Distinguished Lecturer Program

Hydraulic Fracturing of Horizontal Wells
- Realizing the Paradigm Shift that has been 30 years in Development

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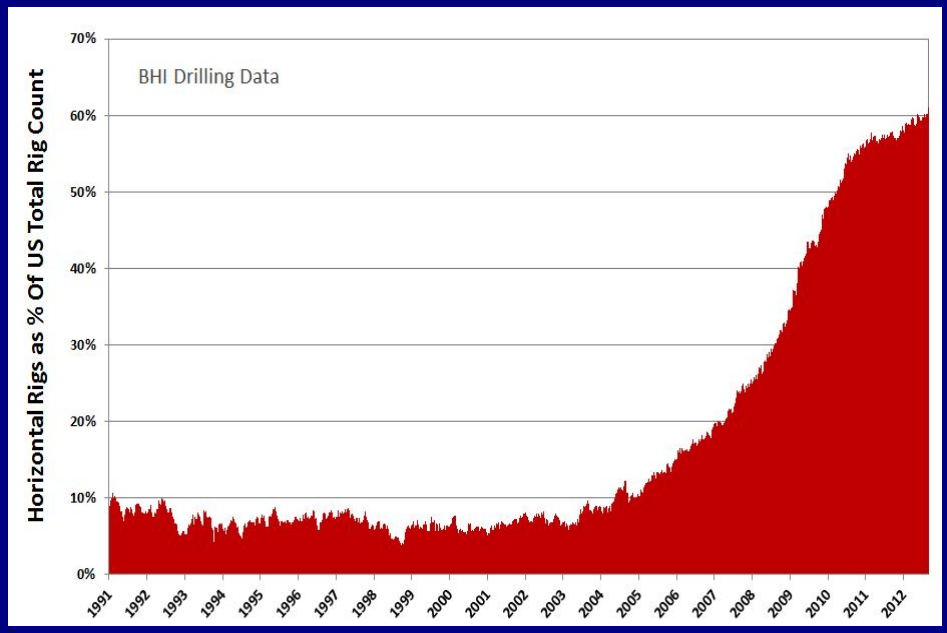
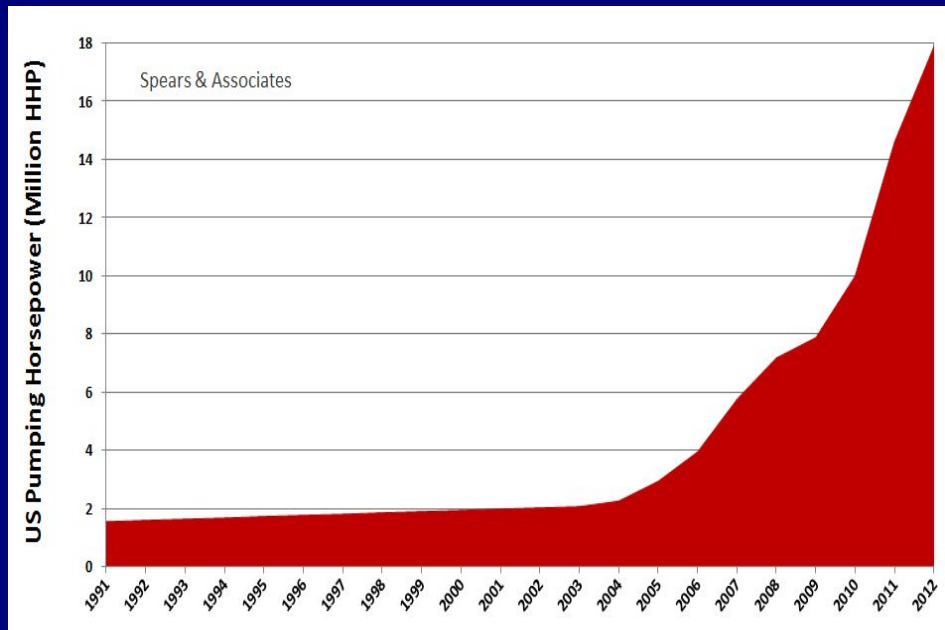
Liberty Resources LLC

Key Technologies

- **Horizontal Wells and Hydraulic Fracturing both stand as separate technologies that have had a significant impact on the petroleum industry and our ability to develop hydrocarbon resources.**
- **The combination of the two technologies have resulted in an industry revolution:**
  - 24000 references to Horizontal Well Fracturing in the SPE/One Petro Database
  - Over 60% of US drilling activity is drilling horizontal wells
  - In 2011, Pressure Pumping Services became the largest single business segment in the Oilfield Services arena.





Outline

- Early Studies and Fracturing of Horizontal Wells
- Current Multi-Stage Completion Designs:
  - Cemented Vs Uncemented Liner / Casing
  - “Plug and Perf” Vs “Sliding Sleeve”
- Bakken Shale – Central Basin Development
- Current Developments / Changes in Completion Practices
- Conclusions

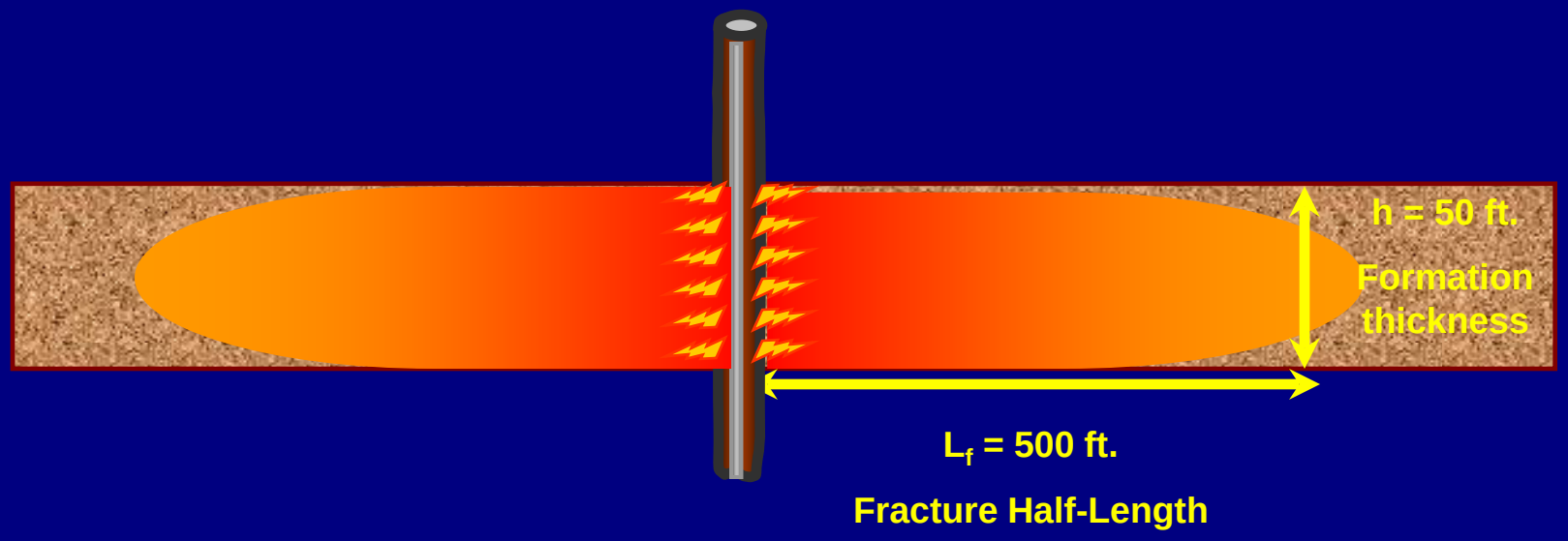
Horizontal Well Drilling

- The first recorded horizontal well was in Texon, Texas in 1929 and another in the Franklin Heavy Oil Field, Pennsylvania in 1944.
- Short radius wells were tested by ARCO in 1979-1982 in the Empire Abo Field, New Mexico.
- Offshore platforms and remote land locations (e.g. Alaska) required the development of directional drilling technology:
  - Downhole motors
  - Measurement While Drilling
  - Steerable assemblies
  - Logging While Drilling
- First Medium Radius Horizontal Well was drilled in the Austin Chalk in May 1985 by ARCO – the John G. Hubbard #1 in Rockwall, Texas; a 1500ft lateral with a 20°/100ft build rate.

Early Application of Horizontal Wells (1980's)

- To handle reservoir issues in some developments that were already using deviated wells – gas coning problems, unconsolidated formations, thin sands development.
- Opportunity to more effectively develop naturally fractured reservoirs – e.g. the Austin Chalk
- By the late-1980's industry was already testing the opportunity to combine the technologies of horizontal drilling and hydraulic fracturing
- Modern horizontal well drilling came of age at the end of the 1980's:
  - 257 horizontal well permits issued in the USA in 1989
  - Over 1000 permits in 1990.
  - API started tracking horizontal drilling in 1991

Reservoir Contact from Fracturing – Vertical Well



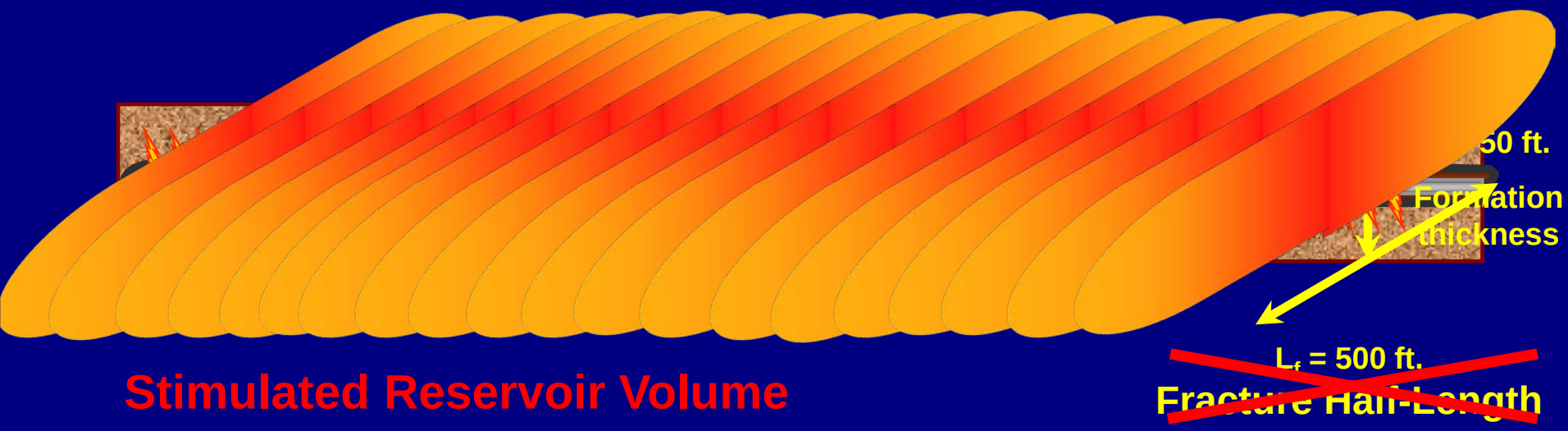
Openhole completion: 8¾″ hole diameter * 50 ft = **115 ft^2 of contact**

Cased hole completion: 4 spf, with 2 ft. penetration beyond cement
200 perf tunnels, ½ inch diameter = **52 ft^2 of contact**

Fracture Stimulated Completion: 500 ft half-length
2 wings * 2 faces * 500 ft * 50 ft = **100,000 ft^2 of contact**

Hydraulic Fracturing can increase reservoir contact in a vertical well by ~1,000 fold!

Reservoir Contact from Fracturing – Horizontal Well



Stimulated Reservoir Volume

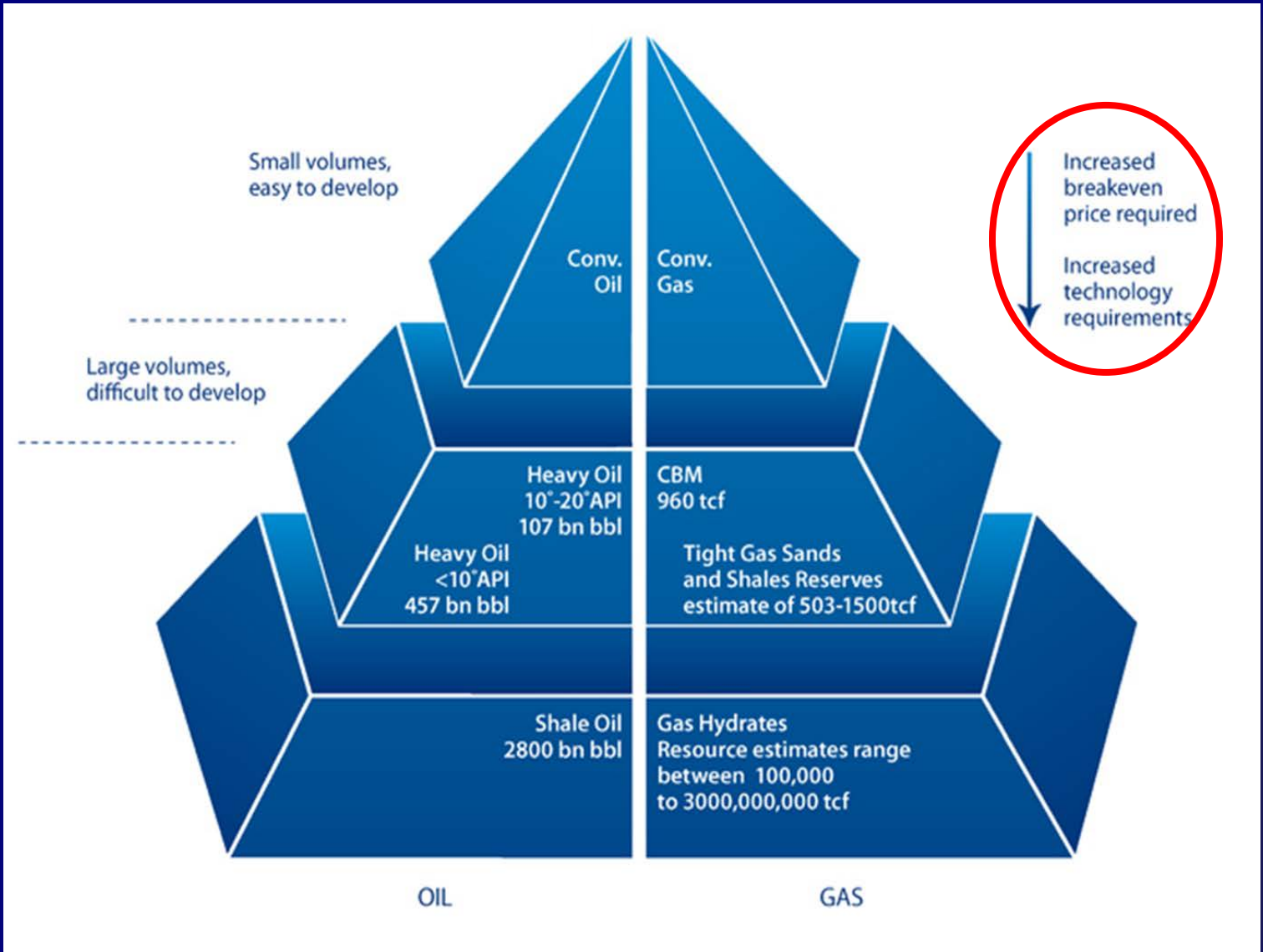
Openhole completion: 6″ hole diameter * 50 ft = **7850 ft^2 of contact**

Cased hole completion: 1 spf, with 2 ft. penetration beyond cement
5000 perf tunnels, ½ inch diameter = **1310 ft^2 of contact**

Fracture Stimulated Completion: 500 ft half-length
20 Stages * 2 wings * 2 faces * 500 ft * 50 ft = **2,000,000 ft^2 of contact**

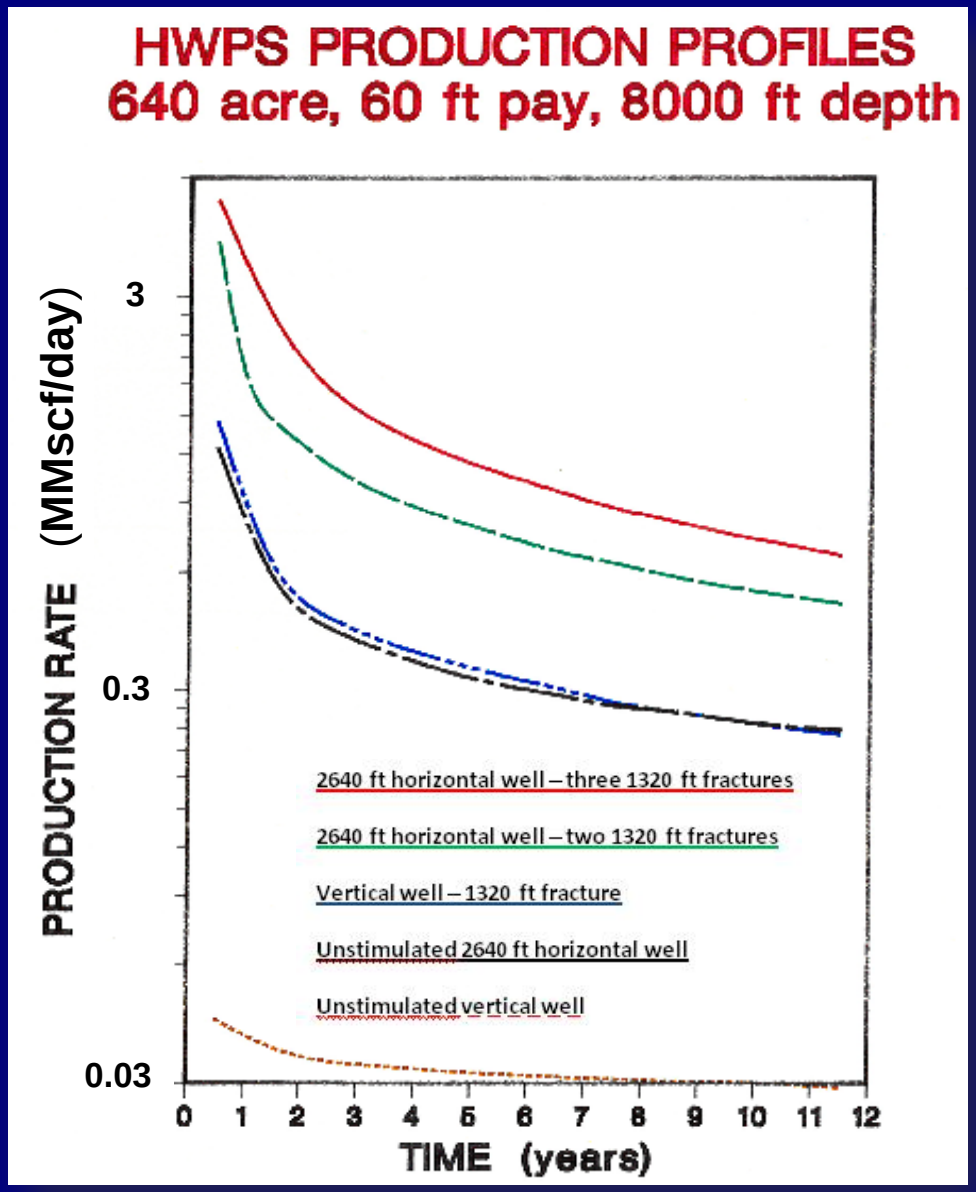
Horizontal Well Hydraulic Fracturing increases Reservoir Contact Area >10,000 fold over a conventional vertical well !

The Resource Triangle



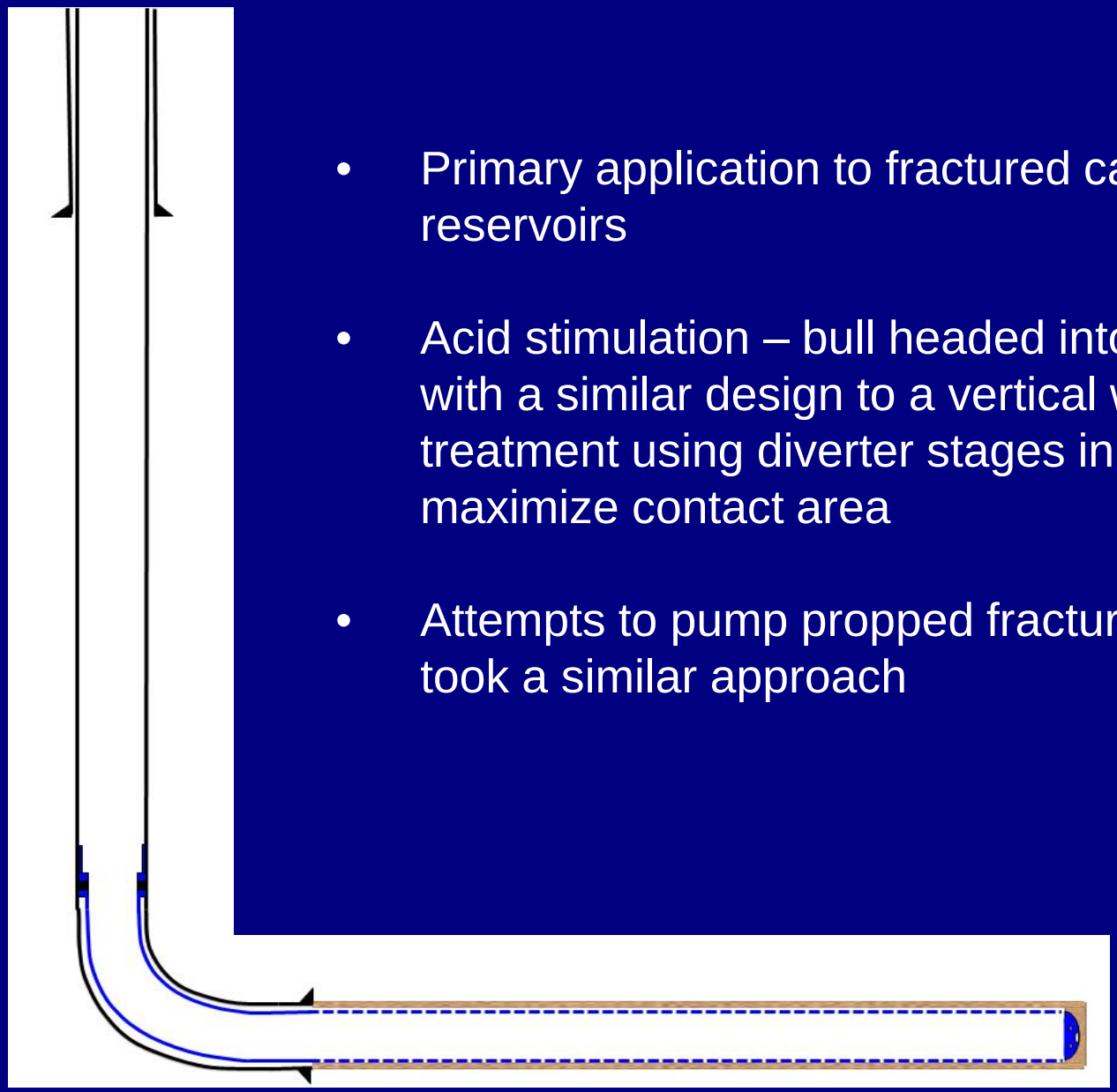
Source: Wood Mackenzie

1983 Gulf R&D Study on Horizontal Wells



- Significant potential for increasing production rates and EUR by fracture stimulating a horizontal well in a tight gas sand
- Completion Problems:
  - Casing Centralization
  - Cement Displacement
- Stimulation Issues:
  - Fracture Re-Orientation
  - Fracture Extension / Growth

1980's Completion Design

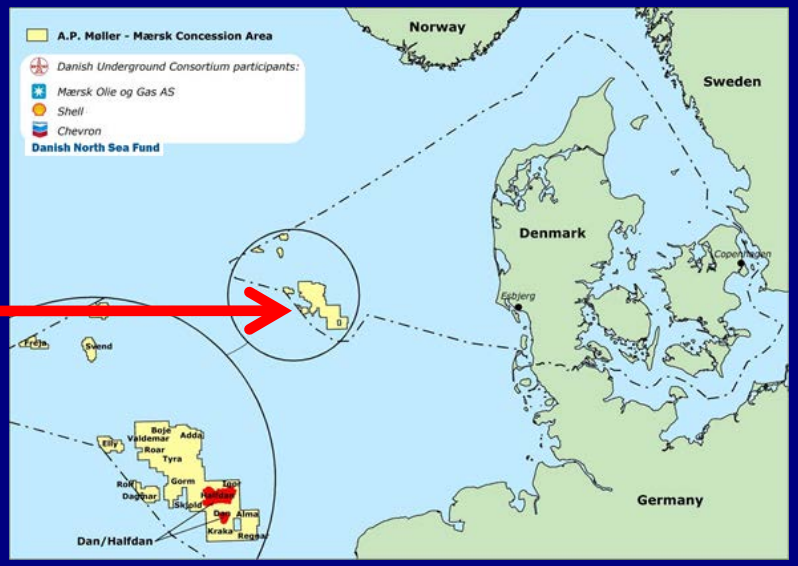


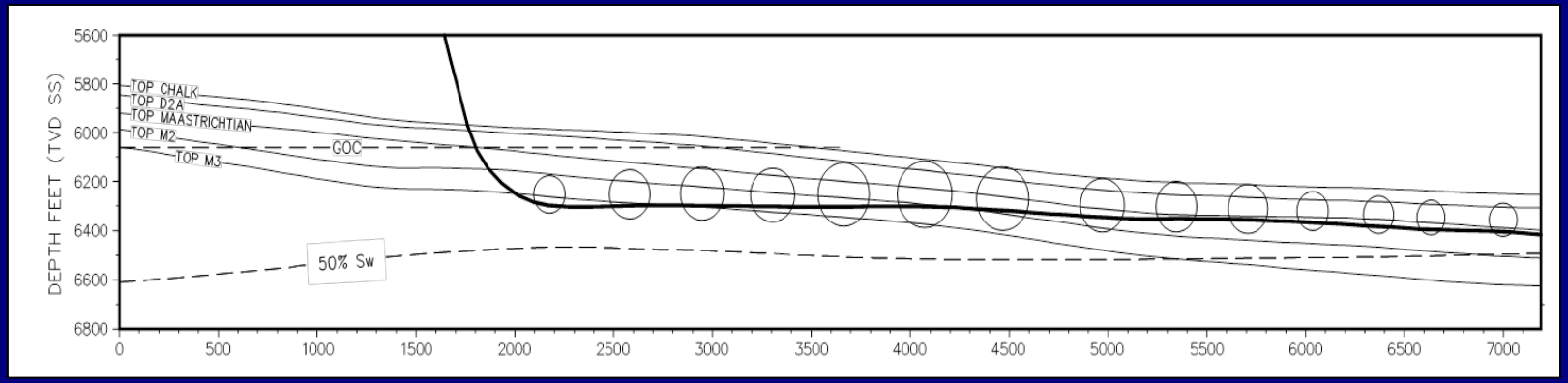
- Primary application to fractured carbonate reservoirs
- Acid stimulation – bull headed into the lateral with a similar design to a vertical well acid treatment using diverter stages in an attempt to maximize contact area
- Attempts to pump propped fracture treatments took a similar approach

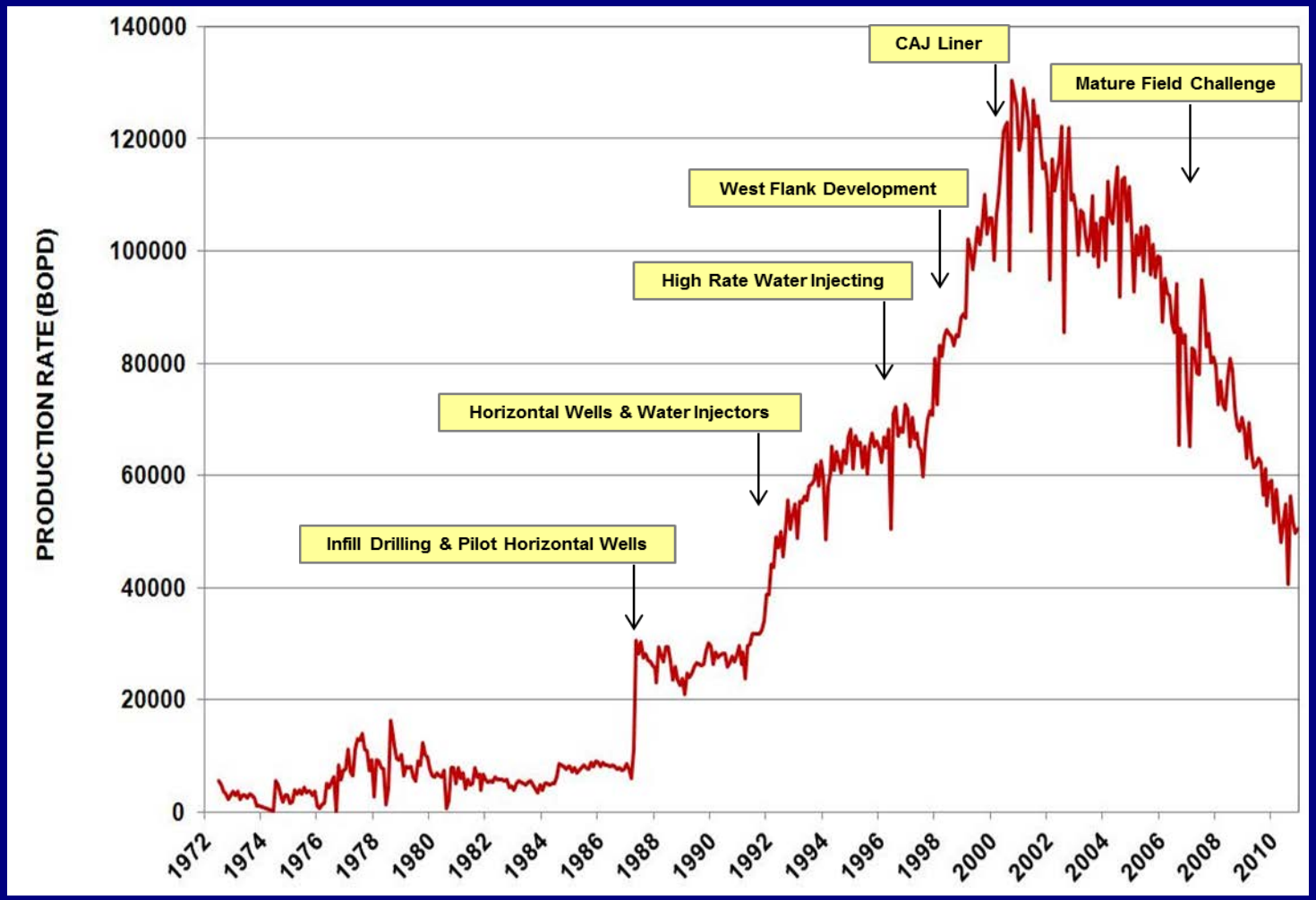
Early Multi-Stage Hydraulic Fractured Well

W M Schrock (26) #8 – Fractured July 7th 1987

Late 1980's/90's – Dan Field Redevelopment Danish North Sea; SPE 25049 (1992)




DEPTH FEET (TVD SS)
5600
5800
6000
6200
6400
6600
6800
TOP CHALK
TOP D2A
TOP MAASTRICHTIAN
TOP M2
TOP M3
GOC
50% Sw
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000

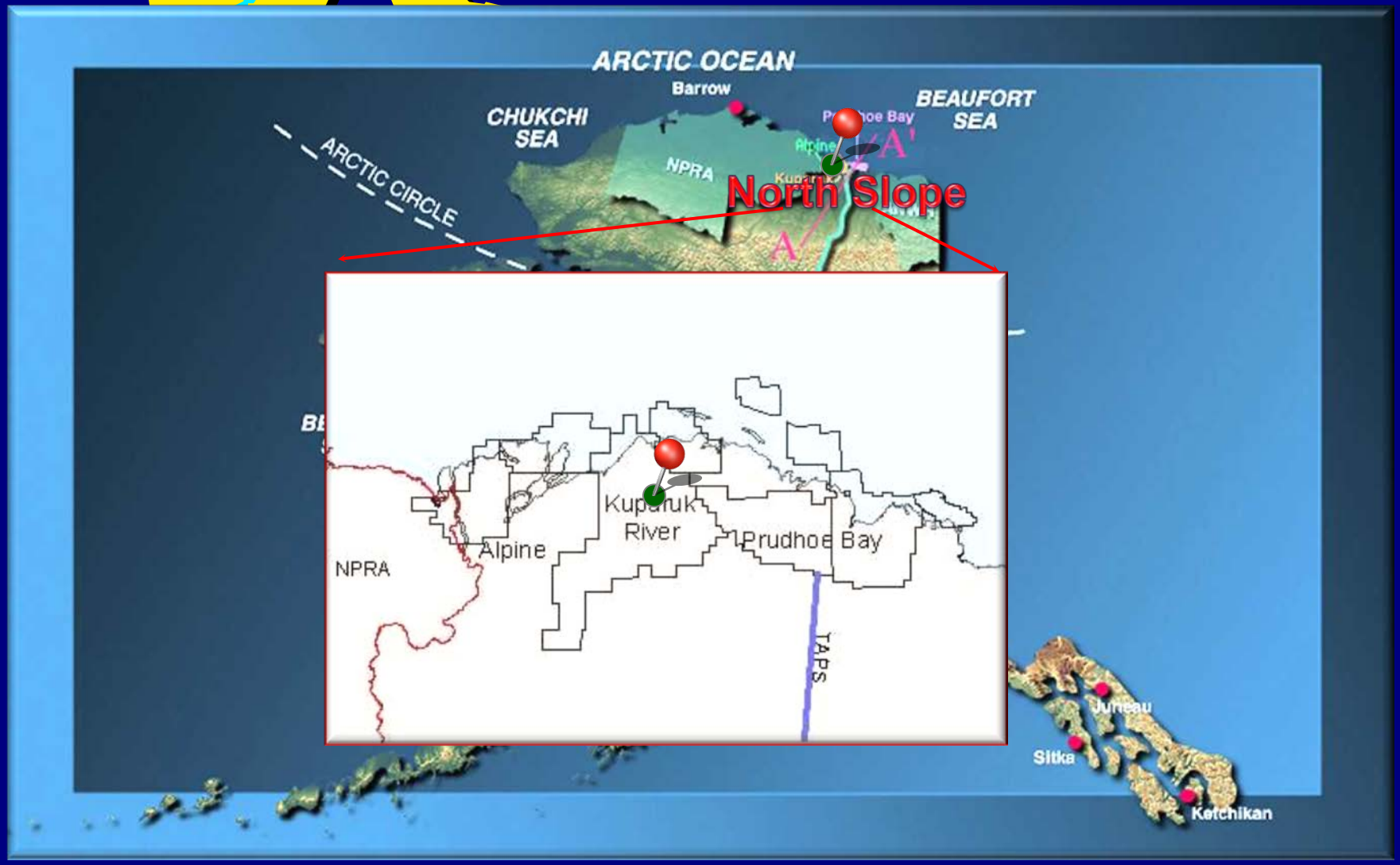

PRODUCTION RATE (BOPD)
140000
120000
100000
80000
60000
40000
20000
0
CAJ Liner
Mature Field Challenge
West Flank Development
High Rate Water Injecting
Horizontal Wells & Water Injectors
Infill Drilling & Pilot Horizontal Wells
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010

1990's – Emergence of Zonal Isolation Technology

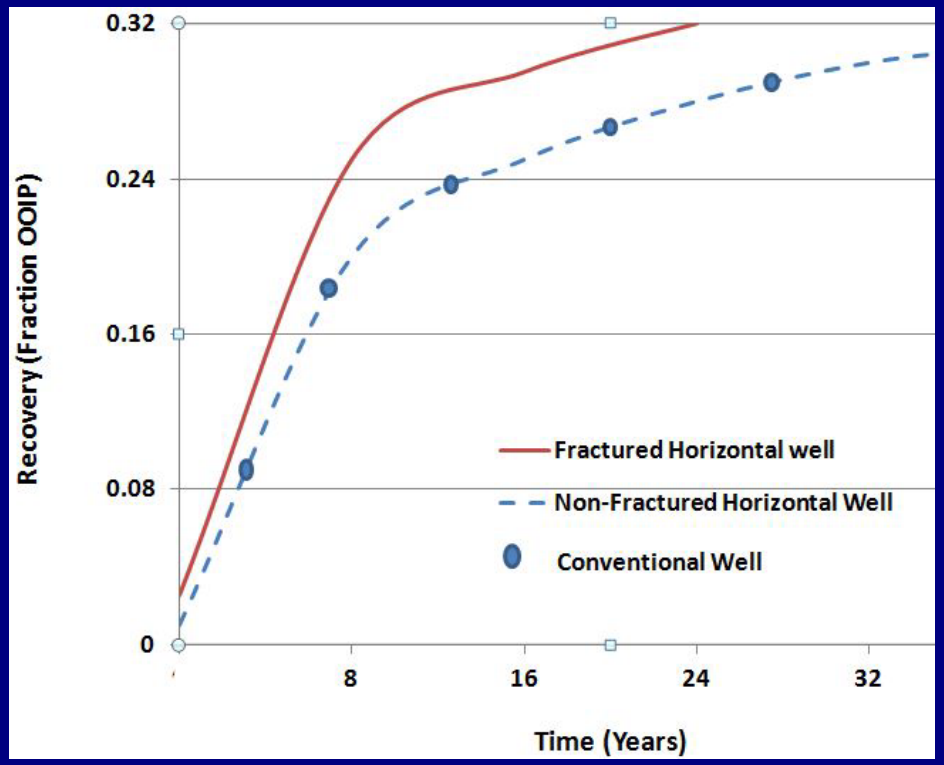
- Fully cemented liners
  - Separate perforated intervals
- Temporary Wellbore Plugs
  - Sand
  - Gel
- External Casing Packers:
  - Hydraulic inflated packer ran on the outside of the casing
  - Typically set with either drilling mud or cement.

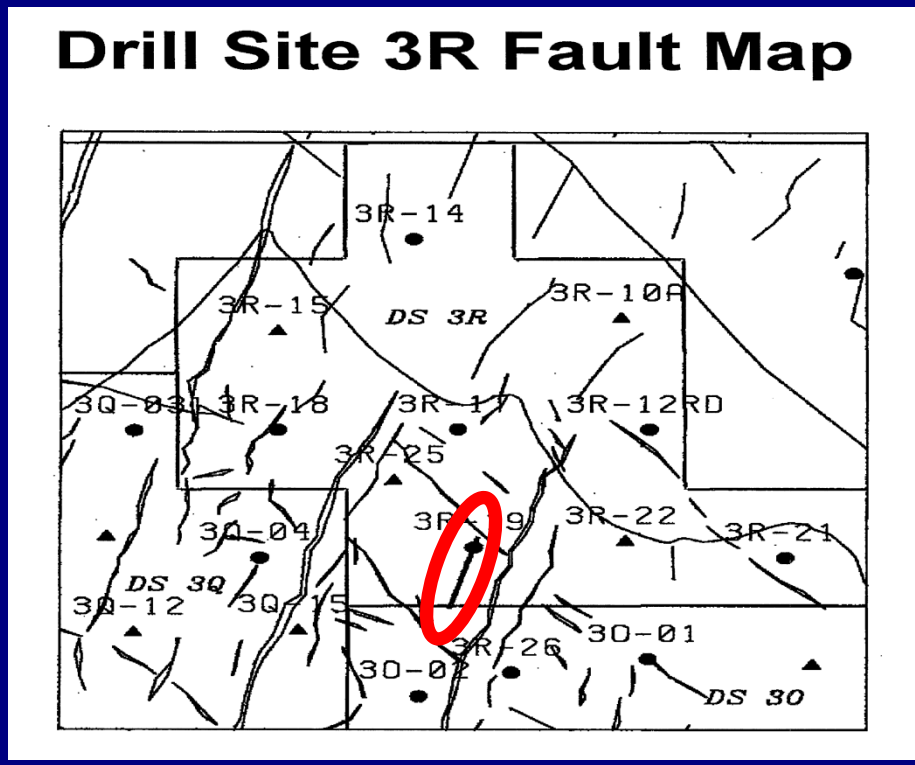
Kuparuk River Field, Alaska

SPE 36454 (1996)



Kuparuk: Use of Longitudinally Fractured Wells





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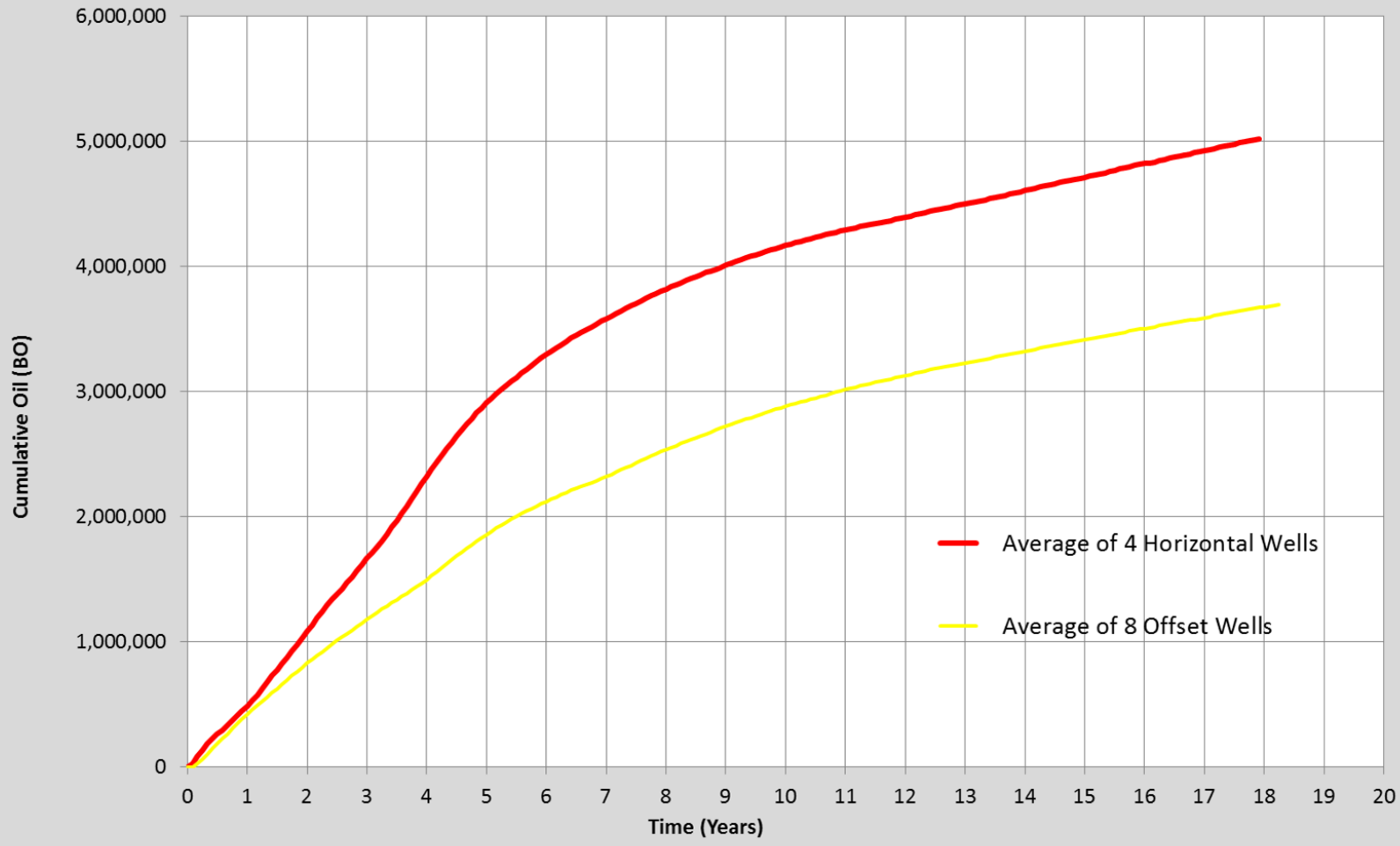
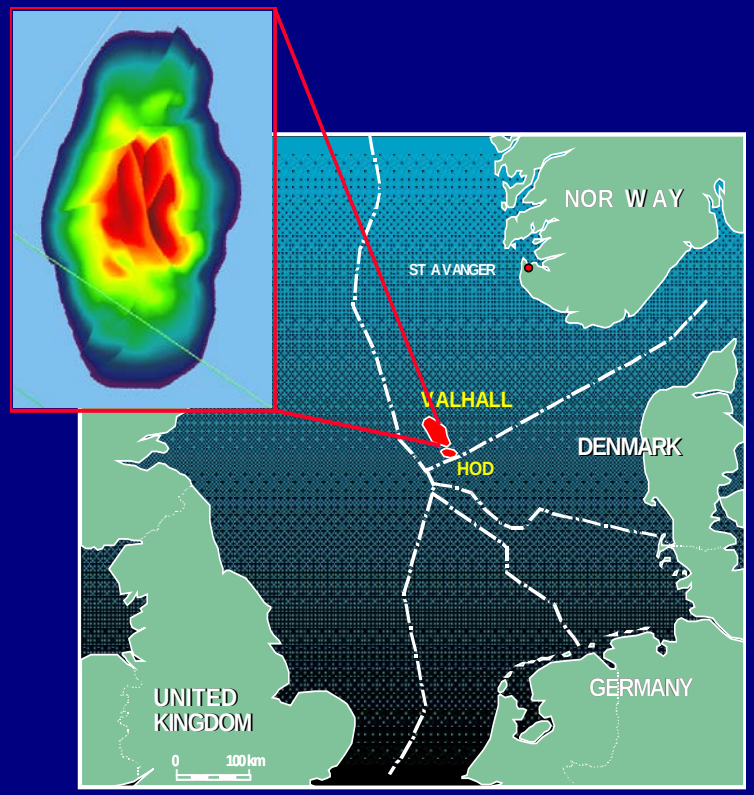
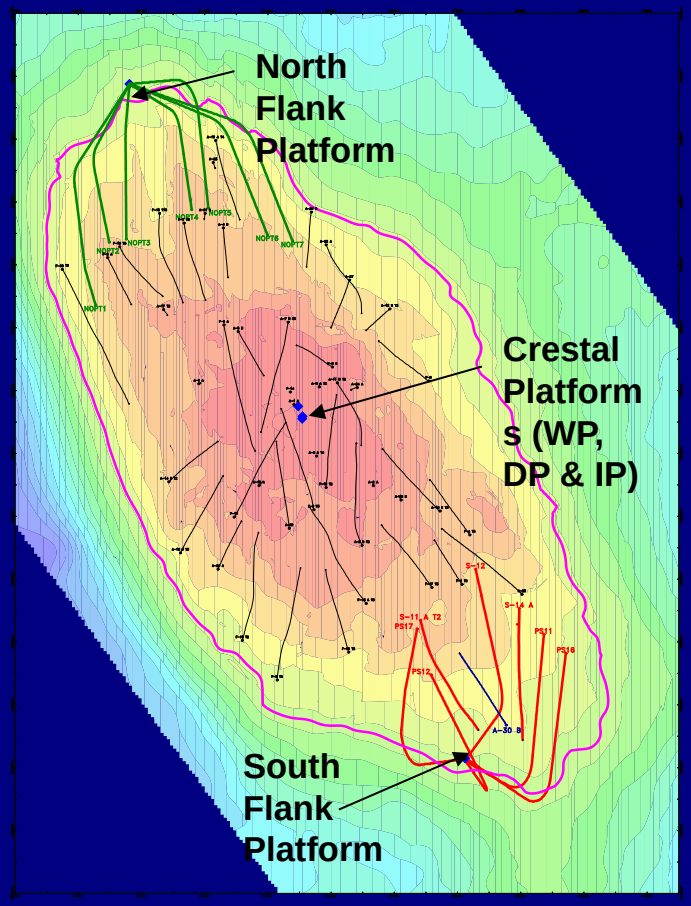


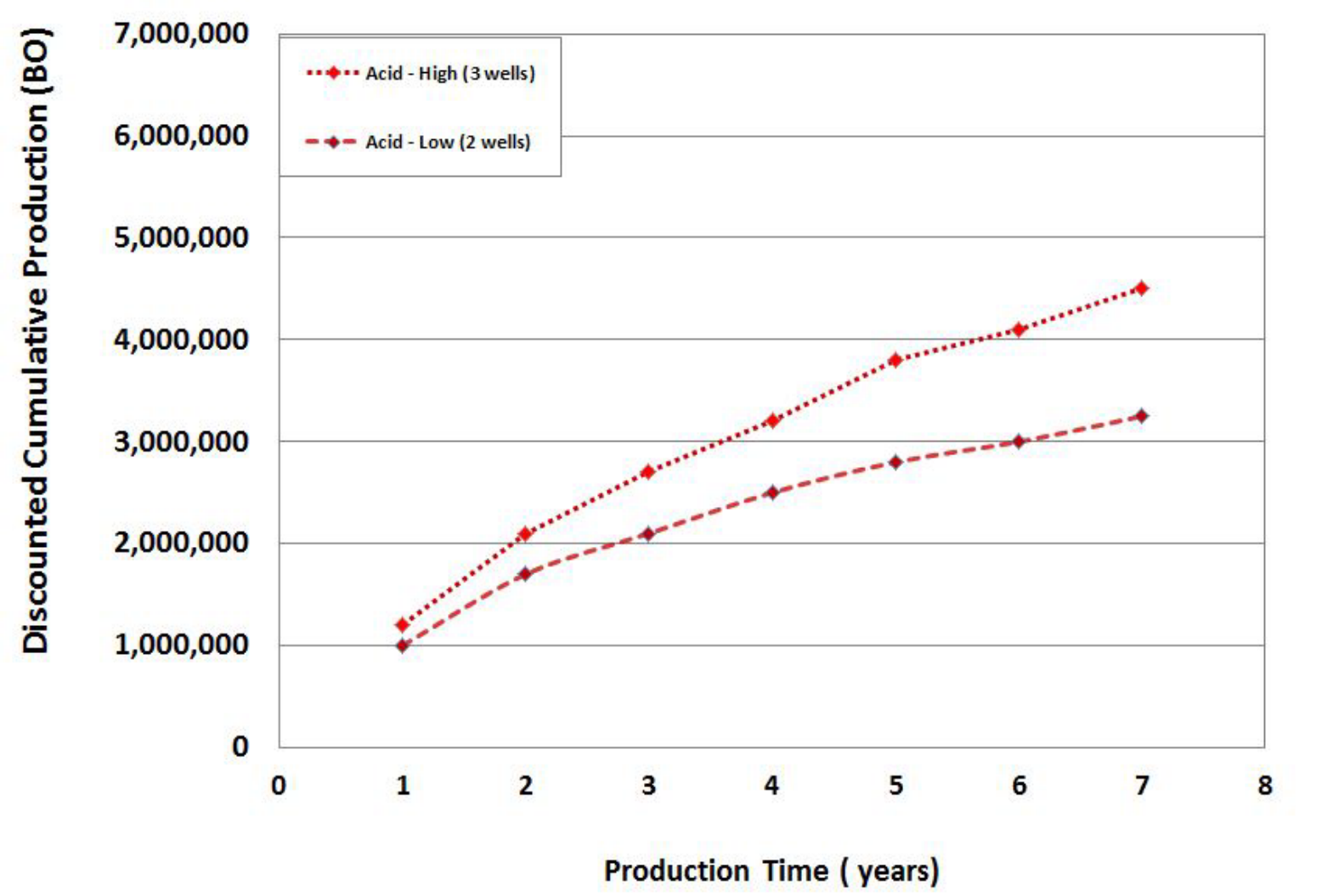
Courtesy of: ConocoPhillips Alaska, Inc. (Unit Operator), BP Exploration (Alaska) Inc., Chevron U.S.A. Inc., ExxonMobil Alaska Production, Inc.

Valhall Field Development
Norwegian North Sea; SPE 84392 (2003)





Valhall Field HFHW Development Results
Comparison of Acid and Proppant Fracturing



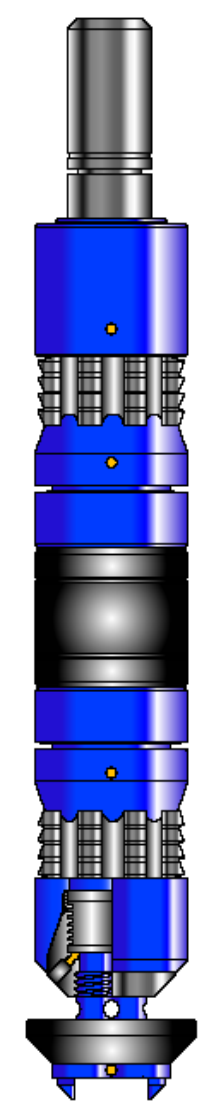
Late 1990's – Horizontal Well Completion Options

1. Openhole "barefoot" completion – no stimulation or single stage acid

2. Uncemented slotted or pre-perforated liner with a single stage acid or frac treatment (with or without diverting materials).

3. Cemented liner / casing – multi-stage perforating with gel or solid plugs allowing multi-stage fracturing

Late 1990's – Composite Plug Development

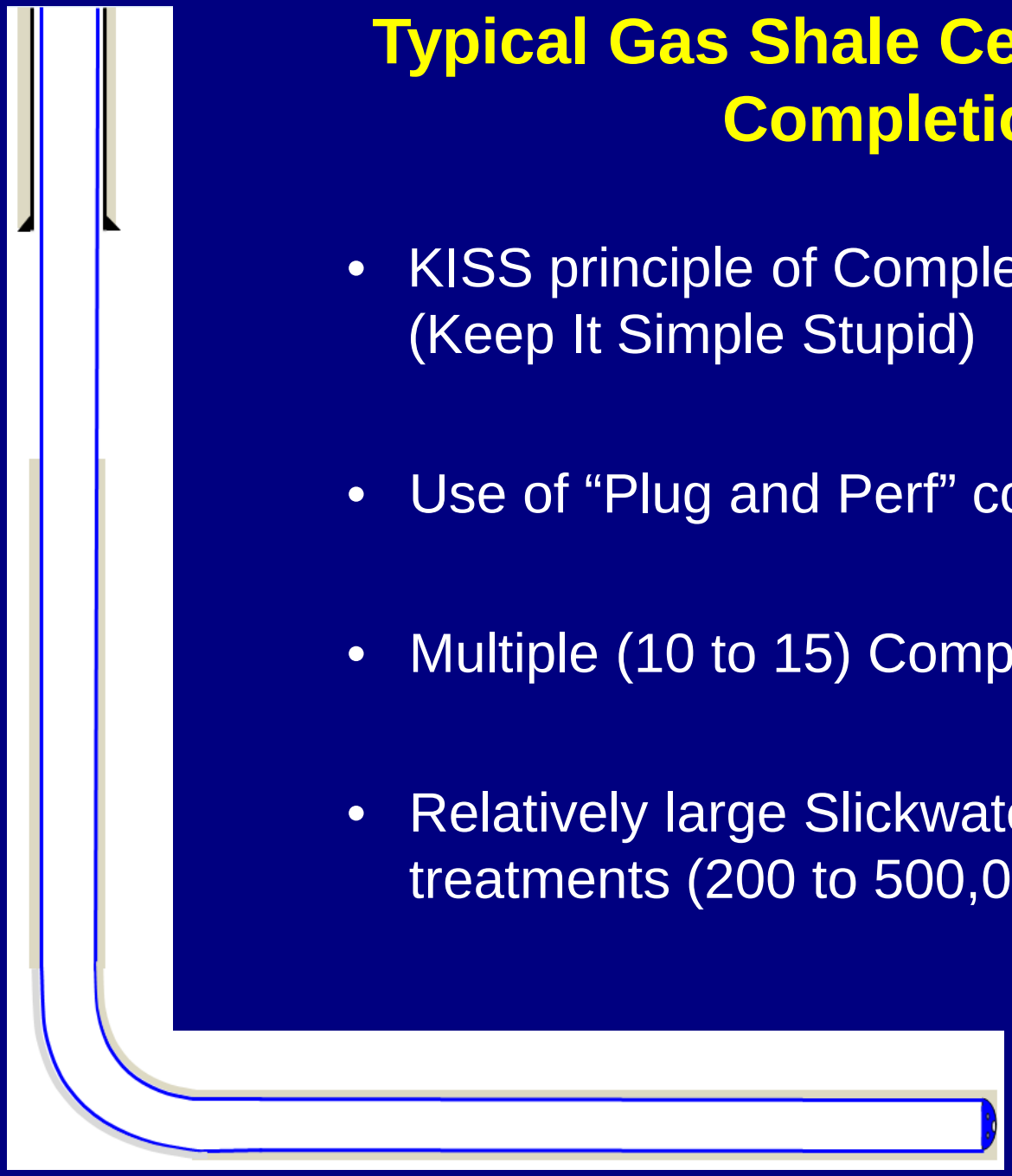


Wireline run below perforating tools

Standard equipment for 4-1/2" and 5-1/2" liners

Up to 12,500 psi differential pressure rating

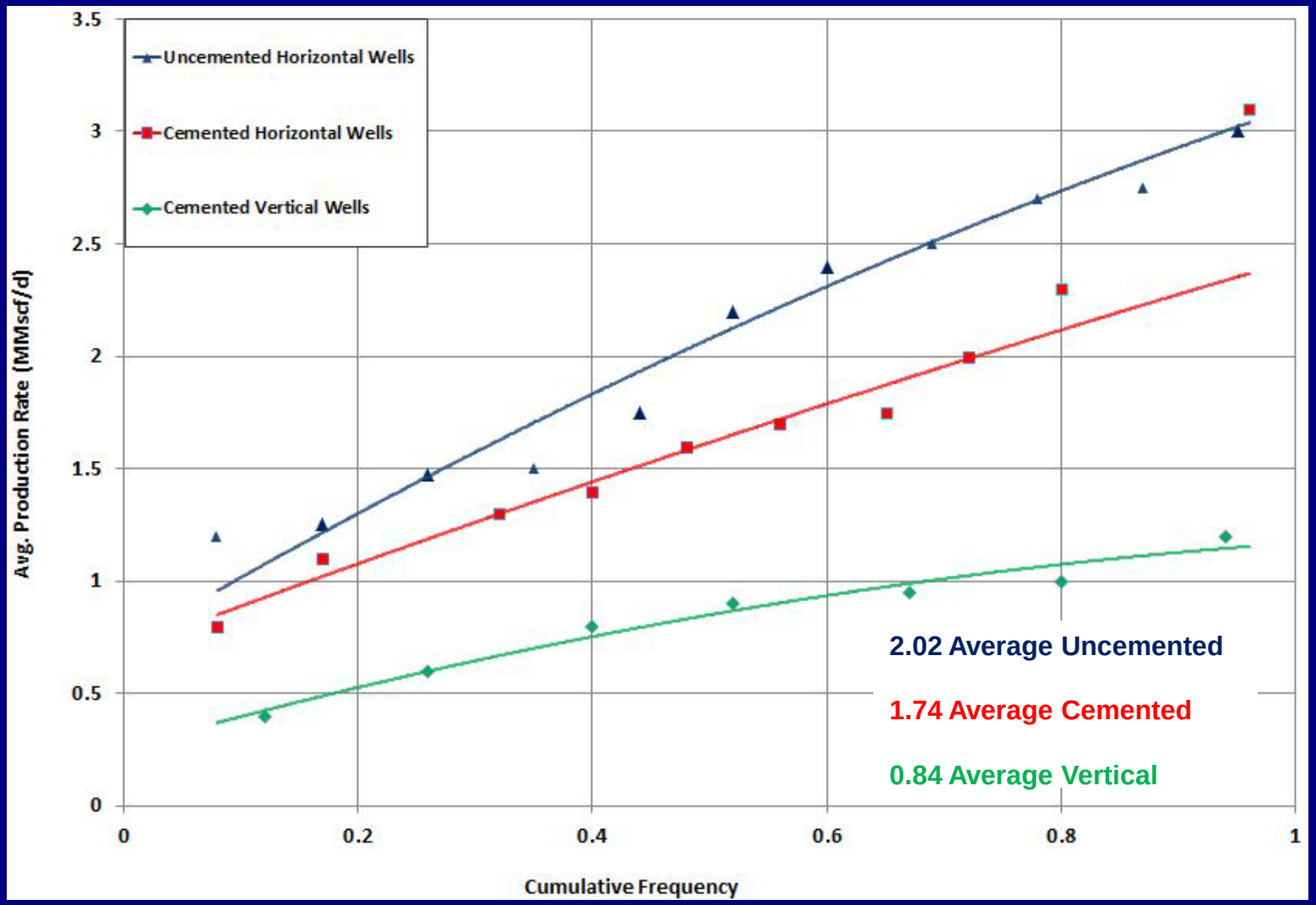
Easily drilled out using either a workover rig or coiled tubing



Typical Gas Shale Cemented Liner Completion

- KISS principle of Completion Design (Keep It Simple Stupid)
- Use of “Plug and Perf” completion technique
- Multiple (10 to 15) Completion Stages per well
- Relatively large Slickwater stimulation treatments (200 to 500,000 lbs per stage)

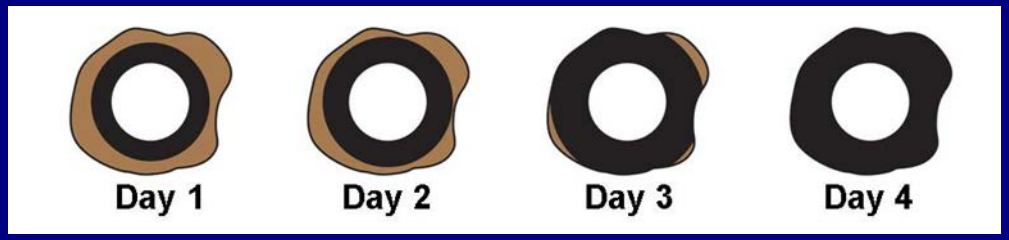
Barnett Shale Horizontal Well Pilot
SPE 90051 (2004)

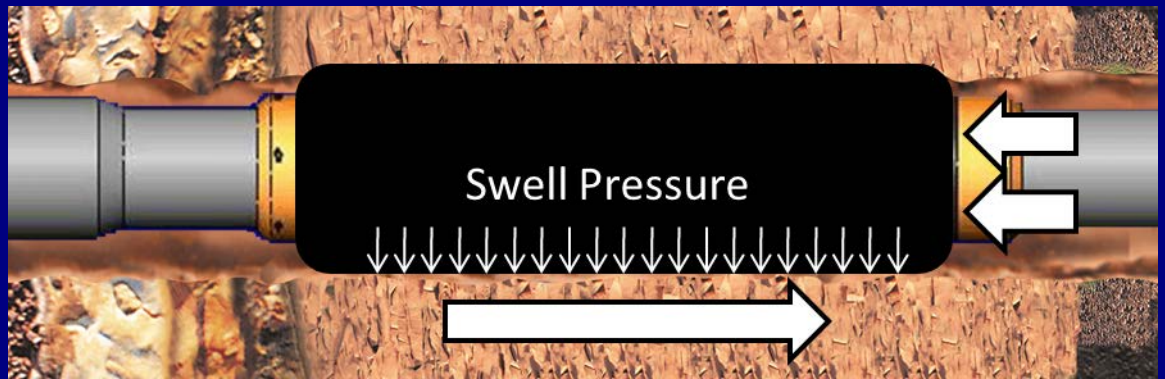


Mid-2000's – Development of Swell Packer Technology

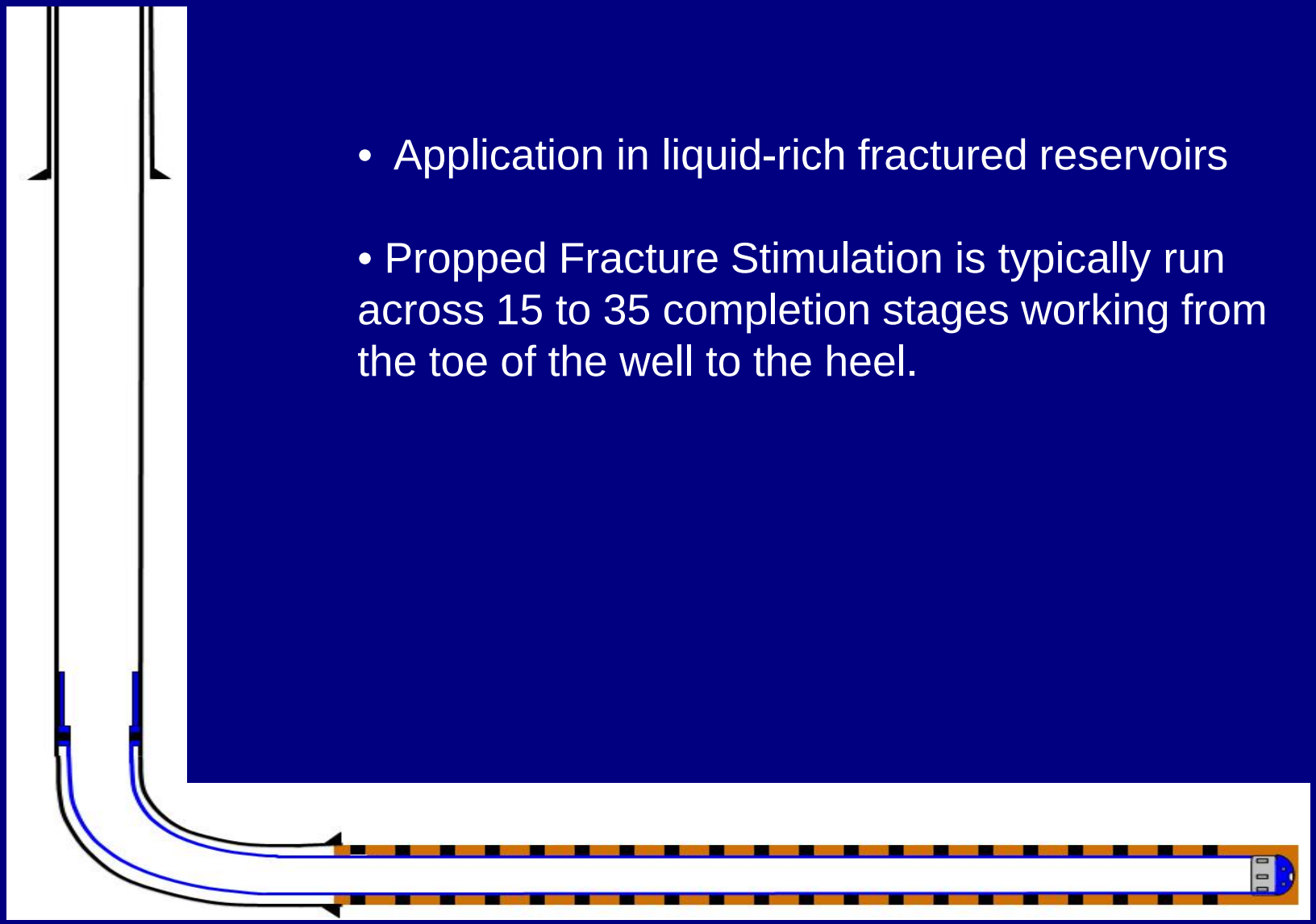
- Bonded element to standard casing / liner pipe; oil or water swellable:

- Typically can withstand 5000 psi differential pressure





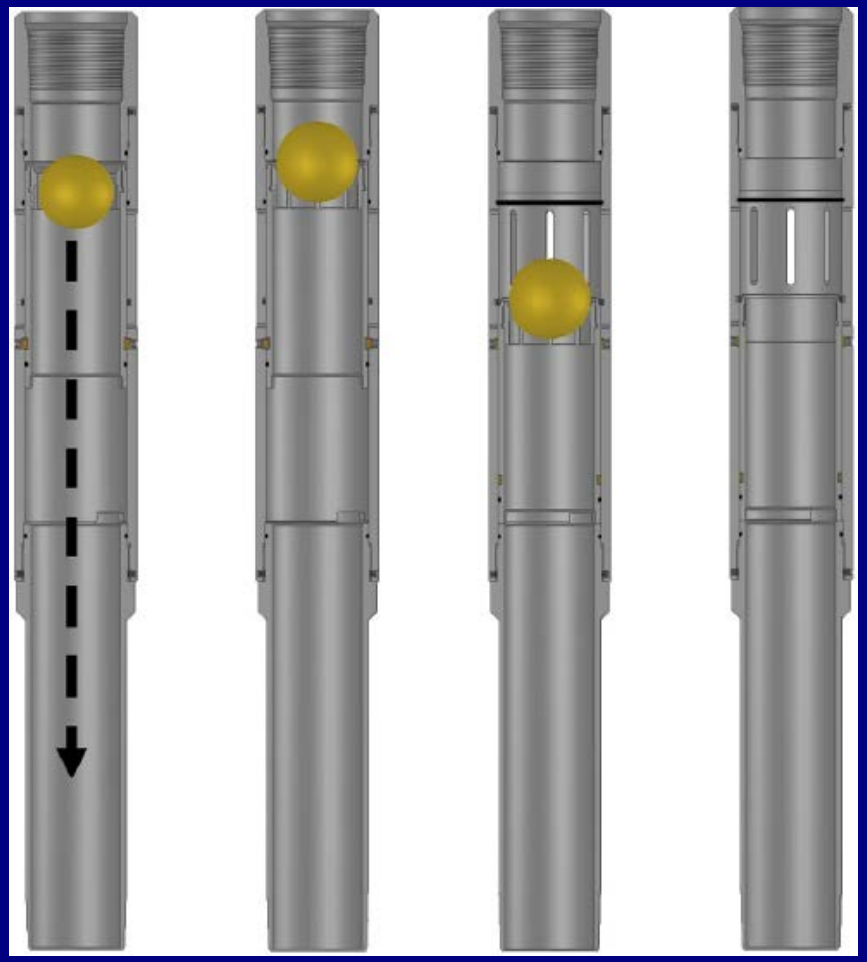
Uncemented Wellbore Schematic
Example 20 stage “Plug and Perf” Completion”



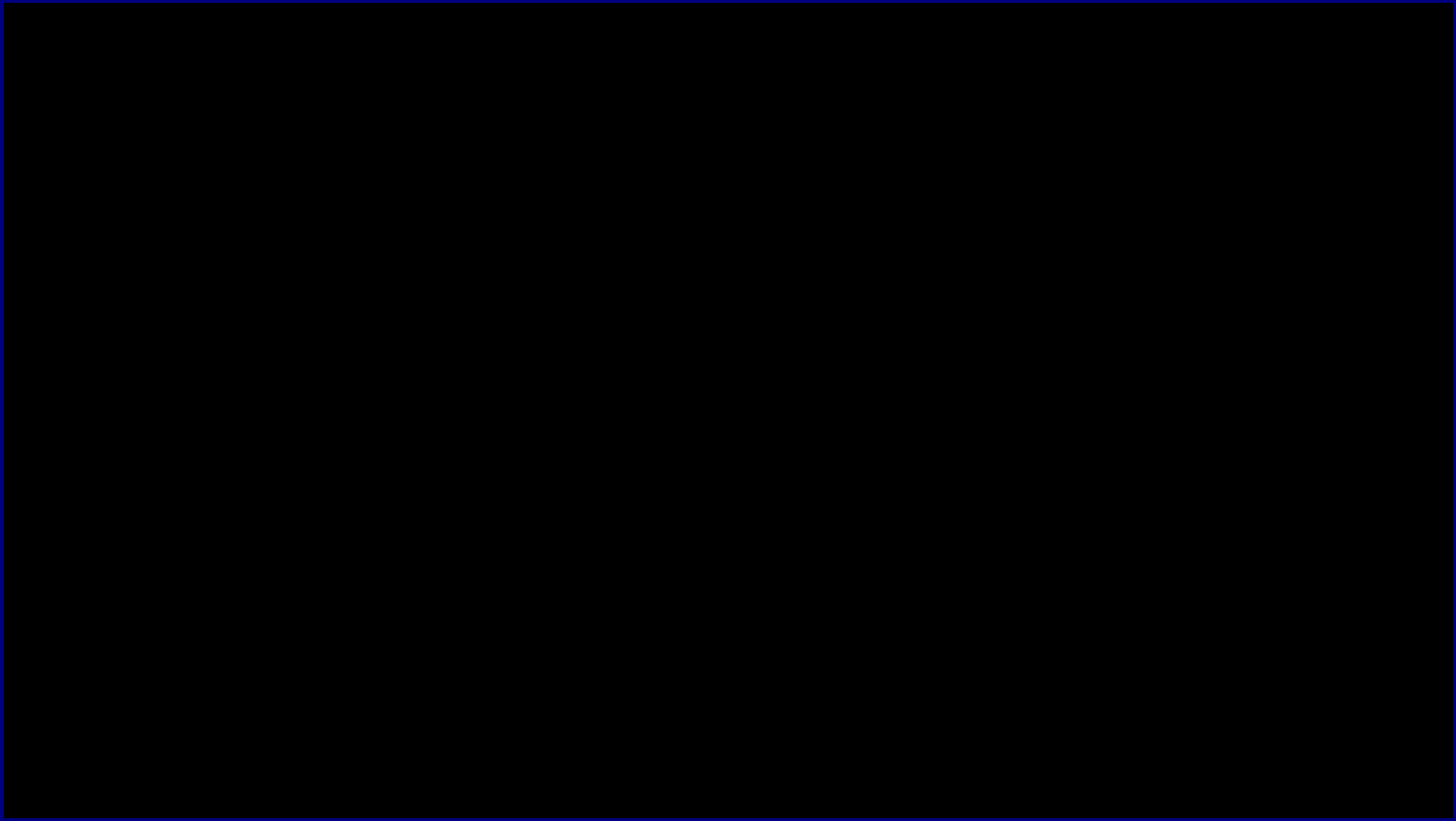
- Application in liquid-rich fractured reservoirs

- Propped Fracture Stimulation is typically run across 15 to 35 completion stages working from the toe of the well to the heel.

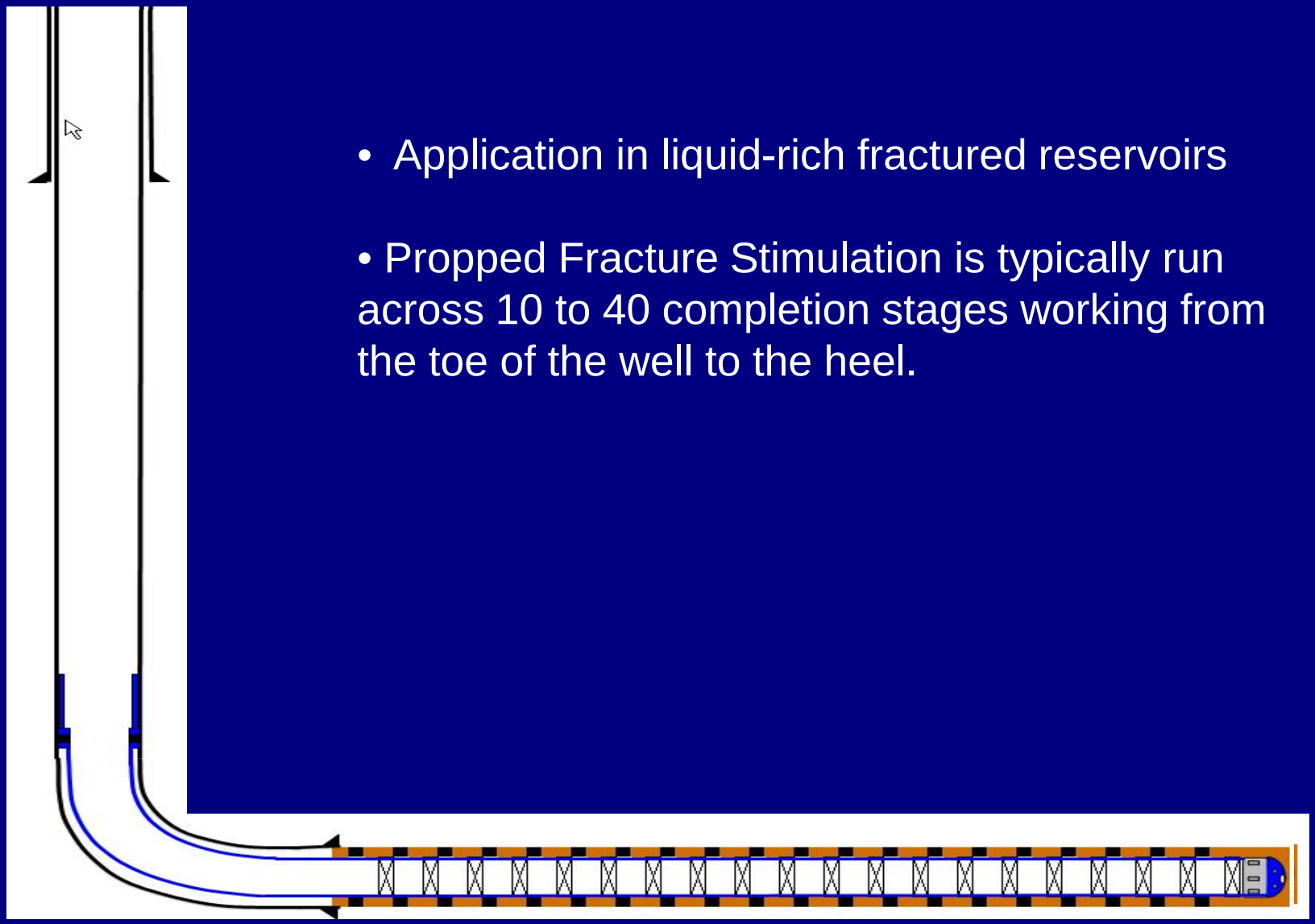
Mid-2000's: Ball Activated Sliding Sleeve Development



Sliding Sleeve Example



Uncemented Wellbore Schematic
Example 20 stage “Sliding Sleeve” Completion”

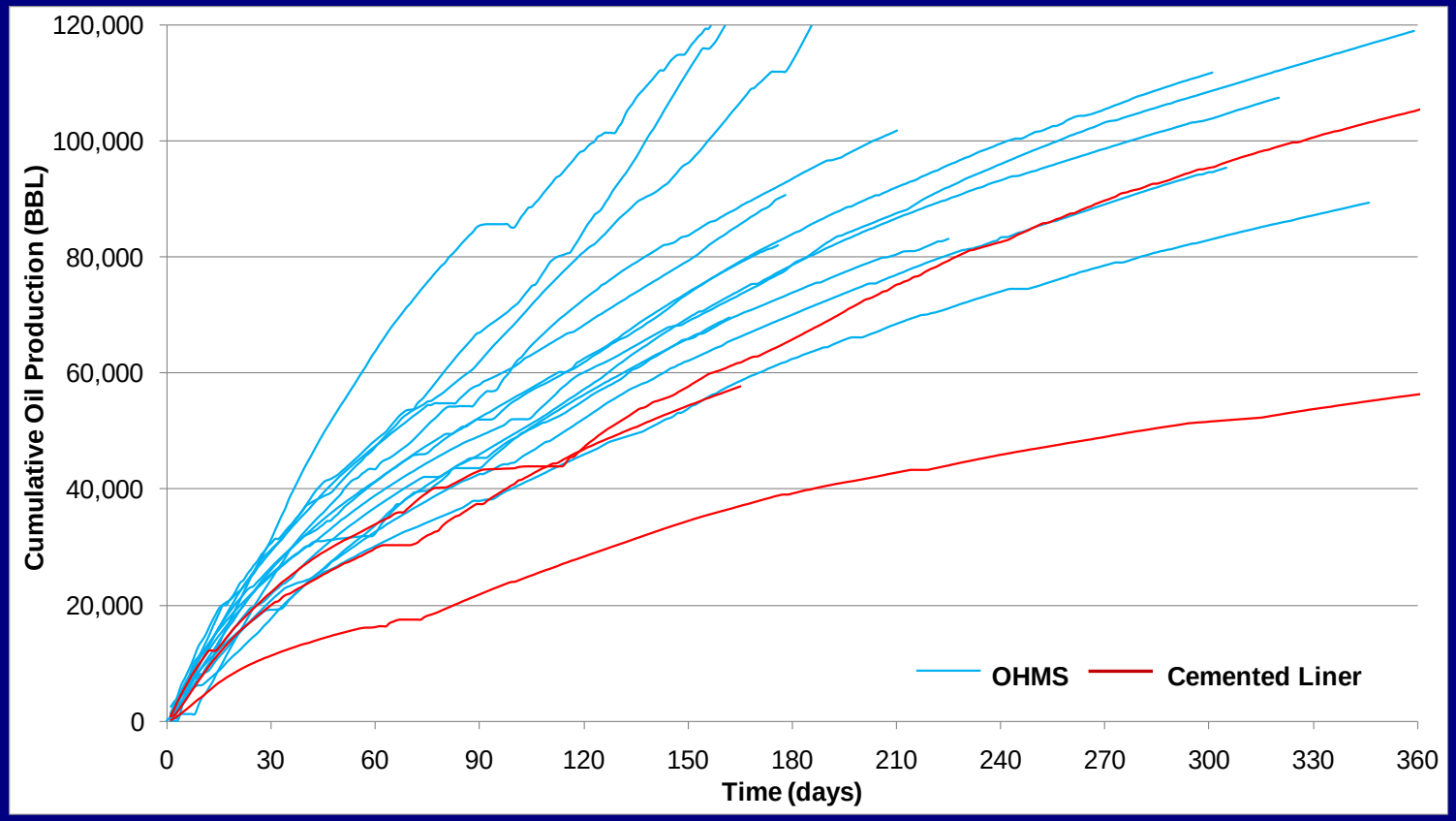


- Application in liquid-rich fractured reservoirs

- Propped Fracture Stimulation is typically run across 10 to 40 completion stages working from the toe of the well to the heel.

Open Hole Multi-Stage Systems; SPE 135584 (2010)

Production of 3 wells with a cemented liner & plug and perf completion Vs. 13 wells in the same field with an openhole liner and sliding sleeves



2012 Current Multi-Zone Completion Techniques

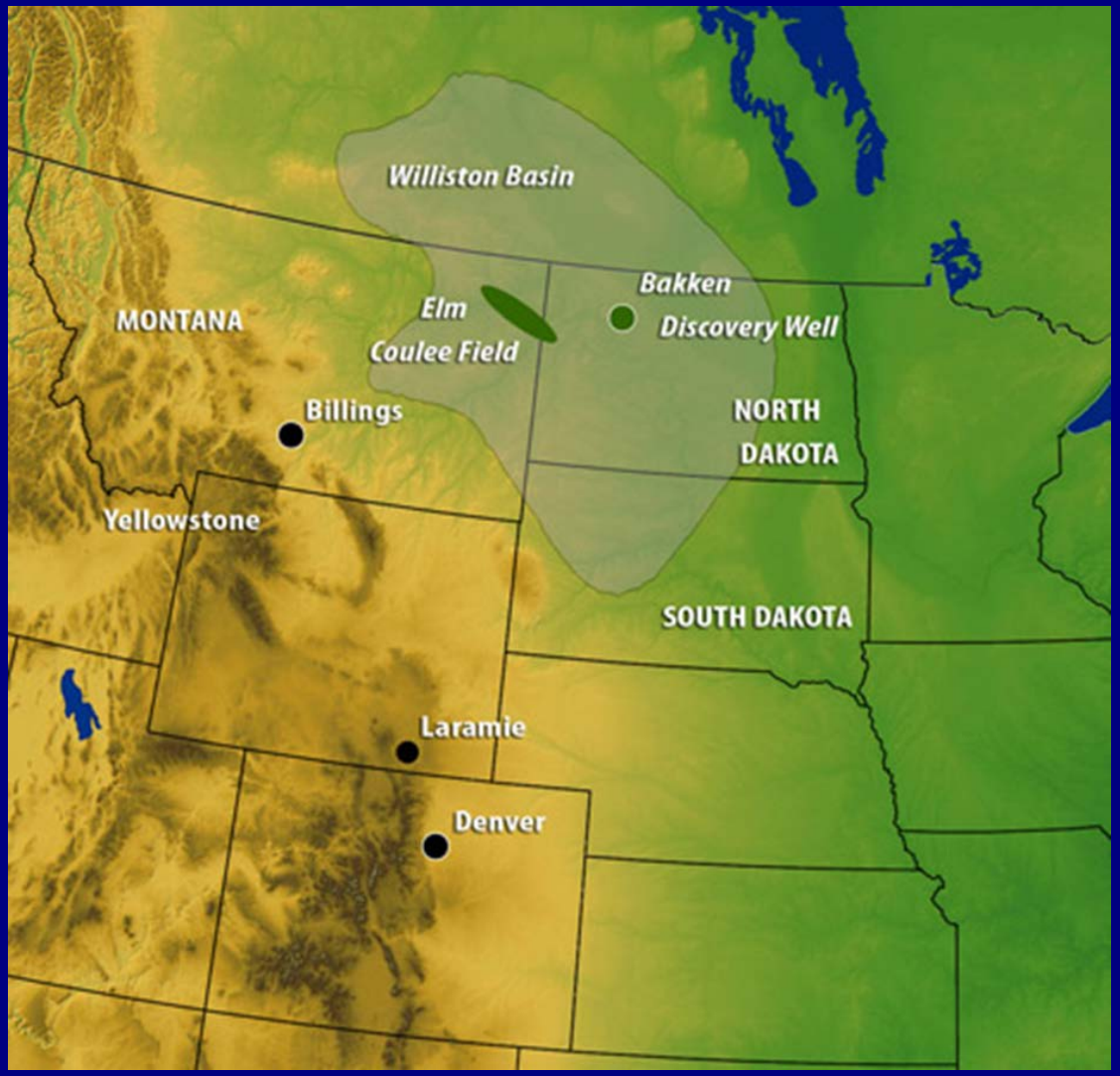
Plug and Perf	Vs.	Sliding Sleeve
Cemented or uncemented		Uncemented
Unlimited # of zones		Typically limited to ~20 stages (repeater port technology increases this)
Multiple perf clusters per stage		Typically 1 opening per stage (mutil-port technology is available)
Slickwater or Gelled Frac		Slickwater or Gelled Frac
Slow - Repetitive perforating and stimulation phases to each stage (3 to 5 hours per cycle)		Fast – timing is driven by the frac design (1–2 hours per cycle)

Estimated Usage:

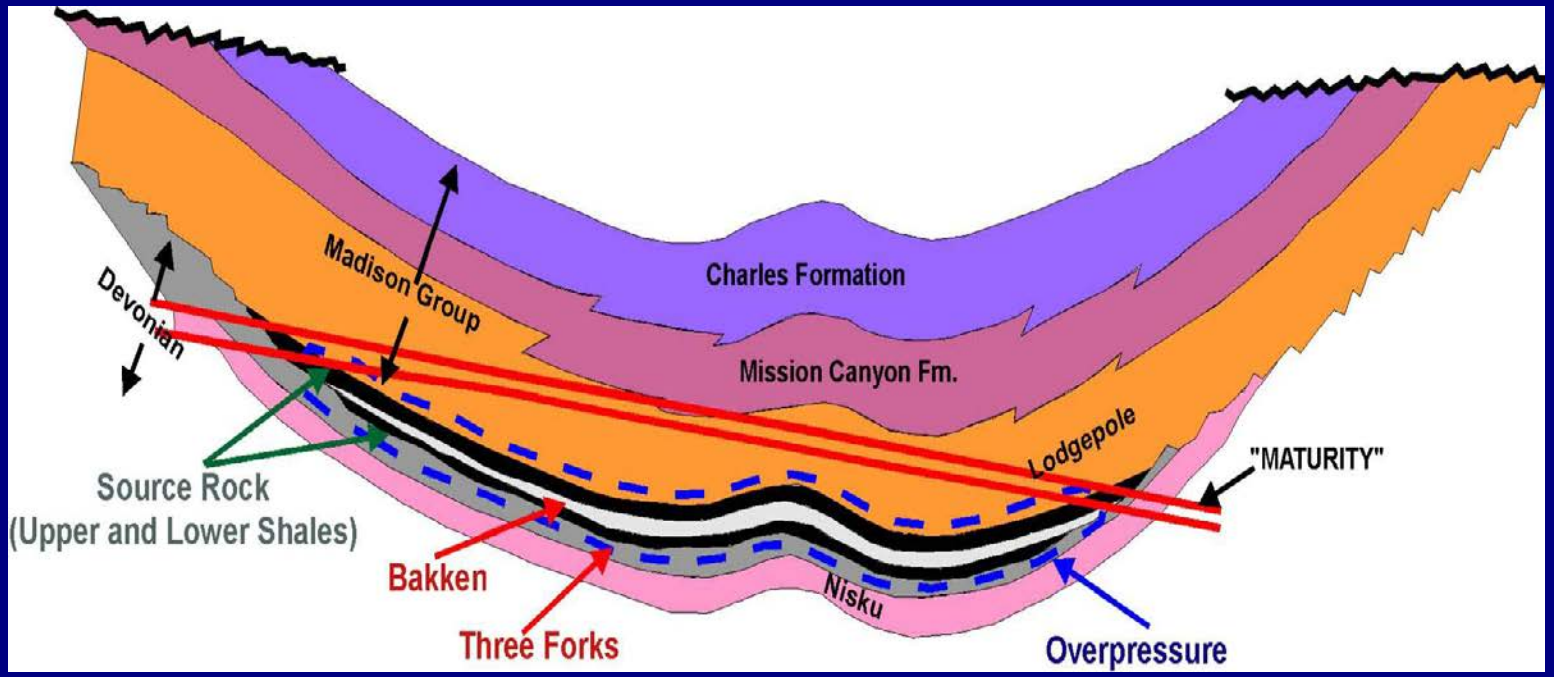
100% of Gas Shale Completions ~30% of Oil Shale Completions

~70% of Oil Shale Completions

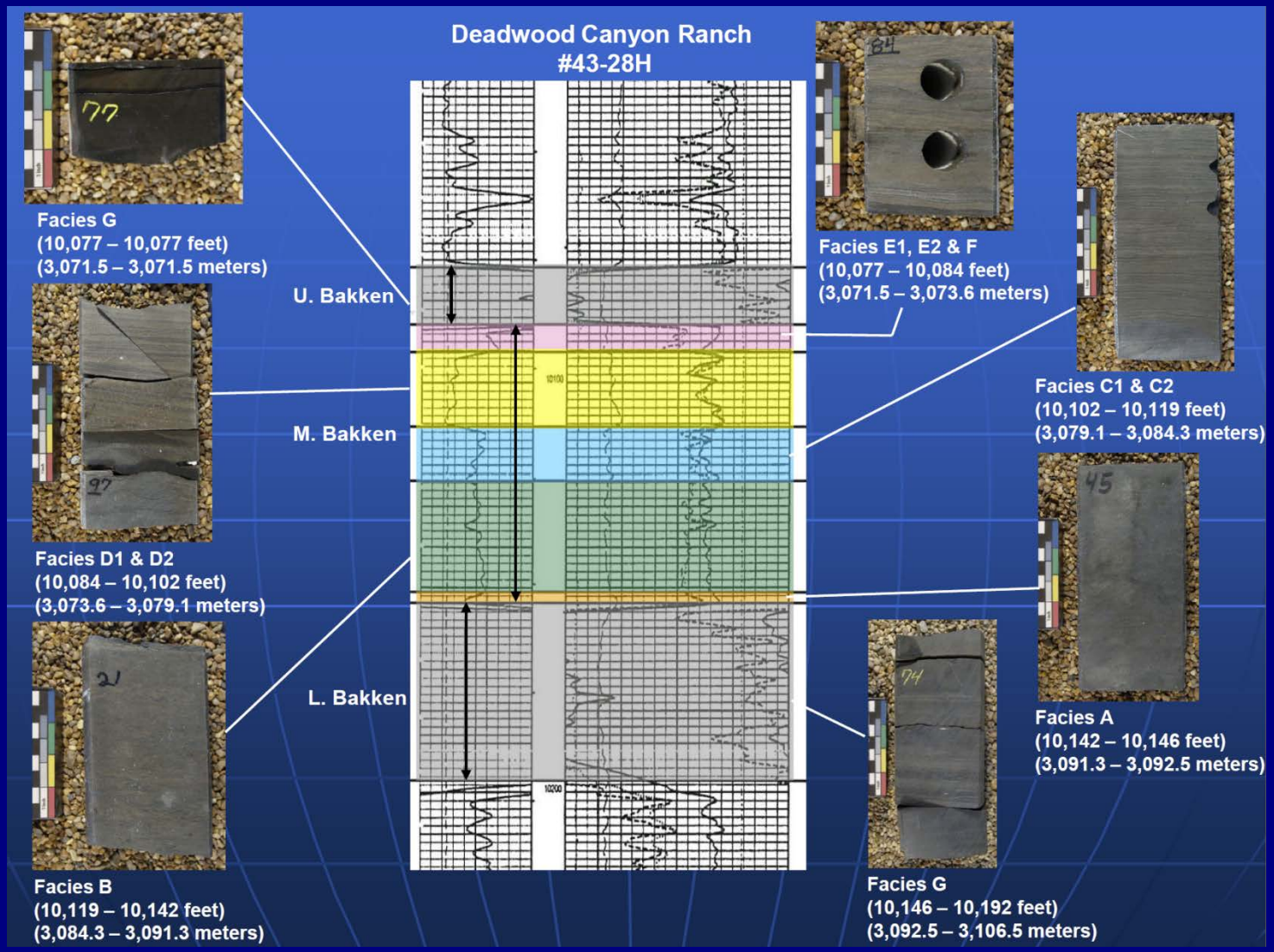
Bakken Oil Shale – Williston Basin
SPE 163827 (2013)



Williston Basin Geological Cross-Section

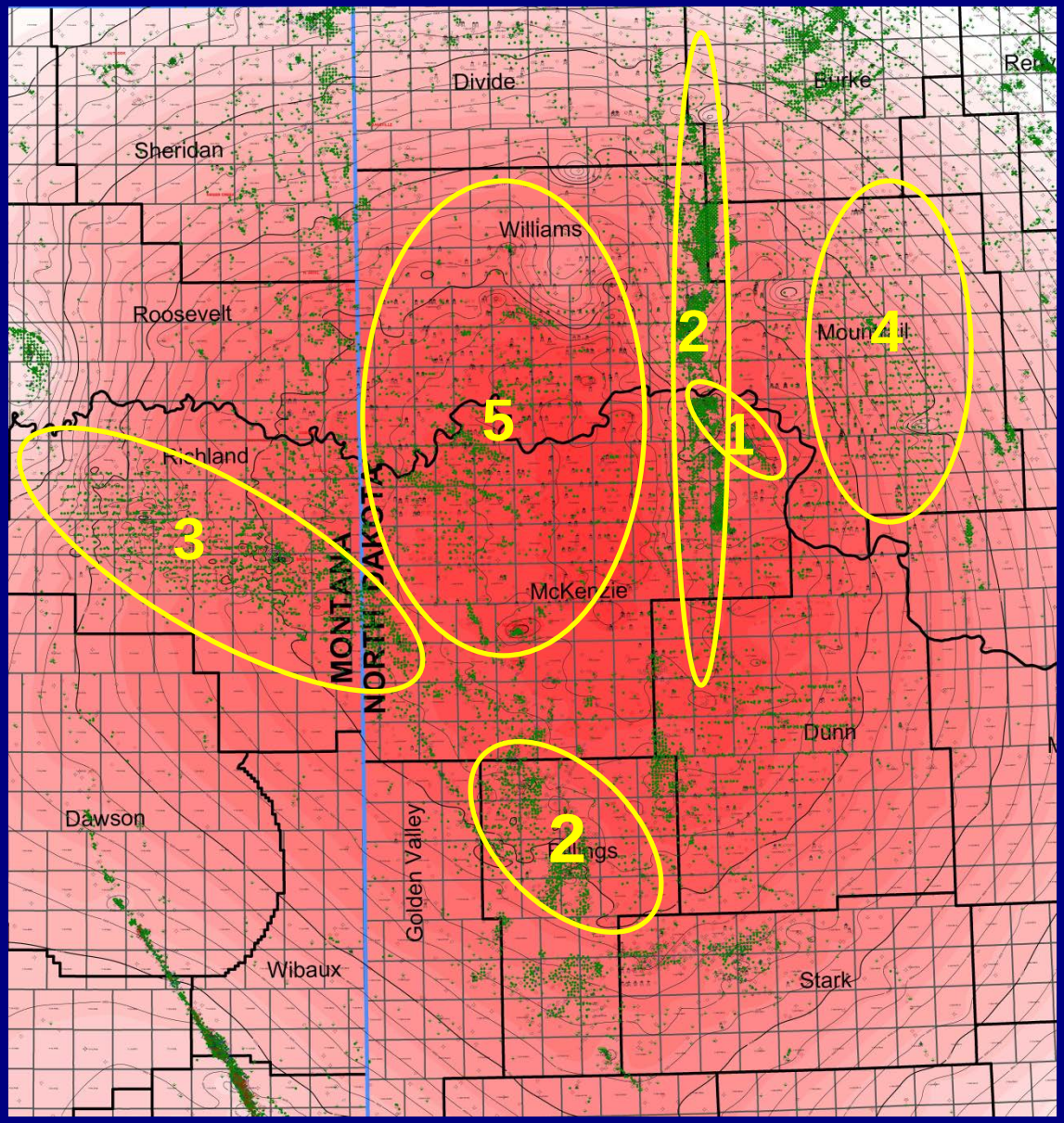


Bakken Lithofacies



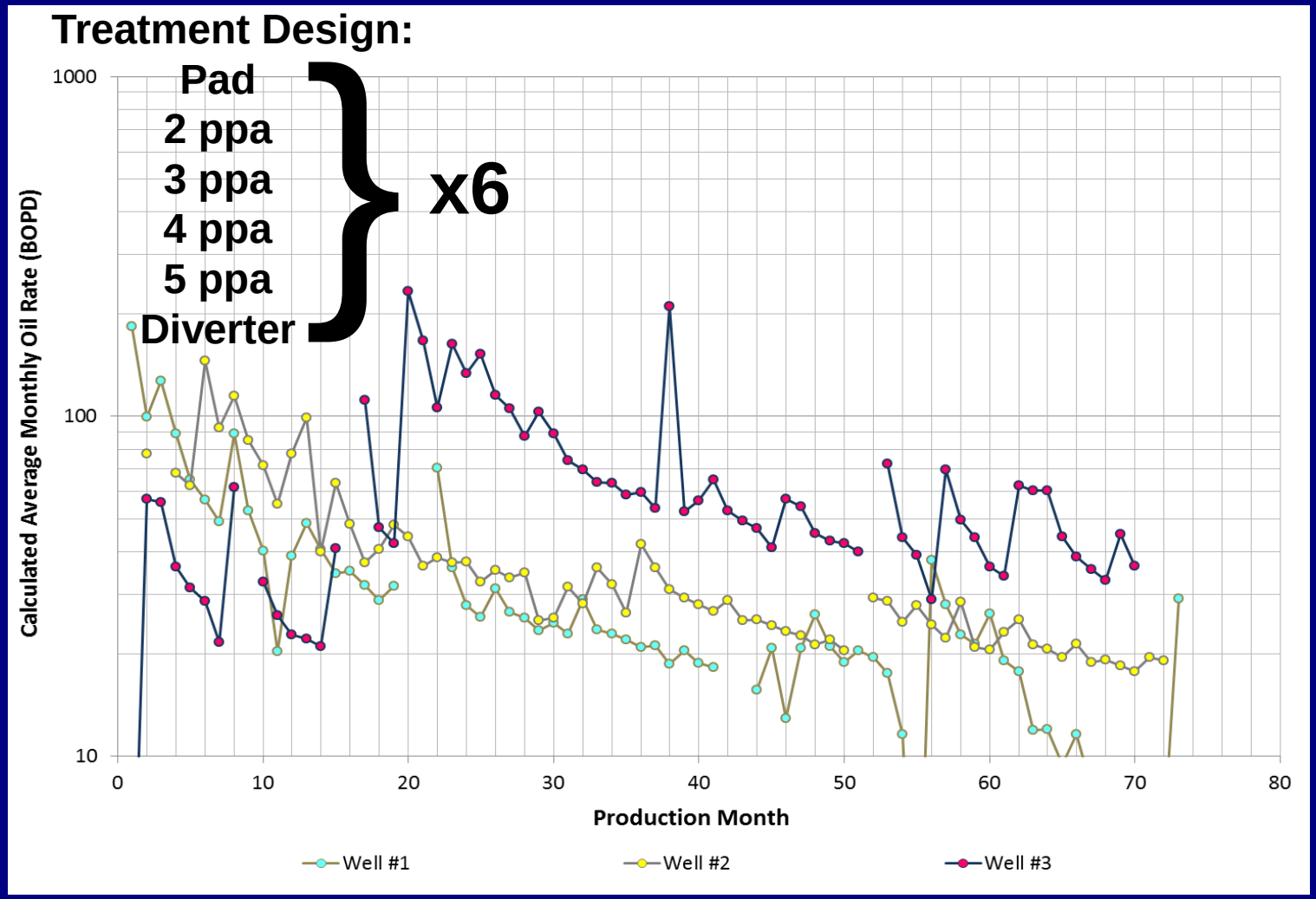
Simenson, 2010

Bakken Case Study: Structure & Development

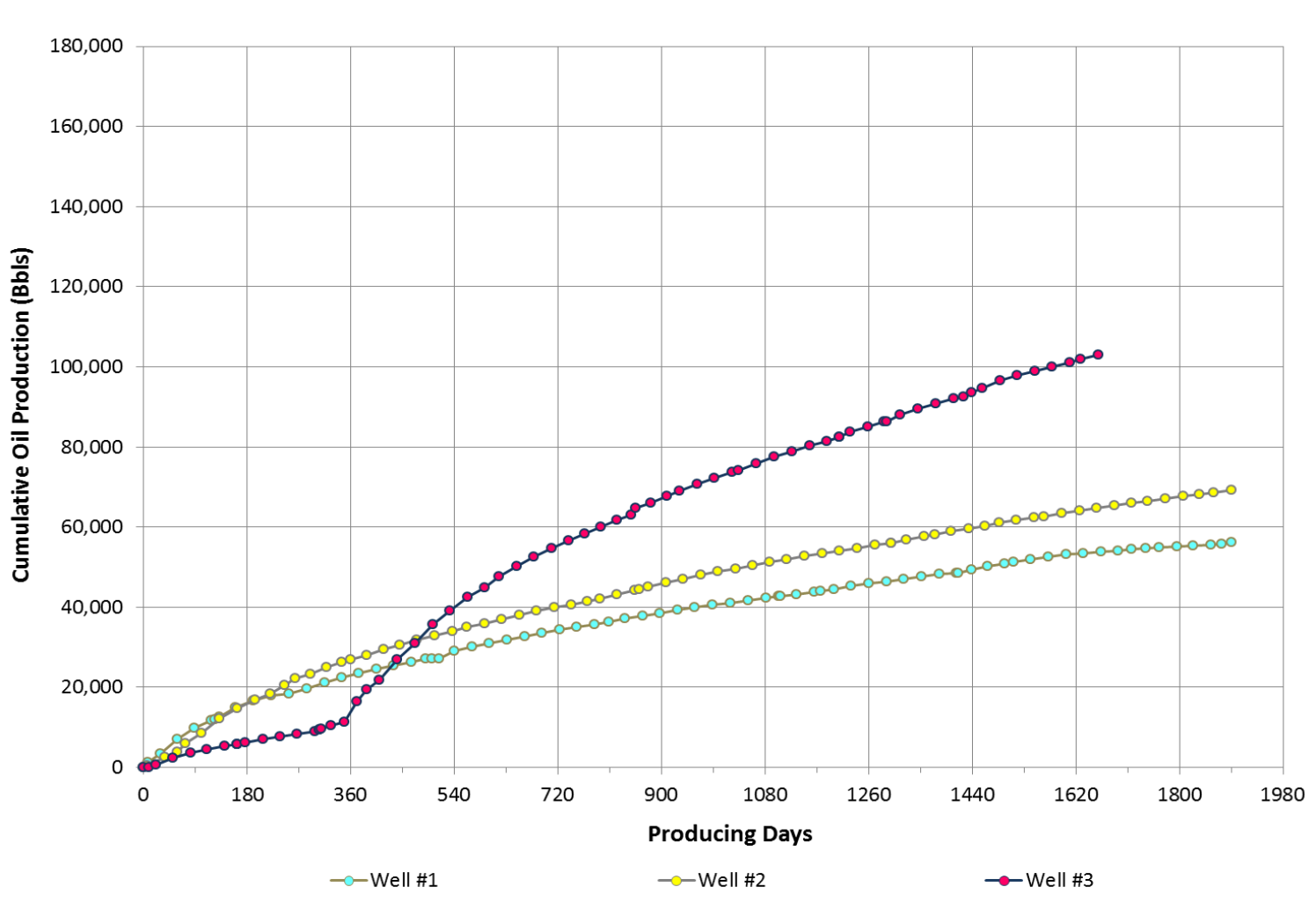


1. Antelope Arch
2. Nesson & Billings Anticlines
3. Elm Coulee Field
4. Sanish / Parshall / Ross Fields
5. Central Basin

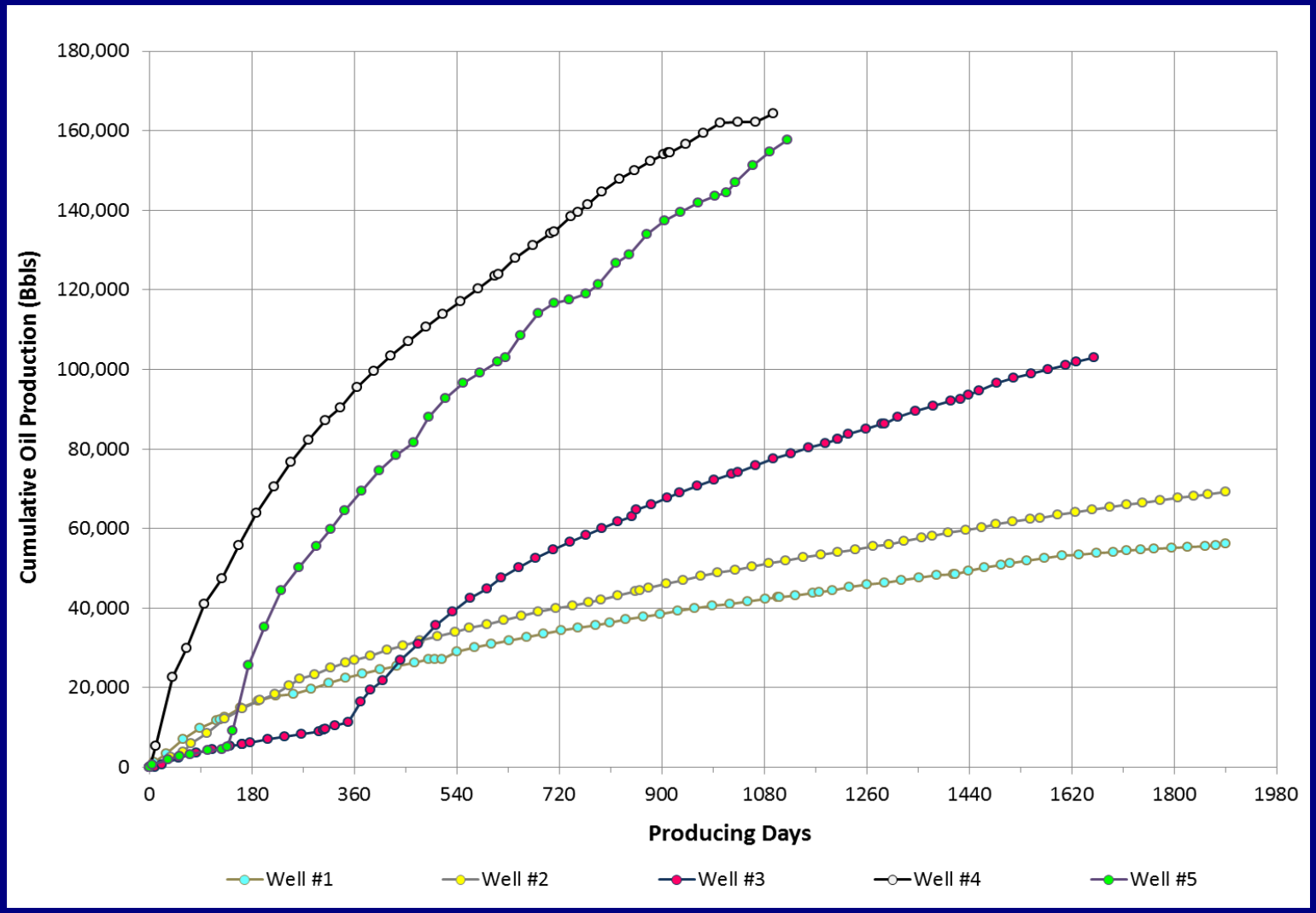
Central Basin Initial Well Results - 2006



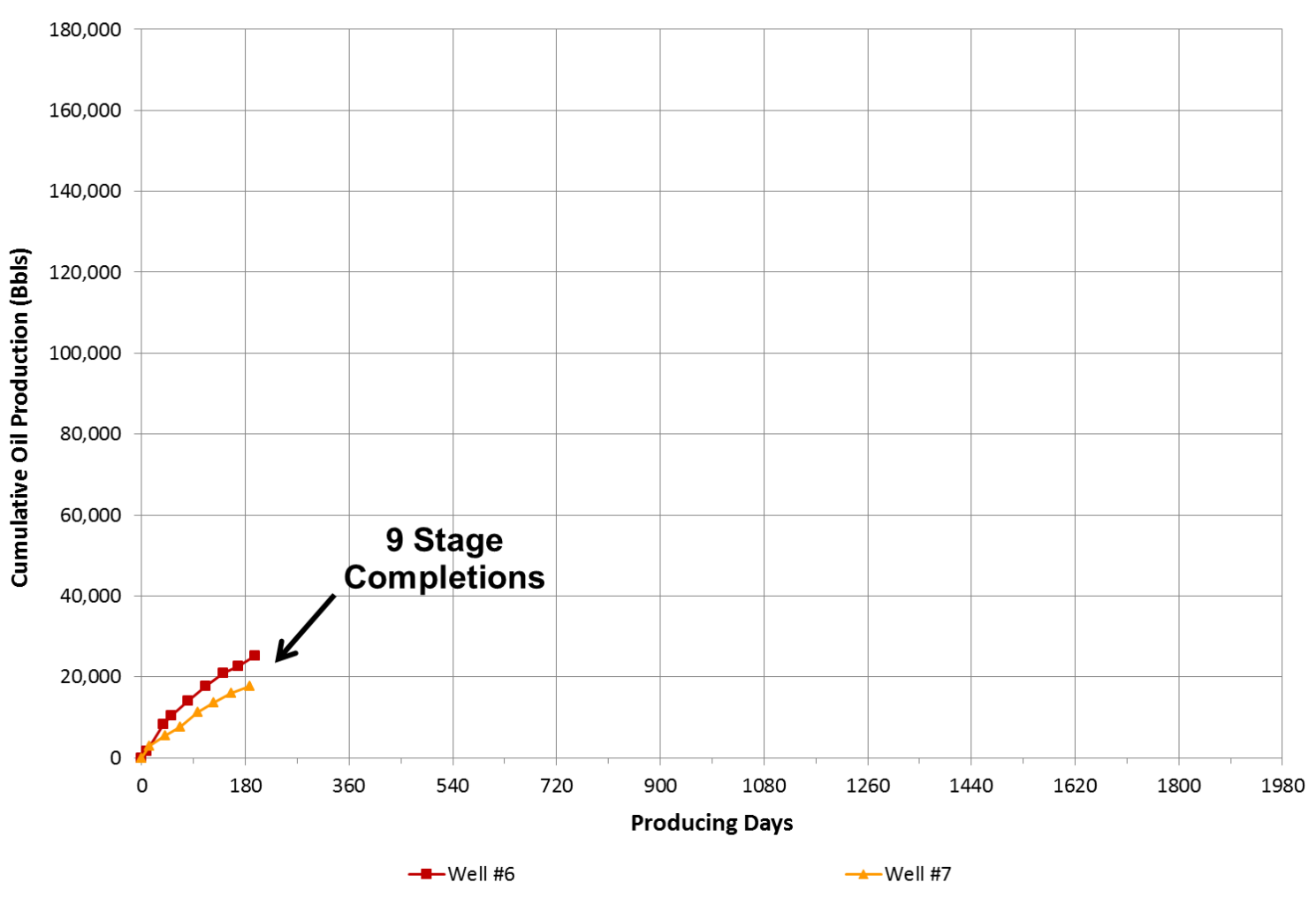
Central Basin Initial Well Results: 2006



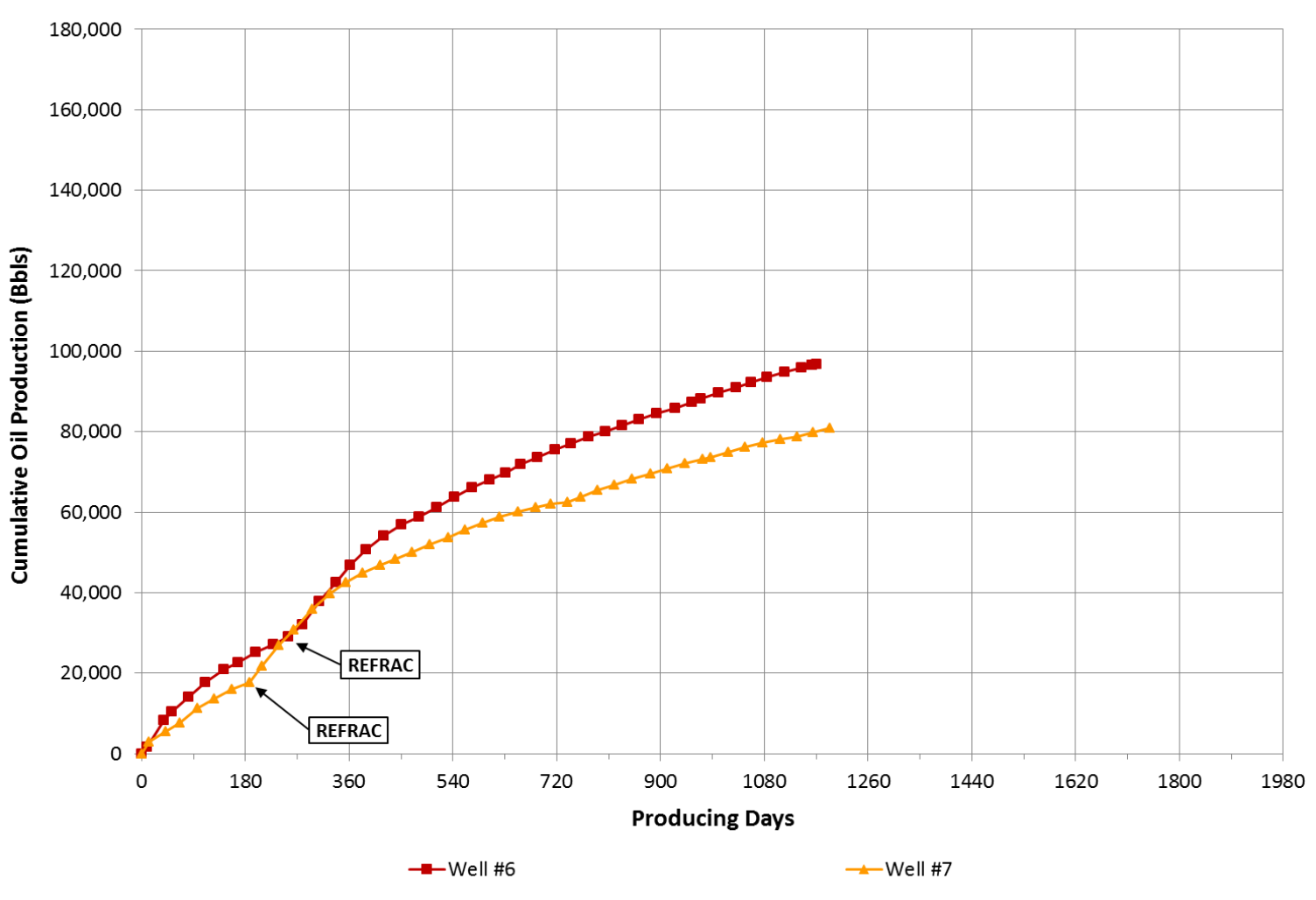
Central Basin Initial Well Results: 2006 & 2008



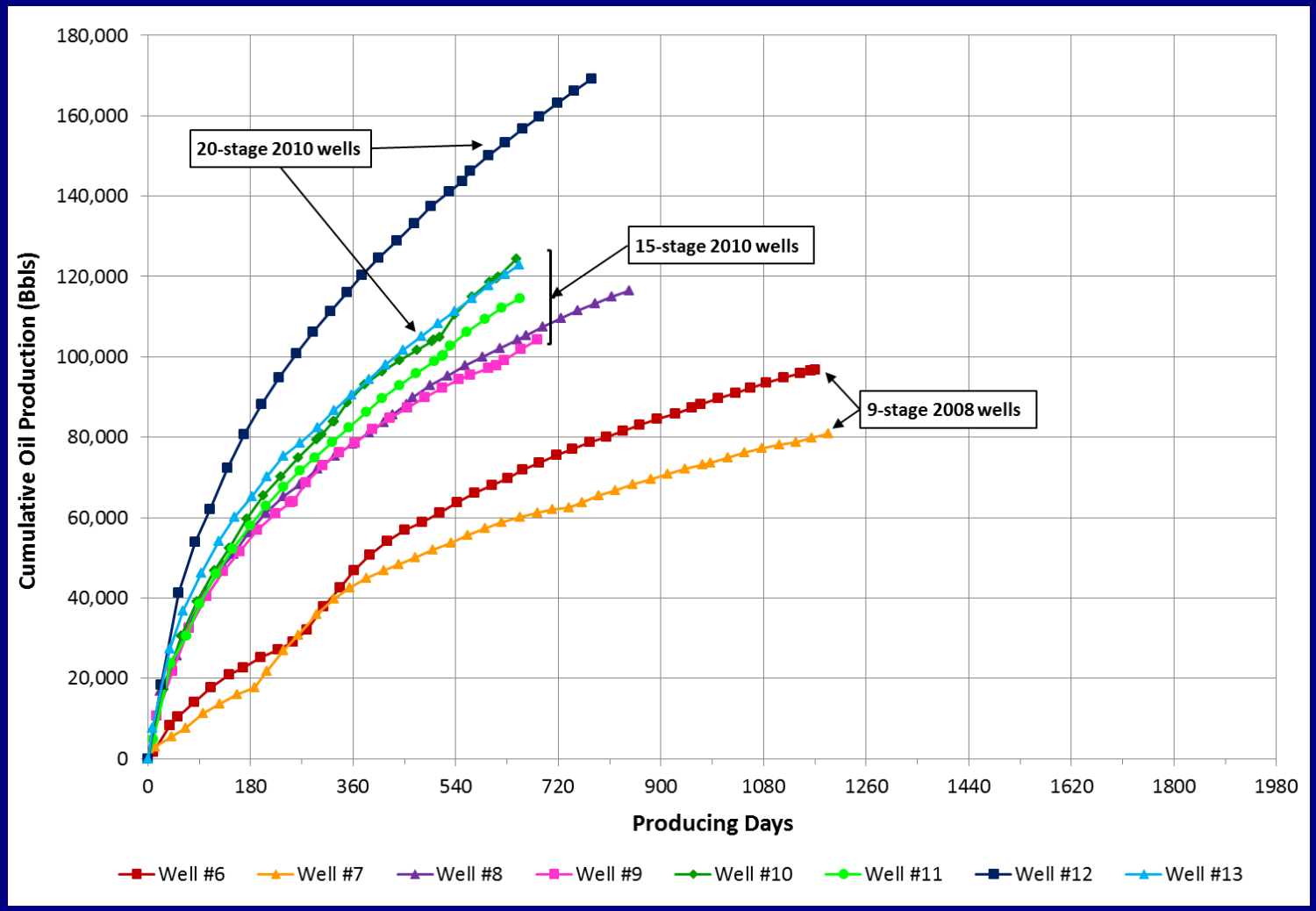
Central Basin Company B Well Results: 2008



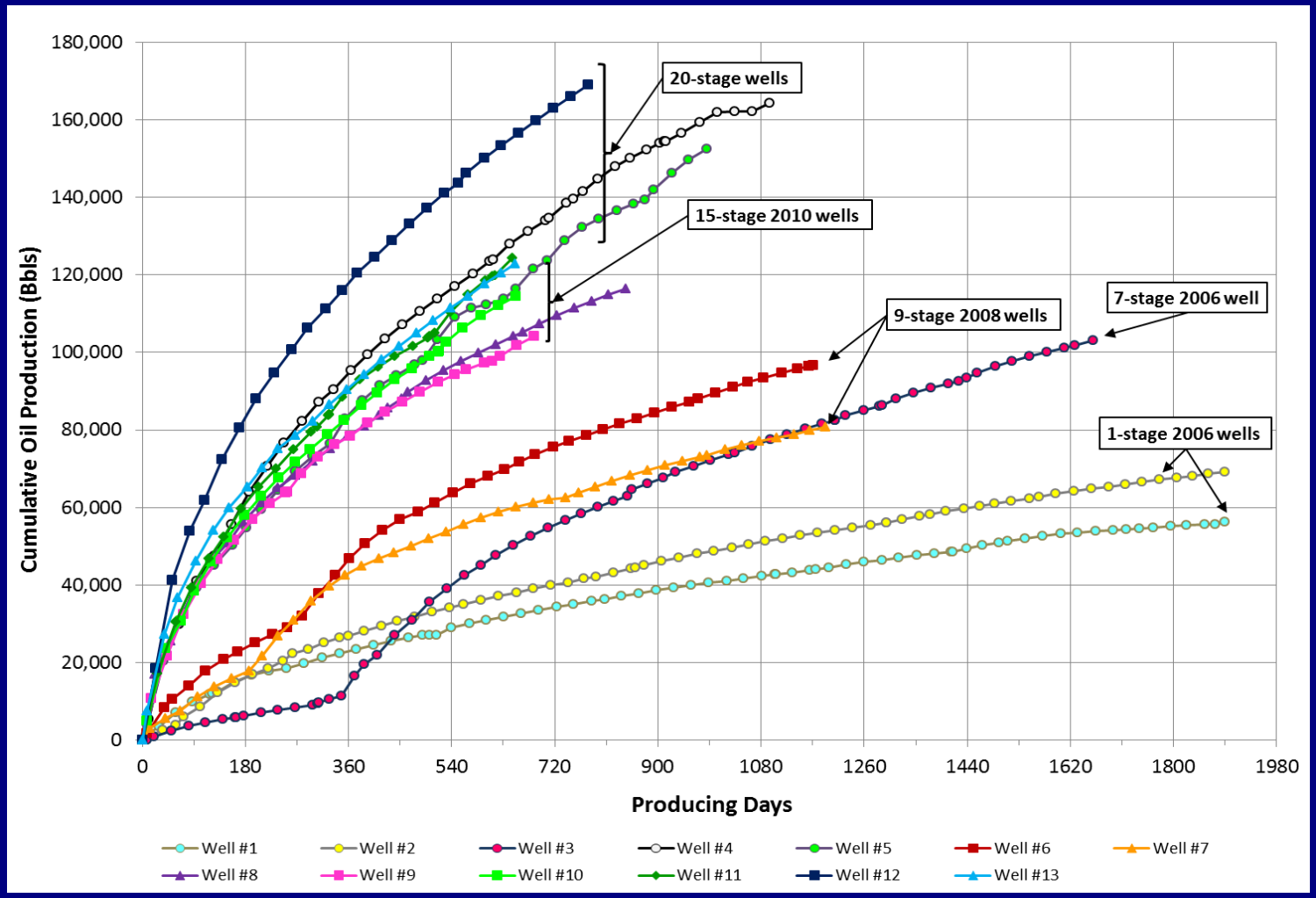
Central Basin Company B Well Results: 2008



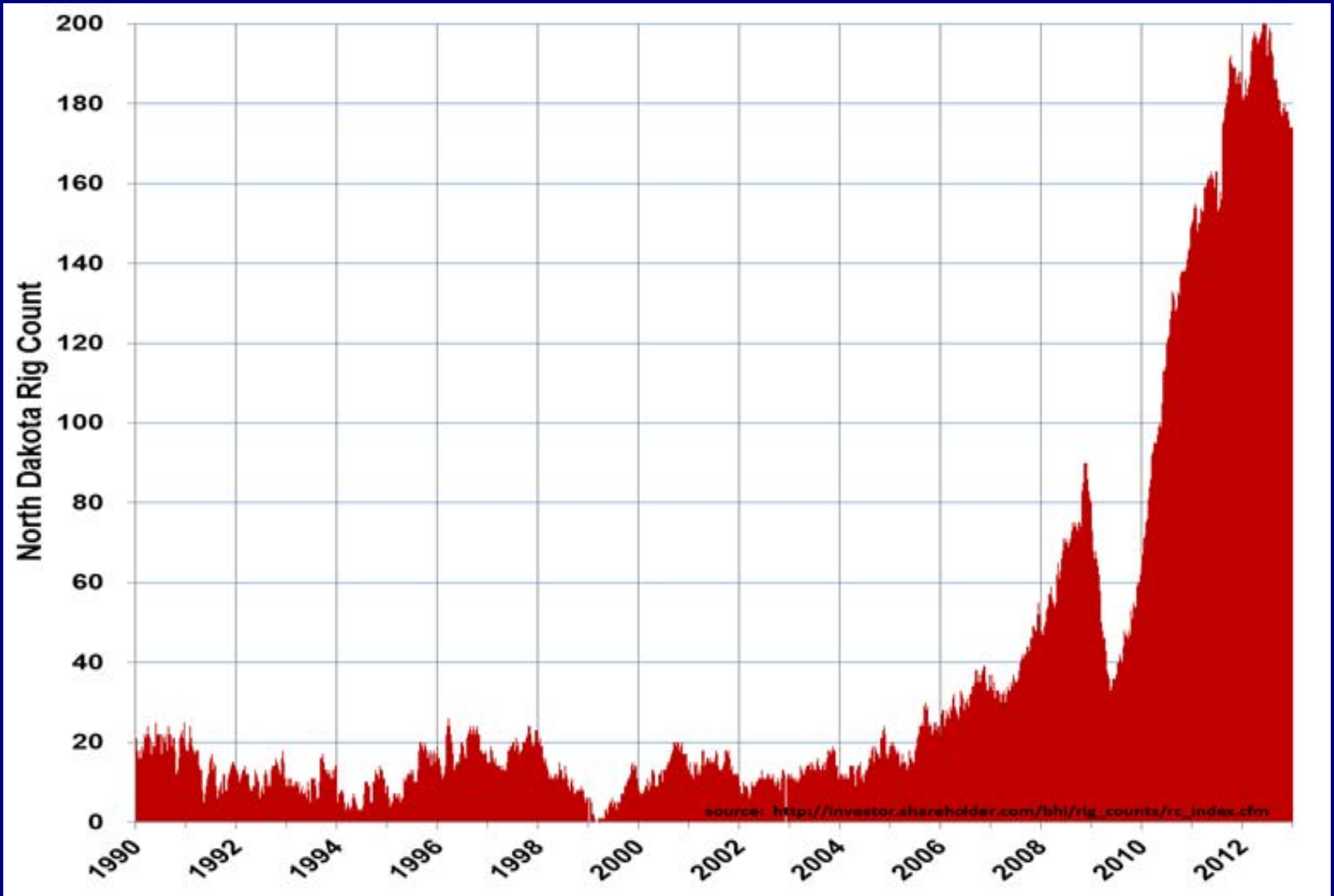
Central Basin Company B Well Results: 2008-2010



Central Basin Company A and B Initial Well Results: 2008-2010



North Dakota Rig-Count and Production



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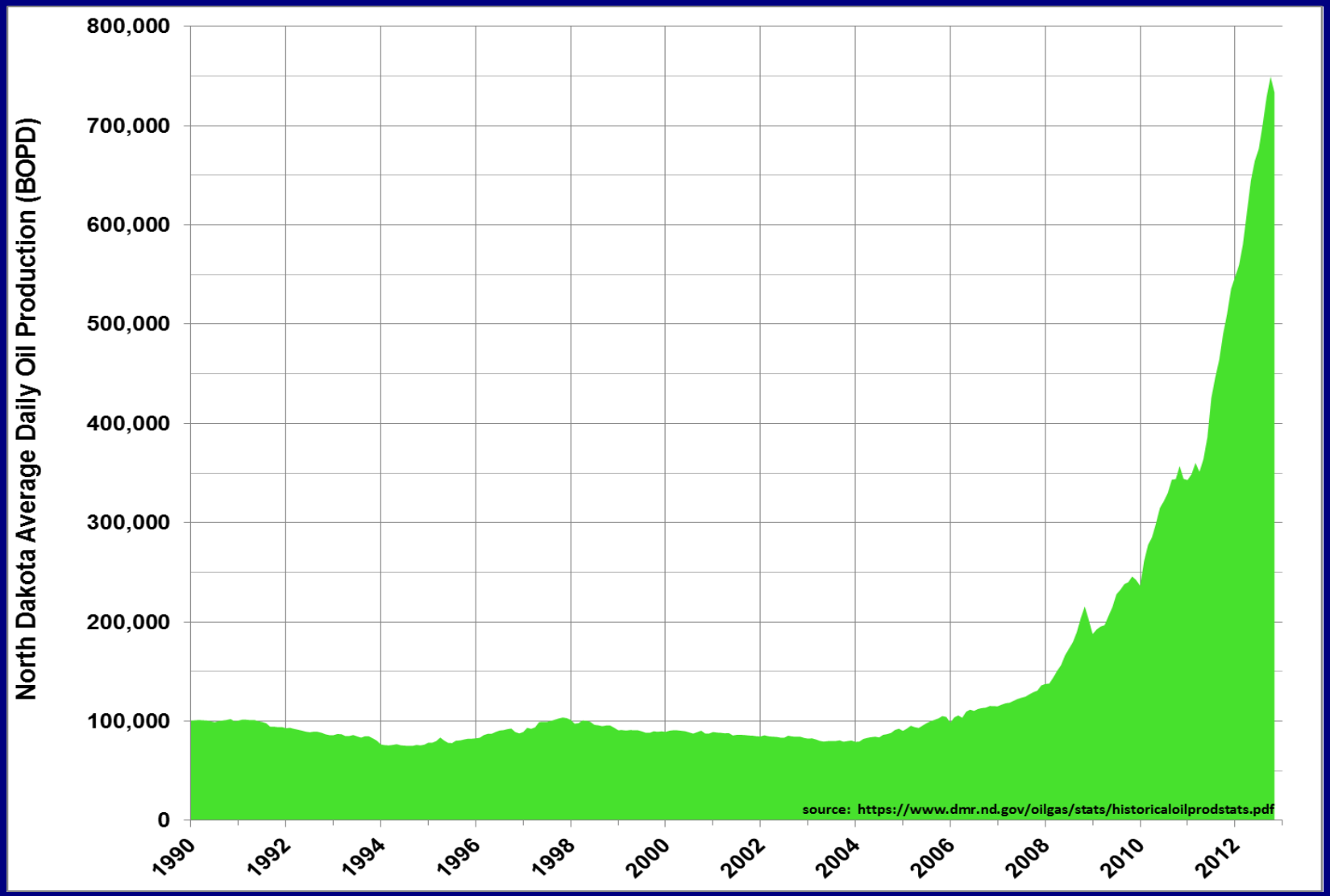
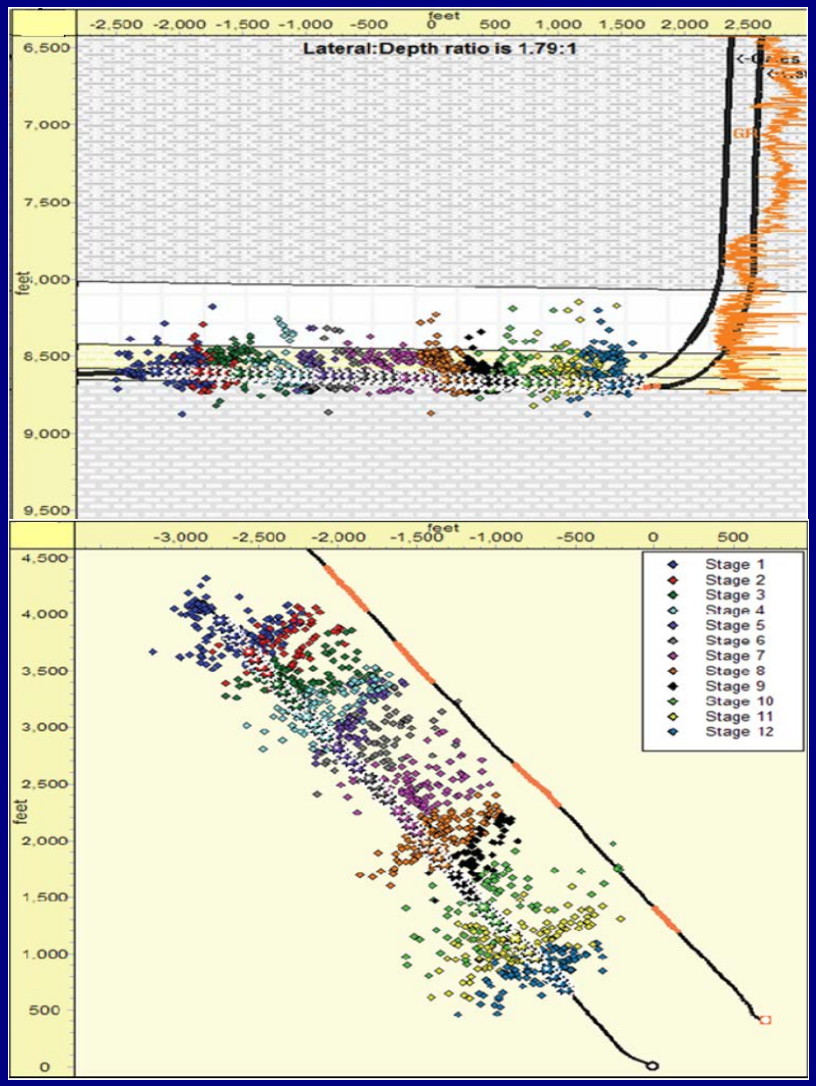


…. and 3% Unemployment Statewide

Current Developments in Multi-Stage Horizontal Wells

- Further development of completion hardware
  - Repeater Ports
  - Multi-Entry Sleeves
  - Cemented Sleeves
- More / better measurement of what how much of the resource we are draining from each well
- A focus on pad developments:
  - Simultaneous operations
  - Simulfrac treatments

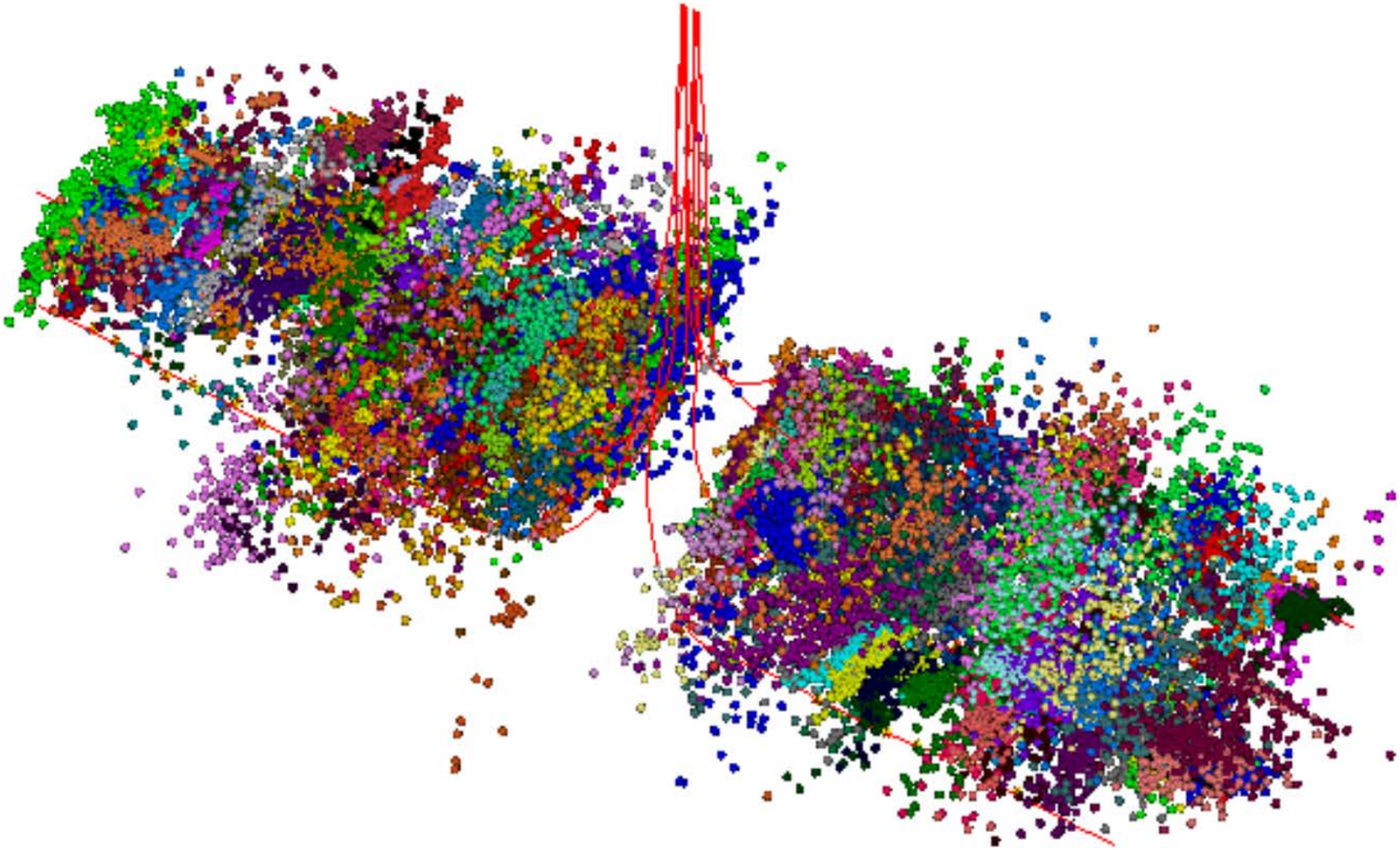


SPE 138425

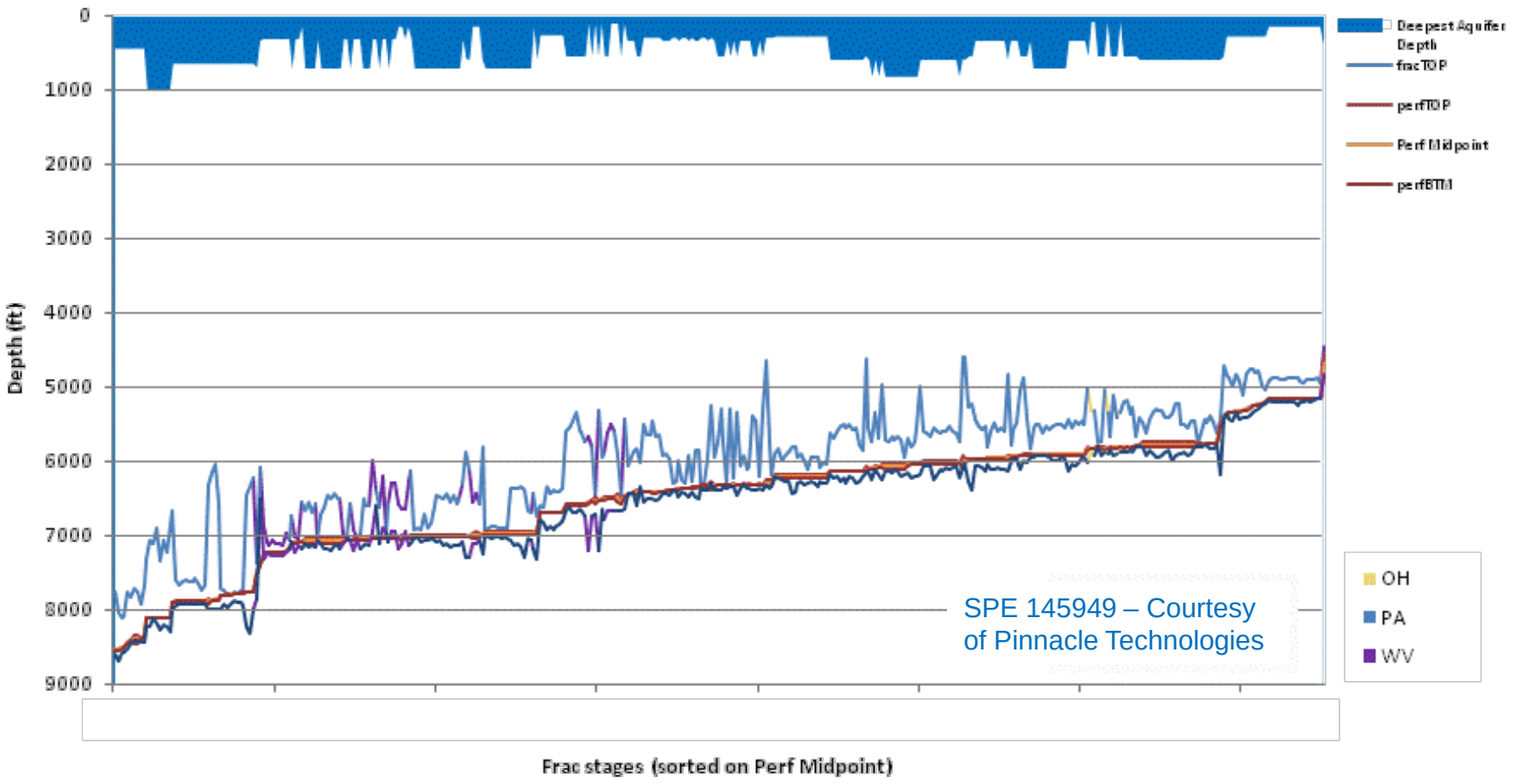
Pad Development – Horn River Basin, BC
SPE 140654 (2011)

Courtesy: Apache Corp.

Example MultiStage Microseismic Mapping at Horn River, BC

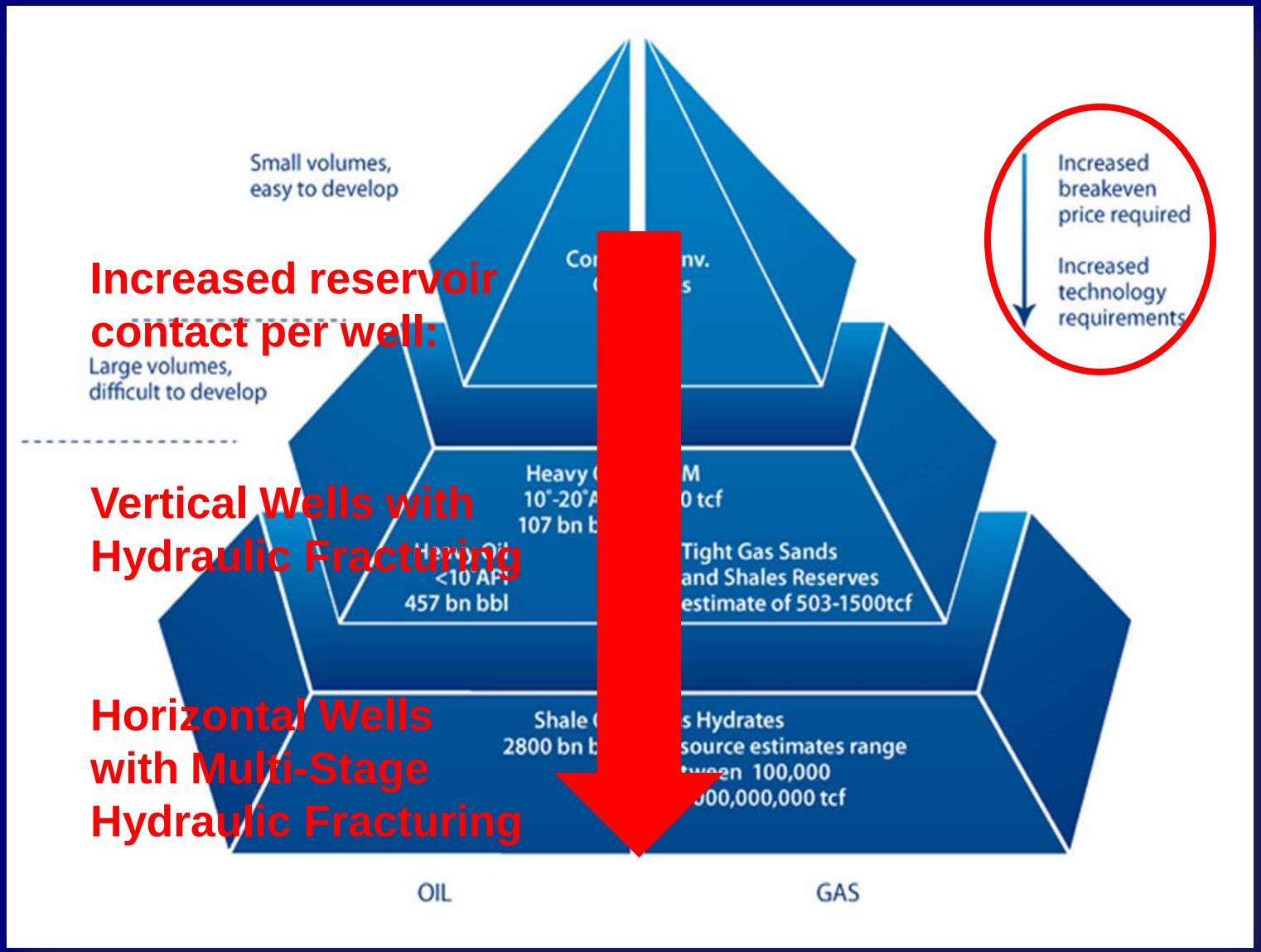


Marcellus Shale Mapped Fracture Treatments



http://nwis.waterdata.usgs.gov/nwis/inventory

The Resource Triangle



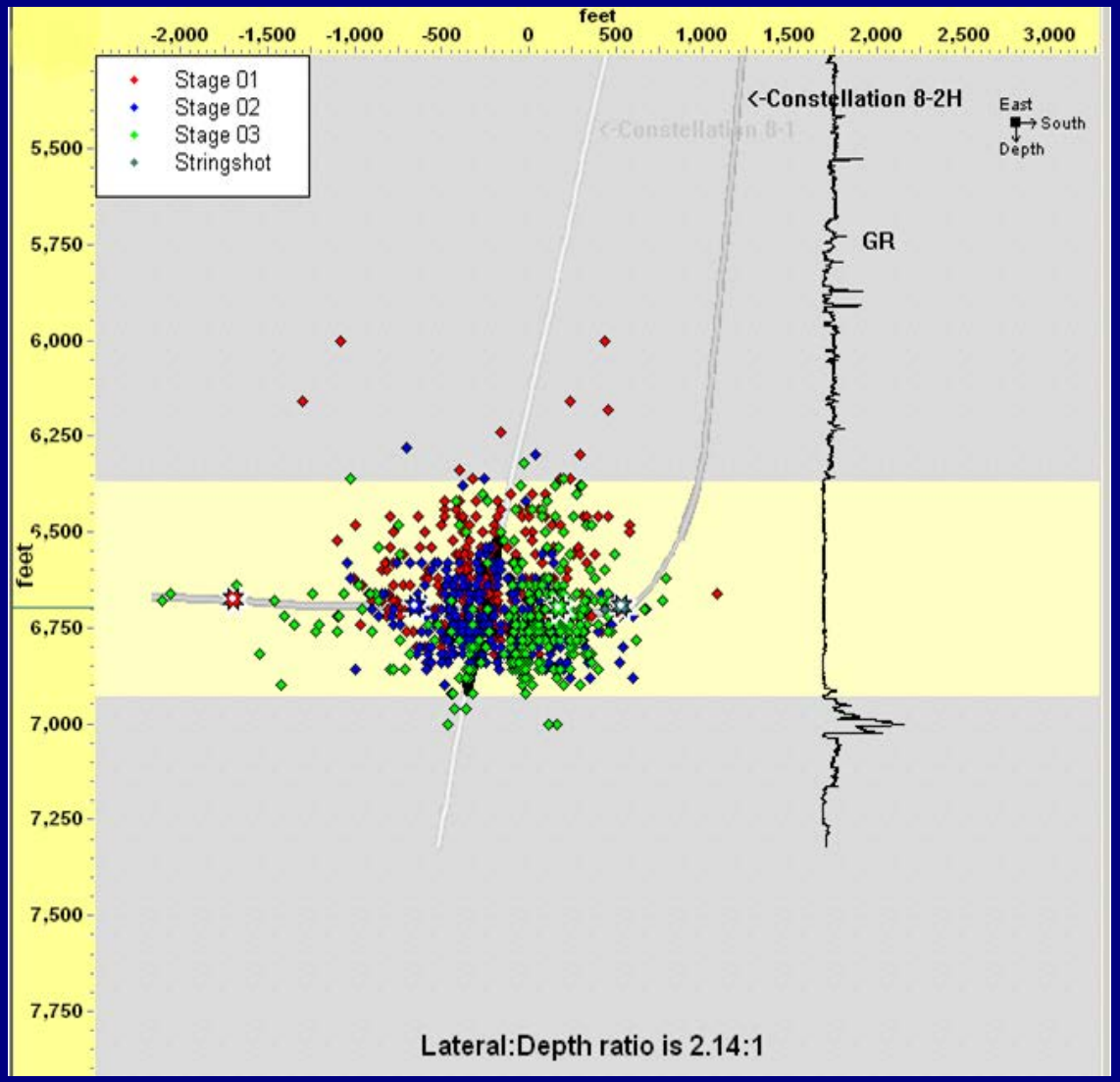
Source: Wood Mackenzie

Conclusions

- Horizontal Drilling technology has been actively used for the past 30 years, but it is only in the last 5 to 10 years that we have seen the widespread application of multi-stage hydraulic fracturing of horizontal wells
- The reservoir productivity gains from multi-stage hydraulic fracturing of horizontal wells is causing a revolution in our industry
  - The number of horizontal rigs
  - The need for pumping services
  - The opportunity for economic exploitation of Unconventional Resources
- Today's Completion Engineer has a variety of completion tools and techniques which can be applied to effectively stimulate horizontal wells
- No one completion design fits all cases

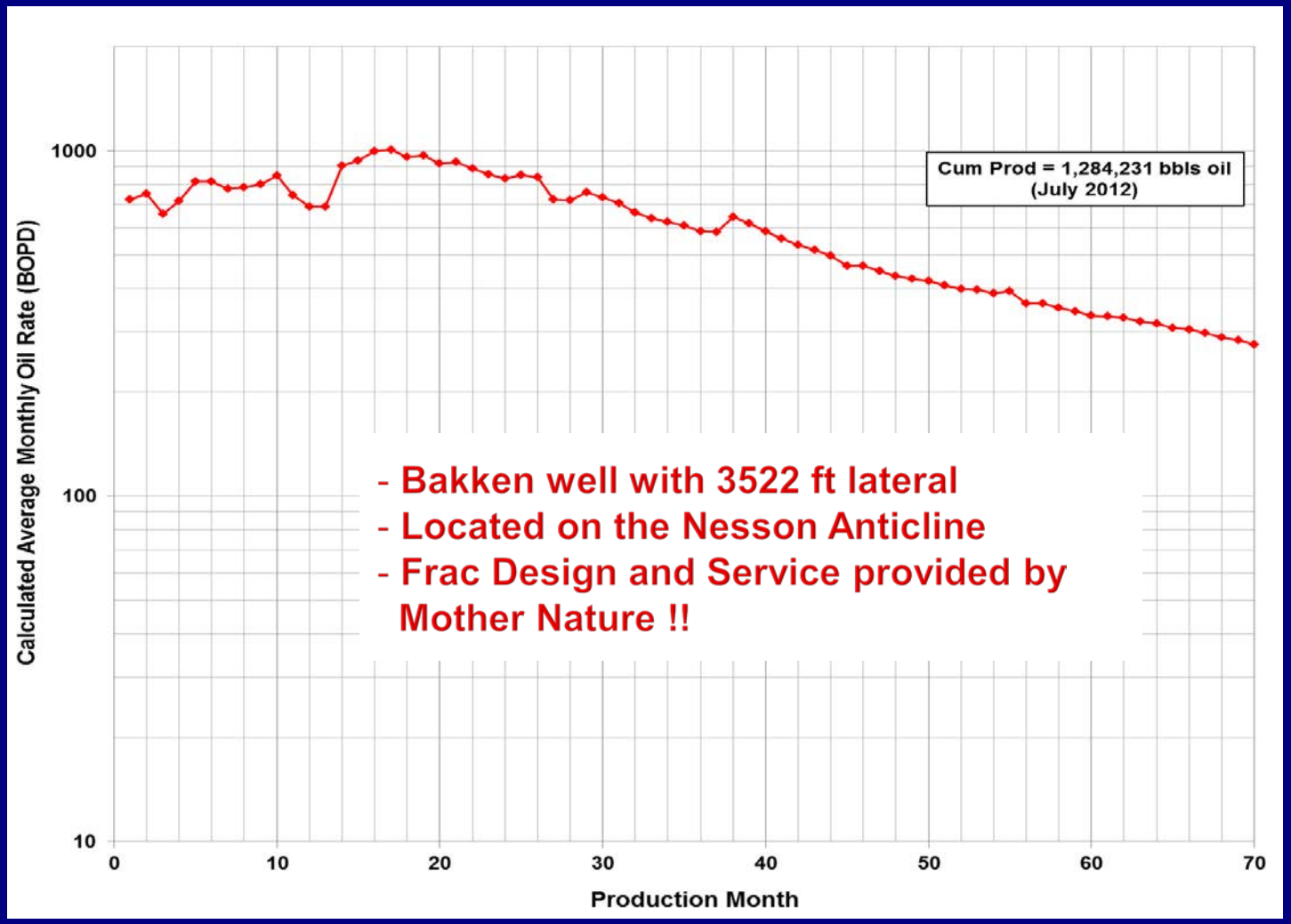
The Technology Doesn't Always Work !!

Mississippian Lime Formation (OK) – 3 Stage Completion (2007)



- **Event locations from all stages plot in the same general area**
- **Width: 1700 ft.**
- **Height: 500 ft.**

What is the Reservoir Potential with an Optimal Stimulation?



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Thank you !!!

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