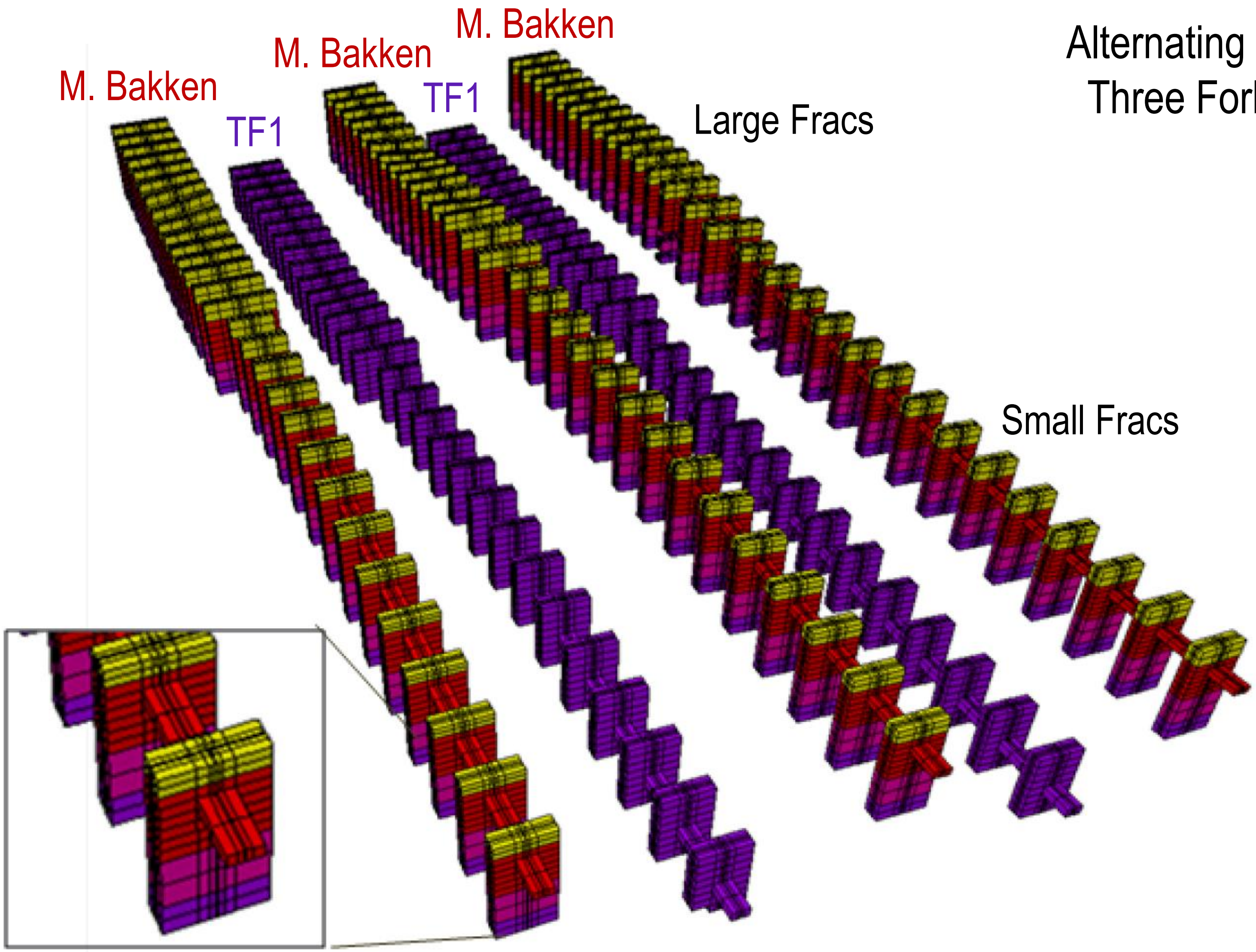


Economic sensitivity analyses to optimize the number of frac stages

Expanding to Field Development: Well Spacing

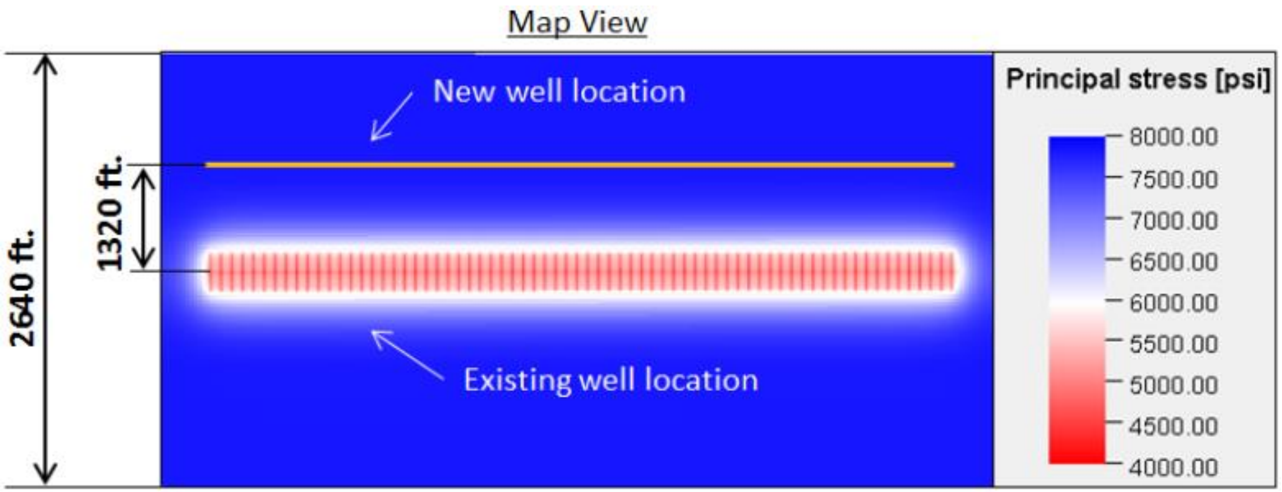


Sustained Vertical Communication?

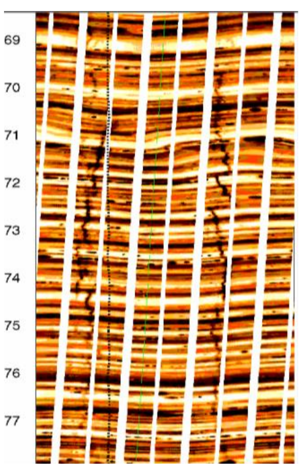


Alternating Bakken and Three Forks Laterals

The Impact of Production



Pore pressure distribution after 600 days of production



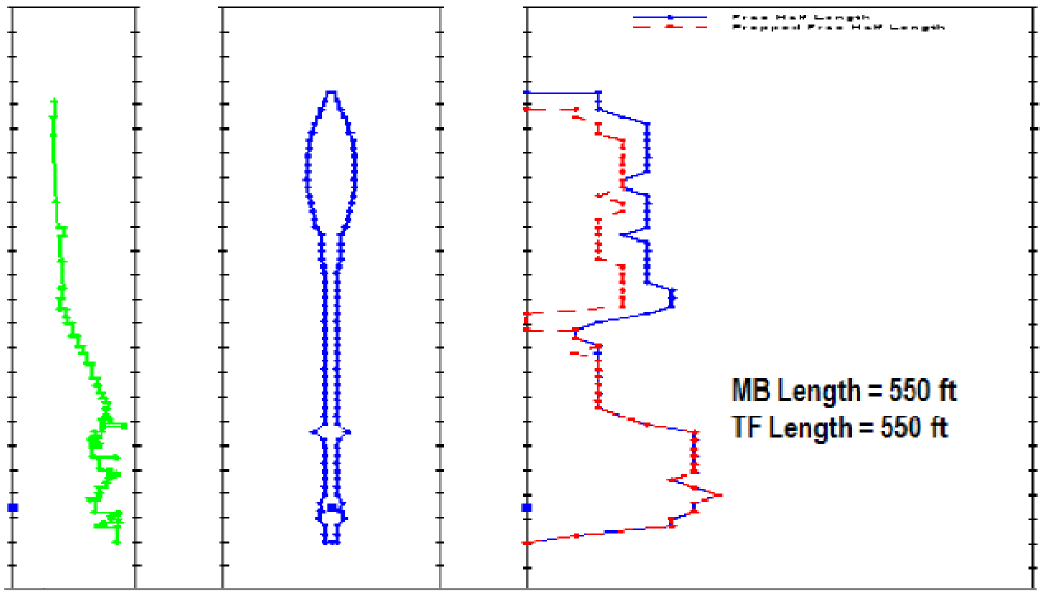
$$\sigma_h = \frac{E_h}{E_v}\frac{\nu_v}{1-\nu_h}\left(\sigma_V - \alpha P_p\right) + \alpha P_p$$

Closure stress reduction is directly proportional to drop in pore pressure

Pore pressure reduction is inversely proportional to mechanical properties anisotropy in TIV rocks

Closure stress does not fall as fast in TIV rocks as isotropic rocks

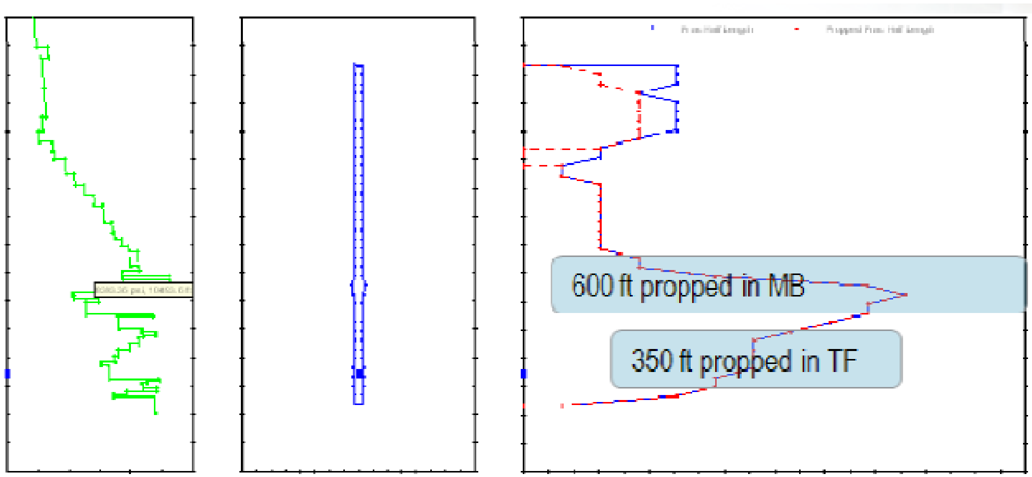
Evolution of Frac Geometry with Time / Depletion



Frac geometry pre Bakken depletion from offset well

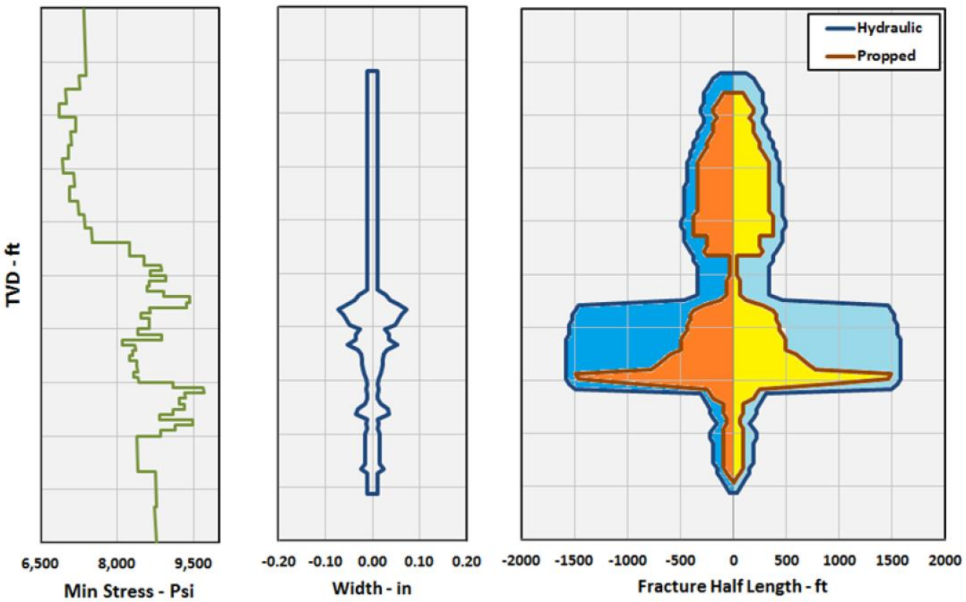
Frac length and height growth can vary with pore pressure depletion

Can the Bakken and Three Forks be produced together?



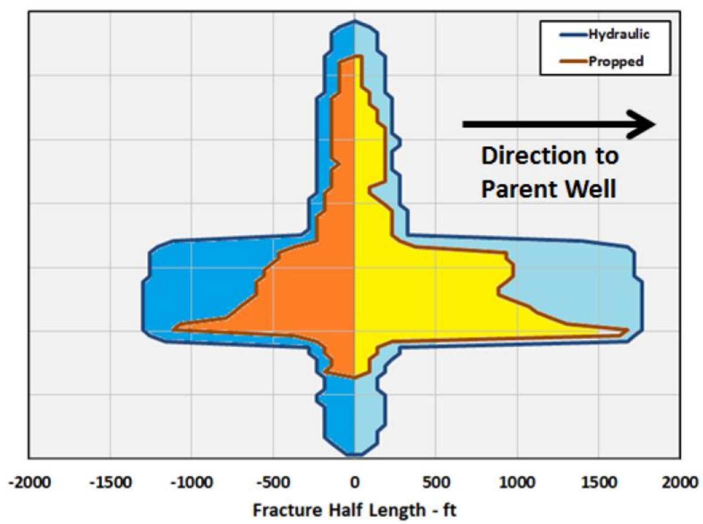
Frac geometry post Bakken depletion from offset well

Asymmetric Fracture Geometry due to Depletion



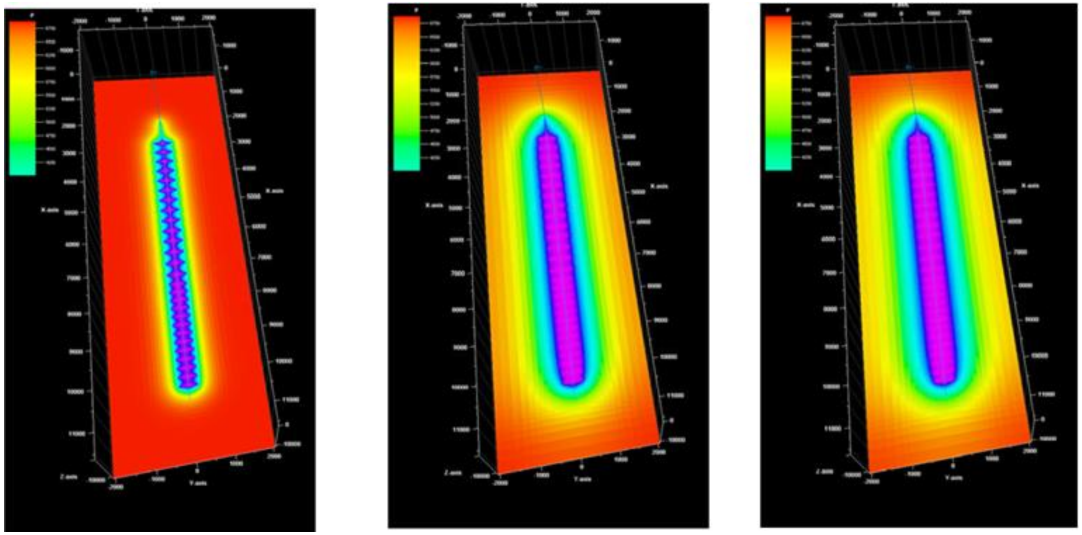
Fracture geometry for initial conditions

Planar3D
Fully 3D asymmetric hydraulic fracturing simulator

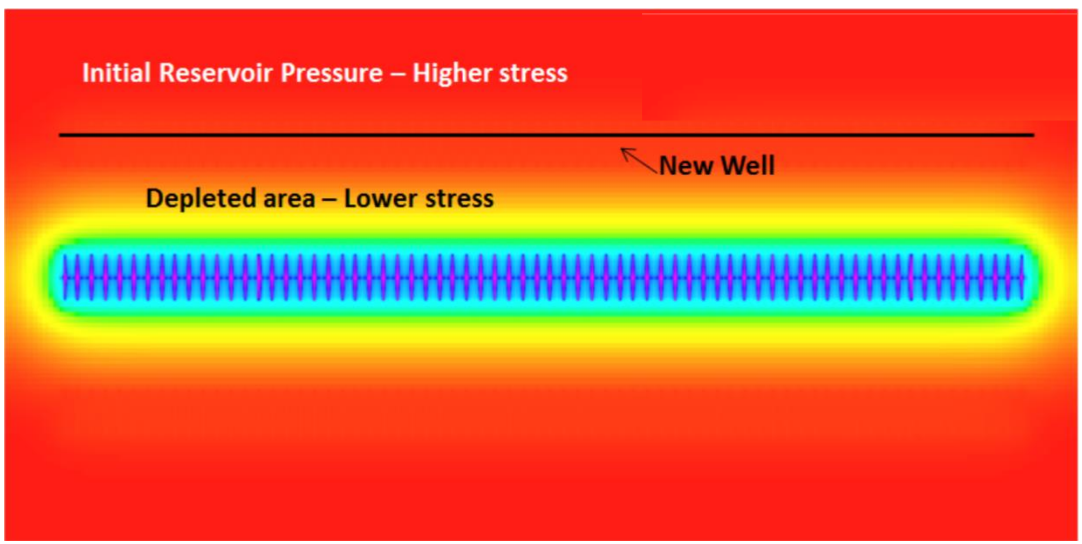


Fracture geometry for infill wells

What is the Impact on Infill Well Production?

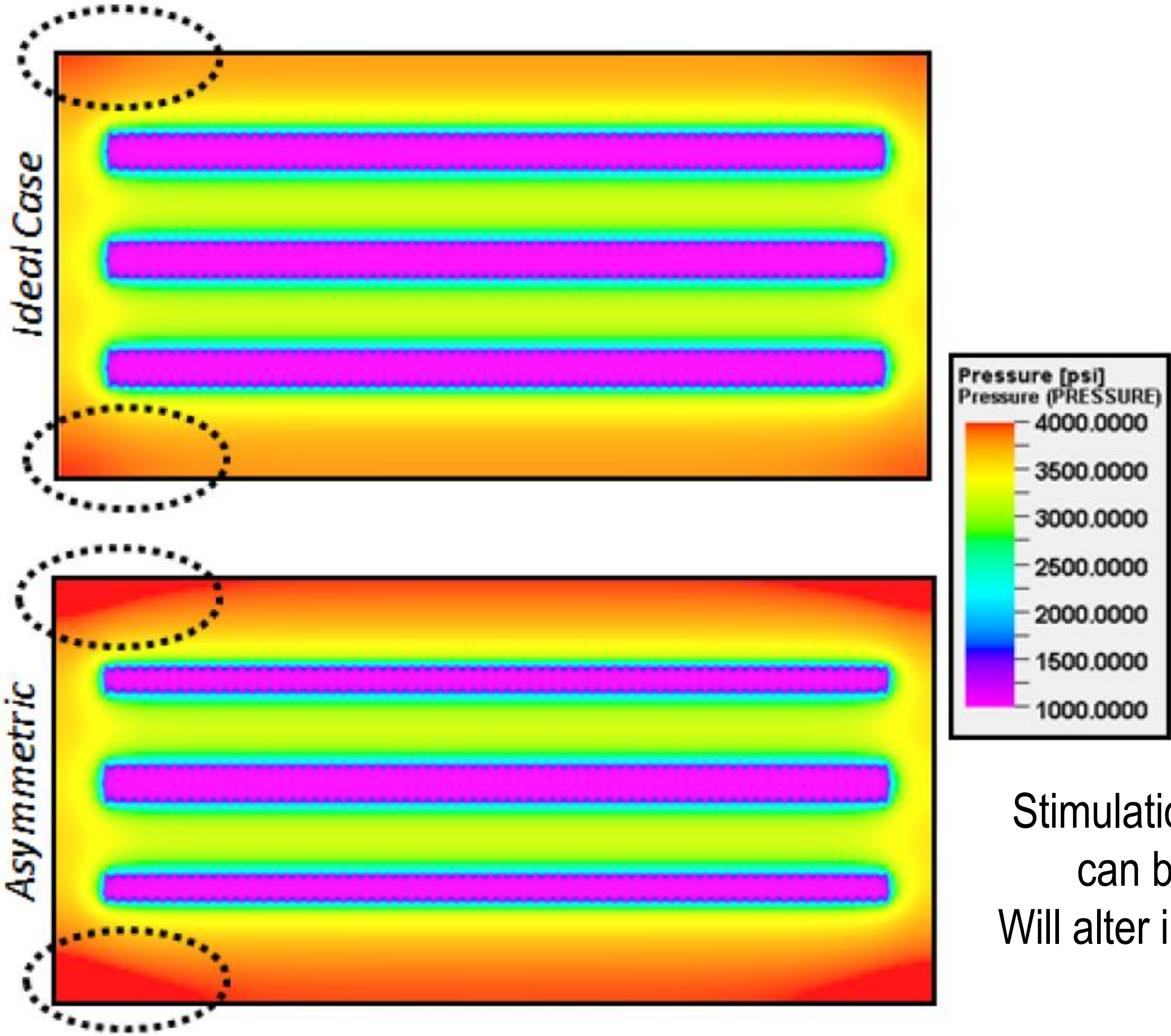


Pressure Profile for parent well evolves with time / depletion



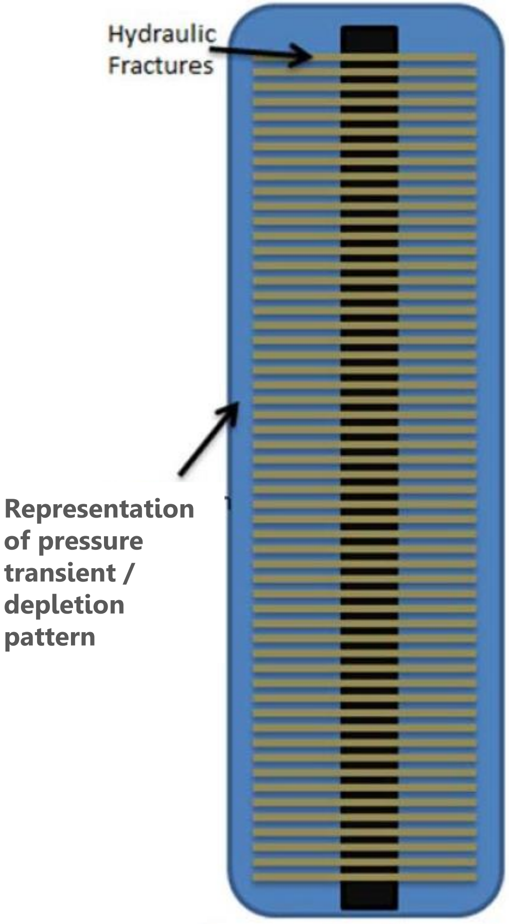
Optimum infill well distance from the parent well will vary with time

Development Challenges due to Depletion



Stimulation away from parent well can be adversely affected.
Will alter infill development strategy

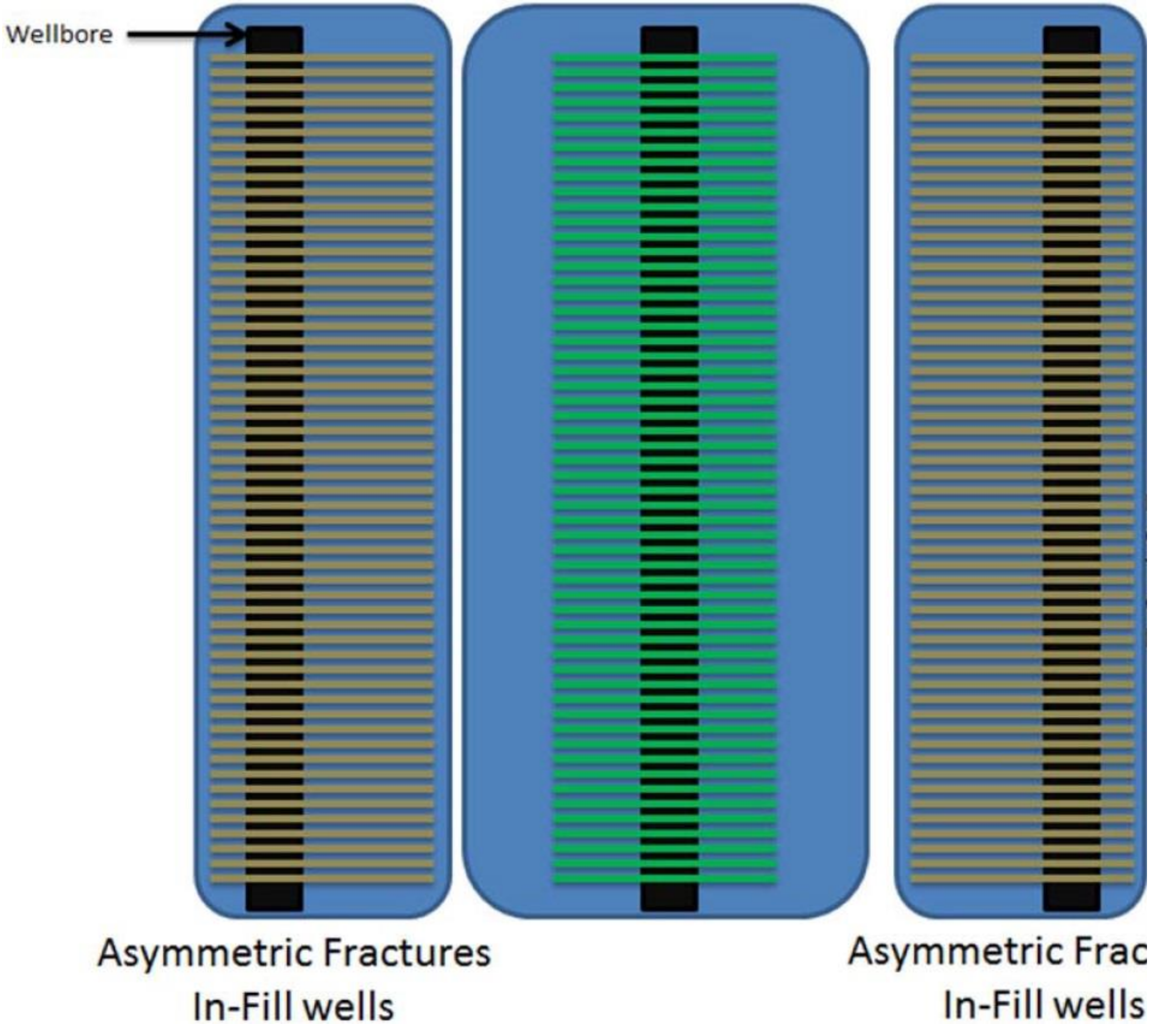
Field Development Strategy due to Depletion



Symmetric Fractures
In-Fill wells

Instead of having this…

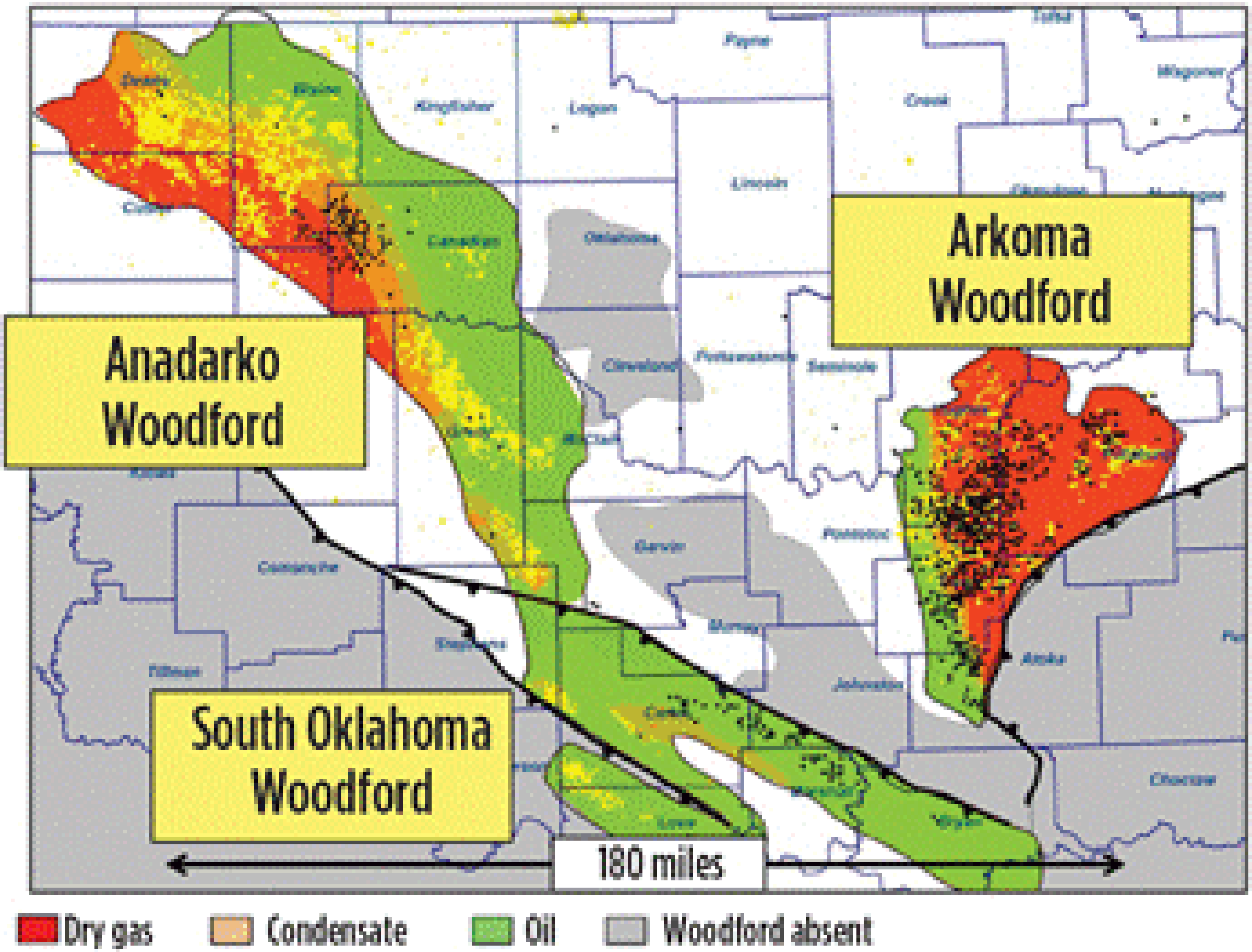
Field Development Strategy due to Depletion



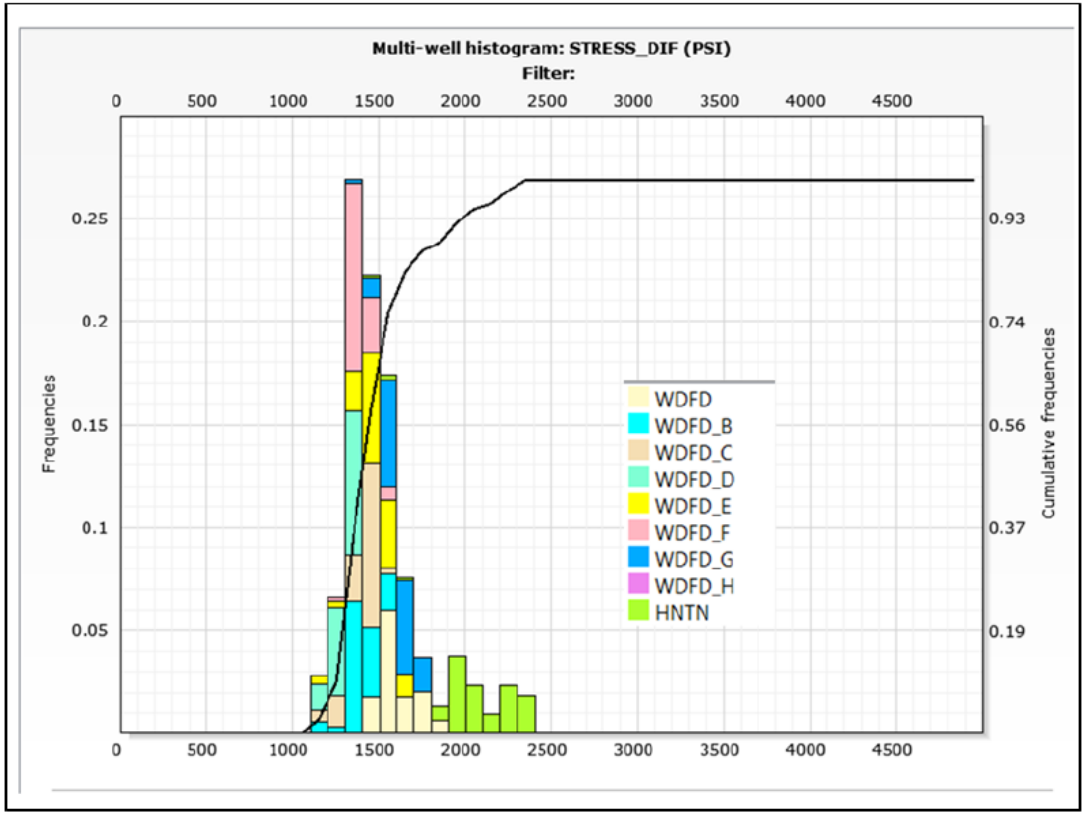
We have this…

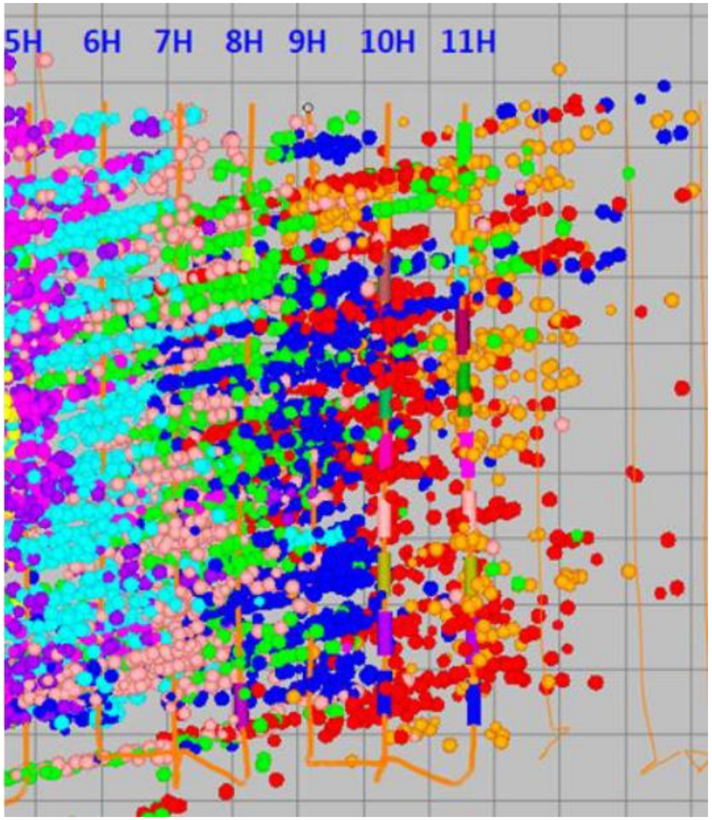
Best addressed with a calibrated reservoir model

Anadarko Basin: Cana Woodford Shale



Woodford Shale Fracture Geometries

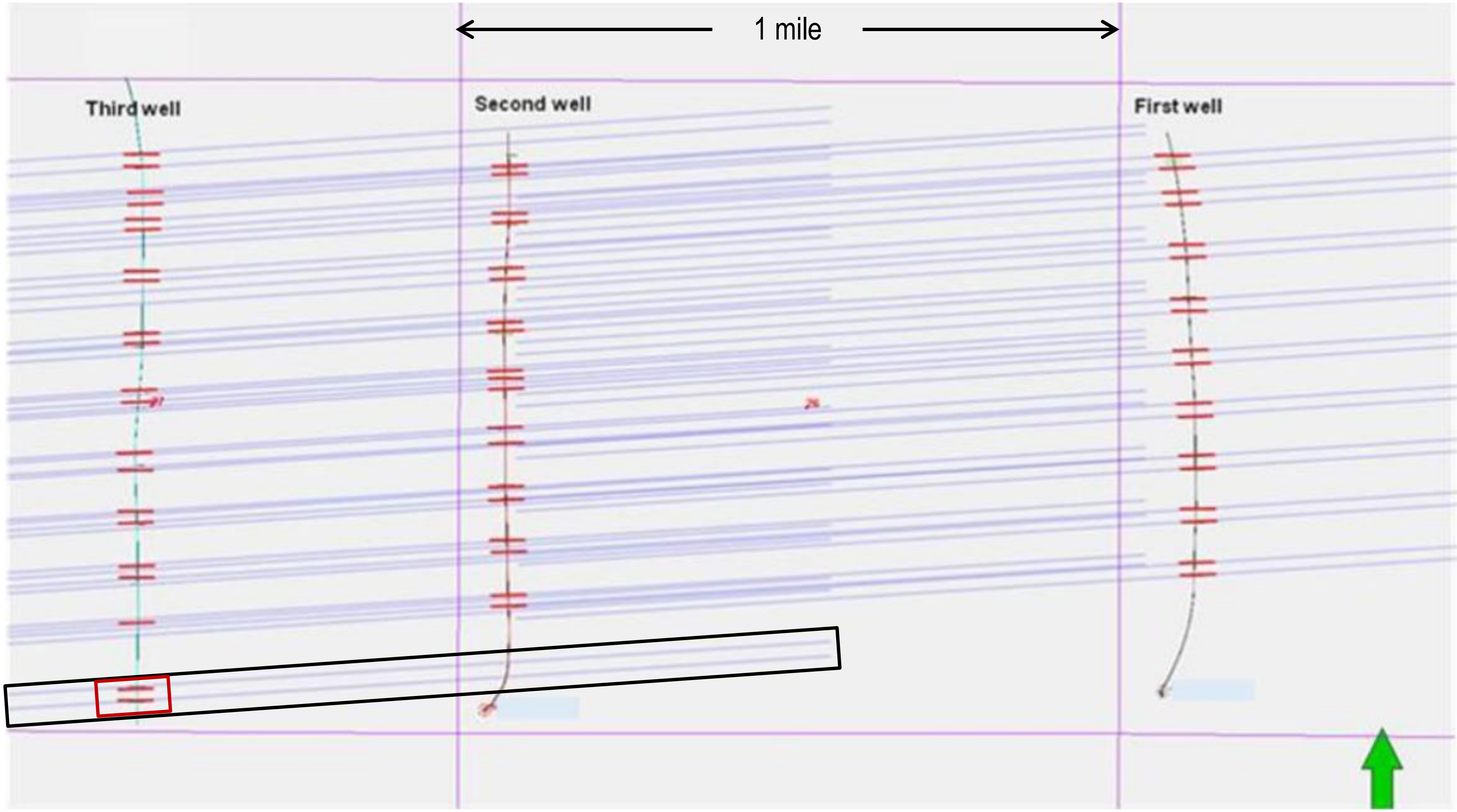




Woodford horizontal stress anisotropy is ~ 1,500 psi from multiple 1D MEMs

Result is Planar Fractures

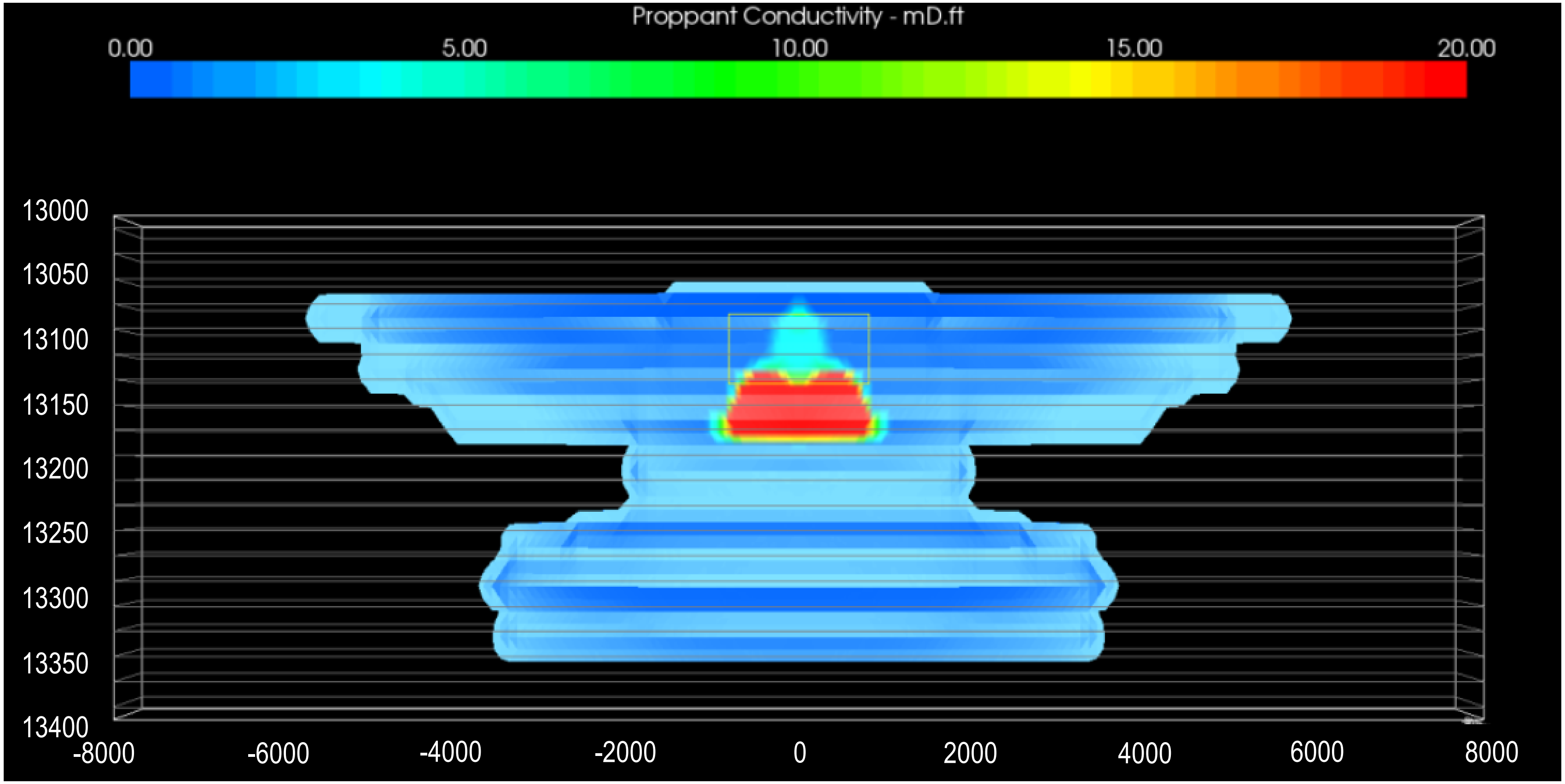
Large Slickwater Fracs = Long Frac Lengths



Hydraulic lengths intersect offset wells

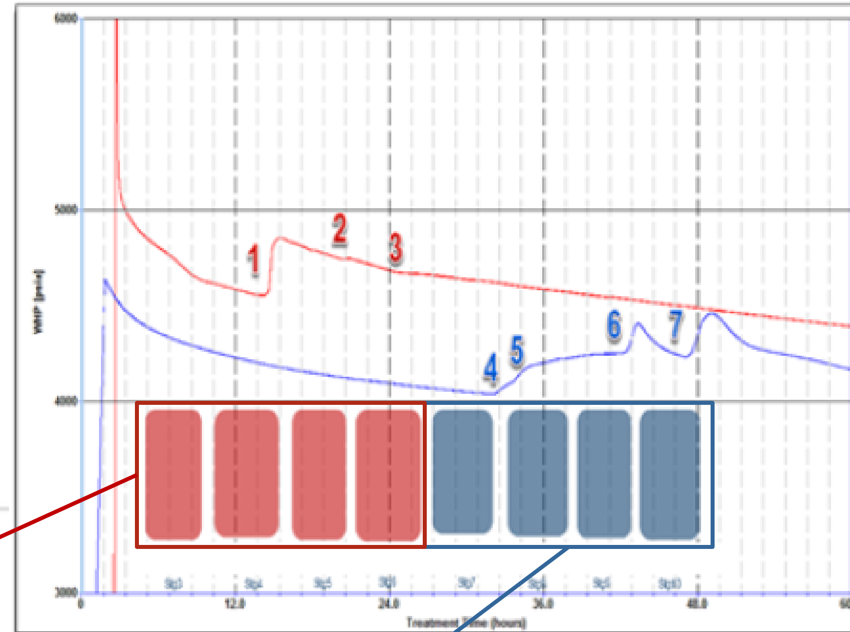
Conductive lengths are much shorter than hydraulic lengths

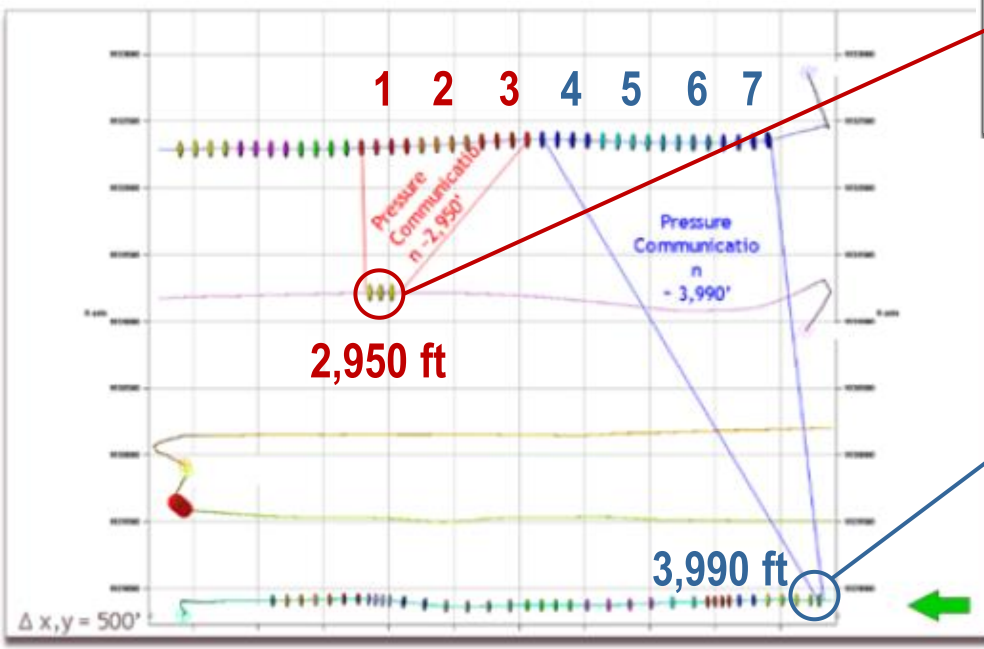
Long Frac Lengths are Modeled



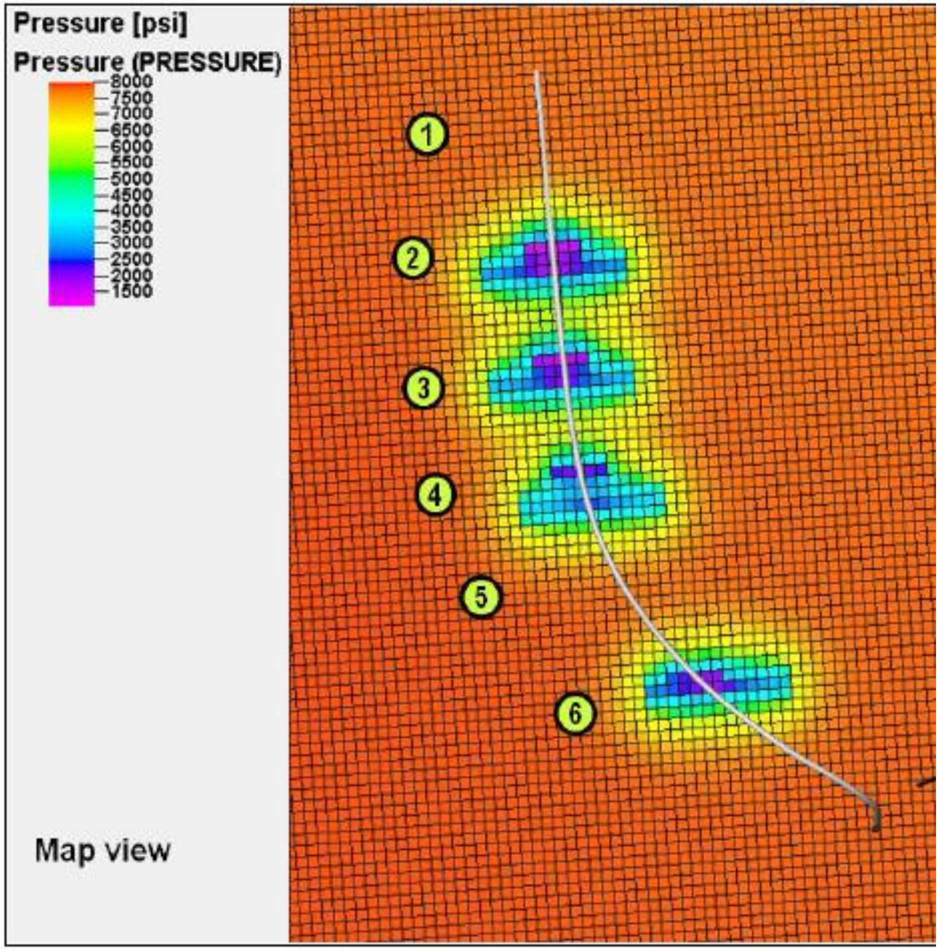
Long Frac Lengths are Measured

Frac pressure communication
with offset wells

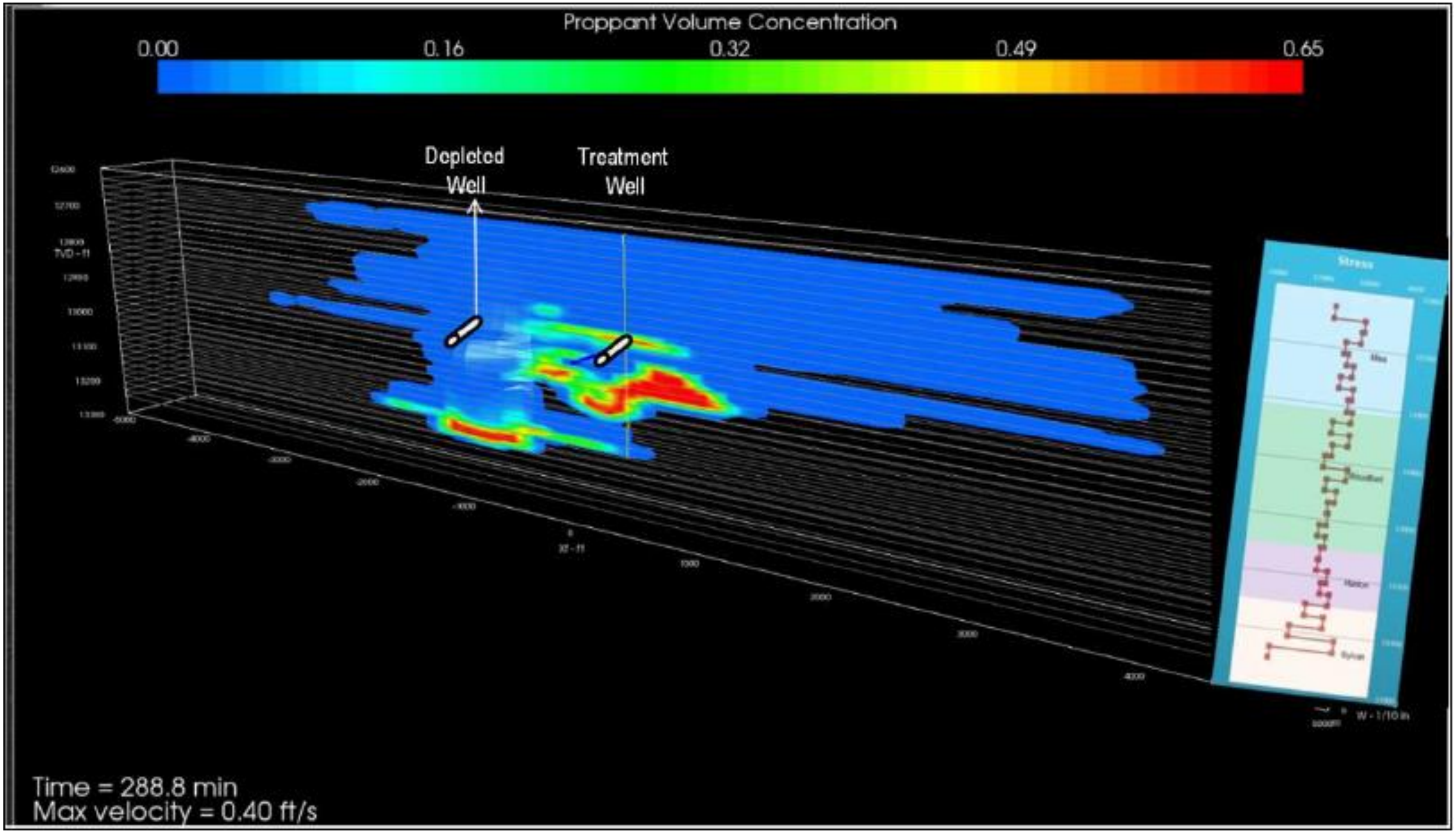




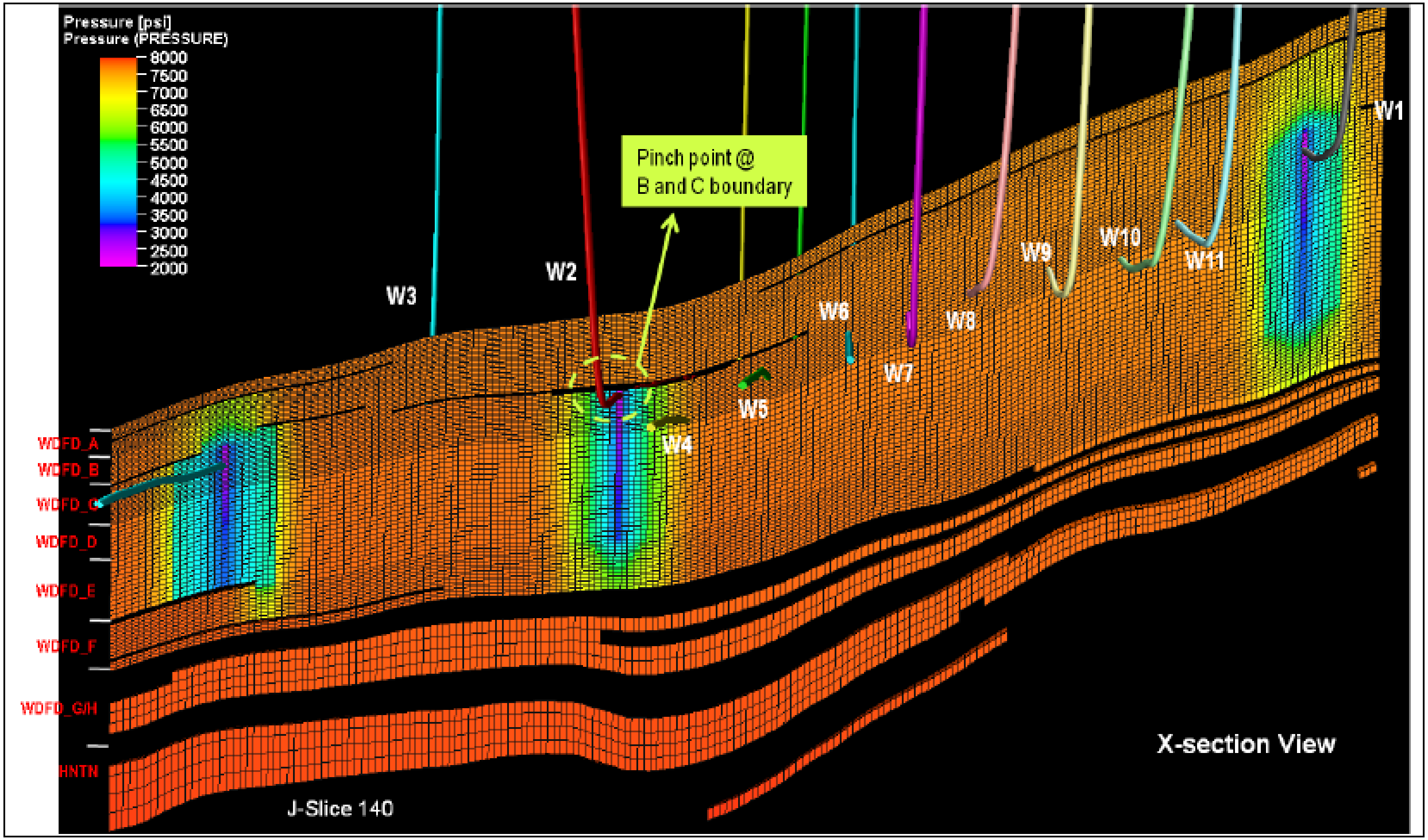
Woodford Pore Pressure Depletion



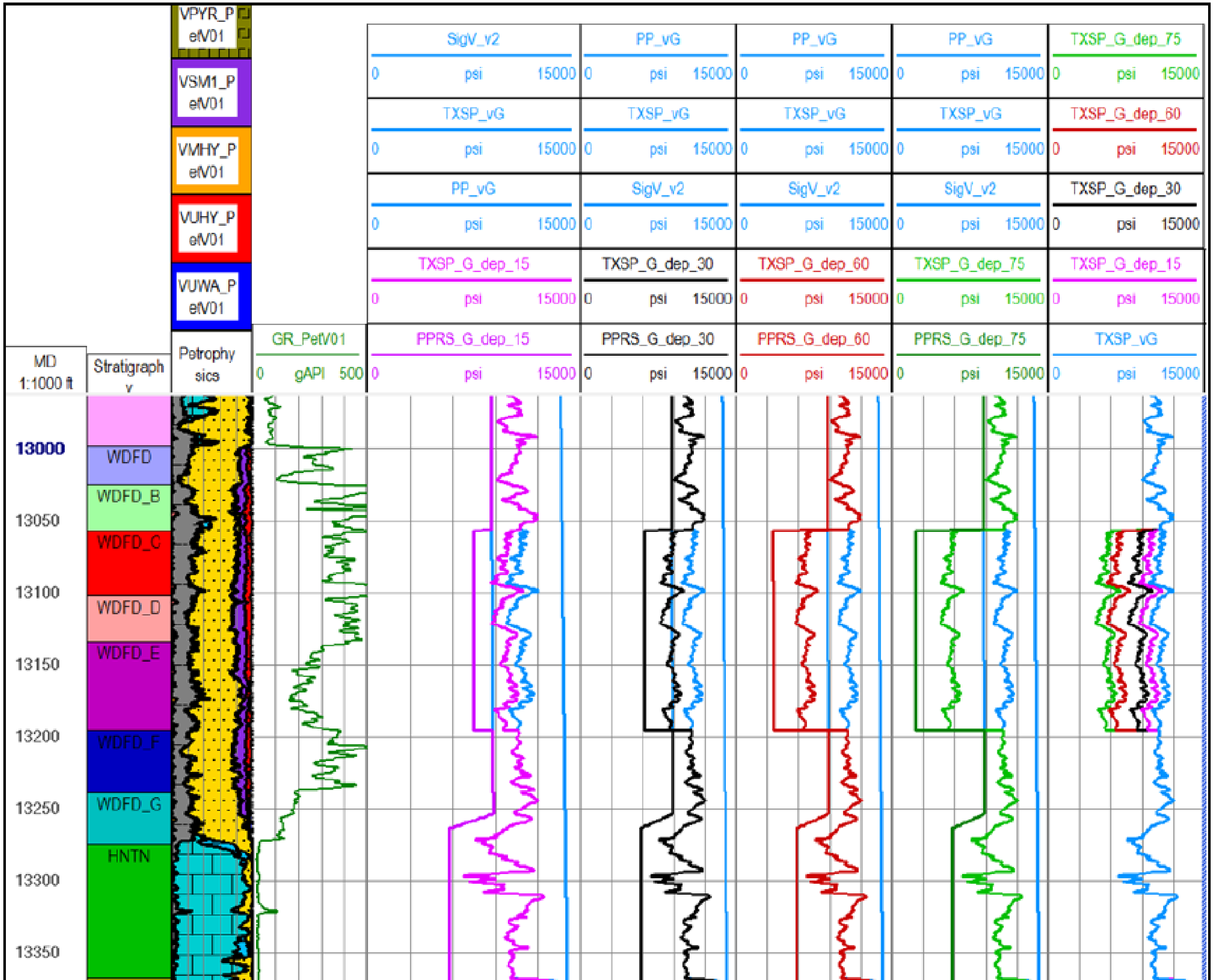
Woodford Shale Frac Assymetry



Woodford Producing Intervals

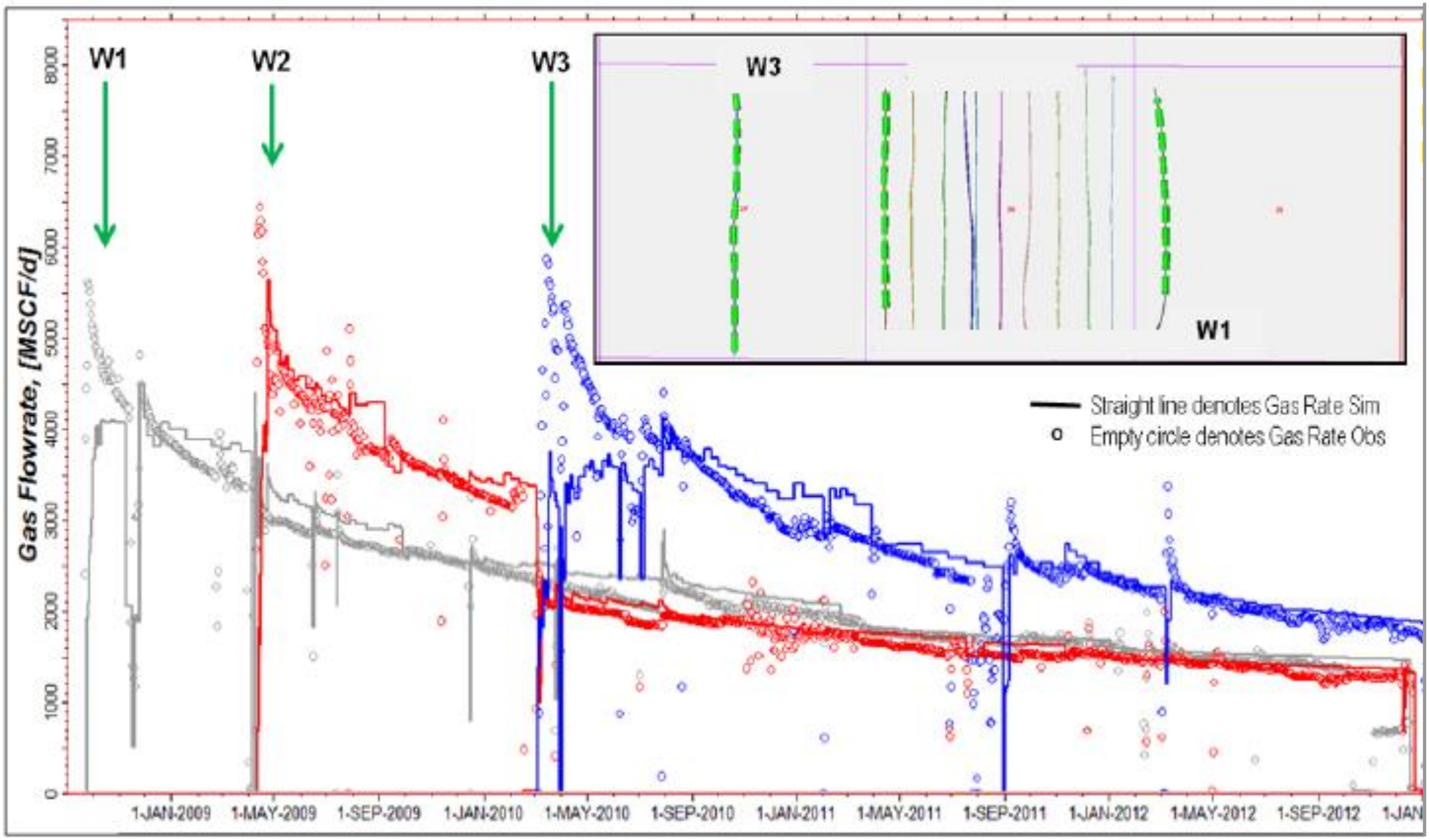


Woodford Shale Productive Intervals

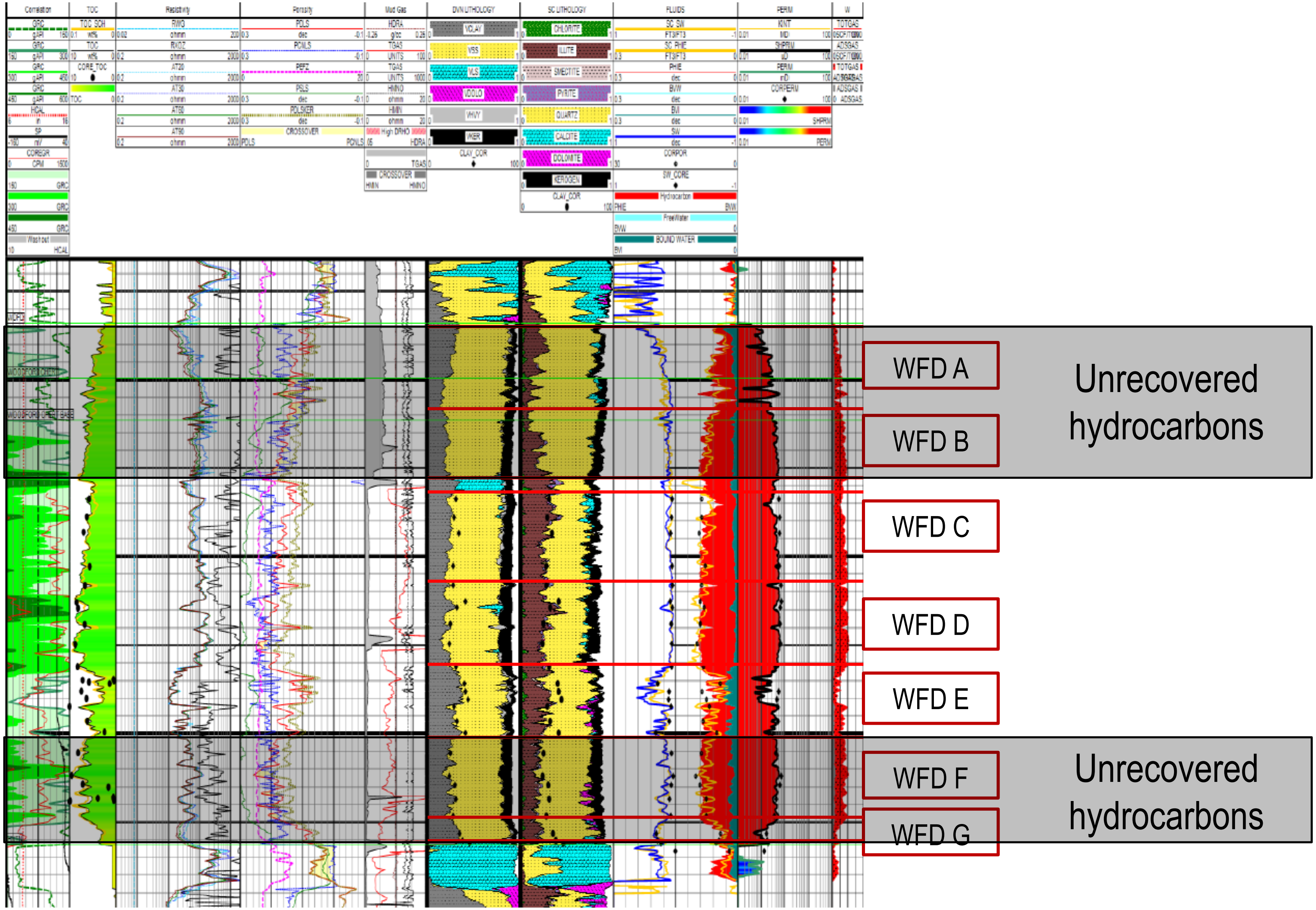


Only Woodford C – E appear to be producing

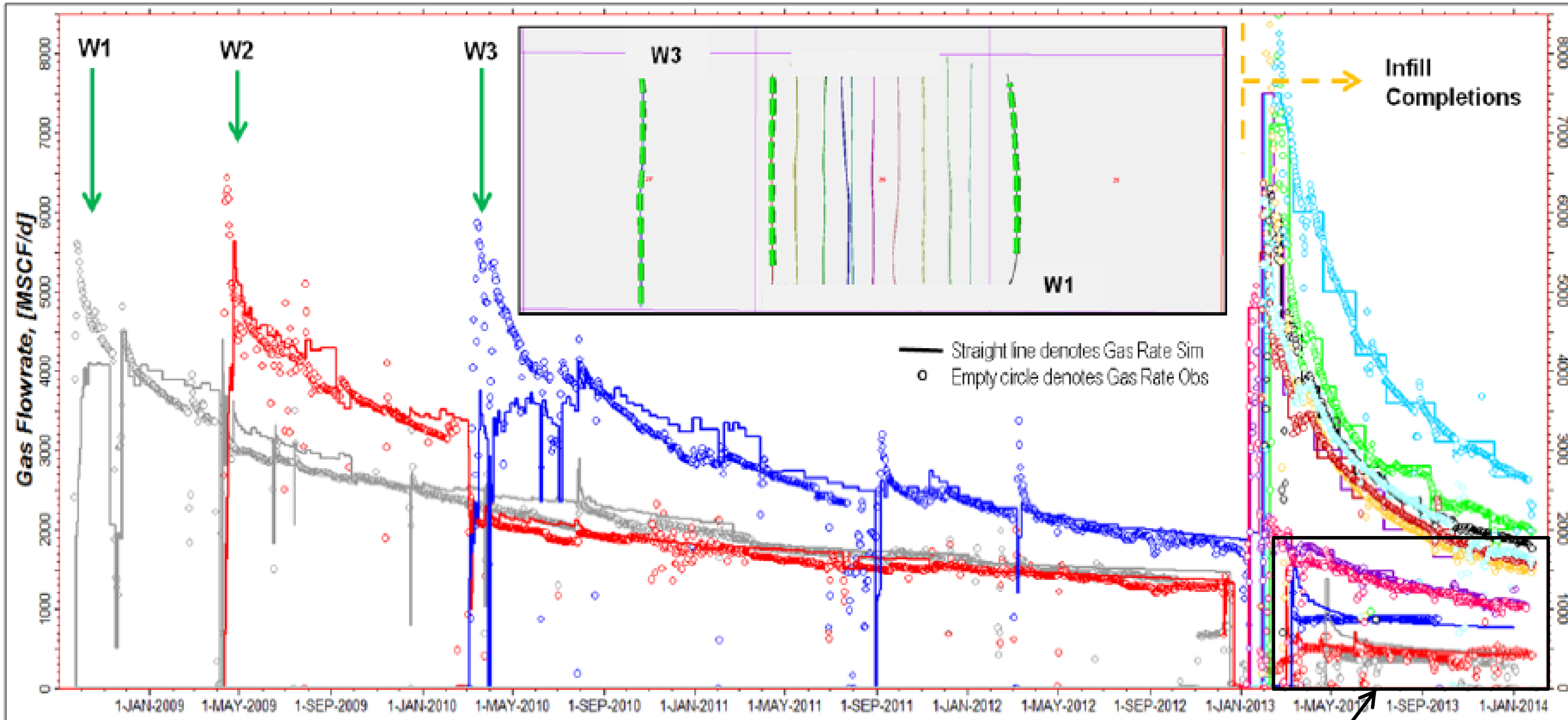
Modeled Production Validates Productive Intervals



Woodford Shale Field Development Challenge



Woodford Shale Field Development Challenge



Infill well development
adversely impacts parent wells

Operational Solutions to Address Challenges

Develop fracture designs to address loss of vertical fracture conductivity

Evaluate reverse hybrid technique:

- Improve effective frac height and infill well proppant transport
- Reduced overall fluid volume for better infill well stimulation results
- Improved propped to unpropped fracture ratio

Change perf design to improve injectivity into all perfs

- Reduced frac lengths by injecting into more clusters

Provide flow back energy to flooded existing producers:

- Re-frac the existing producing well with an energized fluid, distributed along the entire lateral in the fracture system with degradable diverters
- Energized fluids in the new well stimulations

Reservoir depletion management

- Temporal optimization of infill development

Summary

- Field development is controlled by reservoir and completion parameters:
  - Reservoir Parameters

    Perm, natural fractures, geomechanical setting…
  - Completion Parameters

    Perf spacing, stage design, frac fluid type and volume, production management…
- Infill well placement is a function of:
  - Perm, pressure, and stimulated / drainage volume
  - Time of infill well relative to parent well(s)
  - Durability of fracture conductivity, especially vertically
- Parent wells will be impacted:
  - Likely to be adverse on wells with large production volumes
  - Options to protect parent wells:
    - Shut in parent wells
    - Aggressive drawdown of parent wells during infill well fracturing
    - Pressure up parent well with (energized) fluids
    - Refrac parent wells utilizing diversion technologies
    - Use energies fluids on infill wells