File is 197 pages, 24mb.

Selected Rocky Mountain Tight Oil Sandstone Plays*

Richard Bottjer[1], Gus Gustason[2], and Kevin Smith[3]

Search and Discovery Article #80591 (2017)**
Posted August 14, 2017

*Adapted from Course Notes and presentations at Rocky Mountain Association of Geologists (RMAG) Symposium and Core Workshop, Denver, Colorado, March 2, 2017. Please refer to related articles, Tight Oil Sandstone Reservoirs, Wyoming and Colorado: Core Workshop: Part I (Search and Discovery Article #80592 (2017)), Part II (Search and Discovery Article #80593 (2017)), and Part III (Search and Discovery Article #80594 (2017)), which are adaptations of the presentations at, and Guidebook for, the 2015 Short Course No. SDC-17.

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Synopsis

This workshop discussed current tight oil sandstone plays in Cretaceous reservoirs in the Powder River and D-J Basins, Wyoming and Colorado, focusing on the Wall Creek-Turner, Codell, Sussex, and Parkman sandstones. Tight oil sandstone plays have developed where uneconomic vertical producers were drilled in the past and/or between existing vertical oil fields where higher-permeability facies are present. In contrast to “conventional” vertical production from sandstones in the same interval, these tight oil reservoirs are areally extensive and generally contain a high percentage of burrowed or bioturbated lithofacies. Petrophysical evaluations of these tight oil sandstone plays are challenging due to relatively high clay content, thinly interbedded sandstones and mudstones, and/or complex pore networks. These sandstones are characterized by moderate porosities, ranging up to 18%, but low permeabilities, ranging from .001 to .1 millidarcies. Oil and gas resources are recoverable due to the development of multi-stage fracture stimulations in horizontally drilled wells. The reservoir characteristics of each play was demonstrated with approximately 2000 feet of core and core analyses from more than 30 wells and participants will have an opportunity to compare and contrast the different plays.

This workshop and symposium was essentially a re-presentation of a short course offered at the AAPG-ACE convention held in Denver in June, 2015. The format was modified slightly but many of the cores shown are the same.

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RMAG Core Workshop

March 2nd, 2017

Selected Rocky Mountain Tight Oil Sandstone Plays: Symposium and Core Workshop

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Coal Creek Resources

Gus Gustason

Enerplus

Kevin Smith

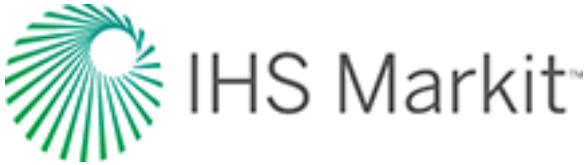
Garnet Ridge Resources

RMAG Core Workshop

March 2nd, 2017

Selected Rocky Mountain Tight Oil Sandstone Plays: Symposium and Core Workshop

Key Data & Support Provided by IHS Markit



Core Workshop Hosted by USGS Core Research Center

Workshop by RMAG

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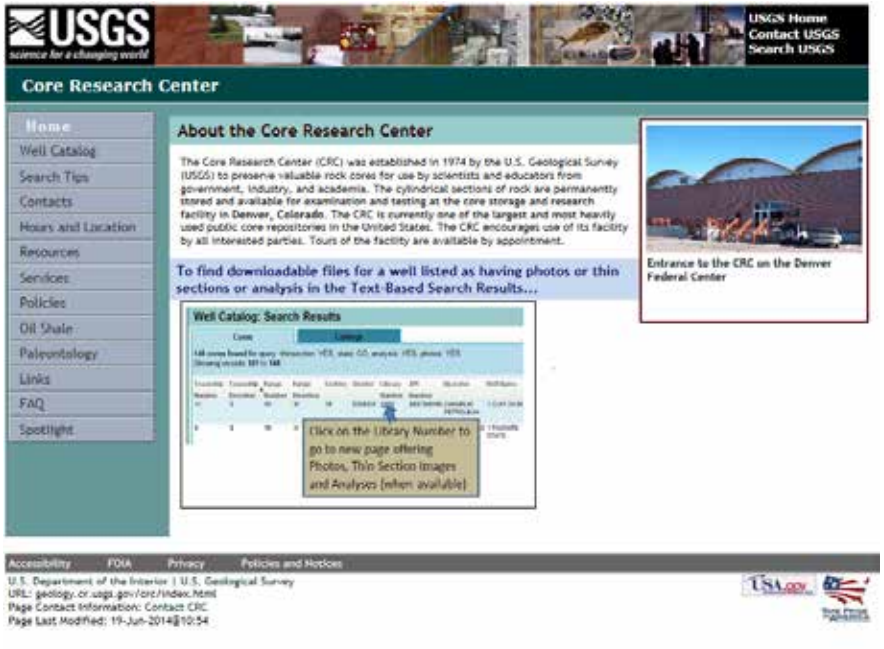
Thanks to the Core Research Center of the U.S.G.S. for preserving and providing access to many cores.

http://geology.cr.usgs.gov/crc/index.html



RMAG Tight Oil Sandstones Core Workshop

March 2nd, 2017

OUTLINE

- **Tight Oil Sandstones Overview**
- **Facies & Depositional Systems**
- **Reservoir Introductions; Core Viewings – Split into 2 Groups; Reservoir Summaries**
- **Summary: Reservoir Properties & Comparisons**

<u>Questions:</u>

- **What do these plays have in common?**
- **Are there any differences between the plays and/or reservoirs?**
- **Are they all really "tight"?**
- **Does each Formation have one or multiple play types?**

RMAG Tight Oil Sandstones Core Workshop

March 2nd, 2017

OUTLINE

8:30 Introductions, Logistics, & Safety

8:45 Tight Oil Sandstones Overview – Conference Room

9:00 Facies & Depositional Systems – Conference Room

9:30 Sussex/Shannon & Turner/Frontier Sandstones Overview – Conference Room

10:00 Sussex/Shannon/Turner/Frontier Core Viewing (break into 2 groups) – Core Viewing Room

11:00 Sussex/Shannon & Turner/Frontier Sandstones Review – Conference Room

12:00 Lunch – Conference Room

RMAG Tight Oil Sandstones Core Workshop

March 2nd, 2017

OUTLINE

12:45 Codell & Parkman Sandstones Overview

– Conference Room

1:15 Codell & Parkman Core Viewing (break into 2 groups)

– Core Viewing Room

2:30 Codell & Parkman Sandstones Review

– Conference Room

3:30 Summary & Discussion – Conference Room

4:30 Conclusion of Workshop

RMAG Tight Oil Sandstones Core Workshop

March 2nd, 2017

USGS Core Research Center

Introduction & Overview

Safety Considerations

- Emergency Exits
- Eye-Wash Stations
- Restrooms

RMAG Tight Oil Sandstones Core Workshop

March 2nd, 2017

POLICIES & PROCEDURES

No Sampling of Cores – No Souvenirs

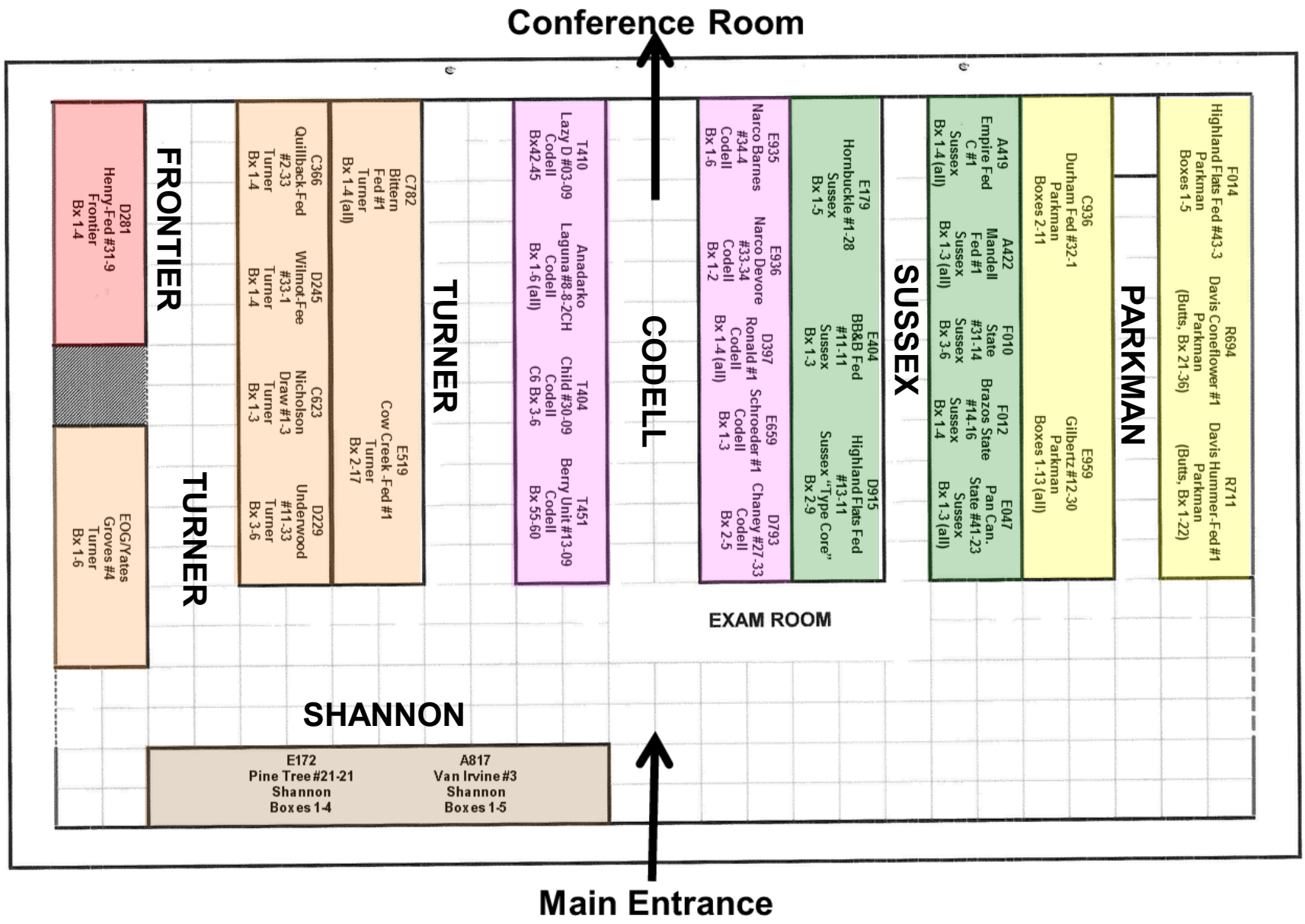
Please don't drop the core boxes

HCl is available to test for CaCO3. Please don't let the HCl fester on the core – spray it with water soon after testing with HCl

If you remove a piece of core for closer examination, mark its location with a credit card so you will put it back in the right place

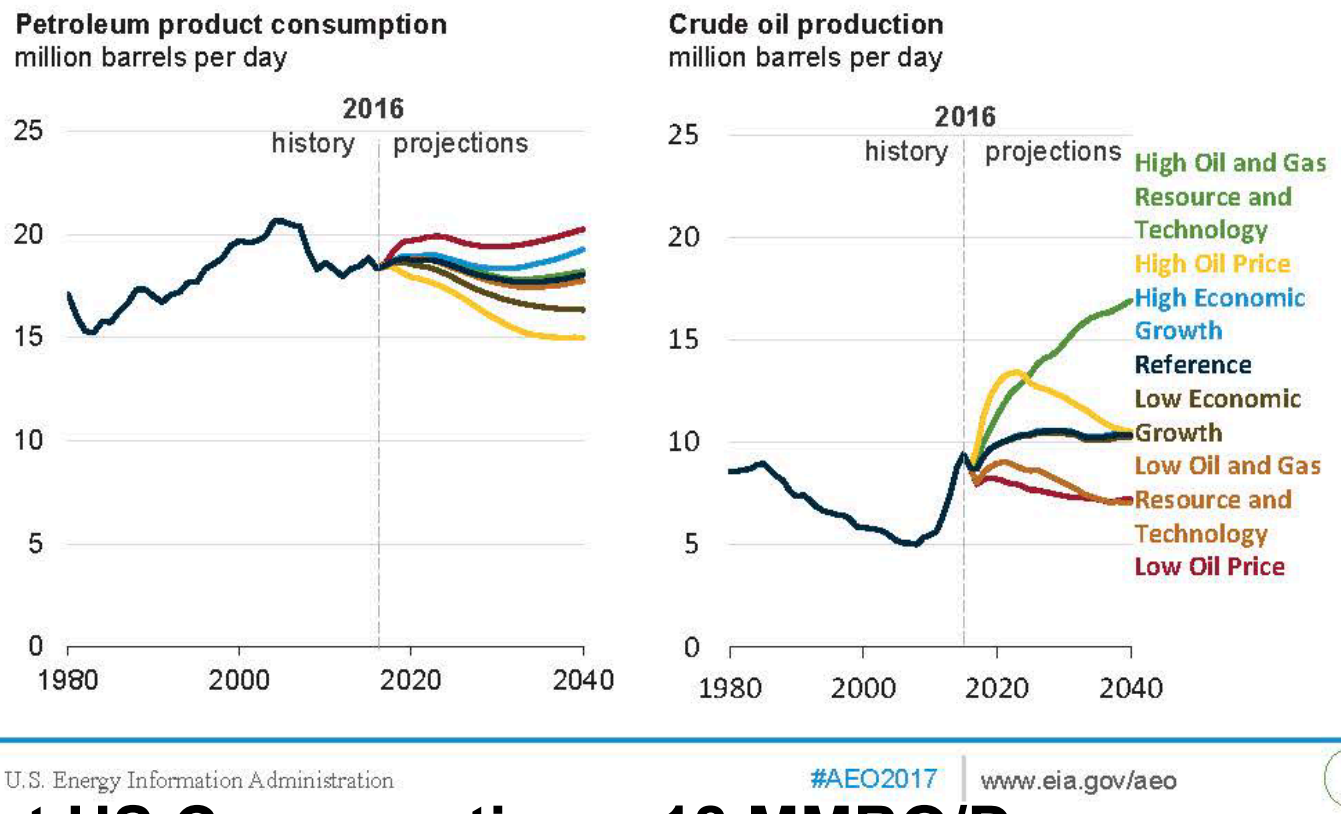
RMAG Tight Oil Sandstones Core Workshop, March 2, 2017

CORES - ORGANIZATION



EIA 2017 Annual Energy Outlook

U.S. petroleum product consumption remains below 2005 levels through 2040 in most AEO2017 cases—

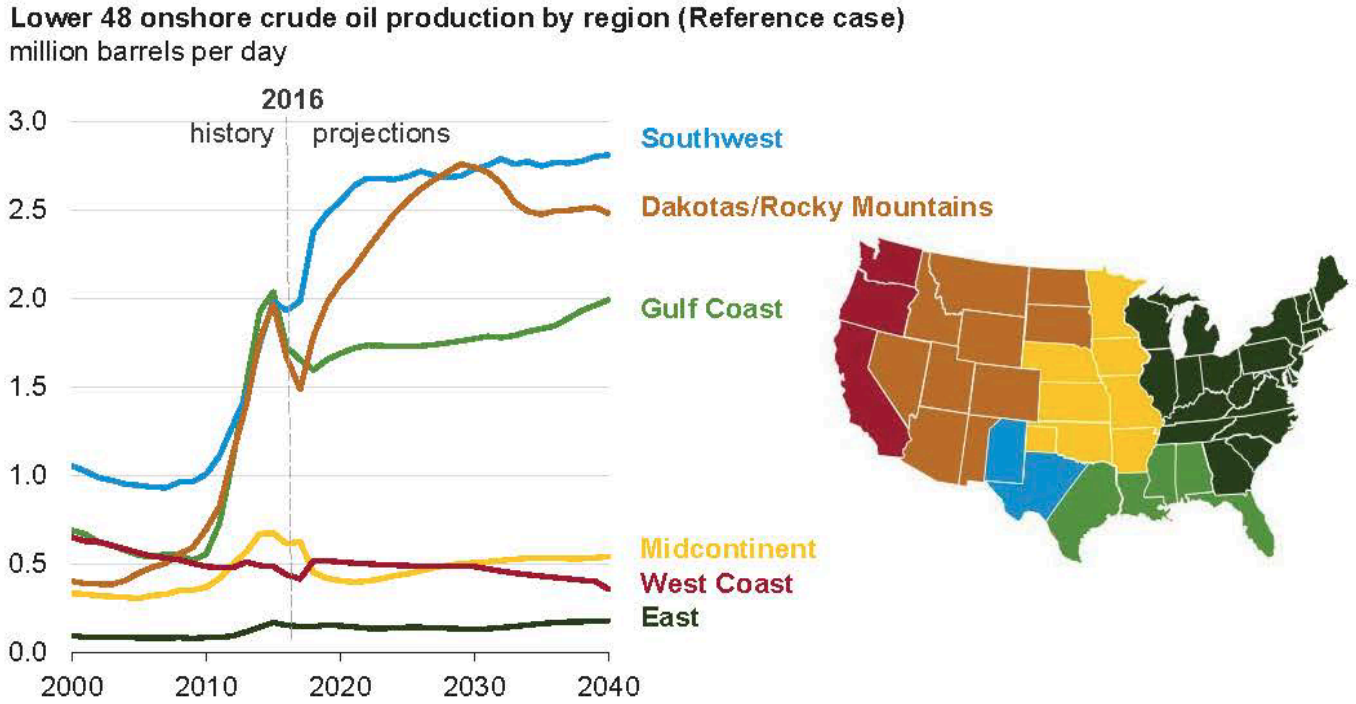


- Current US Consumption ~ 18 MMBO/Day
- Base (Reference) Case – Flat Consumption
- Base Case – Oil Production Recovers to ~ 10 MMBO/Day

Source: EIA webpage, Report Dated January 5, 2017: http://www.eia.gov/outlooks/aeo/pdf/0383(2017).pdf
EnerCom Oil and Gas 360: http://www.oilandgas360.com/u-s-petroleum-production-exports-will-rise-2040-eia/#

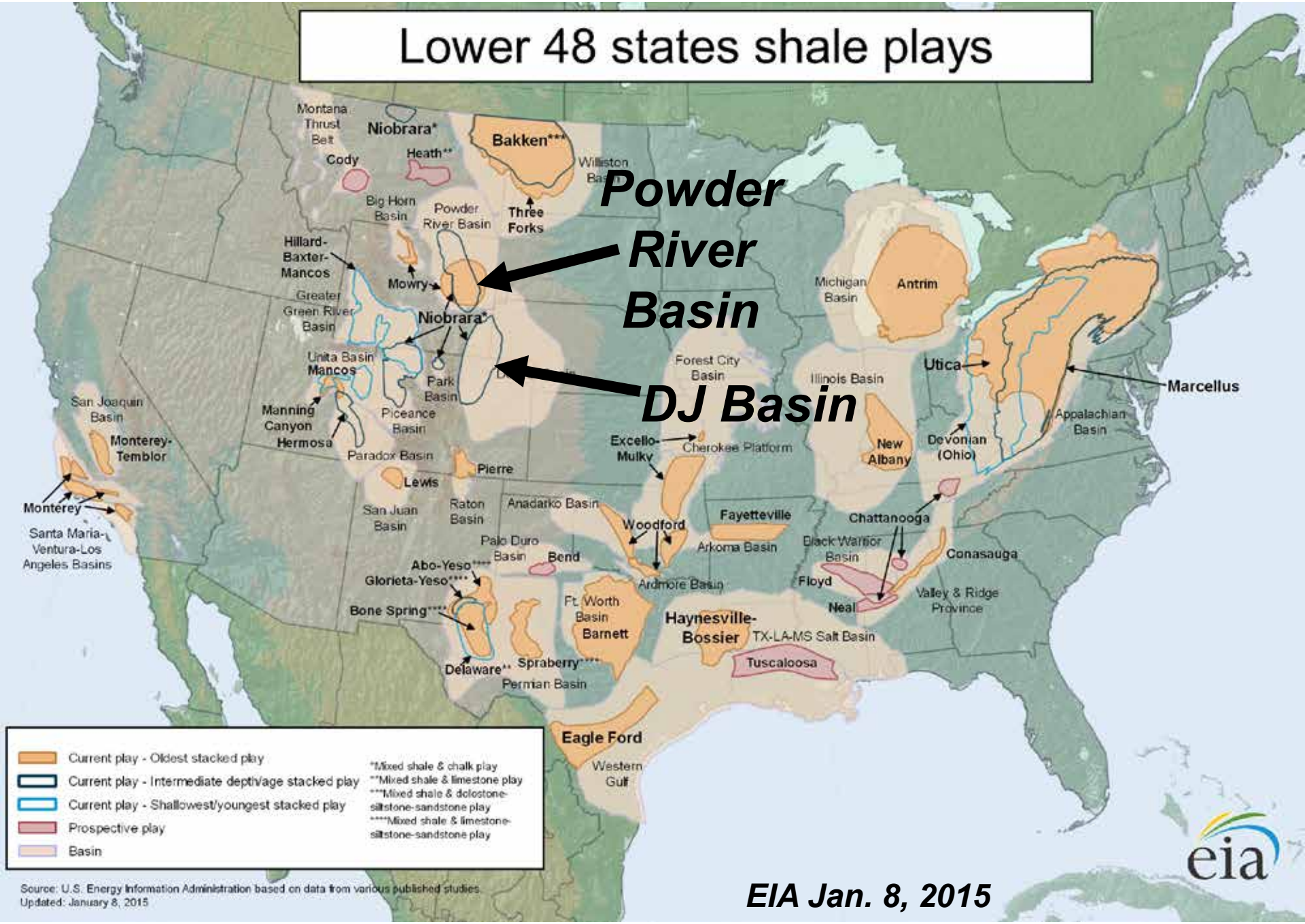
EIA 2017 Annual Energy Outlook

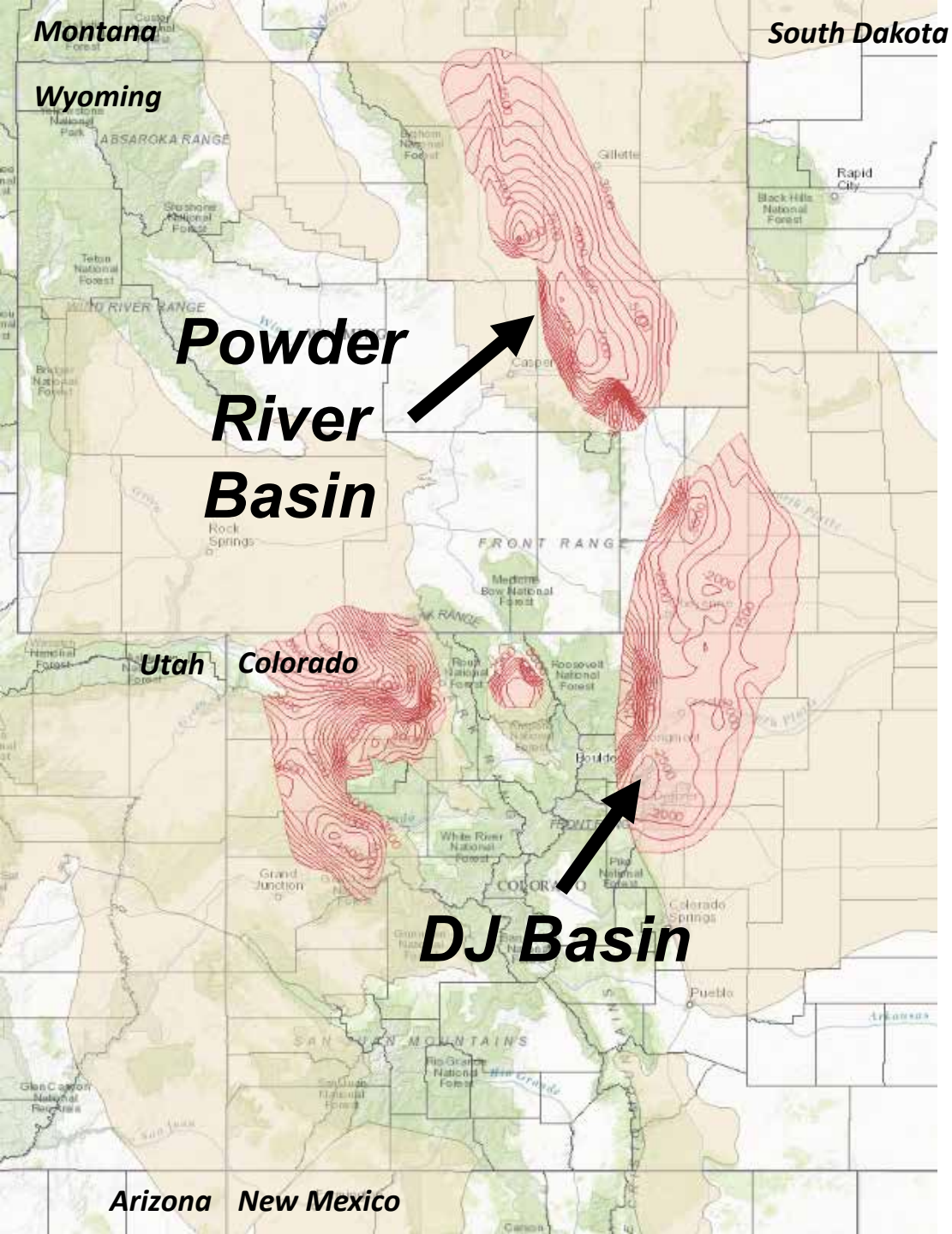
The Southwest and Dakotas/Rocky Mountains regions lead growth in tight oil production in the Reference case—



- **Production Growth – Southwest, Rockies, & Gulf Coast**
- **Primarily Permian, Bakken, & Eagle Ford**
- **Rockies Current ~ 1.5 MMBO/Day; Peak ~ 2.8 MMBO/Day**

Source: EIA webpage, Report Dated January 5, 2017: http://www.eia.gov/outlooks/aeo/pdf/0383(2017).pdf
EnerCom Oil and Gas 360: http://www.oilandgas360.com/u-s-petroleum-production-exports-will-rise-2040-eia/#


Lower 48 states shale plays
Powder River Basin
DJ Basin
Montana Thrust Belt
Niobrara*
Bakken***
Cody
Heath**
Williston Basin
Big Horn Basin
Powder River Basin
Three Forks
Hillard-Baxter-Mancos
Mowry
Greater Green River Basin
Niobrara*
Uinta Basin Mancos
Park Basin
Piceance Basin
Manning Canyon
Hermosa
Paradox Basin
San Joaquin Basin
Monterey-Temblor
Monterey
Santa Maria-Ventura-Los Angeles Basins
Lewis
Pierre
San Juan Basin
Raton Basin
Anadarko Basin
Palo Duro Basin
Bend
Abo-Yeso****
Glorieta-Yeso****
Bone Spring****
Delaware**
Spraberry****
Permian Basin
Ft. Worth Basin
Barnett
Forest City Basin
Excello-Mulky
Cherokee Platform
Woodford
Fayetteville
Arkoma Basin
Ardmore Basin
Haynesville-Bossier
TX-LA-MS Salt Basin
Tuscaloosa
Eagle Ford
Western Gulf
Michigan Basin
Antrim
Illinois Basin
New Albany
Utica
Marcellus
Appalachian Basin
Devonian (Ohio)
Chattanooga
Black Warrior Basin
Floyd
Neal
Conasauga
Valley & Ridge Province
Current play - Oldest stacked play
Current play - Intermediate depth/age stacked play
Current play - Shallowest/youngest stacked play
Prospective play
Basin
*Mixed shale & chalk play
**Mixed shale & limestone play
***Mixed shale & dolostone-siltstone-sandstone play
****Mixed shale & limestone-siltstone-sandstone play
Source: U.S. Energy Information Administration based on data from various published studies
Updated: January 8, 2015
eia
EIA Jan. 8, 2015



ROCKY MOUNTAINS TIGHT OIL PLAYS

EIA Niobrara Structure Maps

- Asymmetrical Laramide Basins
- Reservoirs Deposited in Cretaceous Western Interior Seaway

http://www.eia.gov/special/shaleplays/

TIGHT OIL SANDSTONE RESERVOIRS HISTORY

- **Conventional Exploration – Vertical Drilling**
  - Oil Plays Required Good Porosity & Permeability for Economic Results
  - Low Permeability Led to Uneconomic Wells or Dry Holes
- **Vertical Tight Gas Plays**
  - Low Permeability Sandstone Reservoirs (e.g., Jonah, Pinedale, Cotton Valley, Piceance, etc.)
- **Horizontal Gas Shale Plays**
  - Fine-Grained "Reservoirs", Siliceous & Calcareous Mudstones
- **Horizontal Shale Oil Plays**
  - Apply Techniques Successful in Shale Gas to Oil Window Thermal Maturities
  - Best Performing Oil Wells Are Hybrid Reservoirs (e.g., Bakken)
- **Horizontal Tight Oil Plays (Hybrid)**
  - Low-Permeability Sandstones & Carbonates, Proximity to Oil-Prone Source Rocks (Necessary?)

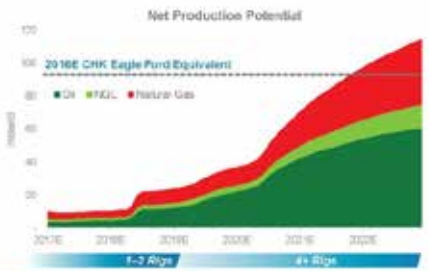
Industry Activity POWDER RIVER BASIN

Chesapeake Investor Relations Update December 2016

RETURNING TO POWDER RIVER BASIN

ONE MILE OF OPPORTUNITY

- ~2.7 bboe gross recoverable resource potential
- ~2,600 risked locations
- Renegotiated midstream unlocks value
- The next oil growth asset
  - CHK rig returned to the basin in November
  - Additional rigs planned for 2017



Chesapeake Investor Relations Update December 2016

SUSSEX SANDSTONE

HIGHLY ECONOMIC OIL PLAY

- Moving to development
- Dominant position in the play
- ~200 undrilled locations
  - Assumes 1,320' spacing
  - Overpressured – high deliverability
- Targeted development
  - EUR: 825 – 1,350 mboe
  - ROR: 50 – 70%
  - 2017 focused drilling program

Oil breakeven price

<$40

Chesapeake Investor Relations Update December 2016

TURNER SANDSTONE

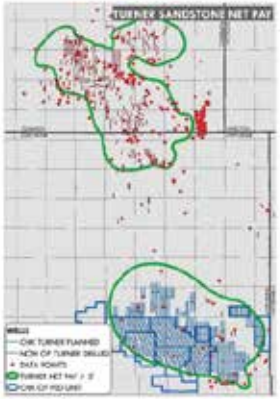
PROVEN RESERVOIR – UNREALIZED VALUE

- Same play as northern hotspot with similar rock properties and anticipated higher pressure
- Offset activity proves potential, but not optimized for drilling and completion

Oil breakeven price

~$40

	Turner North	CHK Turner
Depth	~10,000'	~11,000'
Reservoir Pressure (Est.)	~4,800 psi	~5,800 psi
Avg. Porosity	7%	7%
Avg. Water Saturation	45 – 60%	35 – 60%



Devon IPAA Symposium April 2015

Rockies Oil

Powder River Basin

devon

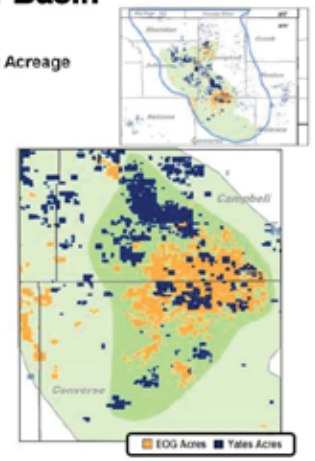
- Emerging light oil opportunity
  - Net acres: 150,000
  - Stacked pay potential
  - 1,000 risked locations in inventory
  - Q4 net production: 19 MBOED
- Notable Q4 development activity
  - 4 wells: 30-day IP avg. 800 BOED
  - Light oil 90% of production mix
- 2015 Outlook
  - 2015 capital: ≈$350 million
  - Running 2 operated rigs

Industry Activity POWDER RIVER BASIN

EOG Resources Barclays Conference September 2016

EOG Resources and Yates Powder River Basin

- Increases Powder River Basin Core Development Acreage Position to 202,000 Net Acres
  - Yates Adds 81,000 Net Acres to EOG's Existing 121,000 Net Acres
- Contiguous to Current EOG Acreage Position
- Doubles Total Powder River Basin Exploration Position to 400,000 Net Acres
  - Yates Adds 200,000 Net Acres to EOG's Existing 200,000 Net Acres
- Prospective for Multiple Stacked-Pay Formations
  - Vertical Section 4,000' - 5,000'
- Yates Acreage 83% Held By Production



eog resources

Barclays_0916-10

Samson Resources Deutsche Bank Conference September 2014

Powder River

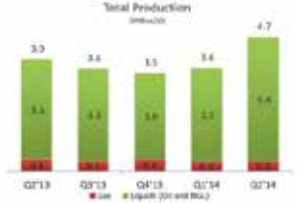
2014 Operations Update:

- Multiple pay basin characterized by conventional (Shannon, Sussex, Frontier, Parkman) and unconventional (Mowry, Niobrara) oil targets ranging from 7,500'- 13,000' TVD
- Industry remains active in basin with approximately 30 rigs as of August '14 (11 Frontier/Turner; 7 Parkman; 5 Shannon/Sussex; 2 Niobrara; ~5 Other)
- 3H'14 Samson activity focused on drilling two mile horizontal Sussex laterals in Hornbuckle and Spearhead fields

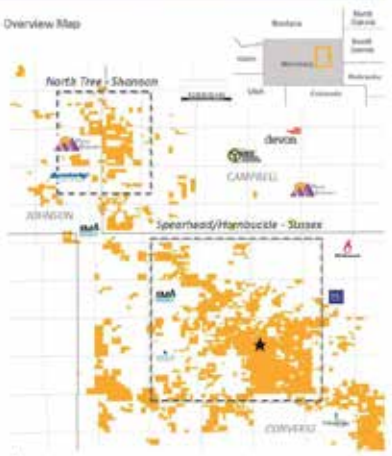
Rig Count: 1 rig

Net Acreage: 299,000[2]

Total Production



Overview Map



★ SAMSON ACTIVE RIG

Note: Peer logo's represent area drilling activity as of August 2014

EOG Resources Bank of America Conference November 2016

Deep Inventory of Crude Oil Assets

Play	Net Acres	Total Locations*	Resource Potential** (MMBoe)	Premium Locations
Eagle Ford	549,000	7,200	3,200	1,925
Bakken/Three Forks				
- Core	120,000	975	620	330
- Non-Core	110,000	1,125	400	-
Delaware Basin				
- Wolfcamp	348,000	2,660	2,900	1,275
- Second Bone Spring	289,000	1,870	1,400	1,140
- Leonard	160,000	1,800	1,700	1,035
Rockies				
- DJ Basin	85,000	460	210	200
- Powder River Basin	400,000	315	190	120
	≈ 2,100,000	≈ 16,000	≈ 10,600	≈ 6,000

Inventory Growing in Quality and Size

* Number of producing and undrilled remaining net wells as of January 1, 2016. Assumes no further downspacing, acreage additions or enhanced recovery.
** Estimated potential reserves (MMBoe) net to EOG, not proved reserves. Includes proved reserves and prior production from existing wells.

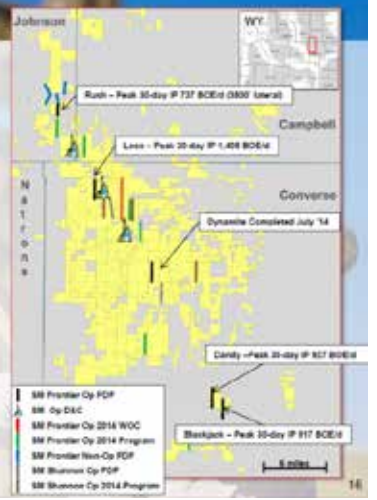
eog resources

BAML_1116-15

SM Energy Barclays Conference September 2014

Powder River Basin Update

- In 2014, the Company has added approximately 33,000 net acres to its Powder River Basin position. The Company now holds approximately 166,000 net acres in the basin.
- Solid results from the Rush State 4277-36-1FH: peak 30-day initial production rate of 737 BOE/d from a ~3,800 foot lateral.
- Increasing activity to accelerate delineation of Frontier interval.
  - The Company has contracted a fourth rig for delivery in 3Q14 and expects to add a fifth rig in 2015.



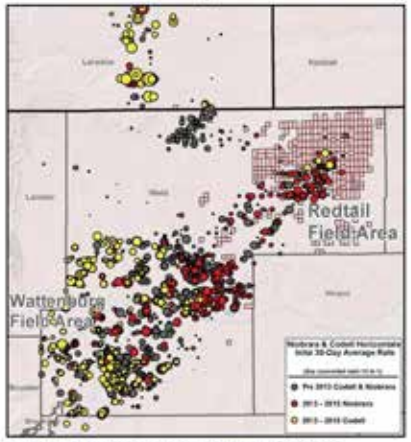
16

Industry Activity CODELL SANDSTONE

Whiting Corporate Presentation January 2017

Redtail Development Program

Economic Sweet Spot in Oil Window *(Weld County, Colorado)*



ACREAGE
- 153,937 gross (129,035 net) acres
- 100% held by production, expires beyond 2018, or can be extended for approximately $3 million.
- Average WI of 84%

MULTIPLE TARGETS
- Niobrara "A" Shale
- Niobrara "B" Shale
- Niobrara "C" Shale
- Codell/Fort Hays

DEVELOPMENT PLAN

Mix of 1,280 and 960-acre spacing units
- Targeting 465 MBOE EUR for 960-acre spaced wells in 2016.
- Targeting 655 MBOE EUR for 1280-acre spaced wells in 2016.
- 6,205 potential gross drilling locations as of September 30, 2016.
- Project approximately 105 drilled uncompleted wells at 12/31/2016.

COMPLETED WELL COST
- 960-Acre Spaced Horizontal: $4.0 MM
- 1,280-Acre Spaced Horizontal: $4.5MM

OPERATIONAL HIGHLIGHTS
- Redtail production averaged 10,945 BOE/d in Q3 2016.

Source: IHS and internal Whiting production database as of 12/31/2015.

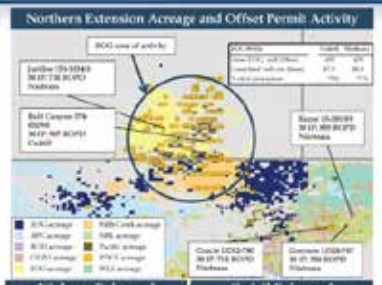
NYSE: WLL 12

Extraction Investor Presentation January 2017

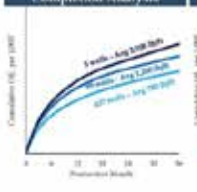
Northern Extension Acreage Overview

Highlights
- Position consists of ~120,000 net acres concentrated in Northern Weld County
  - Represents considerable future development opportunities
- Four delineation wells producing since early 2016 yielding encouraging initial results
- Strong correlation of higher proppant concentrations leading to increased production
- Additional wells planned in 2017 utilizing enhanced completions

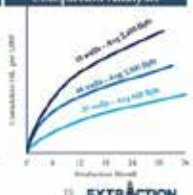
Northern Extension Acreage and Offset Permit Activity



Niobrara Enhanced Completion Analysis



Codell Enhanced Completion Analysis

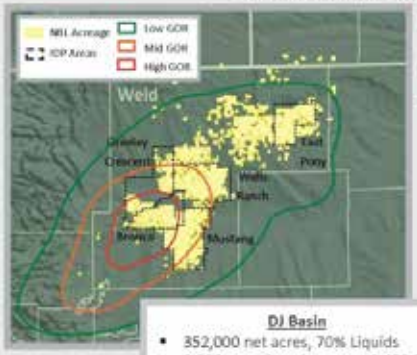


EXTRACTION

Noble Long-Term Outlook November 2016

DJ Basin: Foundational Asset of the USO Portfolio

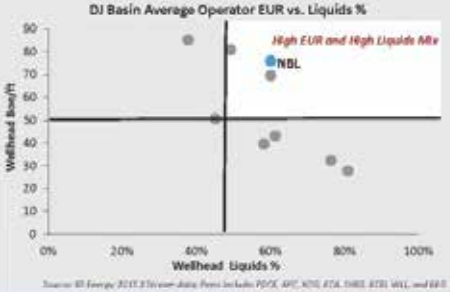
Large, high-quality, contiguous acreage position



- Creating Differential Value with Long Laterals, Midstream Advantage and High Liquids Content
- Increasing Type Curves in Focus Development Areas
- Enhancing Capital Efficiency through Technology and Sub-surface Expertise

DJ Basin
- 352,000 net acres, 70% Liquids
- 3,220 gross locations, avg. 8,400 ft. lateral length
- 2 BBoe net unrisked resources
- 79% Avg. WI

DJ Basin Average Operator EUR vs. Liquids %



NBL 30

Anadarko EnerCom Presentation August 2016

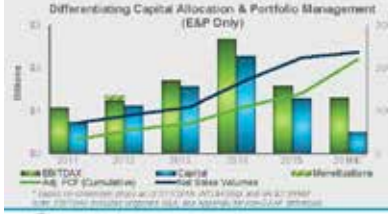
DJ Basin: World-Class Asset

- 1.5+ BBOE Net Resources
  - ~4,000 Identified Drilling Locations
- Leveraging Competitive Advantages
  - Minerals-Interest Ownership
  - Infrastructure in Place

2016 PLANNED OPERATED ACTIVITY		
RIGS	WELLS SPUD	FINAL COMPS
1+	~100	1+

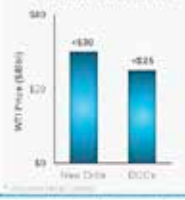
CONSOLIDATED CORE ACREAGE WITH MINERALS-INTEREST UPLIFT

Differentiating Capital Allocation & Portfolio Management (E&P Only)



Enhancing Margins through Capital Efficiencies (SLE 4,000')

BTAX PV-10 Breakeven

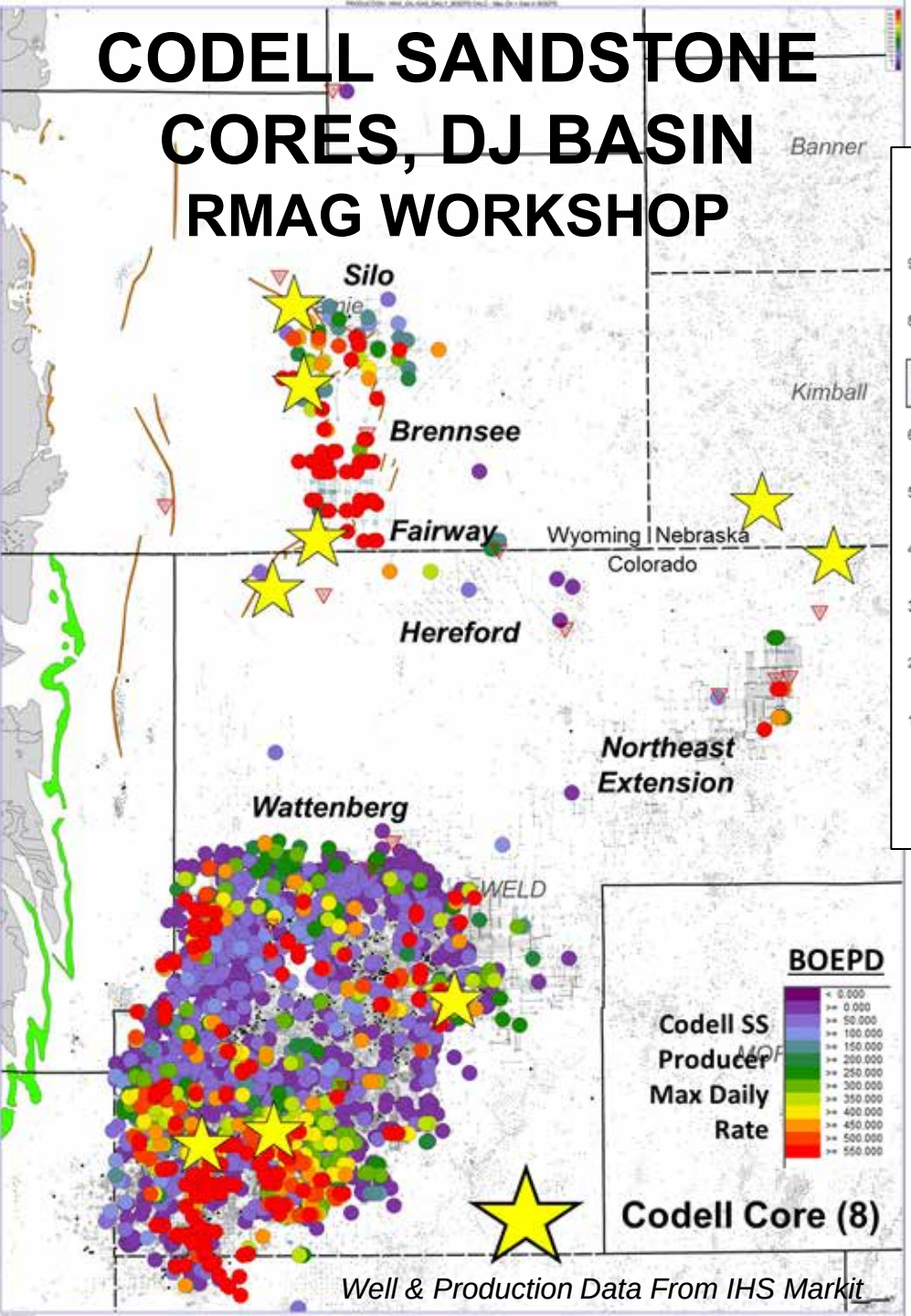


ANADARKO PETROLEUM CORPORATION

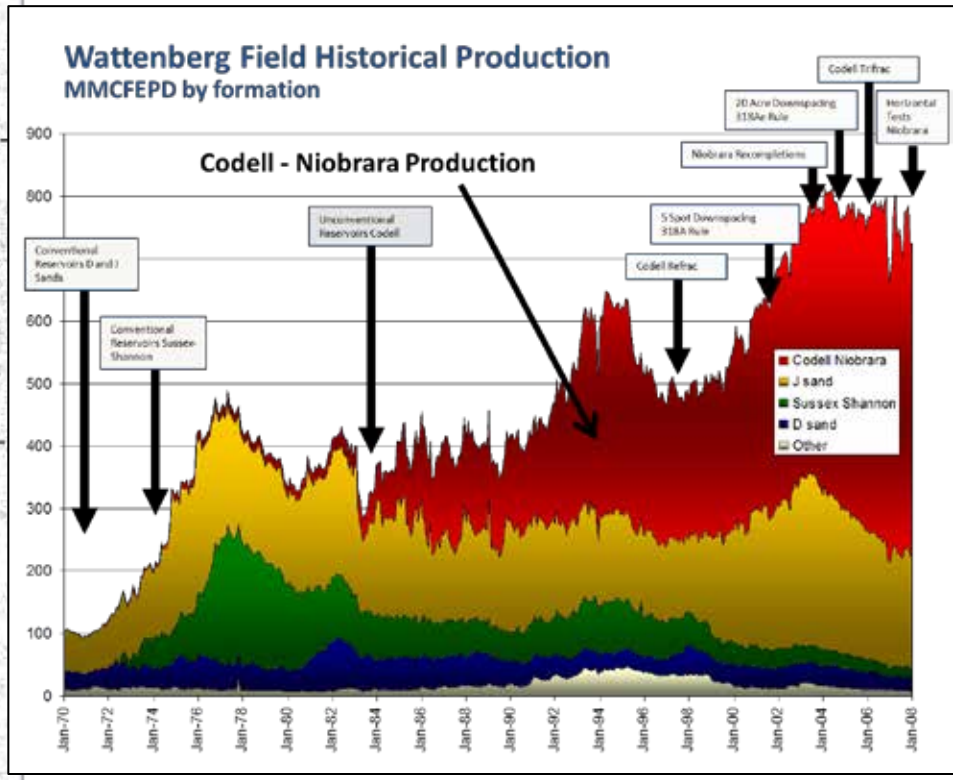
TIGHT OIL SANDSTONE RESERVOIRS
Cores & Plays on Display

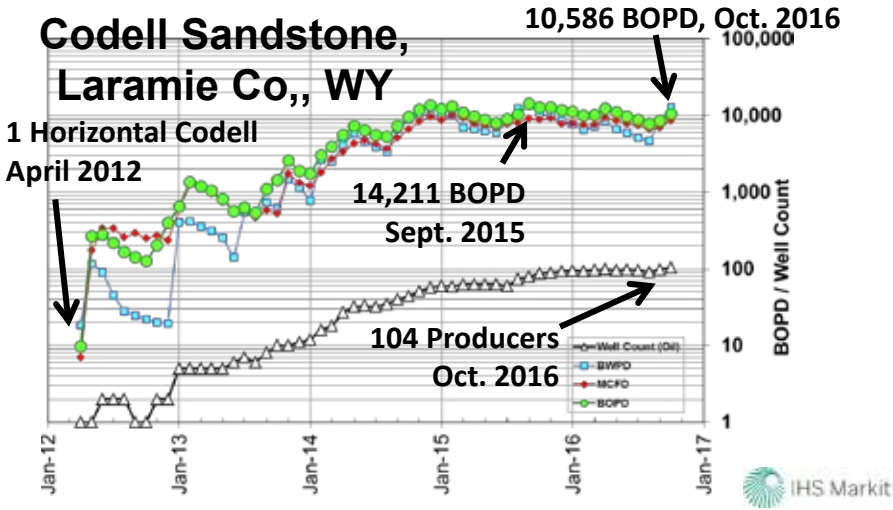
- **Powder River Basin**
  - **Sussex Sandstone – Compare Tight Oil Play vs Conventional Play**
  - **Shannon Sandstone**
  - **Turner Sandstone**
  - **Frontier (Wall Creek) Sandstone**
  - **Parkman Sandstone**
- **DJ Basin**
  - **Codell Sandstone**

CODELL SANDSTONE CORES, DJ BASIN
RMAG WORKSHOP



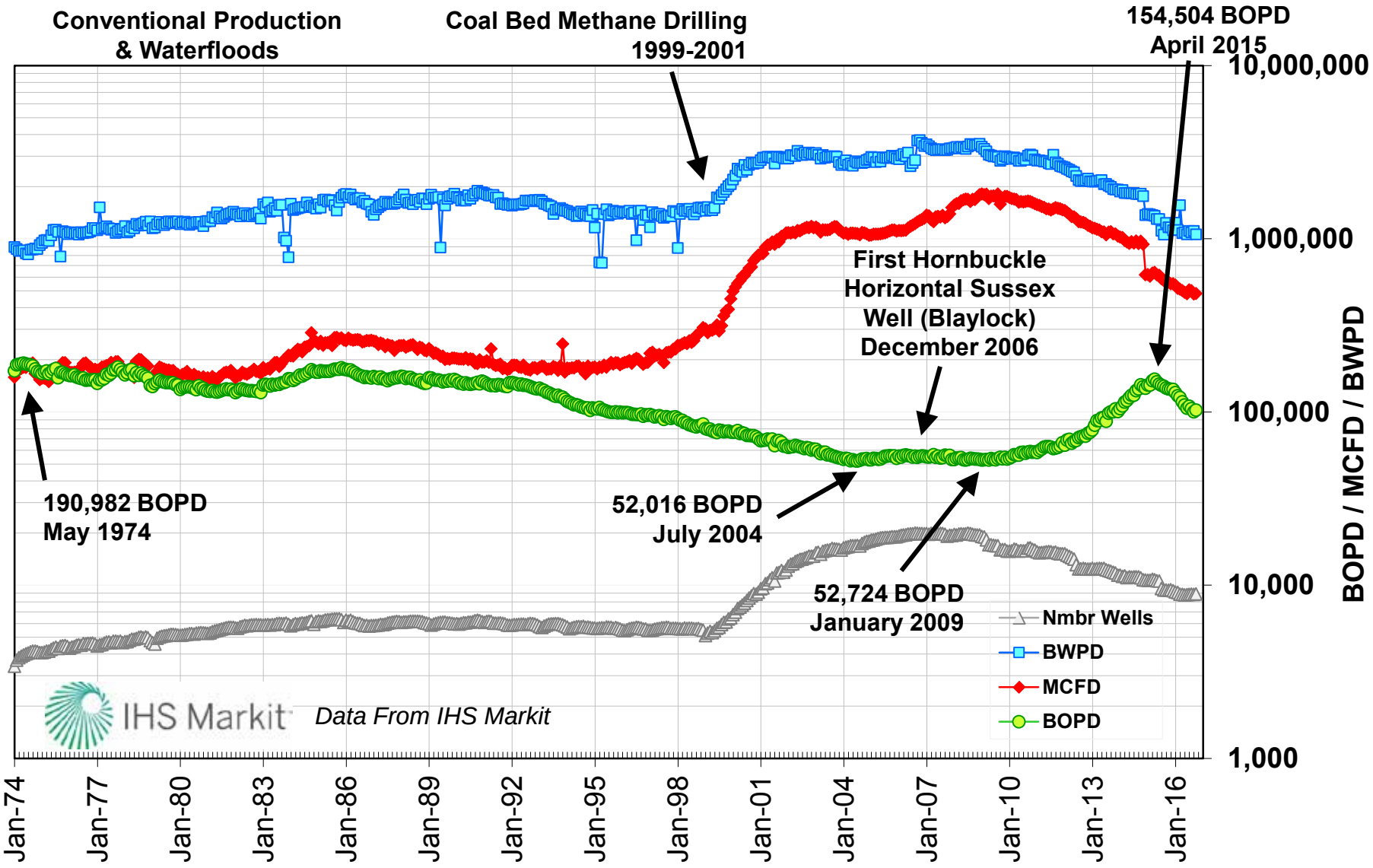
Codell Sandstone – Where it all Started?



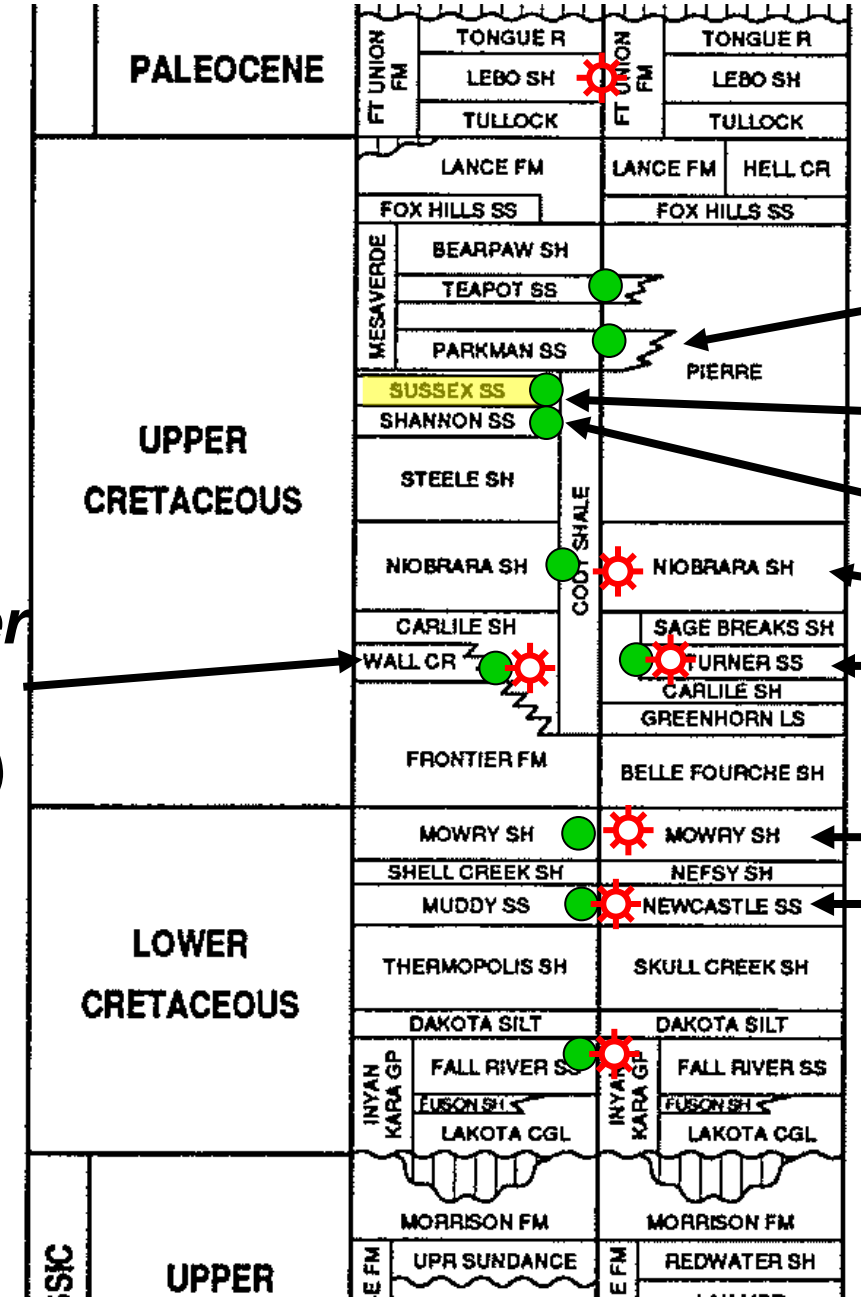


TOTAL PRODUCTION

Powder River Basin, Wyoming, 1974 - 2017



POWDER RIVER BASIN STRATIGRAPHIC CHART
Tight Oil Plays



Parkman SS

Sussex Sandstone

Shannon Sandstone

Niobrara "Shale"

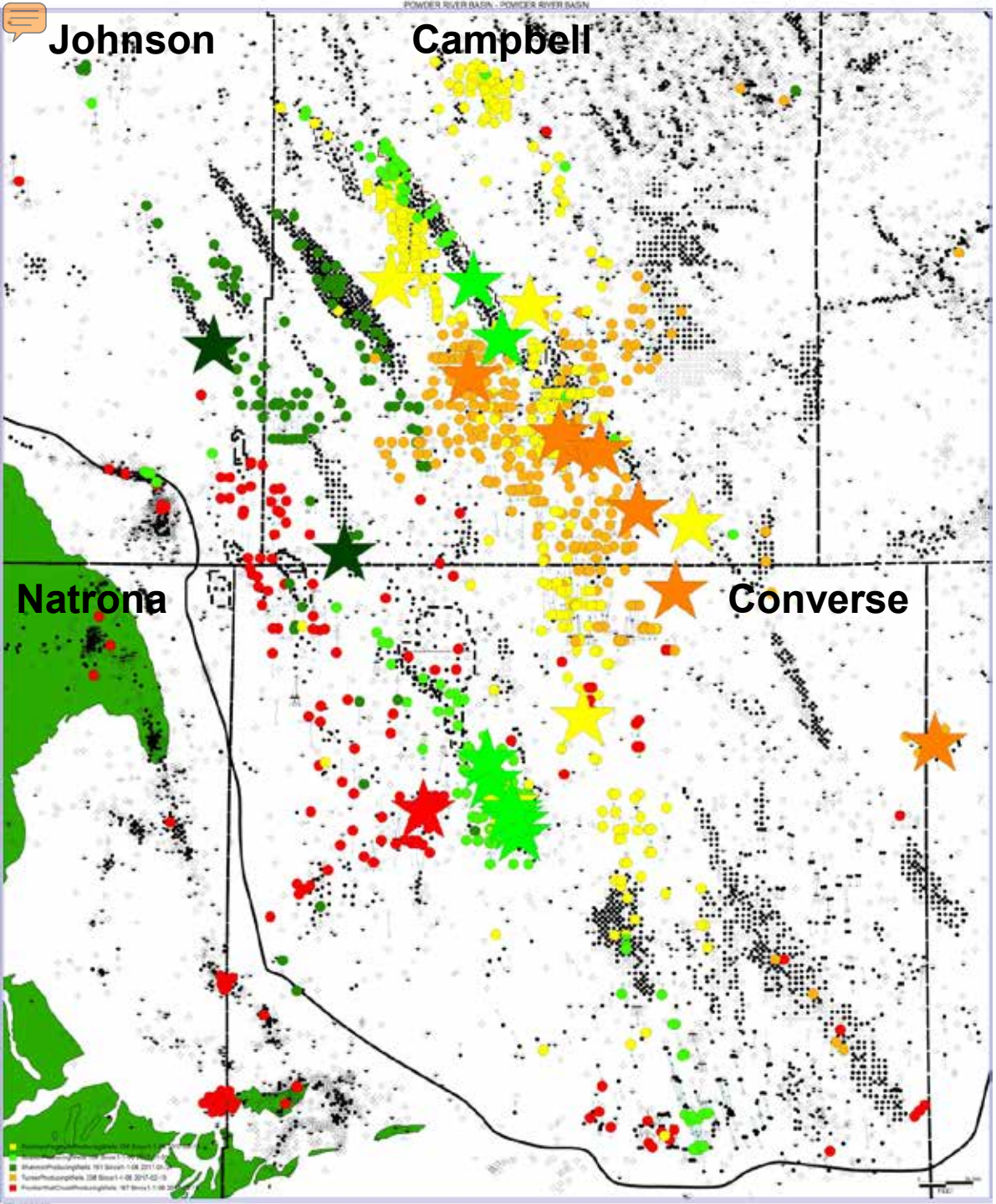
Turner Sandstone

Frontier (Wall Creek) SS

Mowry "Shale"

Muddy Sandstone

After Heasler et al. (1994)



WORKSHOP CORES

Powder River Basin, Wyoming

Tight Oil Sandstone Wells Drilled After Jan. 1, 2006

Parkman (5)

Sussex (8)

Shannon (2)

Turner (7)

Frontier (1)

IHS Markit

Well & Production Data From IHS Markit

TIGHT OIL SANDSTONE RESERVOIRS

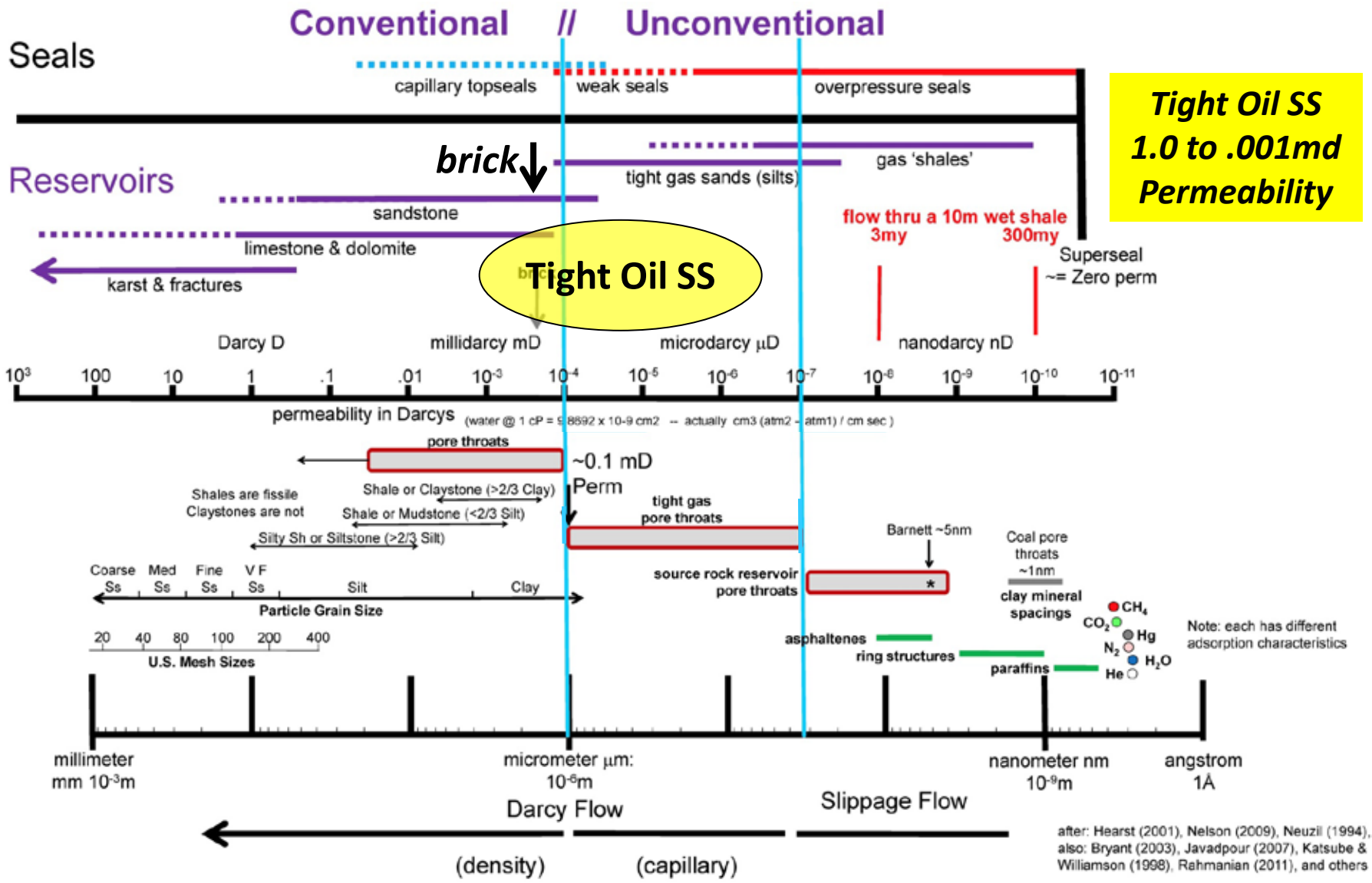
Since Mid-2015 AAPG Core Workshop (1½ Years - Low Oil Prices)

- **115 New Parkman Wells**
- **87 New Turner Wells**
- **55 New Frontier Wells**
- **47 New Shannon Wells**
- **29 New Sussex Wells**

- **54 New Codell Wells in Laramie Co, WY**

Tight Oil vs Shale Oil vs Conventional Oil

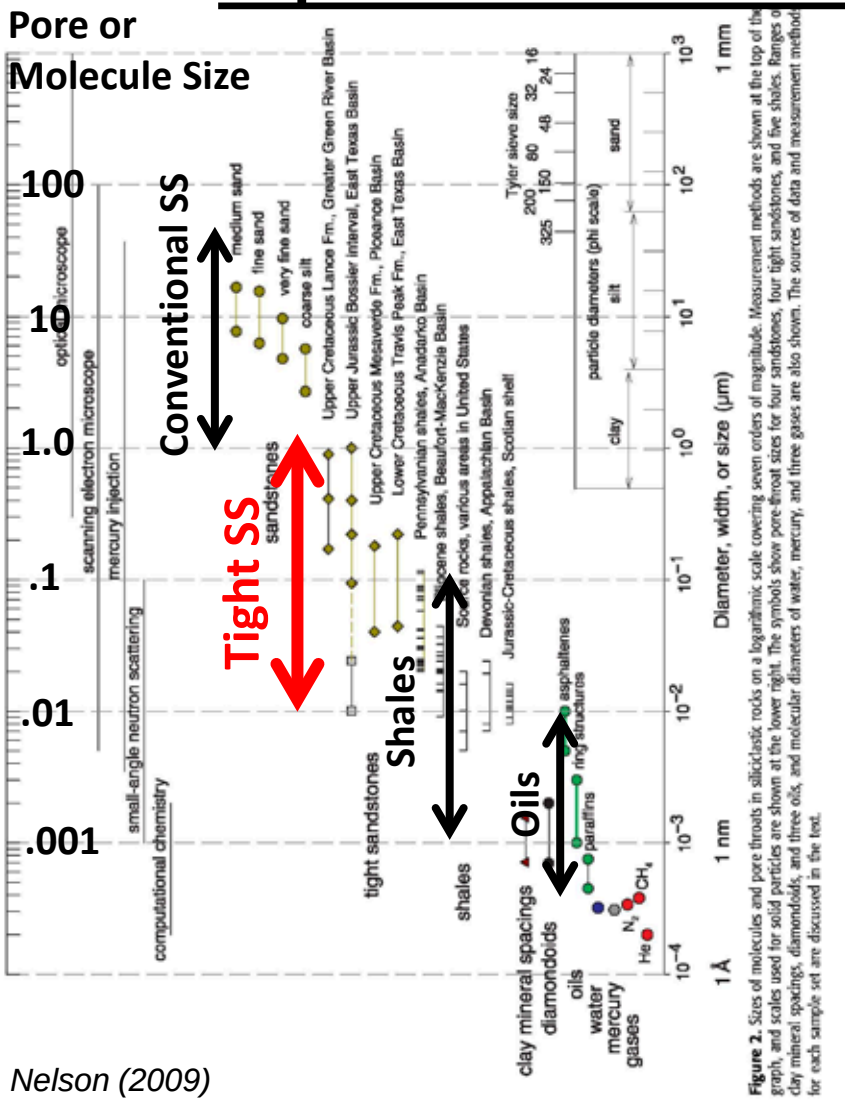
Permeability & Pore Throat Sizes



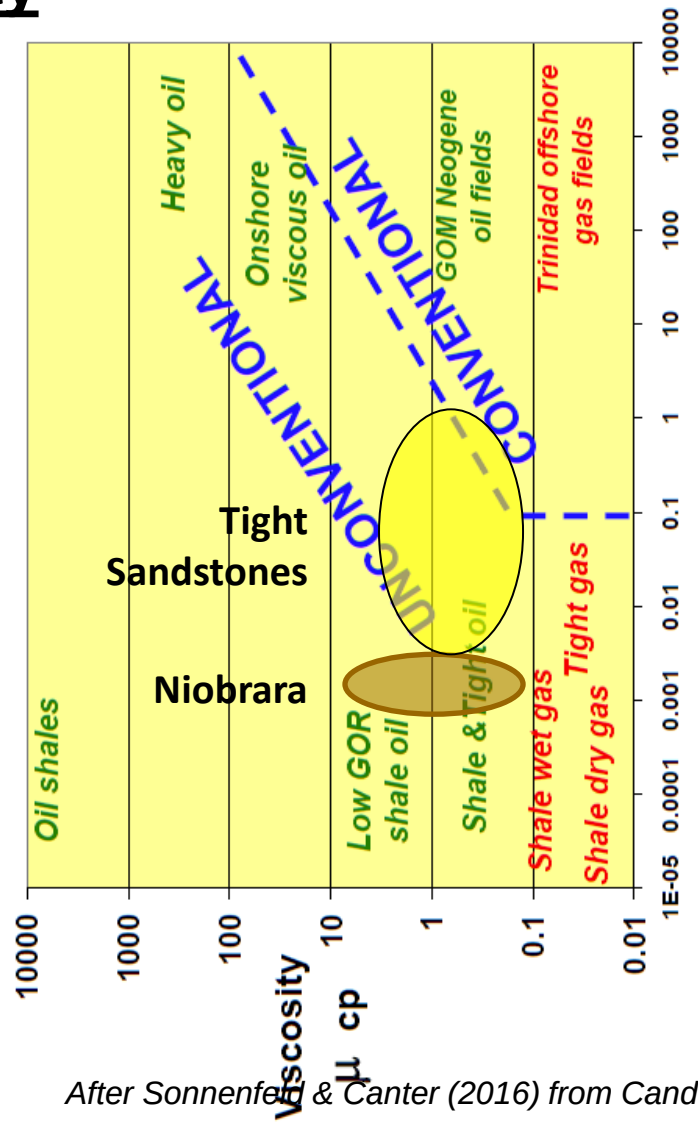
After Williams (2012) AAPG Search & Discovery #40935

Tight Oil vs Shale Oil vs Conventional Oil

- **Pore Throat Sizes & Permeability**
- **Independent of Porosity**
- **Importance of Oil Viscosity**



Nelson (2009)



After Sonnenfeld & Canter (2016) from Cander (2012)

TIGHT OIL SANDSTONE RESERVOIRS
What Should I Look For?

- **What do these plays have in common?**
- **Are there any differences between the plays and/or reservoirs?**
- **Are they all really “tight”?**
- **Does each Formation have one or multiple play types?**
- **How can we identify oil-saturated tight oil sandstones early in the play?**
- **How can we explore for these?**

Shallow Marine Depositional Processes & Facies Overview

Gus Gustason

SUSSEX AND SHANNON SANDSTONES, POWDER RIVER BASIN

SUSSEX OIL PLAY, POWDER RIVER BASIN HISTORY

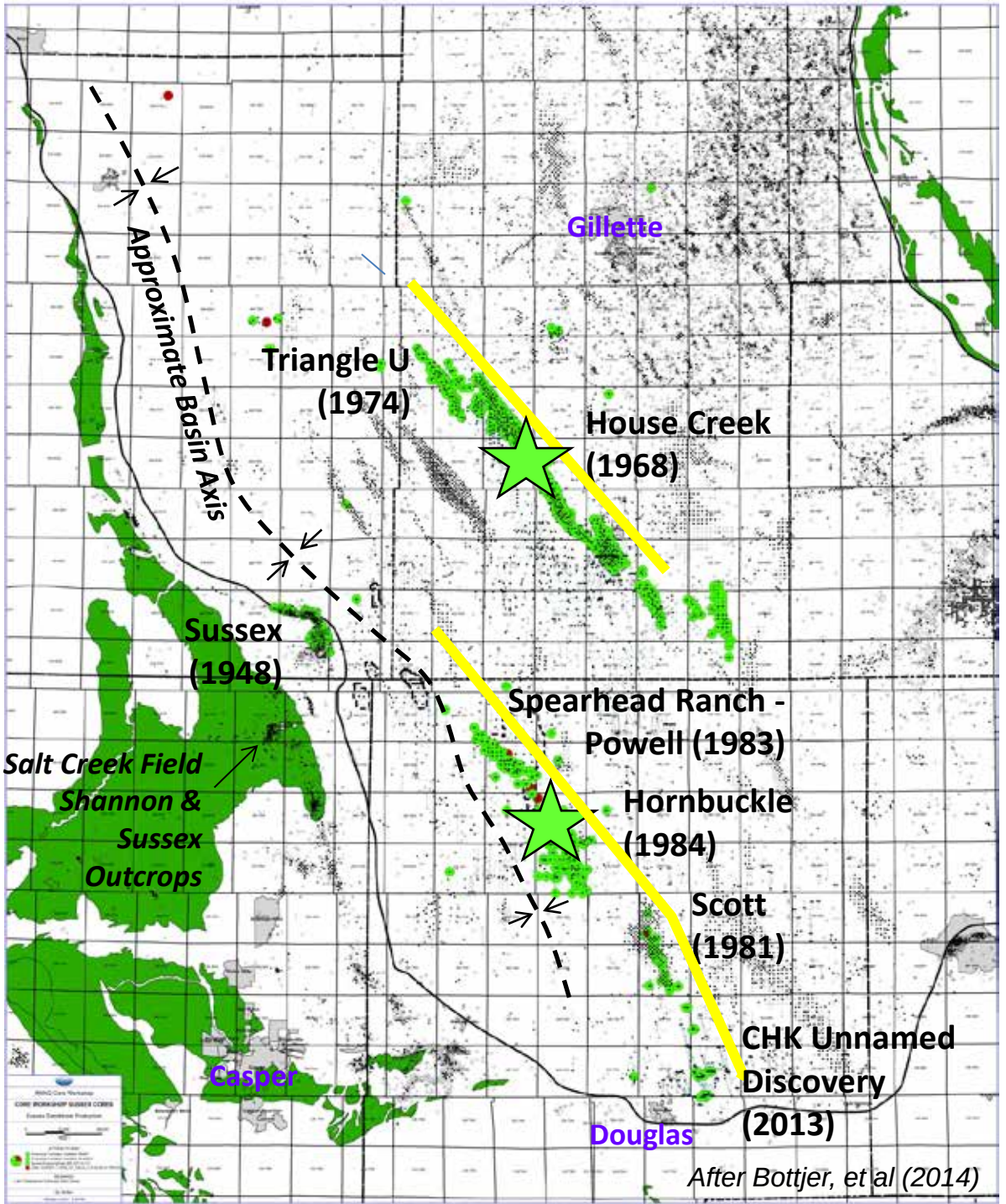
- **Vertical Play – Exploration for "Bars"**
  - **House Creek Discovered 1968**
  - **Development and Exploration 1968-1970s**
  - **House Creek Waterflood Initiated 1992**
- **Horizontal Drilling, Pre-Stimulations**
  - **Apache – 2 Wells at Triangle U Field 1994 & 1997**
- **Vertical Extensions**
  - **Exploration for Deeper Targets (Muddy) Led to Discovery of Scott (1981), Spearhead Ranch (1983), & Hornbuckle (1984)**
  - **Considered Isolated Fields**
  - **Hornbuckle Extension/Development Drilling 1993-1994**
- **Modern Horizontal Drilling & Completions**

SUSSEX OIL PRODUCTION

Powder River Basin

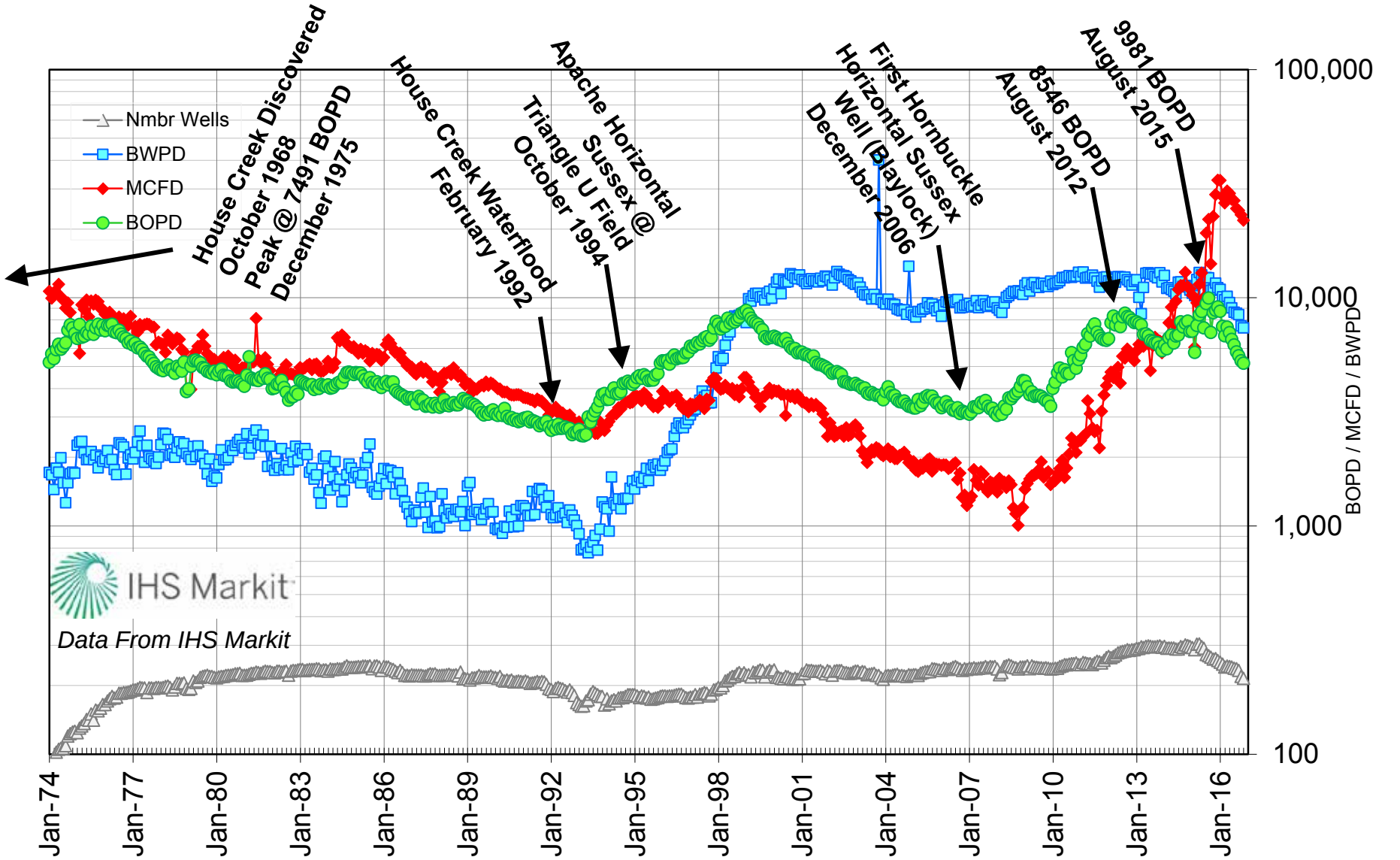
FIELD	DISCOVERY YEAR	OIL CUM MBO (as of 8-13)
Sussex	1948	7,573
Meadow Creek	1950	7,491
House Creek / House Creek	1968	41,008
Payne	1969	2,845
Porcupine	1972	2,367
Triangle U / Triangle U East	1974	4,961
House Creek West	1976	736
Scott	1981	1,531
Spearhead Ranch & Powell	1983	2,582
Hornbuckle	1984	8,714
Total - ALL SUSSEX WELLS		80,756

Well & Production data from I.H.S. Energy



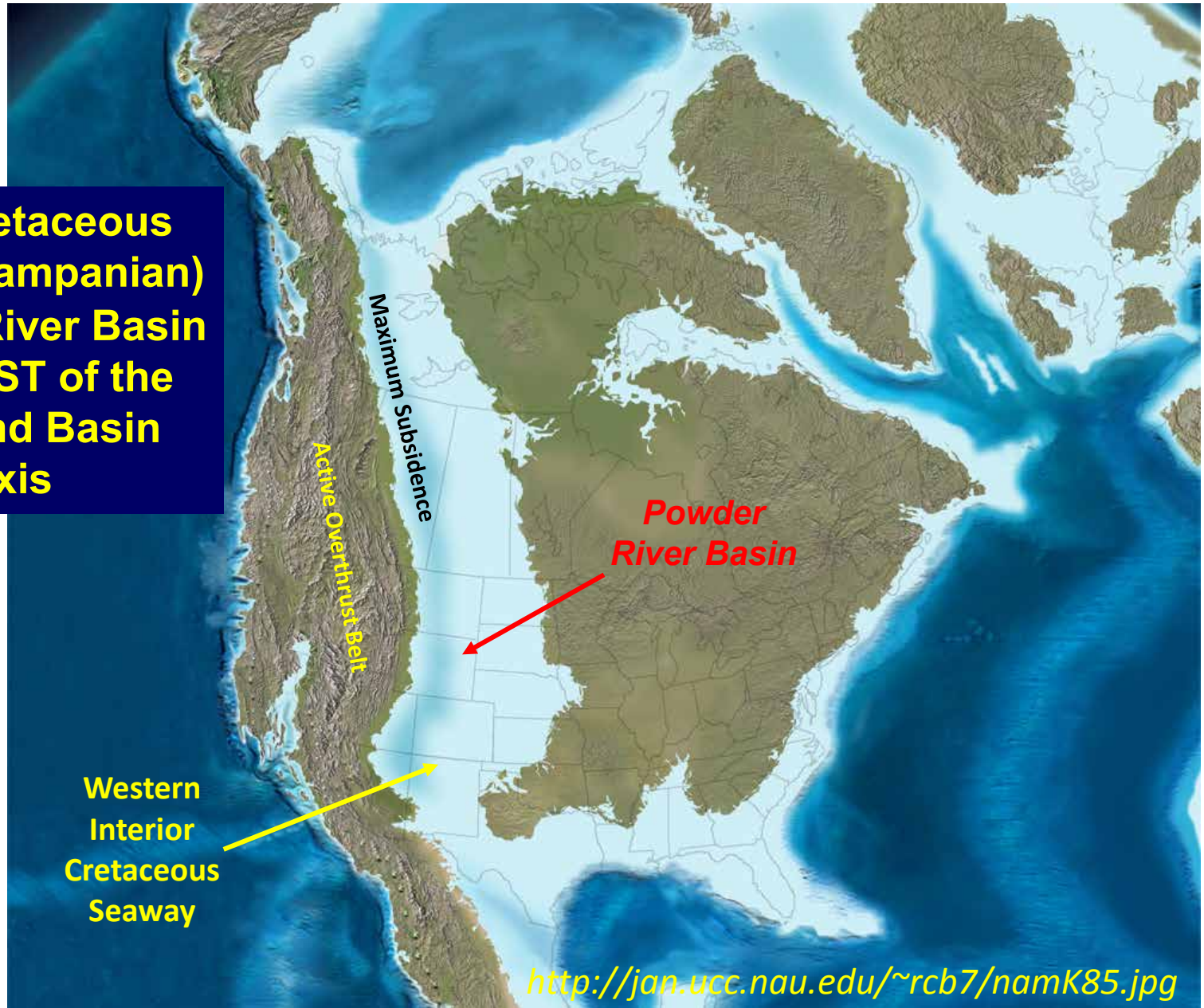
SUSSEX SANDSTONE PRODUCTION

Powder River Basin, Wyoming, 1974 - 2013



Late Cretaceous Paleogeography

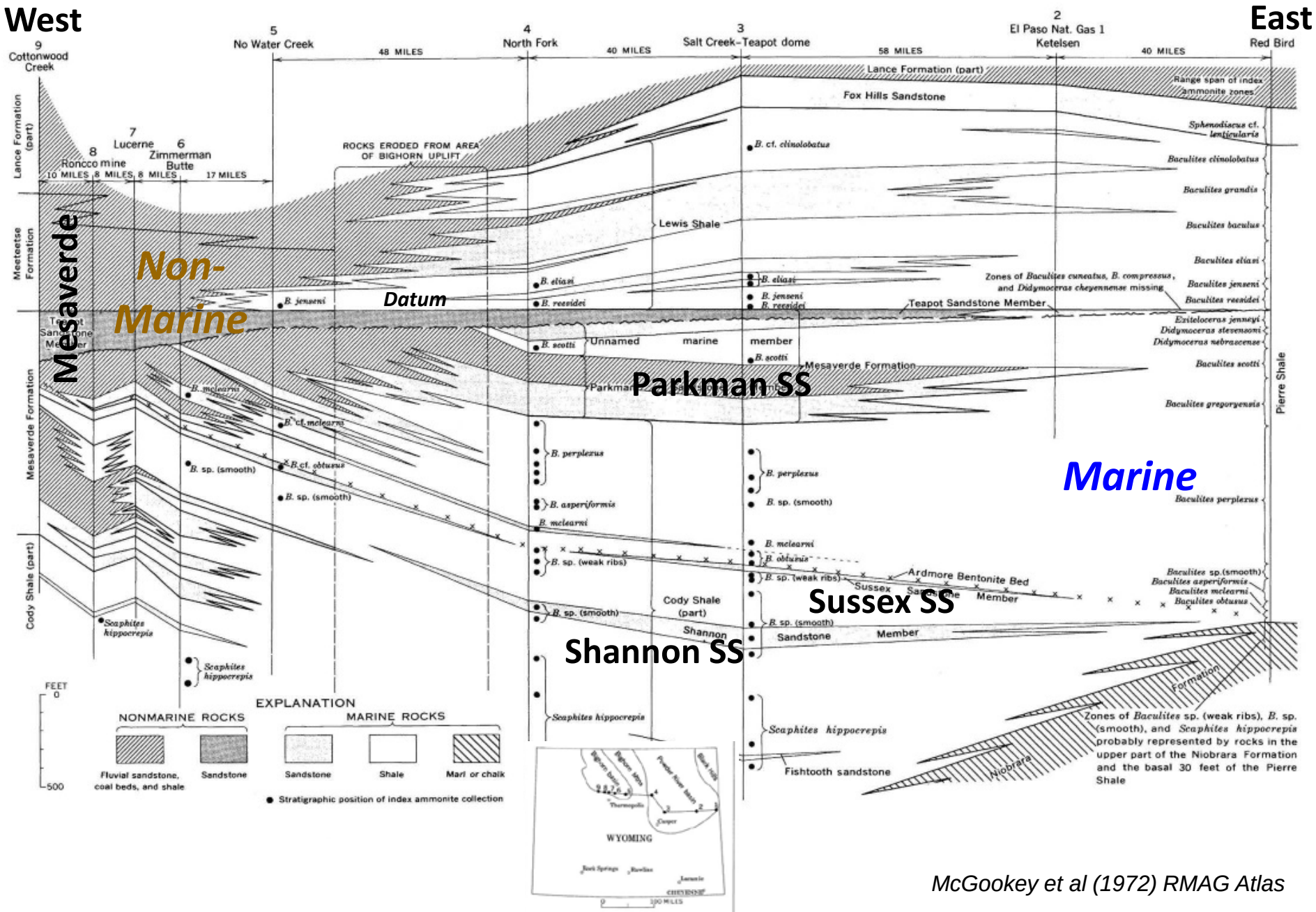
North America ~ 85 MYA (Blakey 2005)



Late Cretaceous (Lower Campanian) Powder River Basin was EAST of the Foreland Basin Axis

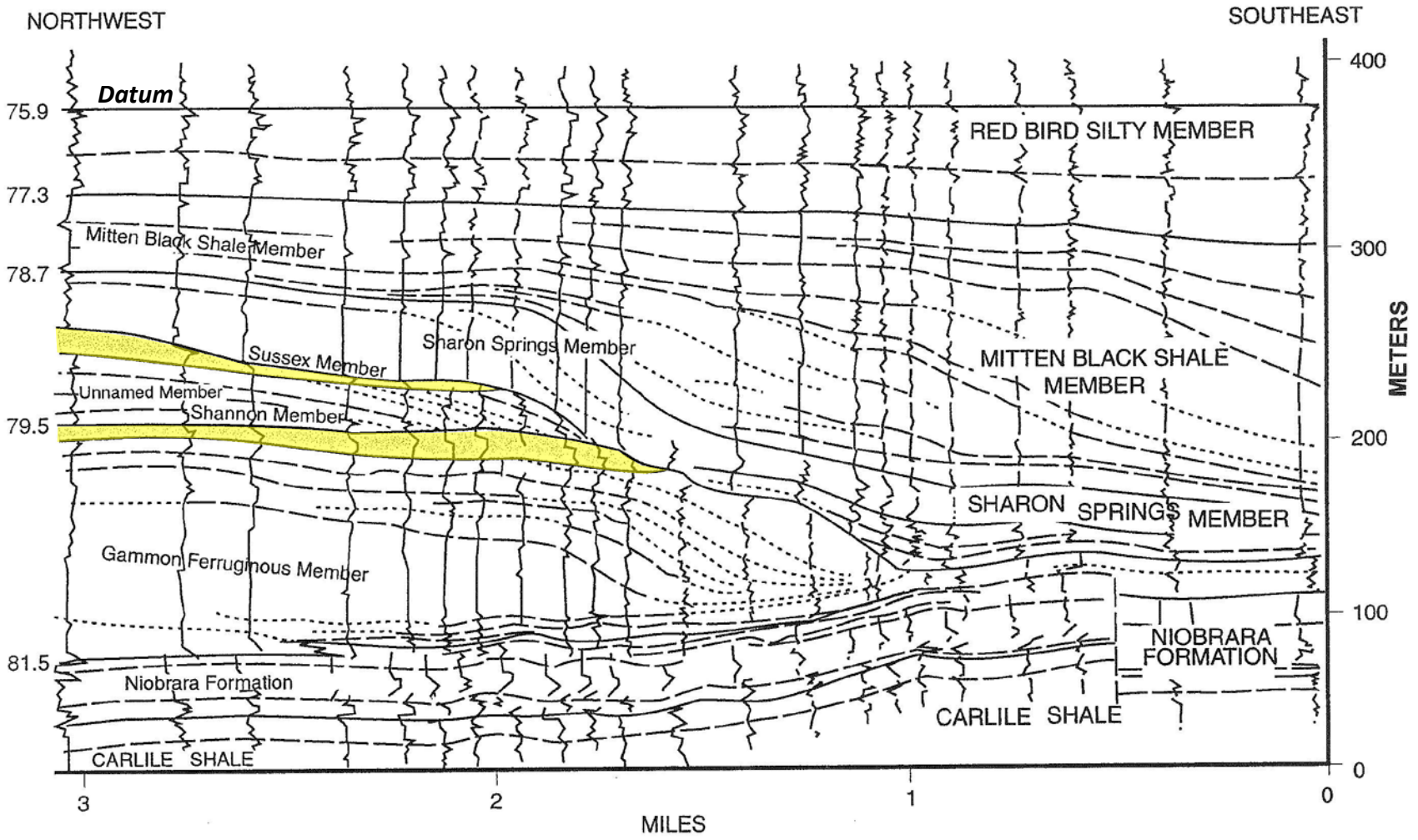
After Bottjer, et al (2014)

Big Horn to Powder River Basin Cretaceous Cross Section



McGookey et al (1972) RMAG Atlas

Powder River Basin Cretaceous Cross Section
Modified by Swift & Parsons (1999) from Asquith (1970)



Swift & Parsons (1999)

CAMPANIAN (SUSSEX-SHANNON) SCHEMATIC SEQUENCE STRATIGRAPHIC CHART
Northern Wyoming

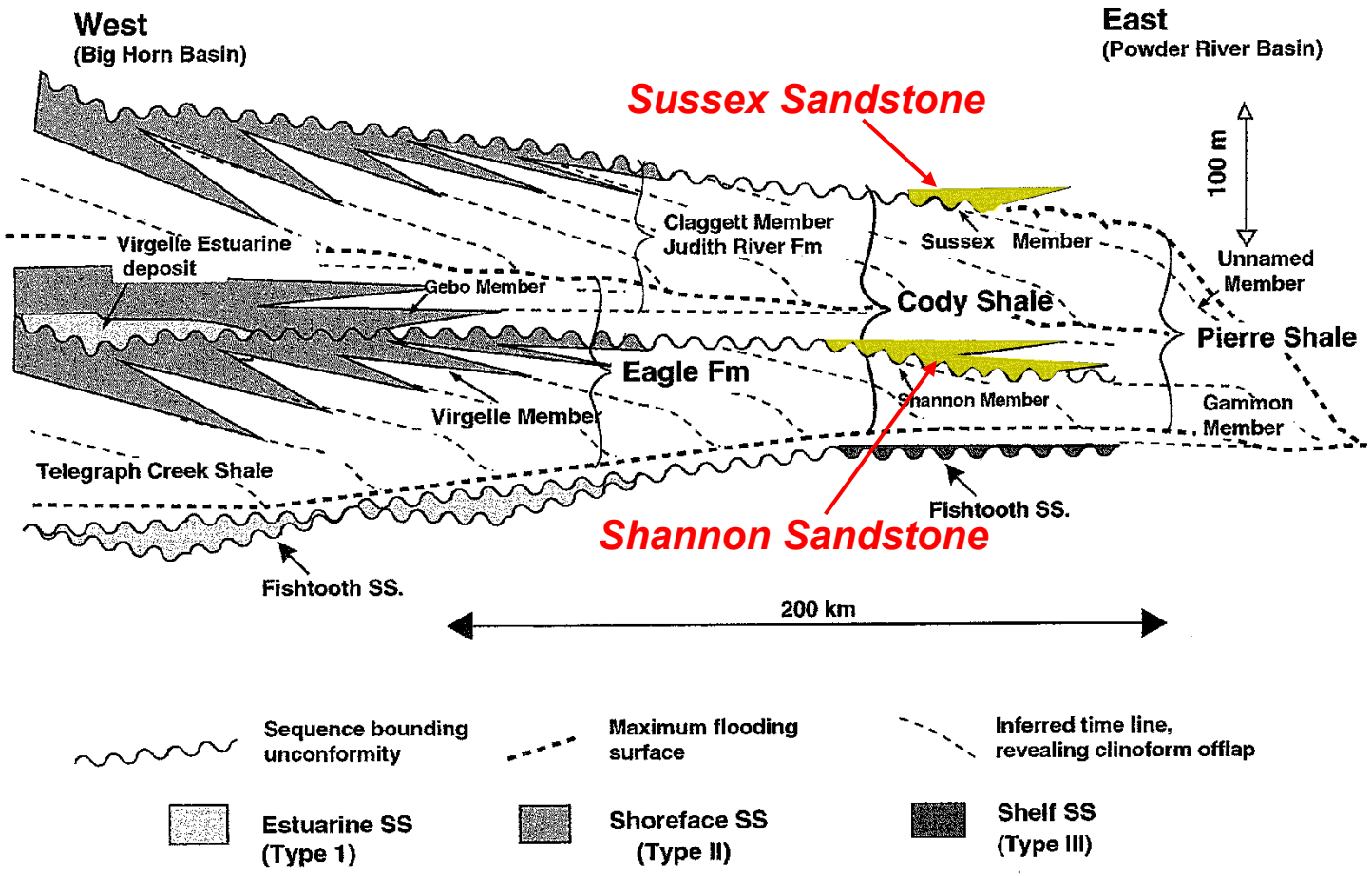
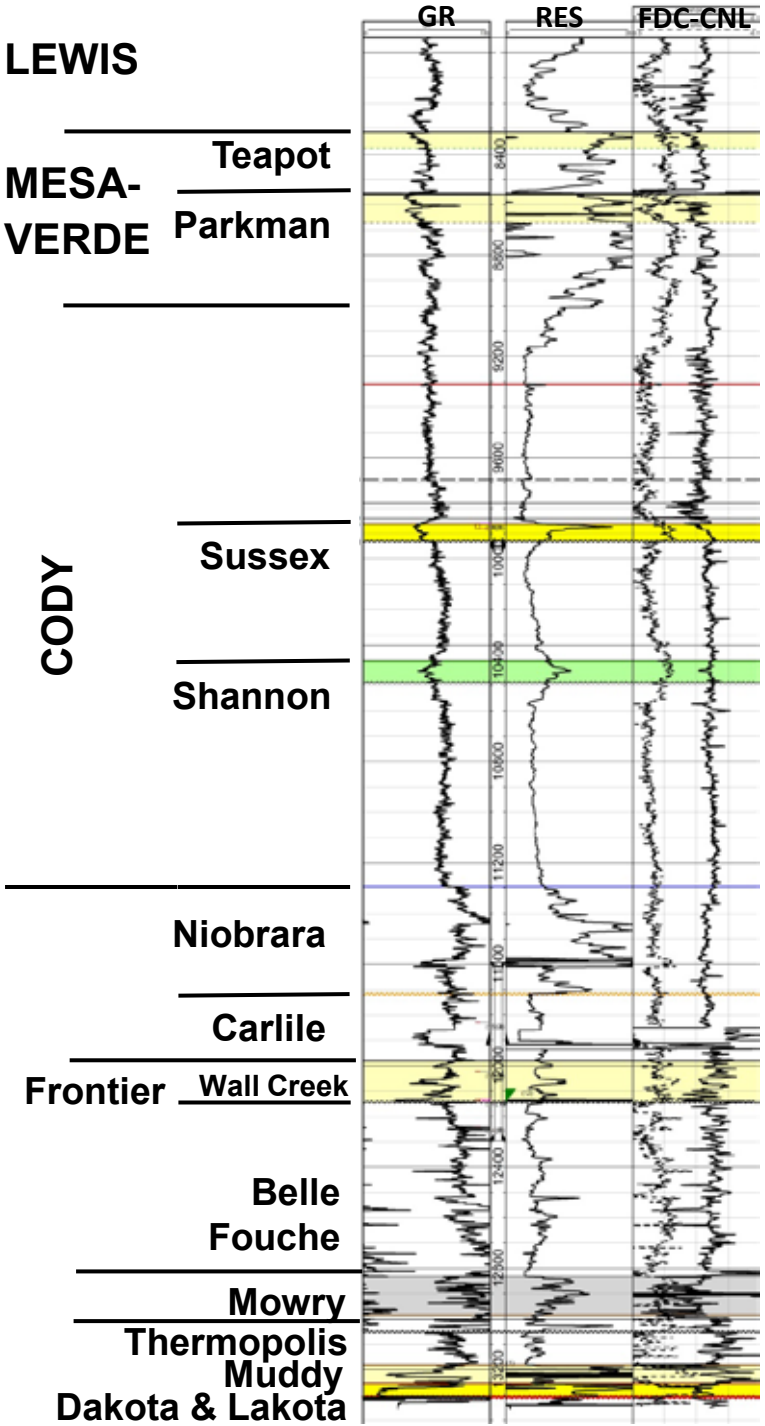


Fig. 4.—Sketch of recent modifications to Lower Campanian stratigraphy, Wyoming. R. Fitzsimmons and S. Johnson have resolved a Virgelle and a Claggett depositional sequence on the western margin of the basin, while Asquith (1970) has resolved the Lower Campanian epicontinental shelf edge and slope. See Fig. 2 for location. Sketch is not to scale.

Swift & Parsons (1999)



TYPE LOG
HORNBUCKLE FIELD
Sussex Pool Discovery Well

LL & E
Federal #32-2
SW-NE-2-T37N-R73W
Converse Co., WY
Compl. 1-8-84

SUSSEX

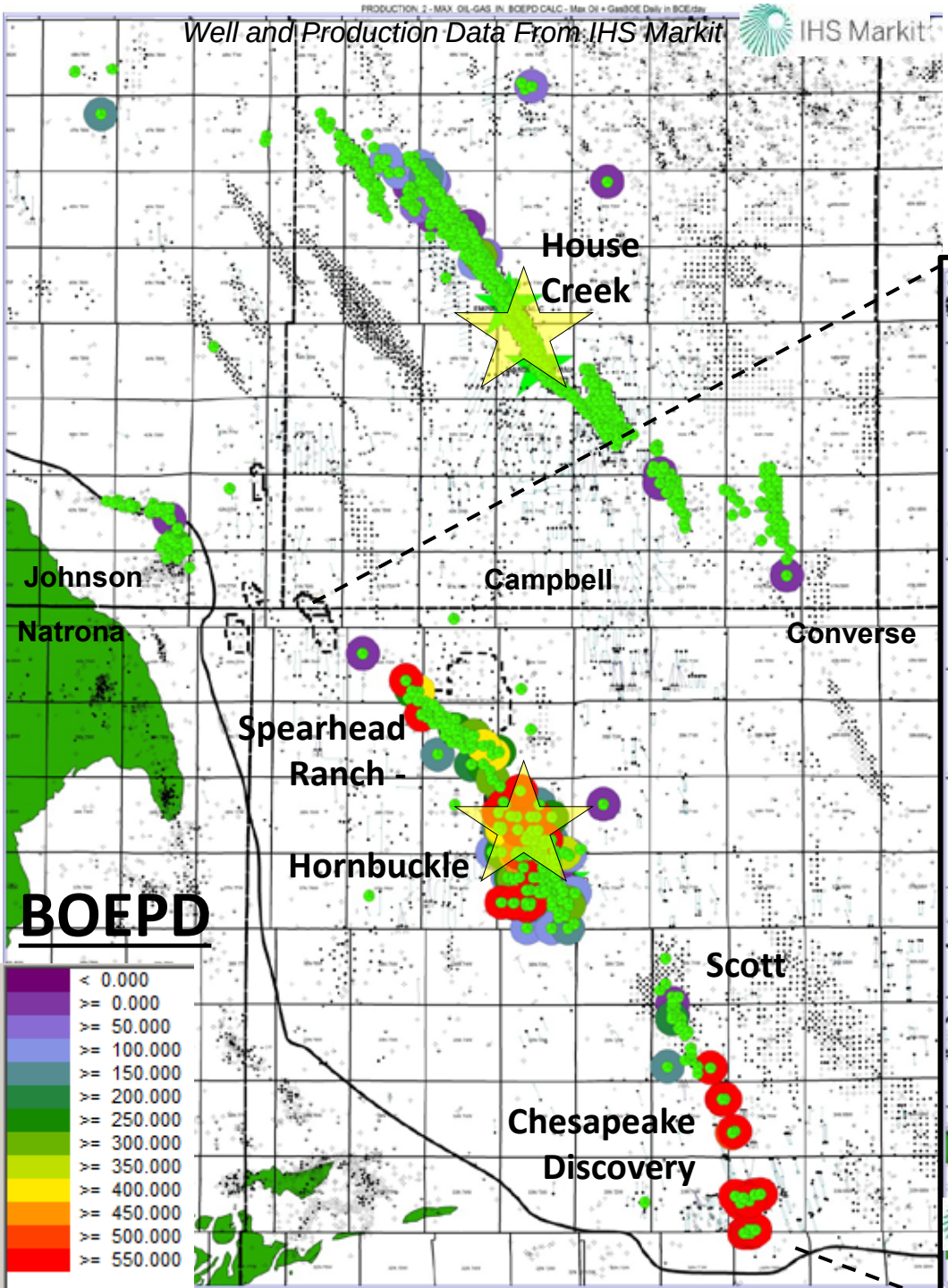
6 Cores @ Hornbuckle
2 Cores @ House Creek

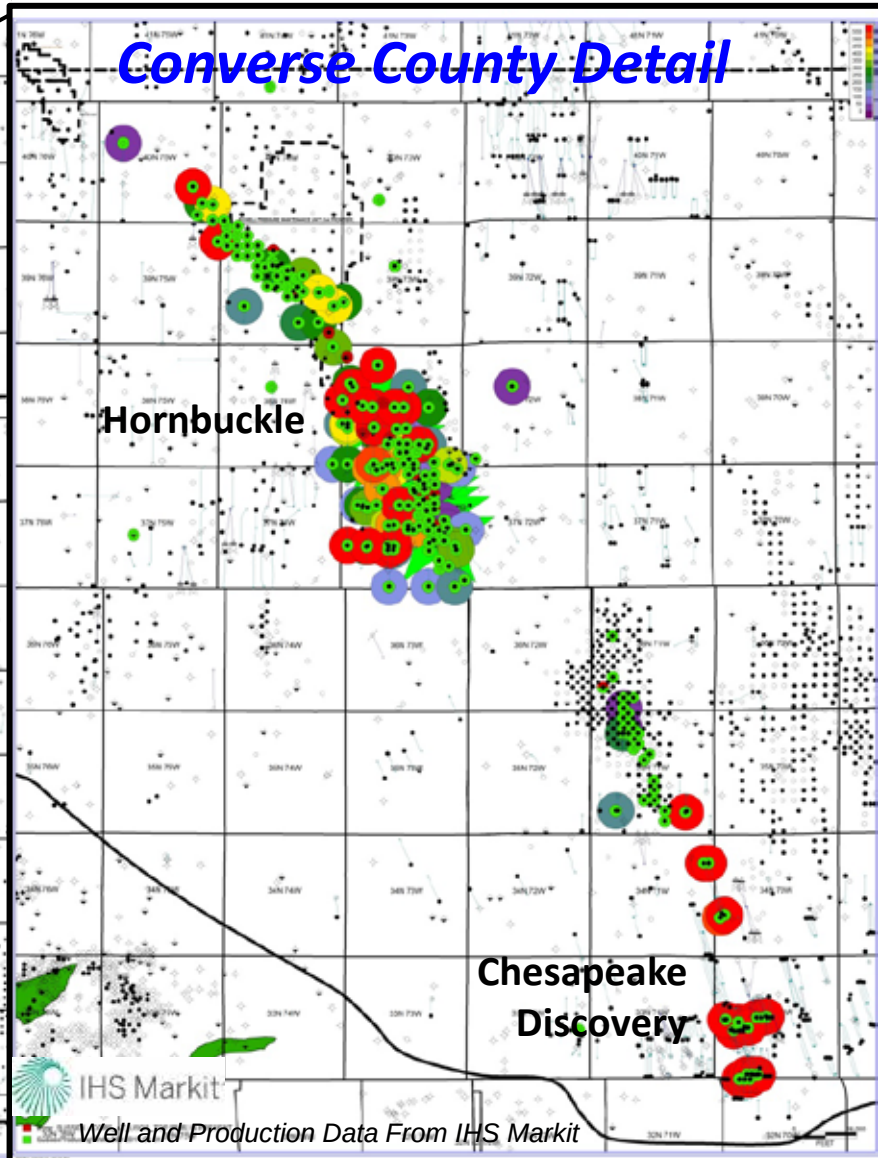
SHANNON

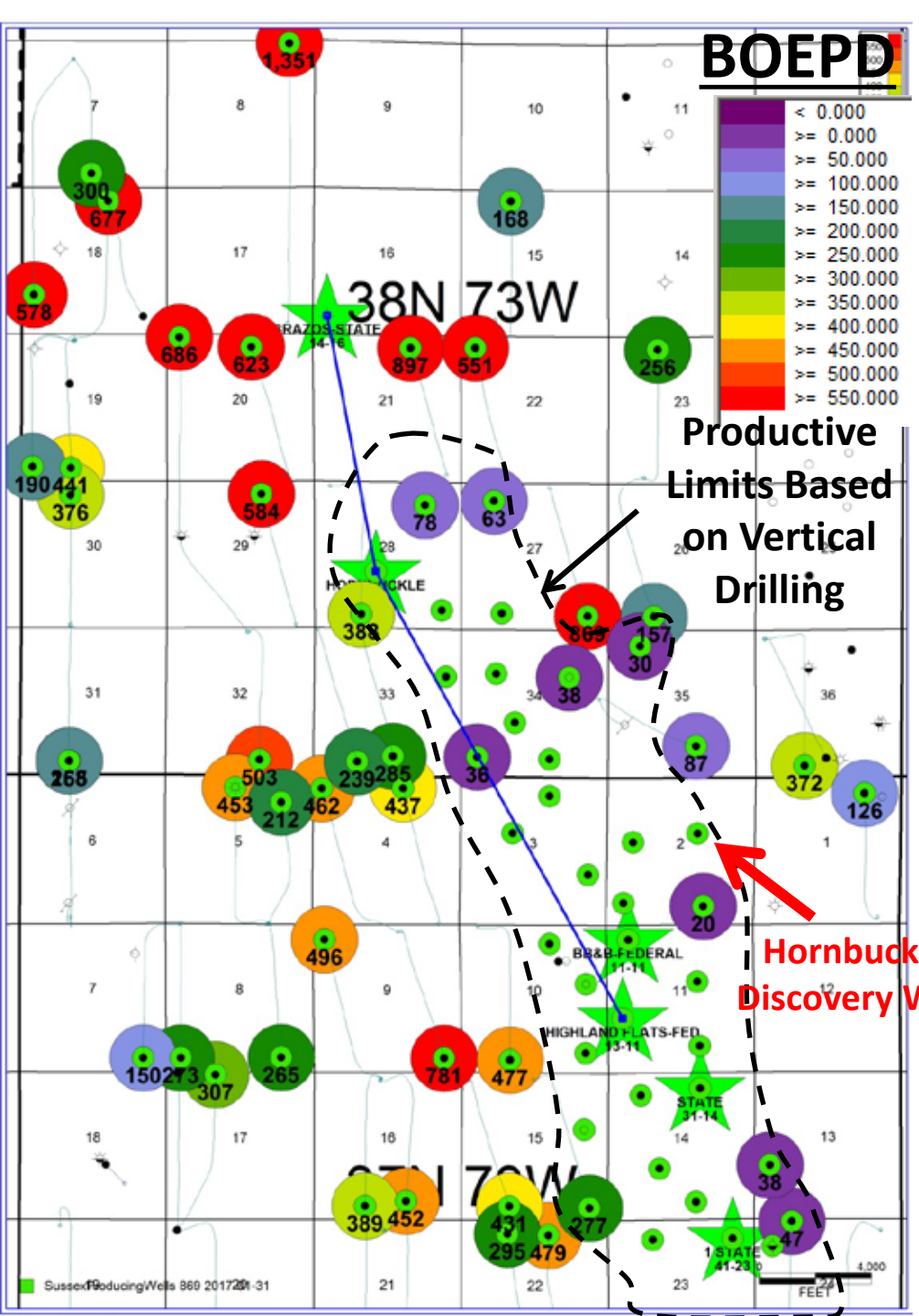
2 Cores

Sussex Horizontal Wells Drilled Since Jan. 1, 2006

Maximum Monthly Production in BOE/day







Hornbuckle Field Area

Sussex Cores (6)

Sussex Sandstone

Maximum Monthly Production in BOE/day

Wells Drilled After Jan. 1, 2006

Vertical Production Discovered 1984

- **Depth 10,000 – 10,500 Ft**
- **30-Day IPs 30-200 BOPD**
- **Long Well Life, Long-Term 2-6% Decline**
- **Overpressured to 0.61 psi/ft (DST)**
- **160 Acre Spacing, Wells Not Effectively Draining Spacing Units**
- **Few Dry Holes At Field Edges**

IHS Markit

Well and Production Data From IHS Markit

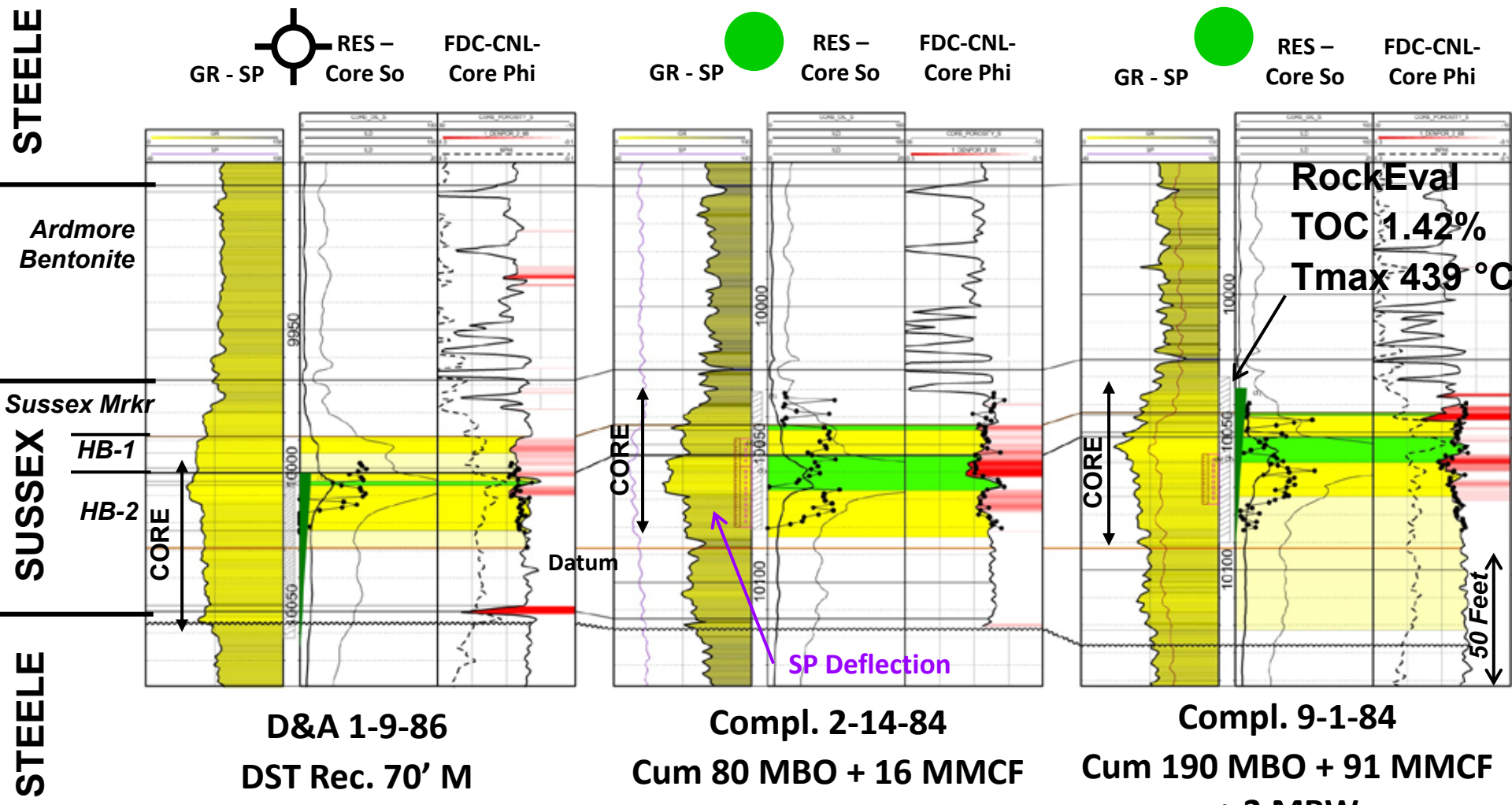
Hornbuckle Field Area – 3 Sussex Cores

HORNBUCKLE FIELD

LL & E
Brazos State #14-16
SW-SW-16-T38N-R73W

Woods Petroleum
Hornbuckle #28-1
NE-SW-28-T38N-R73W

LL & E
Highland Flats Federal #13-11
NW-SW-11-T37N-R73W

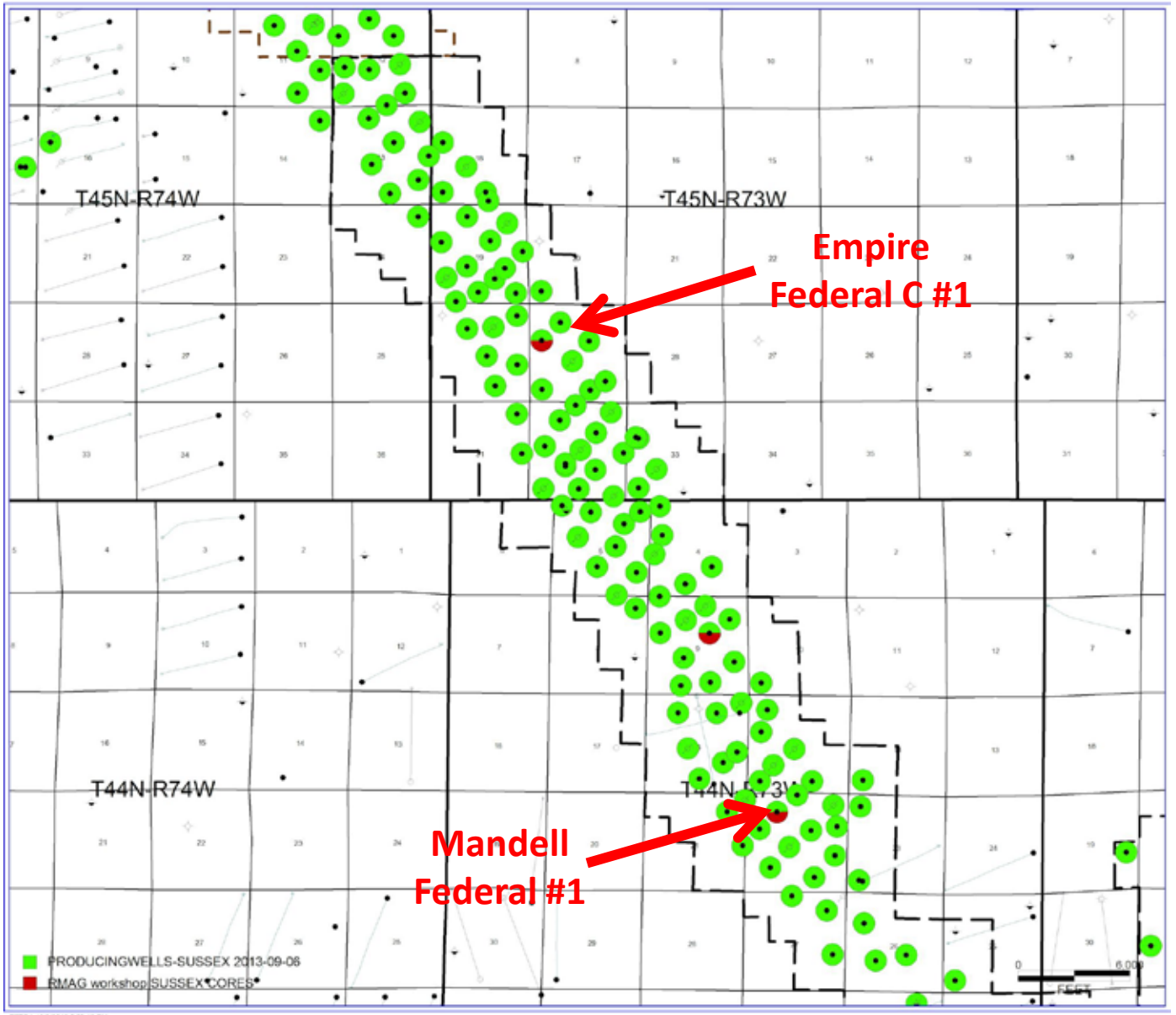


D&A 1-9-86
DST Rec. 70' M

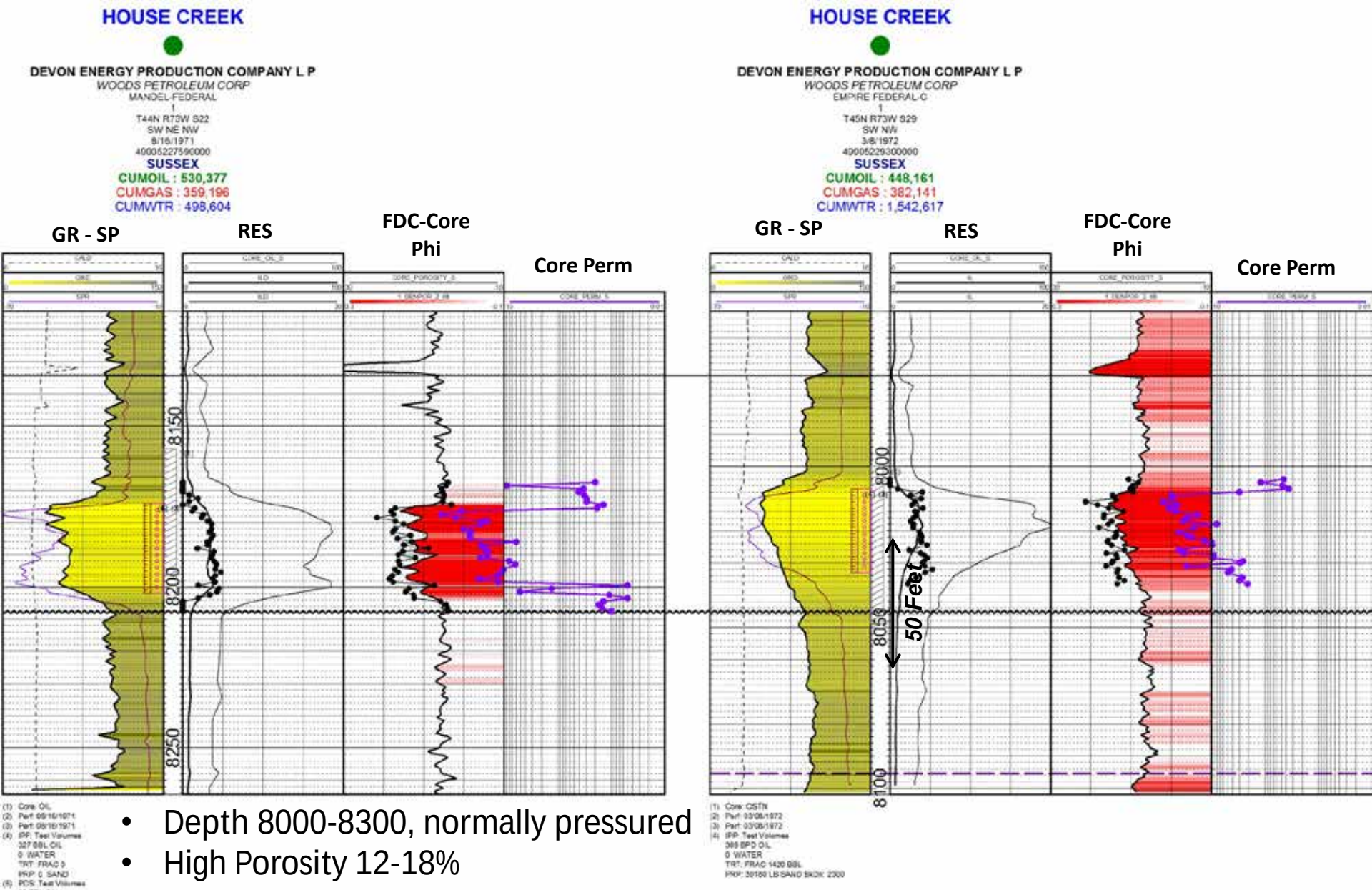
Compl. 2-14-84
Cum 80 MBO + 16 MMCF + 2 MBW

Compl. 9-1-84
Cum 190 MBO + 91 MMCF + 3 MBW

Central House Creek Field
Core Wells Studied



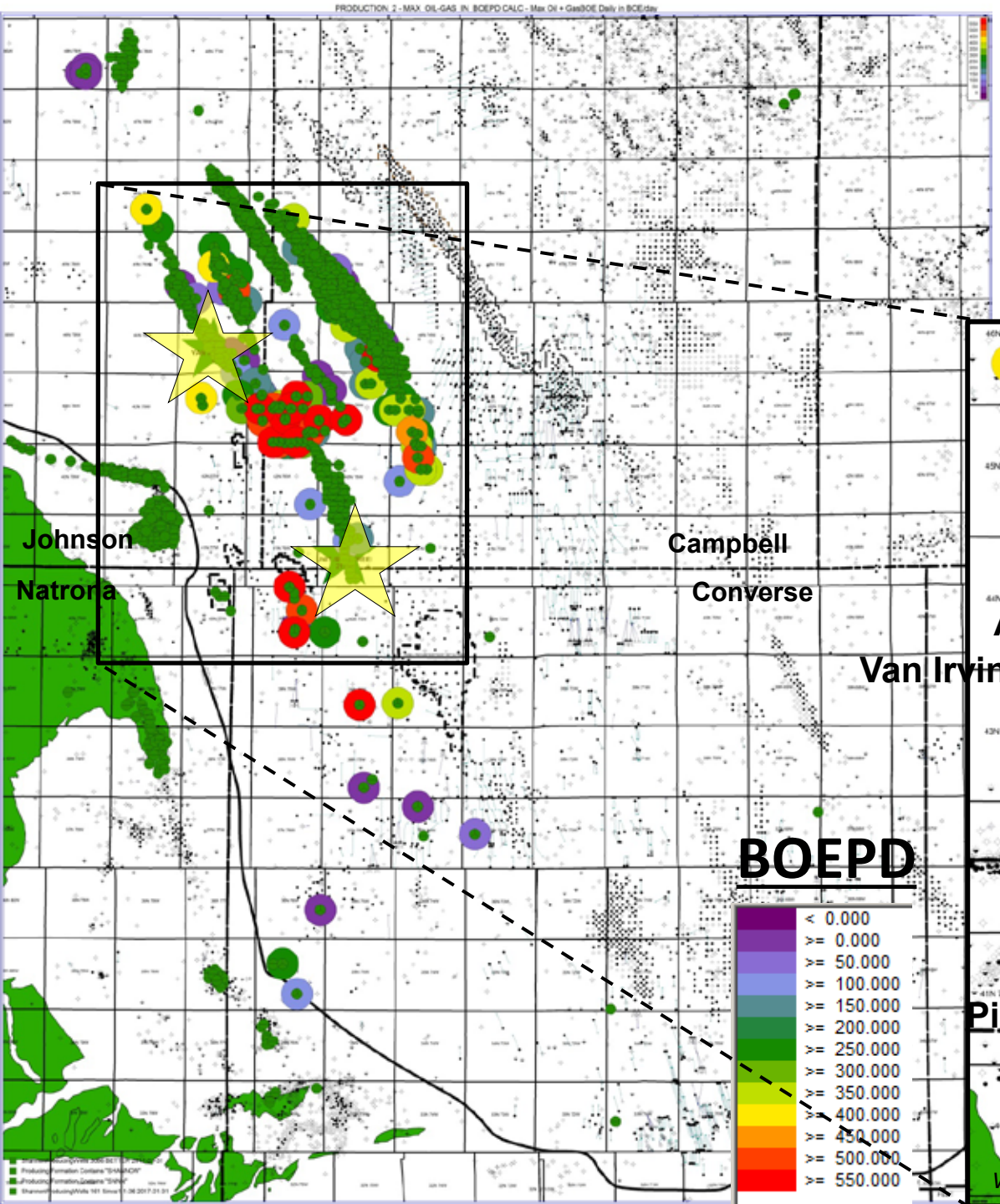
House Creek Field – 2 Sussex Cores

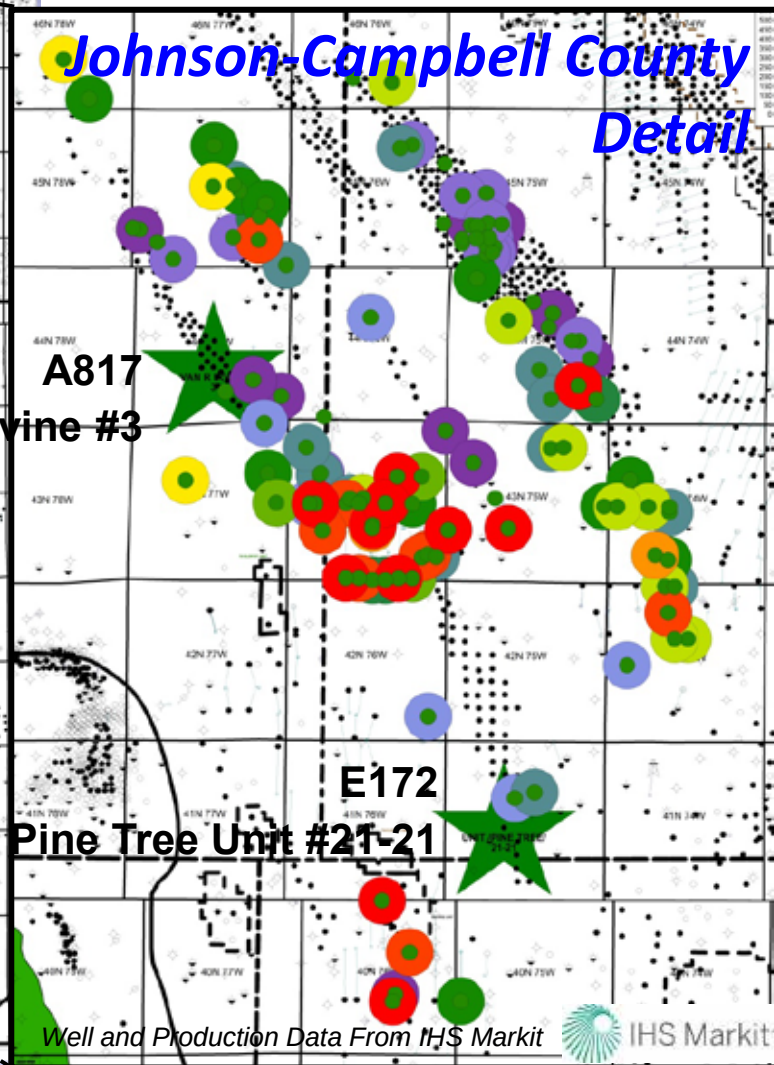


- Depth 8000-8300, normally pressured
- High Porosity 12-18%
- 2.68 gm/cc matrix underestimates core porosity

Shannon Horizontal Wells Maximum Monthly Production in BOE/day

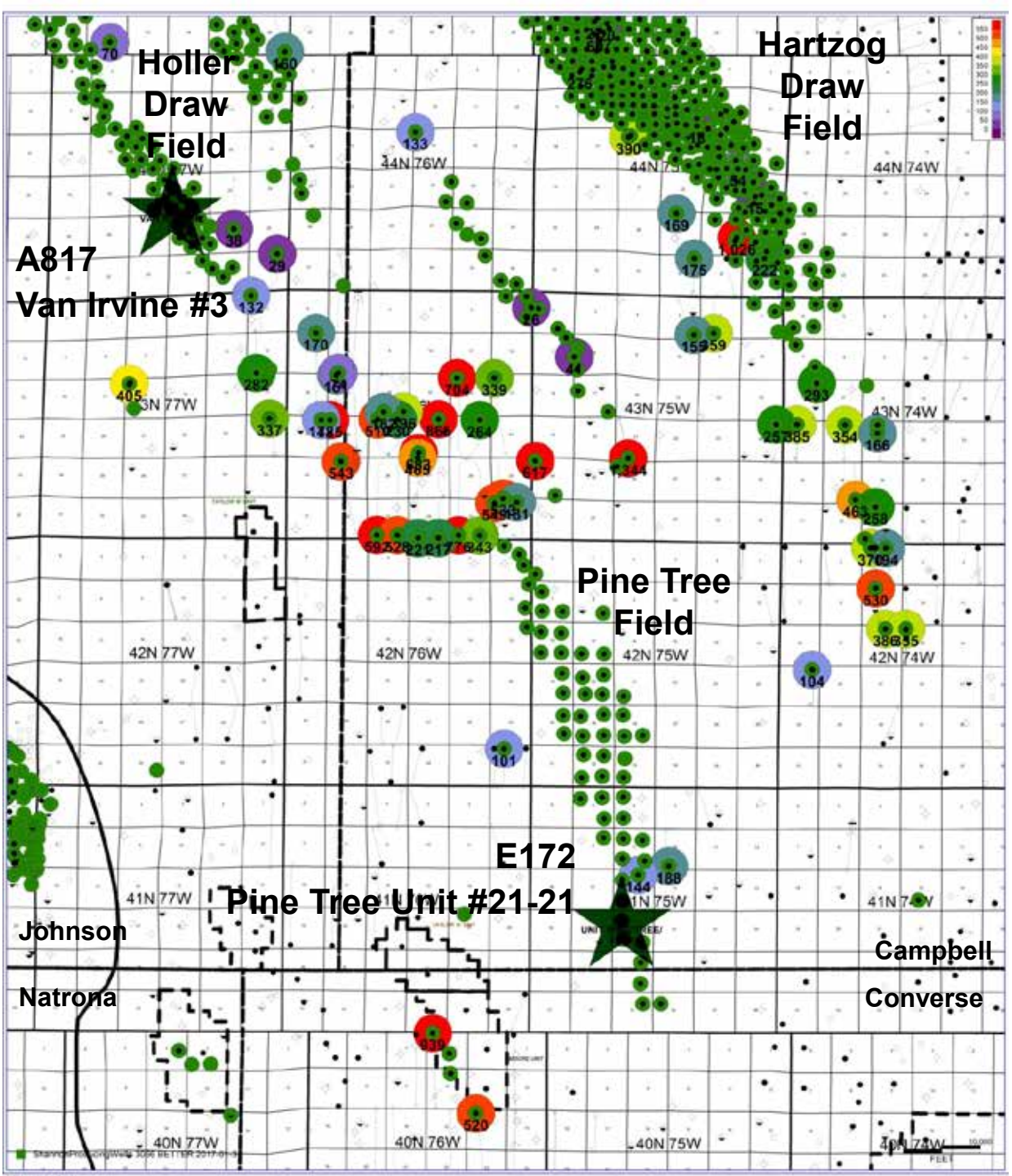
Wells Drilled After Jan. 1, 2006





Well and Production Data From IHS Markit

IHS Markit



SHANNON ACTIVITY

Pine Tree Field To Holler Draw Field

Bubbles Max Rate in BOE/day for wells after 1-1-2006

Most Successful Shannon Activity Between and Along Strike With Existing Vertical Fields

BOEPD

- < 0.000
- >= 0.000
- >= 50.000
- >= 100.000
- >= 150.000
- >= 200.000
- >= 250.000
- >= 300.000
- >= 350.000
- >= 400.000
- >= 450.000
- >= 500.000
- >= 550.000

IHS Markit

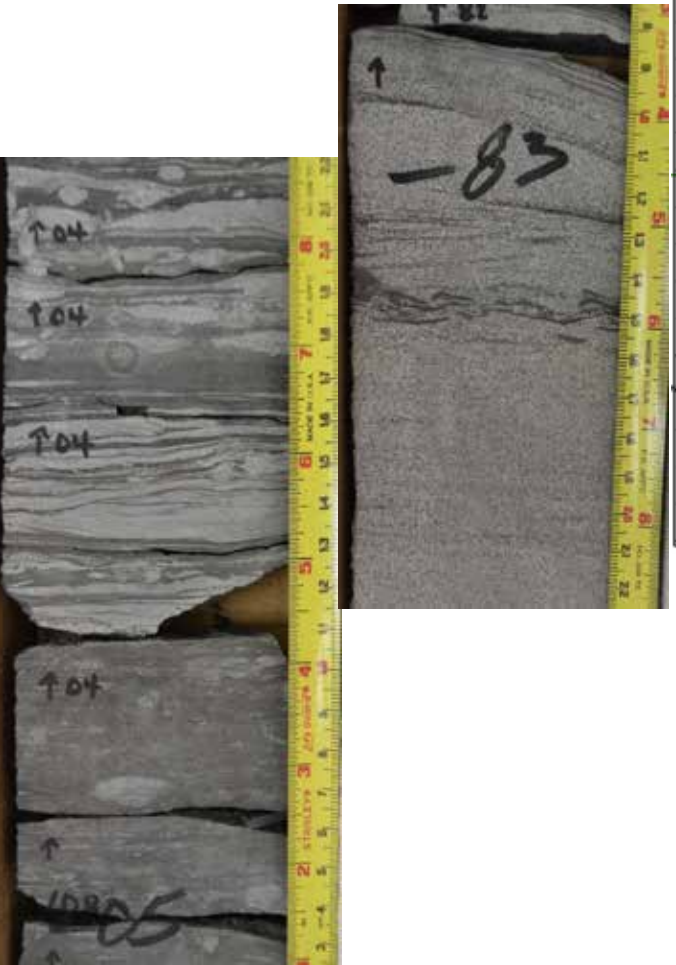
Well & Production Data From IHS Markit

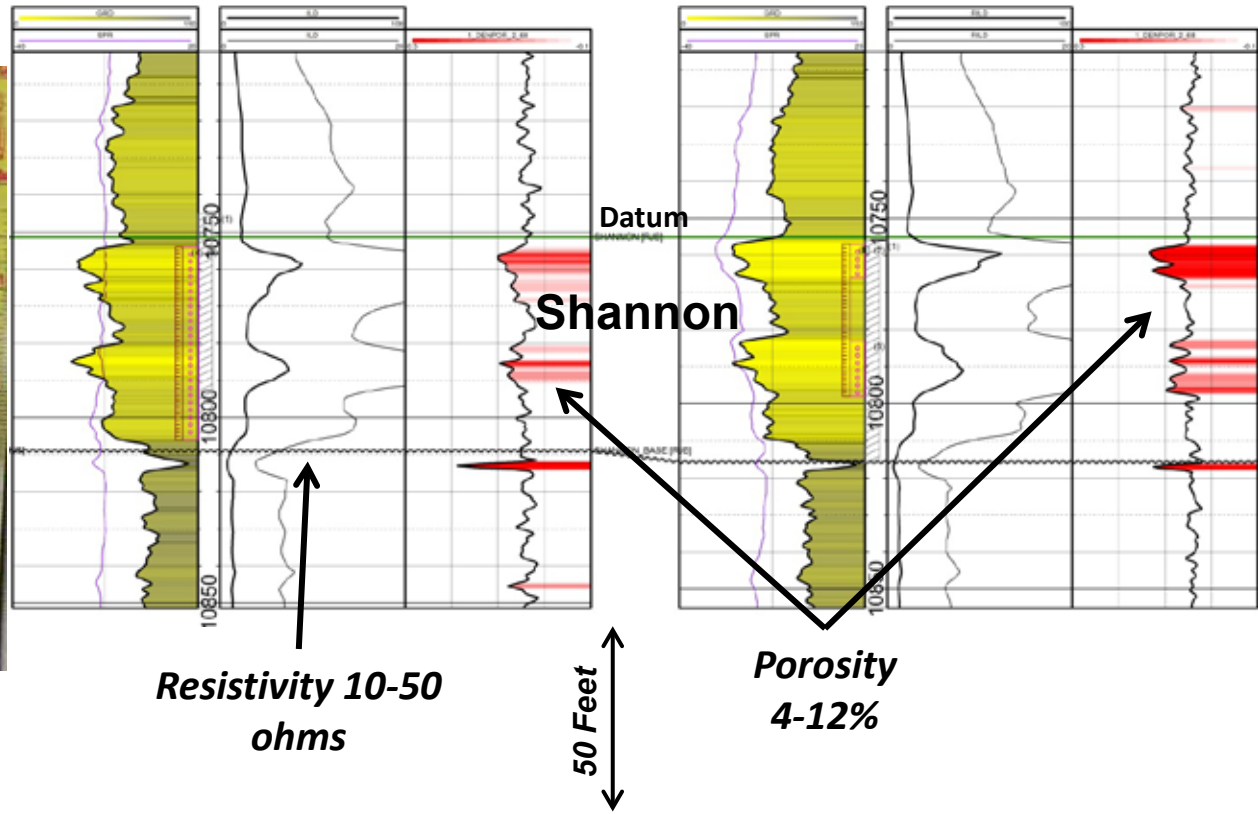
SHANNON SANDSTONE

PINE TREE UNIT AREA, Campbell Co.

Pine Tree Unit #21-20
NE-SW-21-T41N-R75W

E172
Pine Tree Unit #21-21
NW-NW-21-T41N-R75W



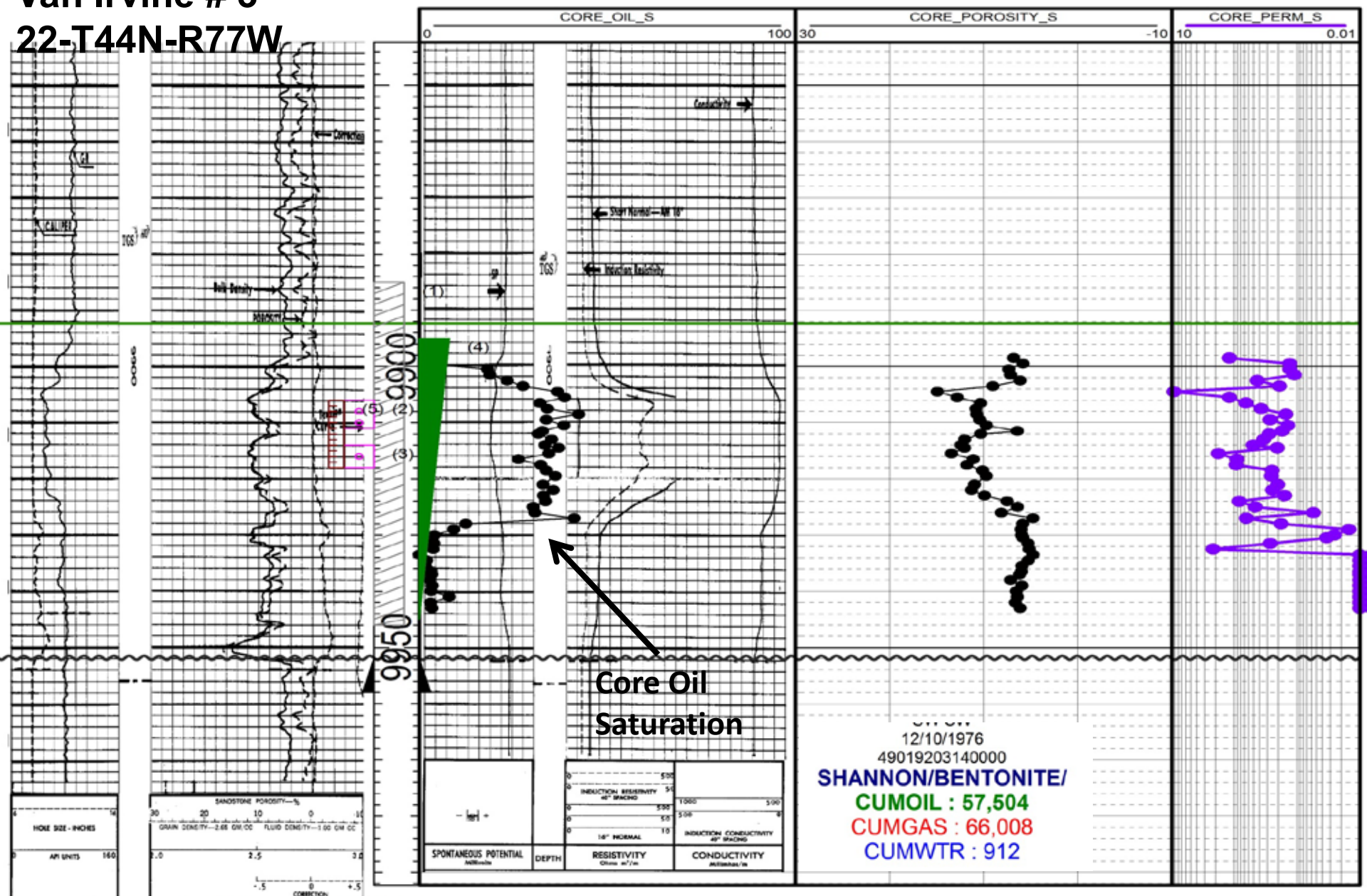


Vertical Well Cum
83 MBO + 103 MMCF + 3 MBW

Vertical Well Cum
100 MBO + 128 MMCF + 3 MBW

A817
Southland Royalty
Van Irvine # 3
22-T44N-R77W

Shannon Sandstone
Conventional Vertical Production



SUSSEX & OTHER TIGHT OIL RESERVOIRS
Lithologic Terms Used (Bottjer)
Facies are Commonly Gradational

- **Mudstone** **< 50% Sand**
- **Sandstone** **> 50% Sand**

- **Bioturbated** **> 75% Burrowing (most primary sedimentary structures reworked by burrowers)**
- **Burrowed** **~ 25-75% Burrowed, burrowed beds interbedded with laminated beds**
- **Bedded** **< 25% Burrows, > 75% Bedded or Laminated**

SUSSEX & SHANNON CORES
What Should I Look For?

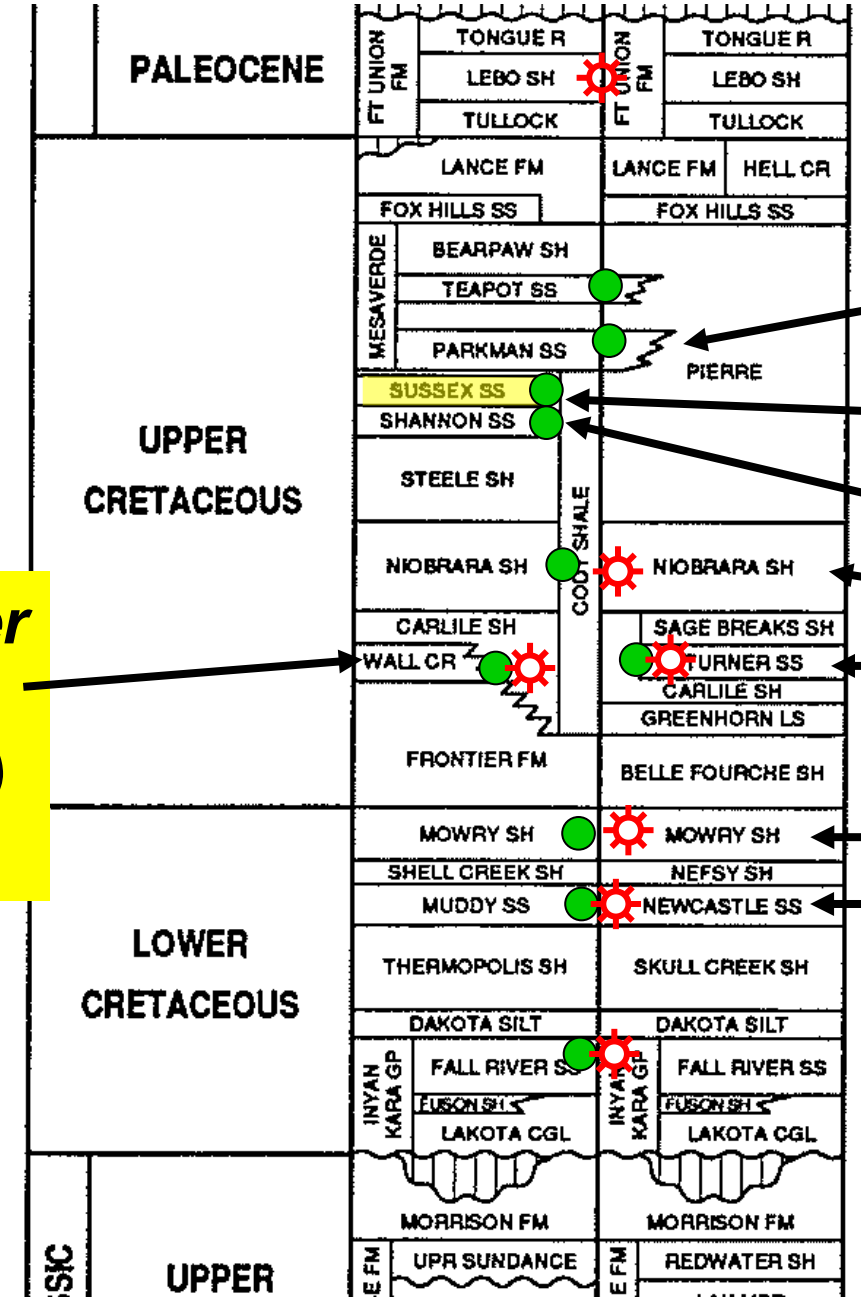
- **Sedimentary Structures & Facies – What Lithologies Have Porosity and Oil Saturation?**
- **Burrow Density, Types & Diversity? (ichnofacies)**
- **Key Surfaces – Erosion? TSE? LSE?**
- **Compare House Creek Sussex to Hornbuckle Sussex – Similarities & Differences?**
- **Differences Between Shannon & Sussex?**
- **What Makes the Sussex a Horizontal Drilling Target?**
- **Evidence for Reservoir Heterogeneities or Compartments?**

TURNER & FRONTIER SANDSTONES, POWDER RIVER BASIN

Introduction

POWDER RIVER BASIN STRATIGRAPHIC CHART

Tight Oil Plays



Parkman SS

Sussex Sandstone

Shannon Sandstone

Niobrara "Shale"

Turner Sandstone

Mowry "Shale"

Muddy Sandstone

Frontier (Wall Creek) SS

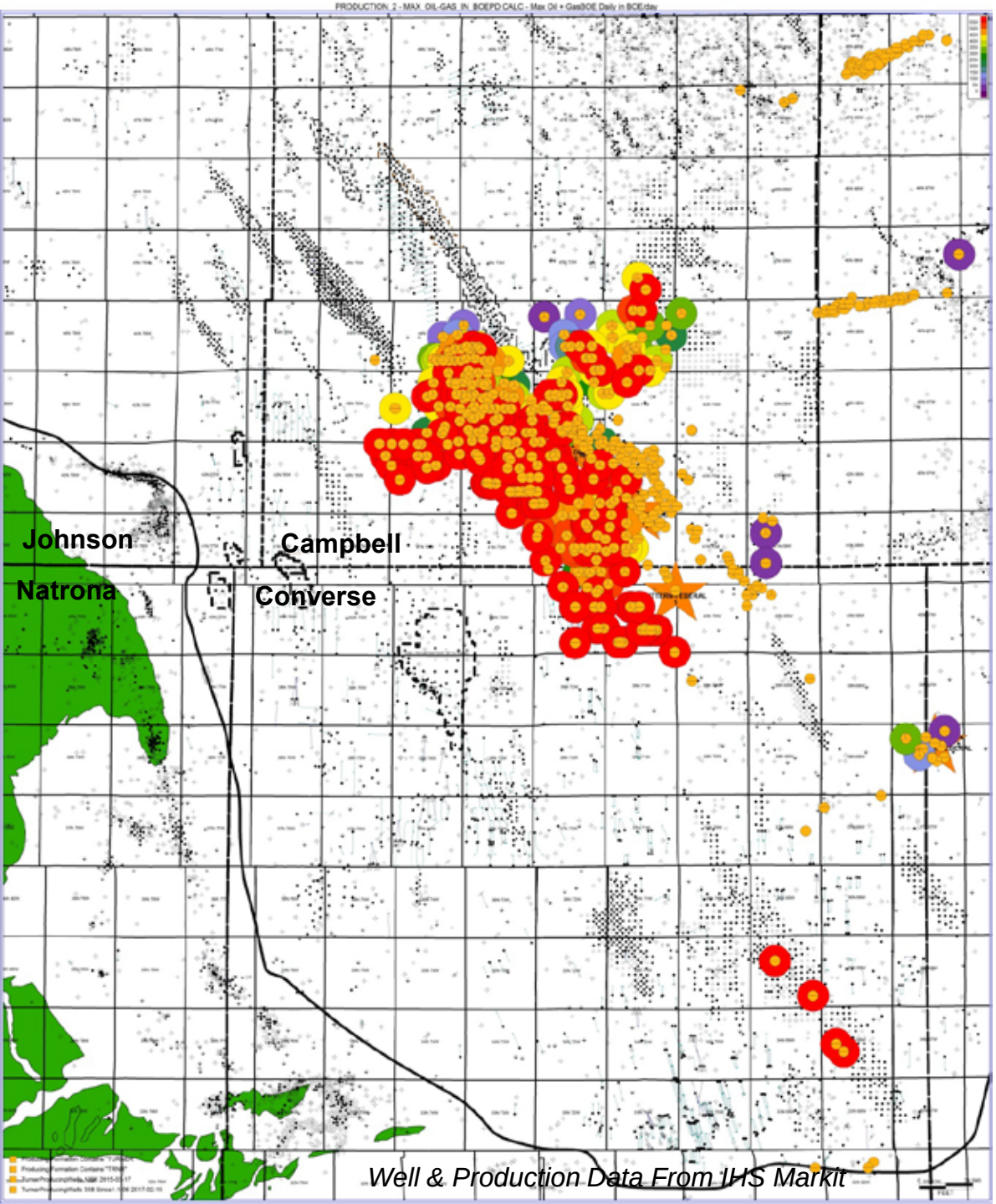
After Heasler et al. (1994)

TURNER SANDSTONE,

Bubbles Max Rate in BOE/day for wells after 1-1-2006

Turner

7 Turner Sandstone Cores

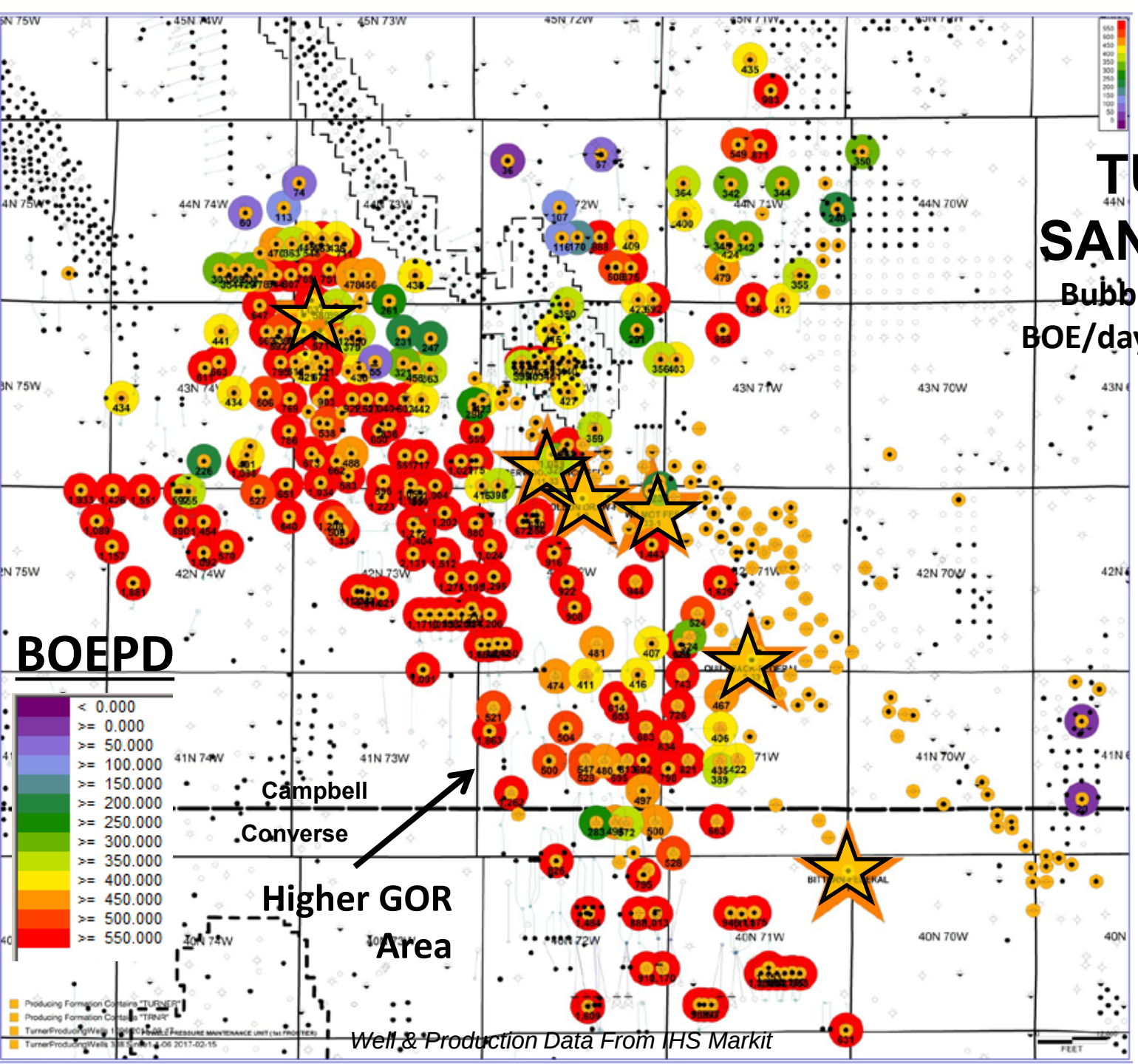


Well & Production Data From IHS Markit

BOEPD

< 0.000
>= 0.000
>= 50.000
>= 100.000
>= 150.000
>= 200.000
>= 250.000
>= 300.000
>= 350.000
>= 400.000
>= 450.000
>= 500.000
>= 550.000

IHS Markit

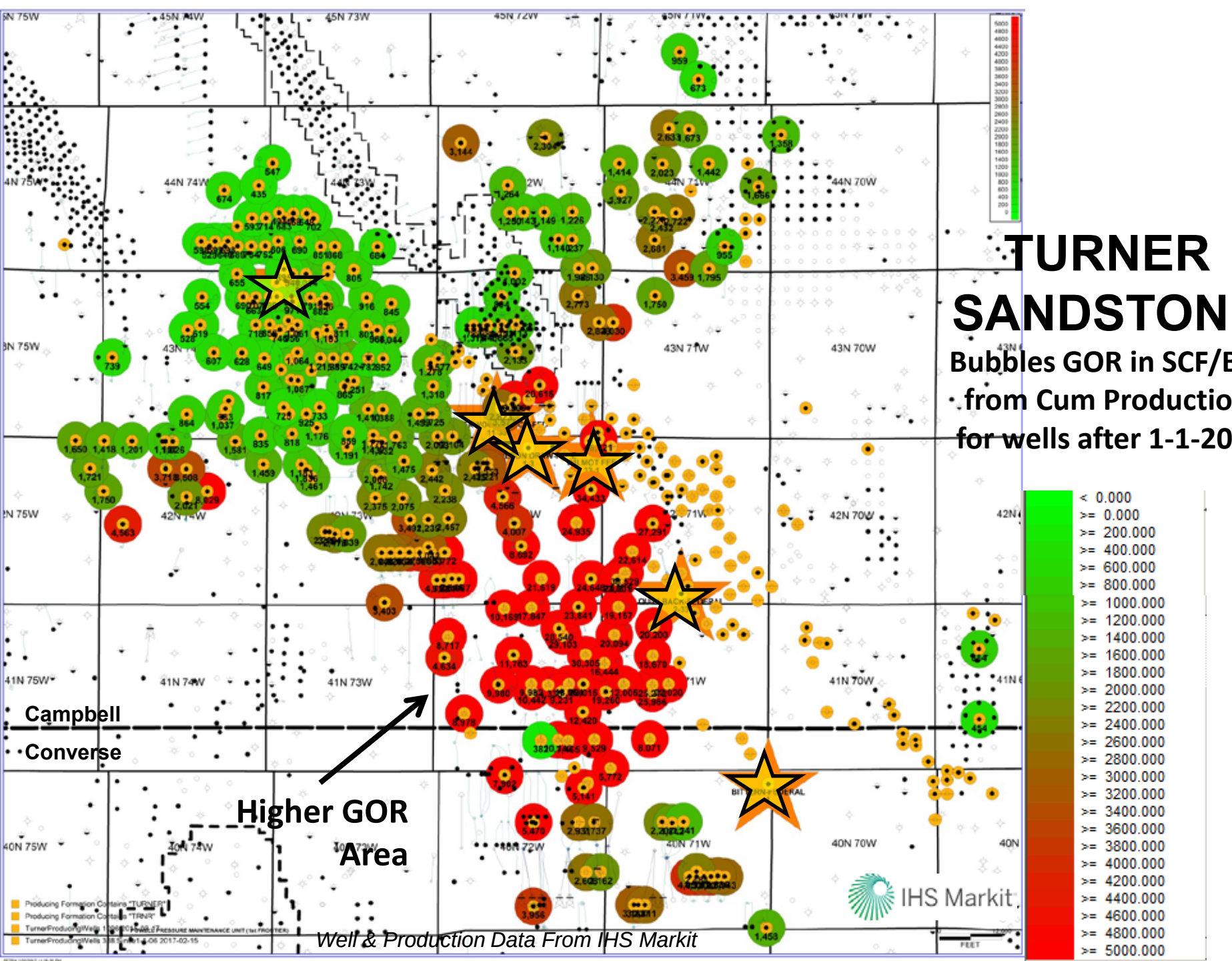


TURNER SANDSTONE

Bubbles Max Rate in BOE/day for wells after 1-1-2006

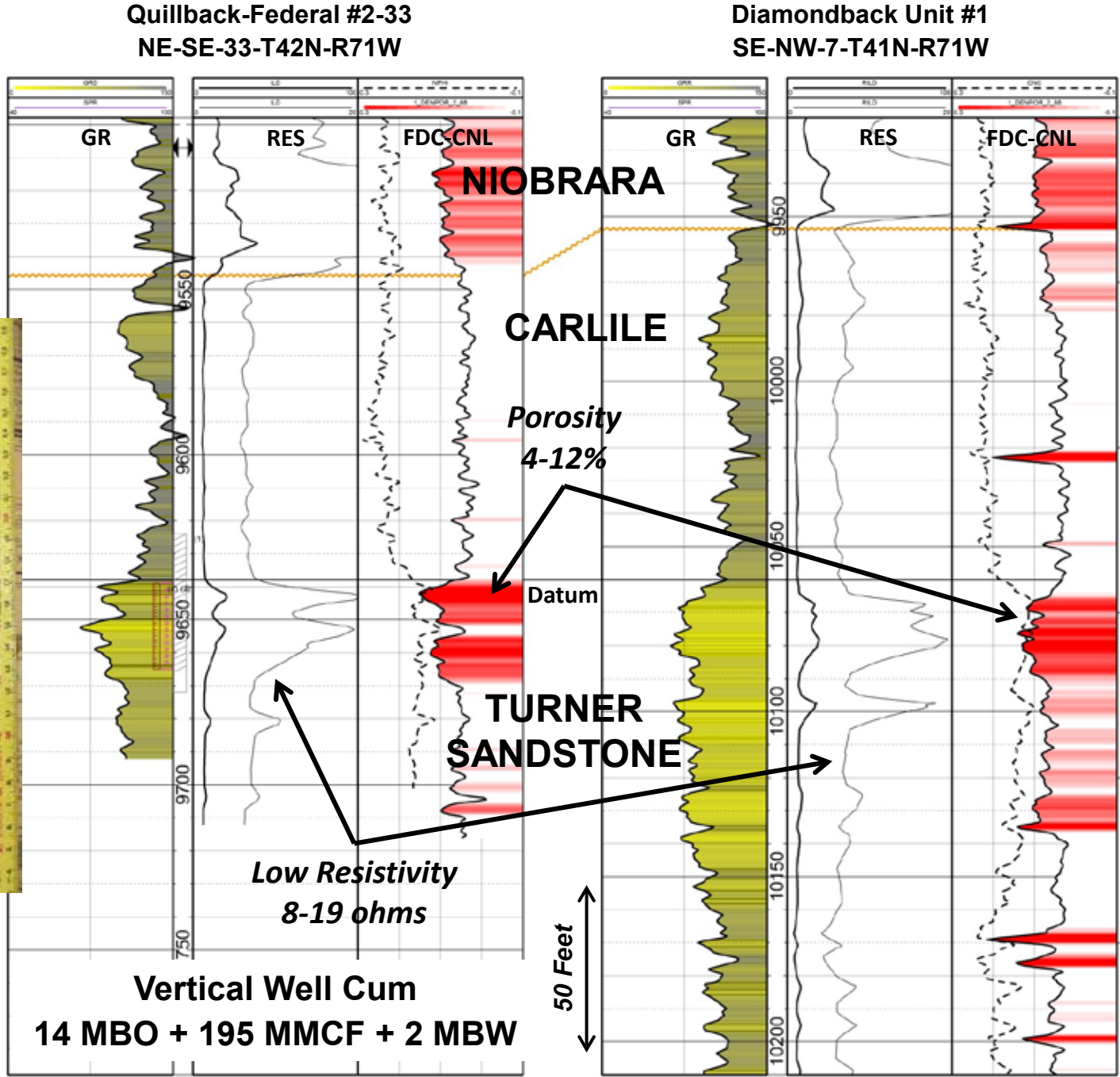
7 Turner Sandstone Cores

IHS Markit


TURNER SANDSTONE
Bubbles GOR in SCF/Bbl from Cum Production for wells after 1-1-2006
< 0.000
>= 0.000
>= 200.000
>= 400.000
>= 600.000
>= 800.000
>= 1000.000
>= 1200.000
>= 1400.000
>= 1600.000
>= 1800.000
>= 2000.000
>= 2200.000
>= 2400.000
>= 2600.000
>= 2800.000
>= 3000.000
>= 3200.000
>= 3400.000
>= 3600.000
>= 3800.000
>= 4000.000
>= 4200.000
>= 4400.000
>= 4600.000
>= 4800.000
>= 5000.000
Campbell
Converse
Higher GOR Area
IHS Markit
Well & Production Data From IHS Markit

TURNER SANDSTONE

CROSSBOW AREA, Cambell Co.



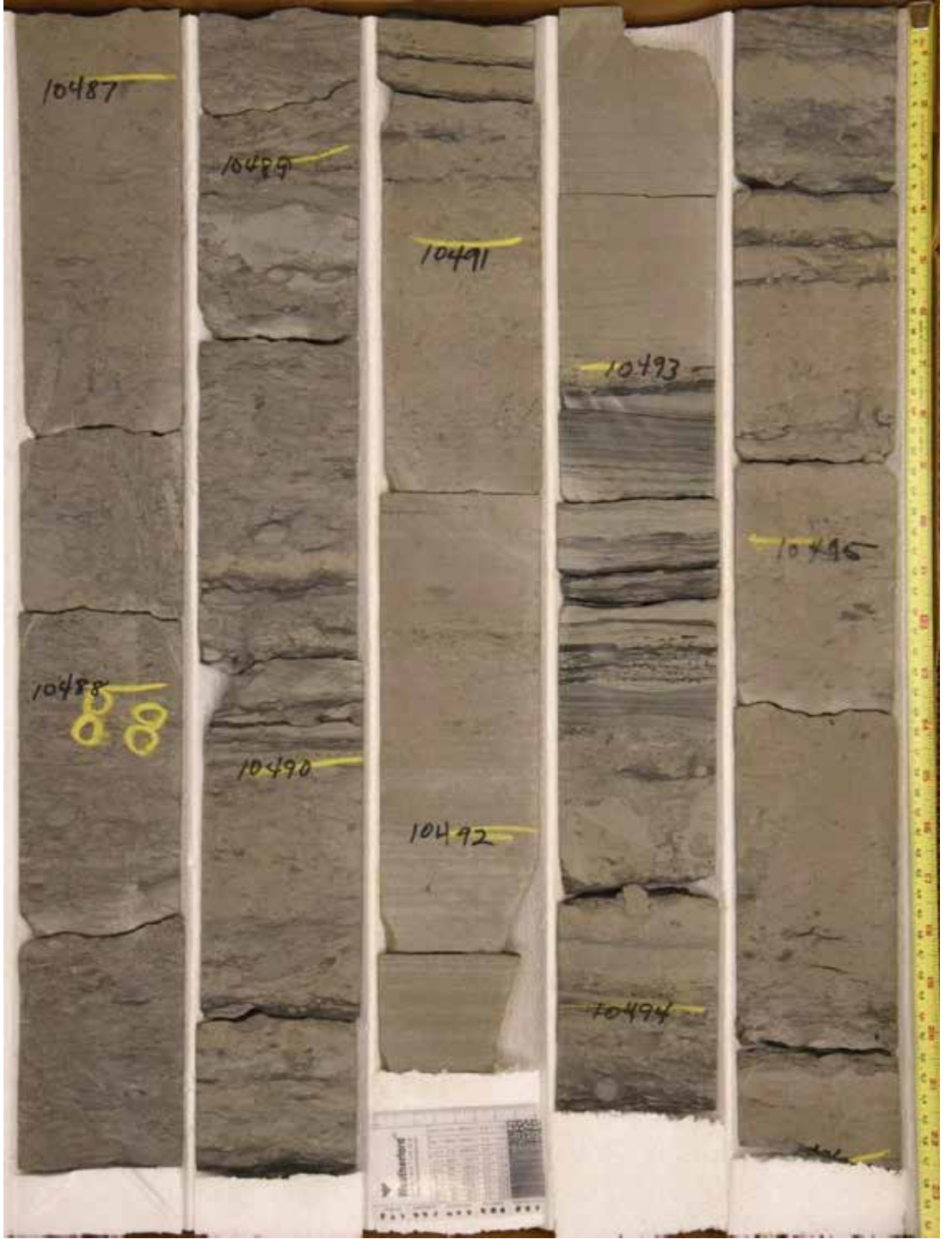
Vertical Well Cum
14 MBO + 195 MMCF + 2 MBW

TURNER SANDSTONE

Groves #4
4-T43N-R73W

Reservoir Consists of Multiple Facies & Mixed Lithologies

- Laminated (Sub-Parallel to Horizontal to Hummocky) Sandstone
- Bioturbated Sandstone
- Bioturbated Muddy Sandstone
- Bioturbated Sandy Mudstone



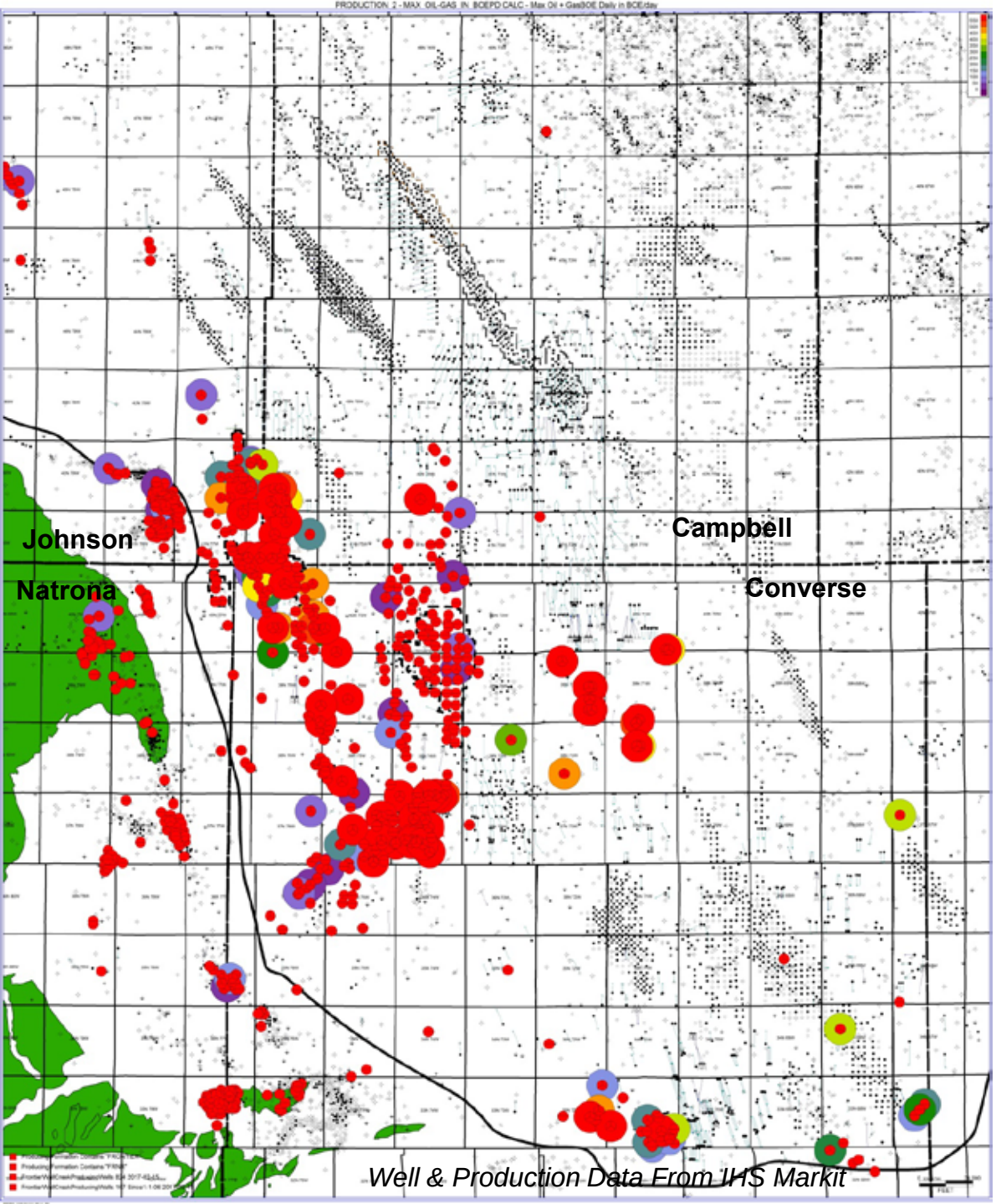
FRONTIER SANDSTONE

Bubbles Max Rate in BOE/day

for wells after 1-1-2006

Frontier

1 Frontier (Wall Creek) Sandstone Core



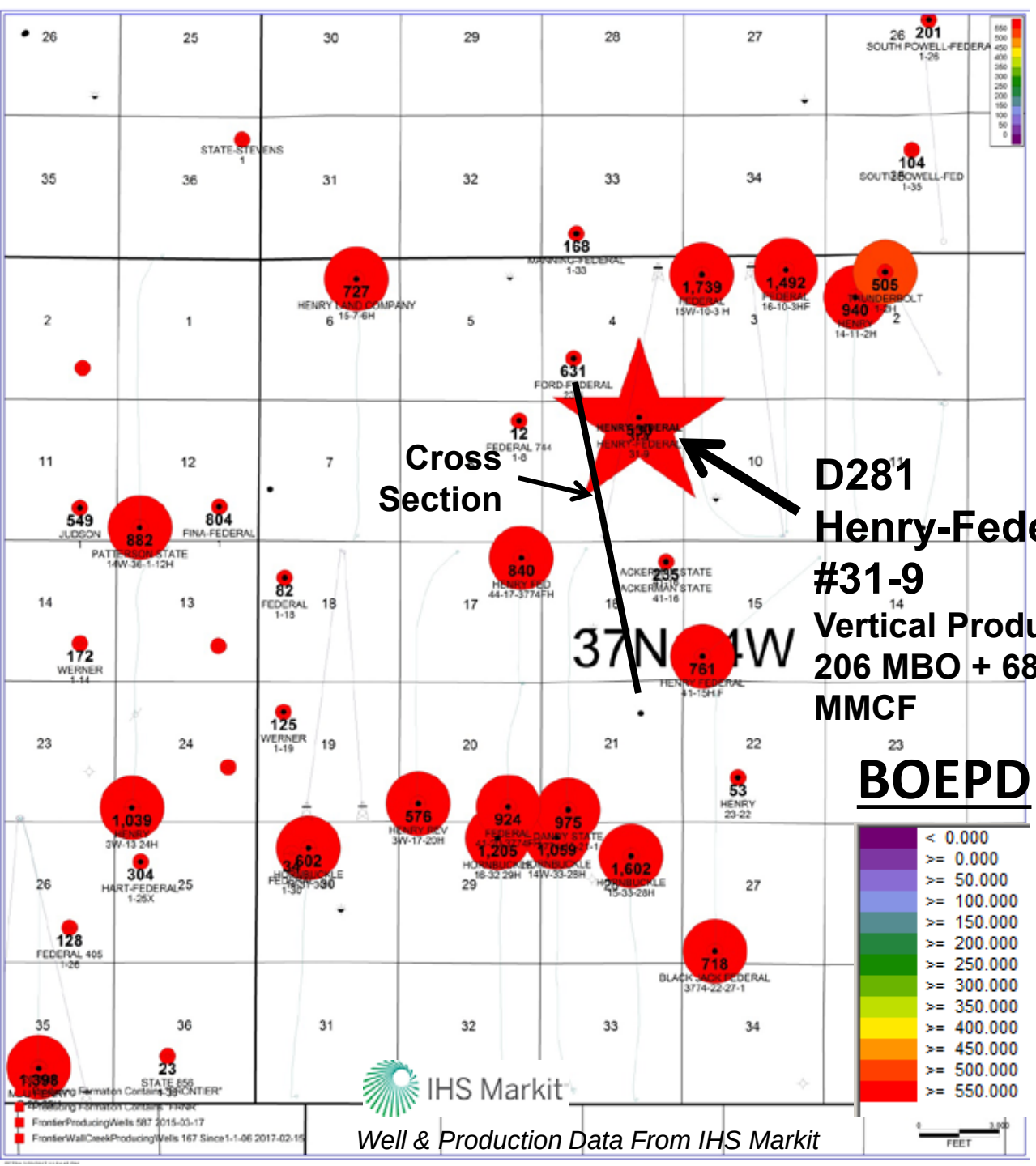
BOEPD

< 0.000
>= 0.000
>= 50.000
>= 100.000
>= 150.000
>= 200.000
>= 250.000
>= 300.000
>= 350.000
>= 400.000
>= 450.000
>= 500.000
>= 550.000

IHS Markit

FRONTIER SANDSTONE Spearhead Ranch Field Area Converse Co.

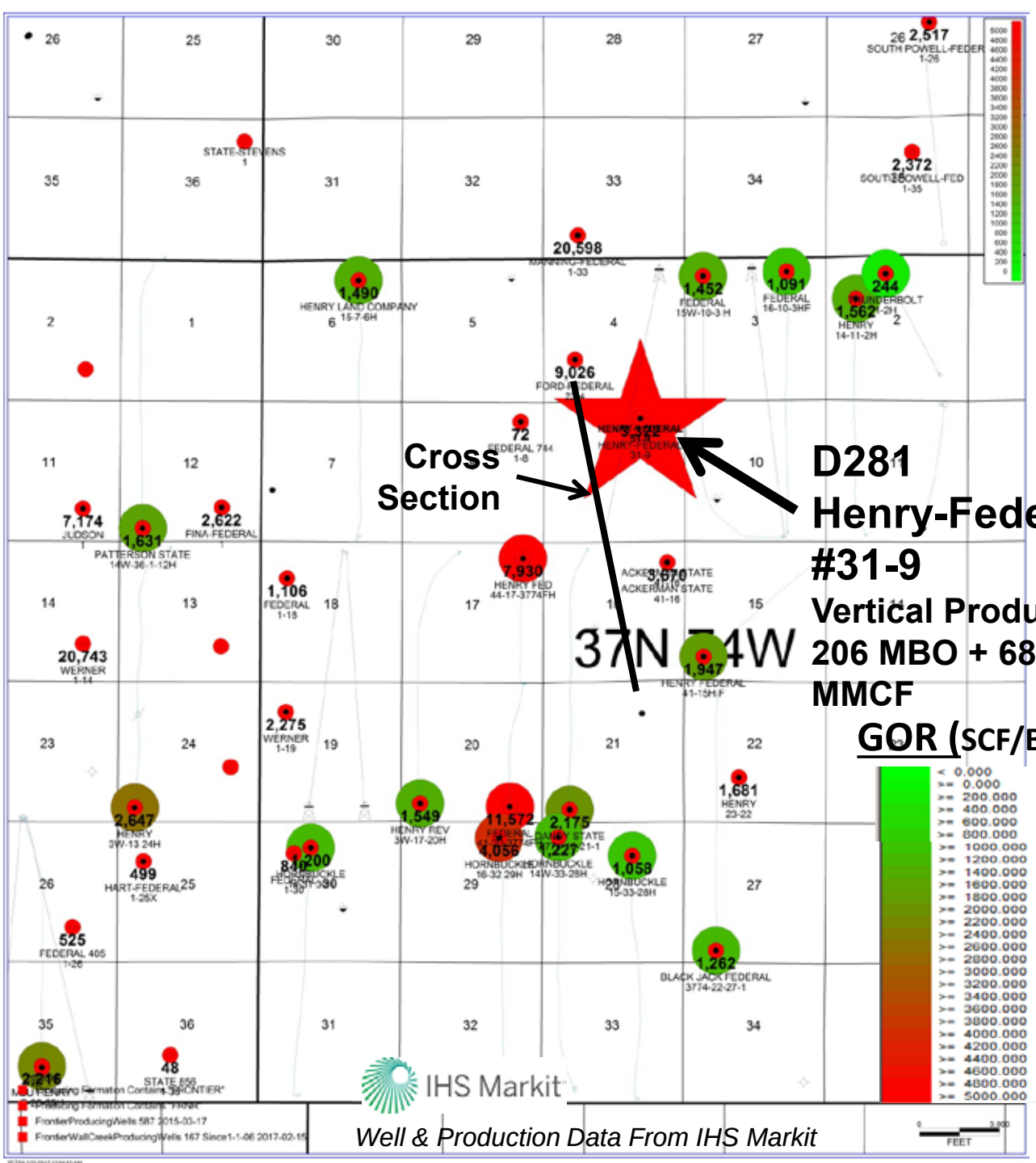
Bubbles Max Rate in BOE/day for wells after 1-1-2006



- High Pressure
- Mostly 2-Mile Laterals
- Horizontals have Lower GOR than old Vertical Wells
- High Rates, High EURs
- Deep > 12,000' TVD

Well & Production Data From IHS Markit

FRONTIER SANDSTONE GOR Spearhead Ranch Field Area Converse Co.



Bubbles GOR in SCF/Bbl from Cum Production for wells after 1-1-2006

- High Pressure
- Mostly 2-Mile Laterals
- High Rates, High EURs
- Deep > 12,000' TVD

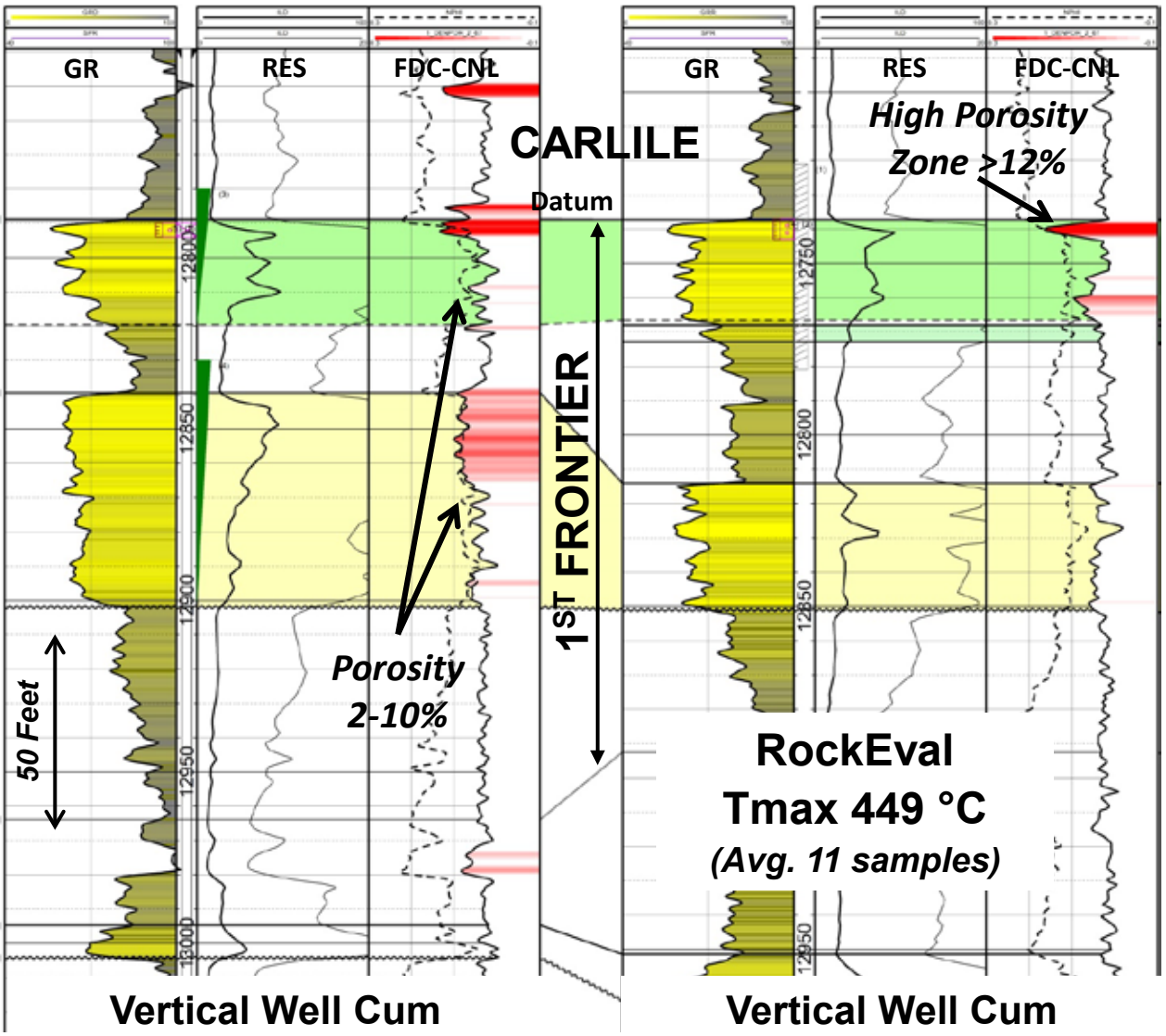
IHS Markit

Well & Production Data From IHS Markit

FRONTIER SANDSTONE

Waters-Fee #31-21
NW-NE-21-T37N-R74W

Ford-Federal #23-4
NE-SW-4-T37N-R74W



Vertical Well Cum
360 MBO + 382 MMCF + 6 MBW

Vertical Well Cum
229 MBO + 2,071 MMCF + 7 MBW

SPEARHEAD RANCH AREA, Converse Co.

Phi 14.9%
k 136 md

Break into 2 Groups to Look at Cores

SUSSEX CORES

- Start at D915 Highland Flats Federal #13-11
- Compare Vertical Producer Cores to F012 Brazos State
- Note that F012 Brazos State is offset by >500 BOPD Horizontal Wells
- Compare Hornbuckle Sussex Cores with House Creek Cores
- How does Shannon Compare with Sussex?

TURNER CORES

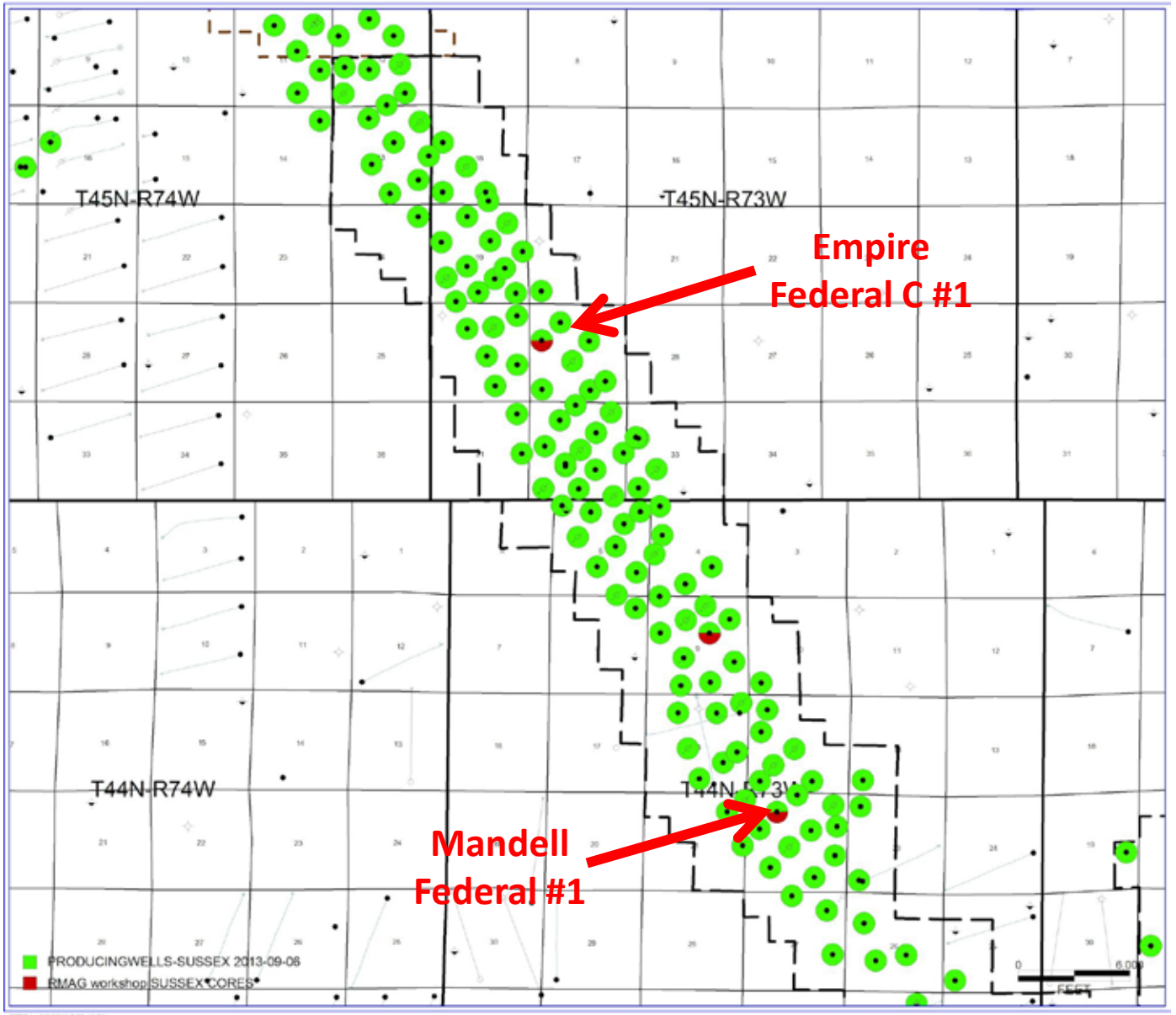
- Start at Groves #4
- Note Turner Changes from North to South
- Compare Turner with Frontier

SUSSEX SANDSTONE

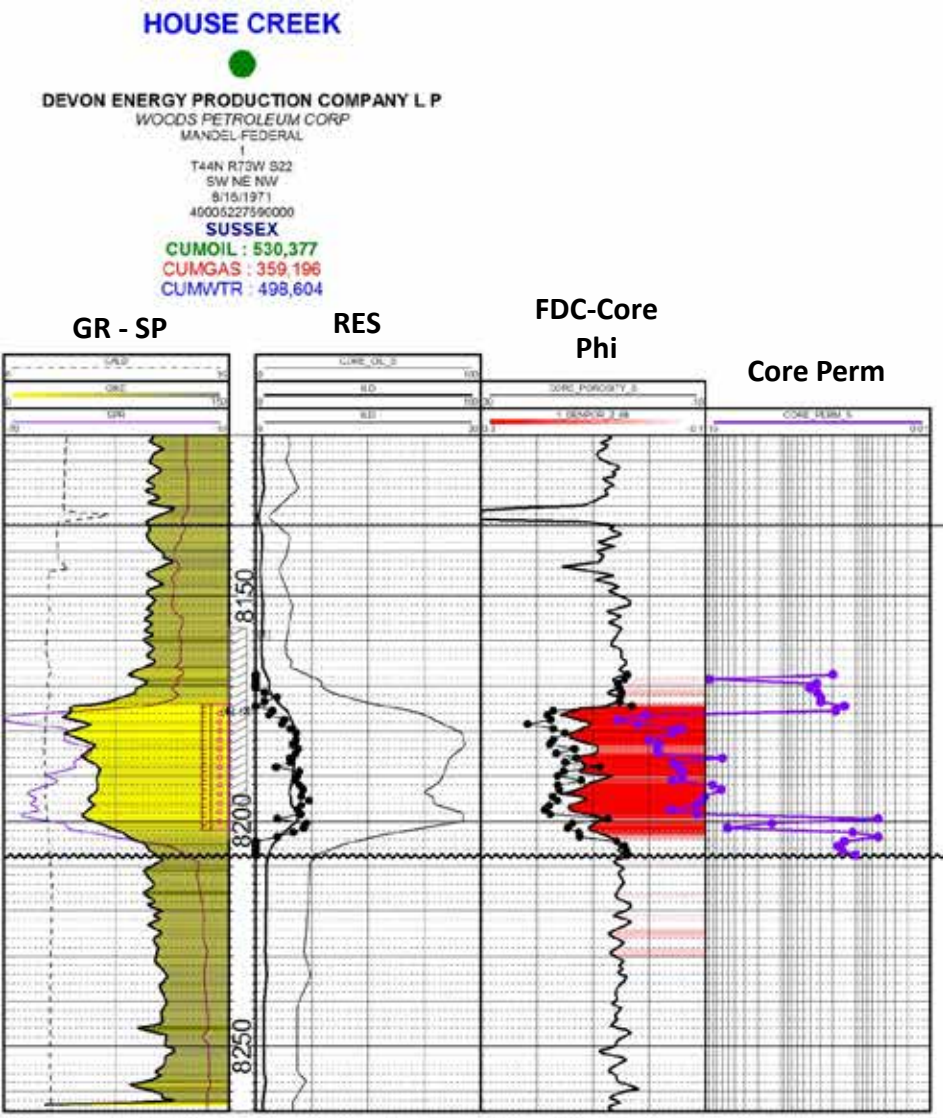
Conclusions – Where is the Oil?

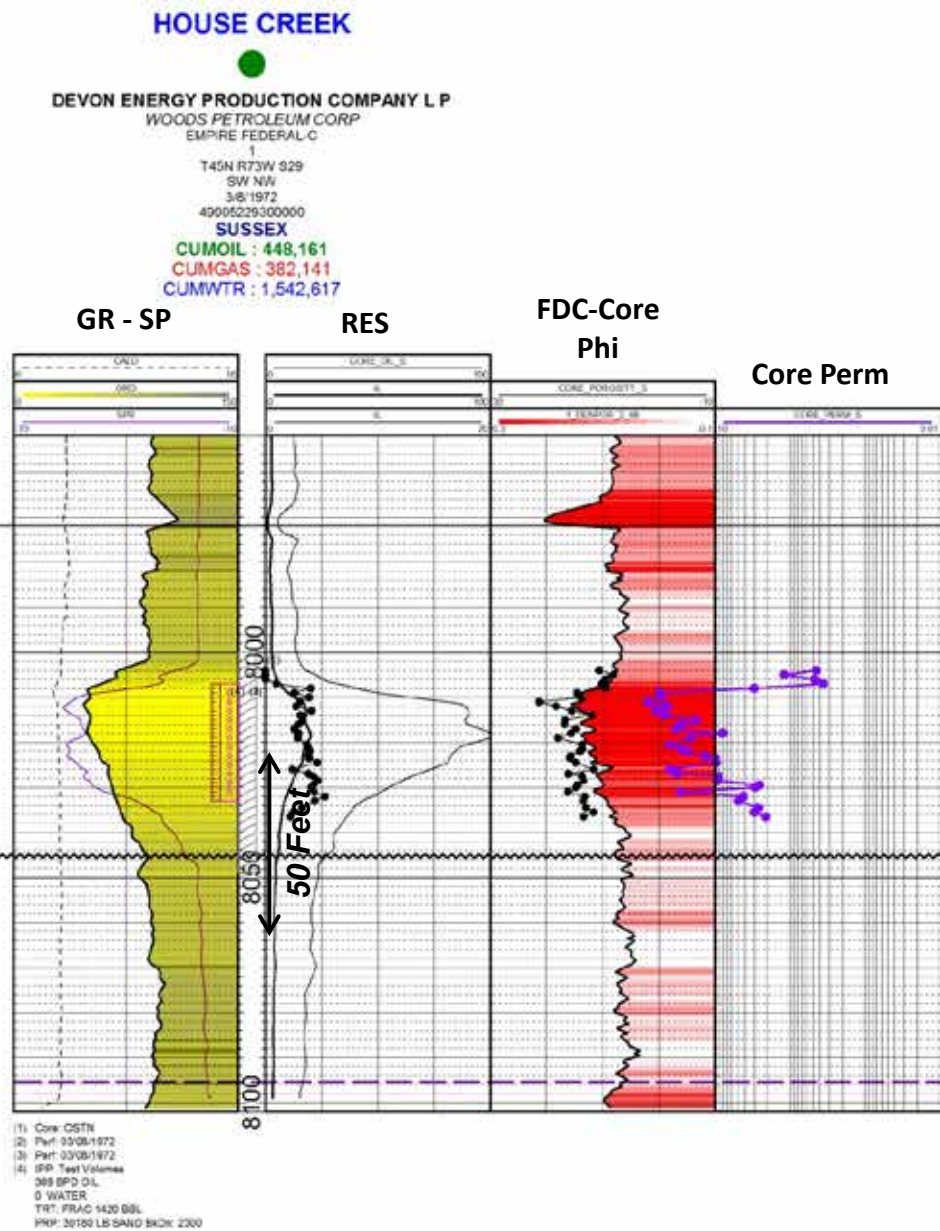
- **Sedimentary Structures & Facies – What Lithologies Have Porosity?**
- **Depositional Environments – Origin of Sandstones?**
- **Burrow Types & Diversity? (ichnofacies)**
- **Key Surfaces – Erosion? TSE? LSE?**
- **Compare House Creek Sussex to Hornbuckle Sussex – Similarities & Differences?**

Central House Creek Field
Core Wells Studied



House Creek Field – 2 Sussex Cores





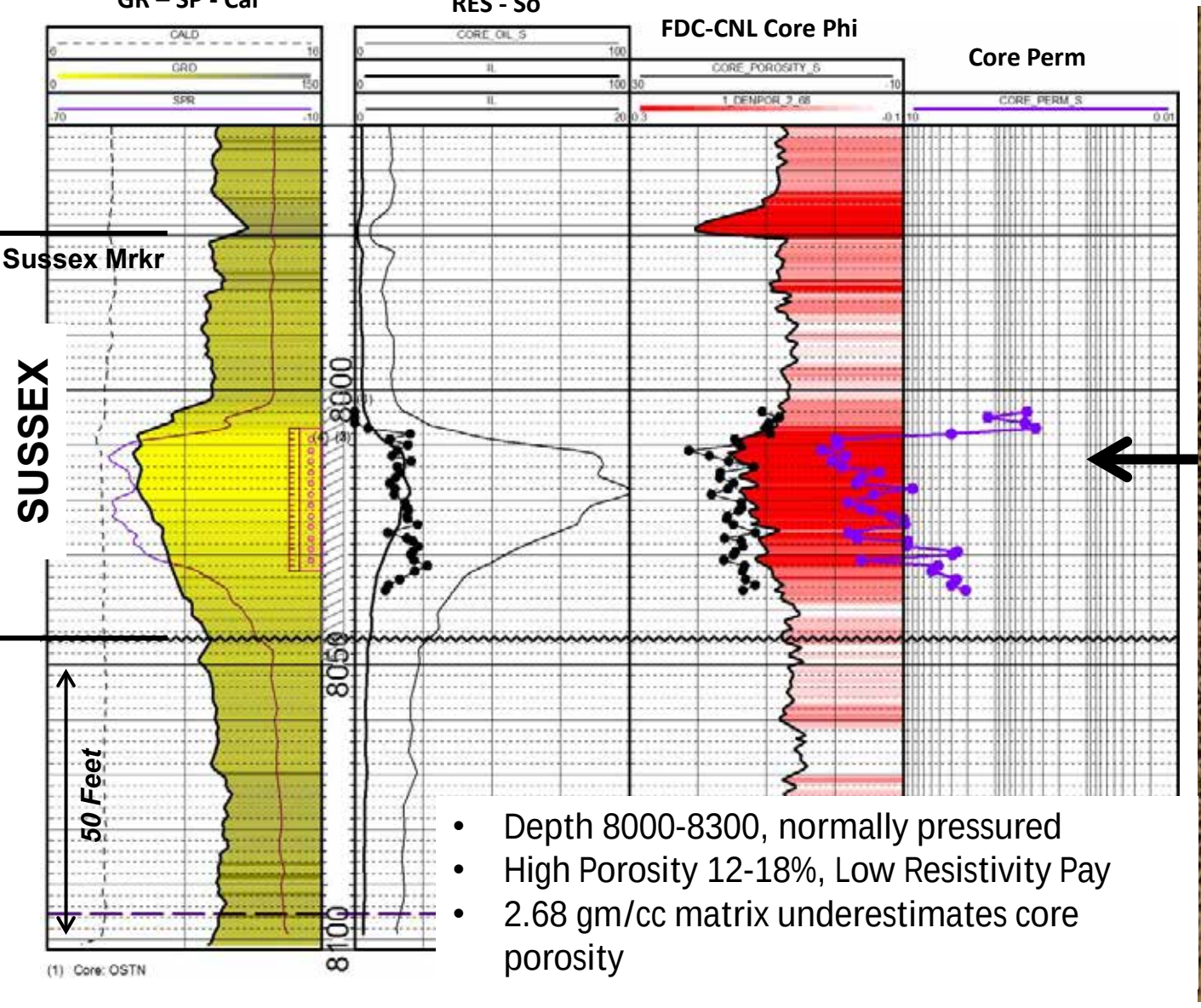
- Depth 8000-8300, normally pressured
- High Porosity 12-18%
- 2.68 gm/cc matrix underestimates core porosity

House Creek Field - Conventional

High-Energy Cross-Bedded to Horizontally Bedded Sandstone

8,013-8,014

Woods Petroleum
Empire Federal C #1
SW-NW-29-T45N-R73W
Comp. 3-8-72
CUM = 447 MBO



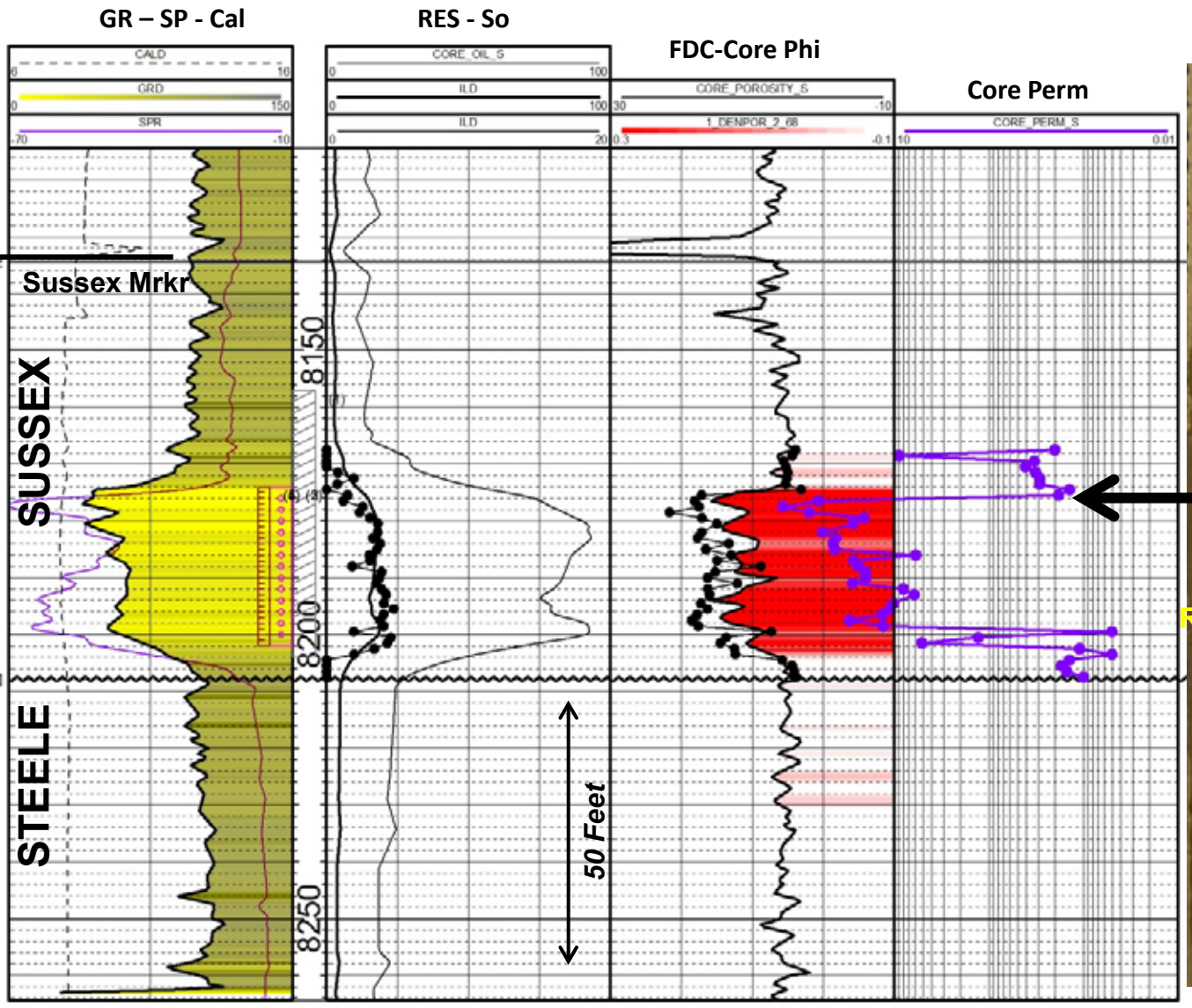
- Depth 8000-8300, normally pressured
- High Porosity 12-18%, Low Resistivity Pay
- 2.68 gm/cc matrix underestimates core porosity

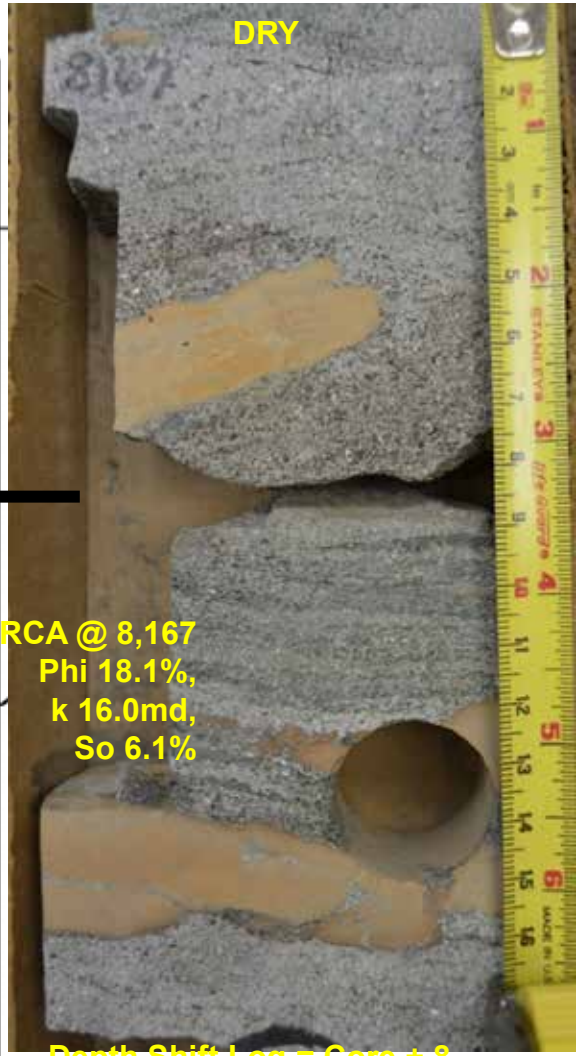
House Creek Field

High-Energy Cross-Bedded Sandstone

8,167 (8,175 Log)

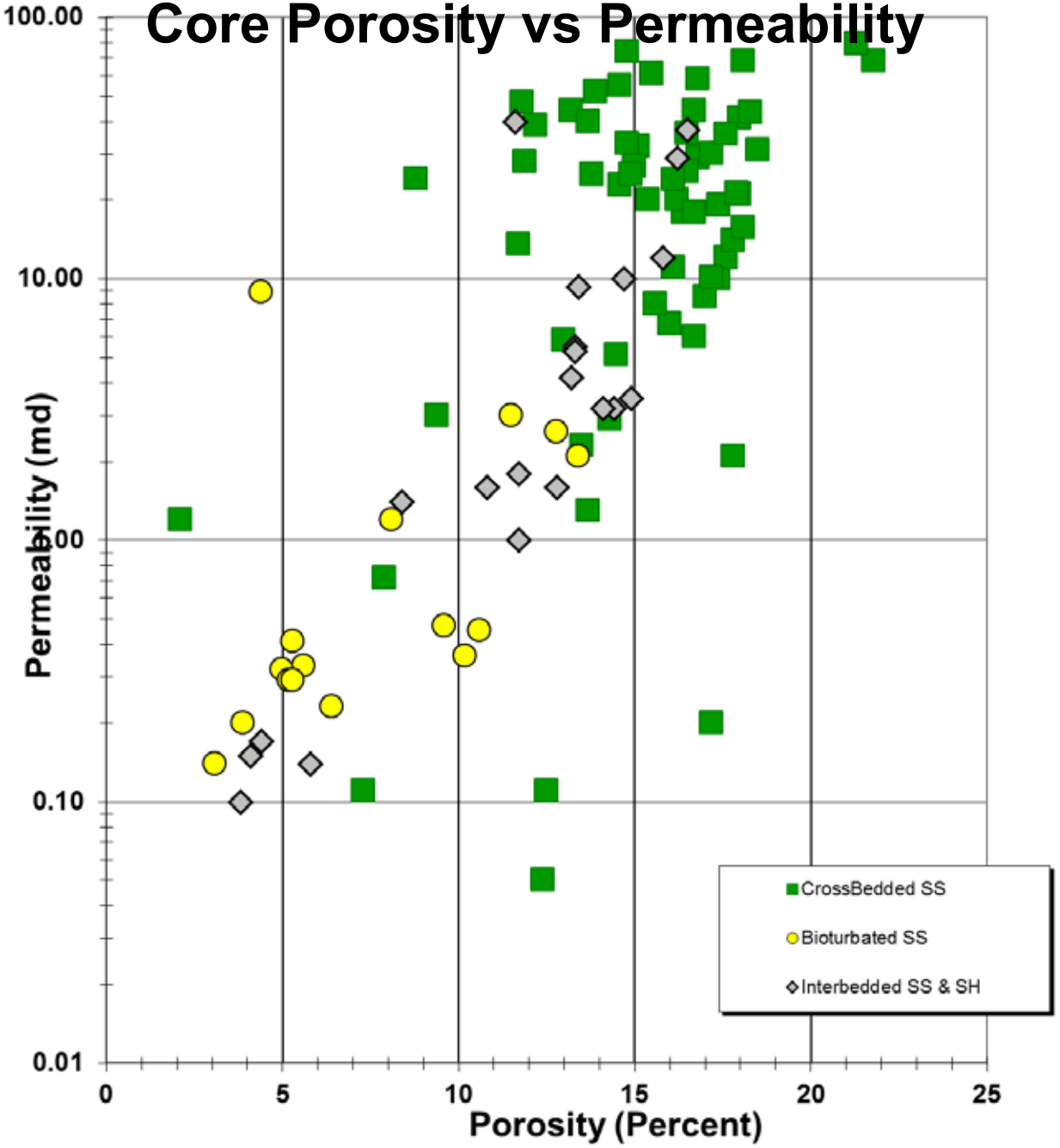
Woods Petroleum
Mandell Federal #1
NE-NW-22T44N-R73W
Comp. 8-16-71
CUM = 528 MBO





Depth Shift Log = Core + 8

House Creek Field
Core Porosity vs Permeability



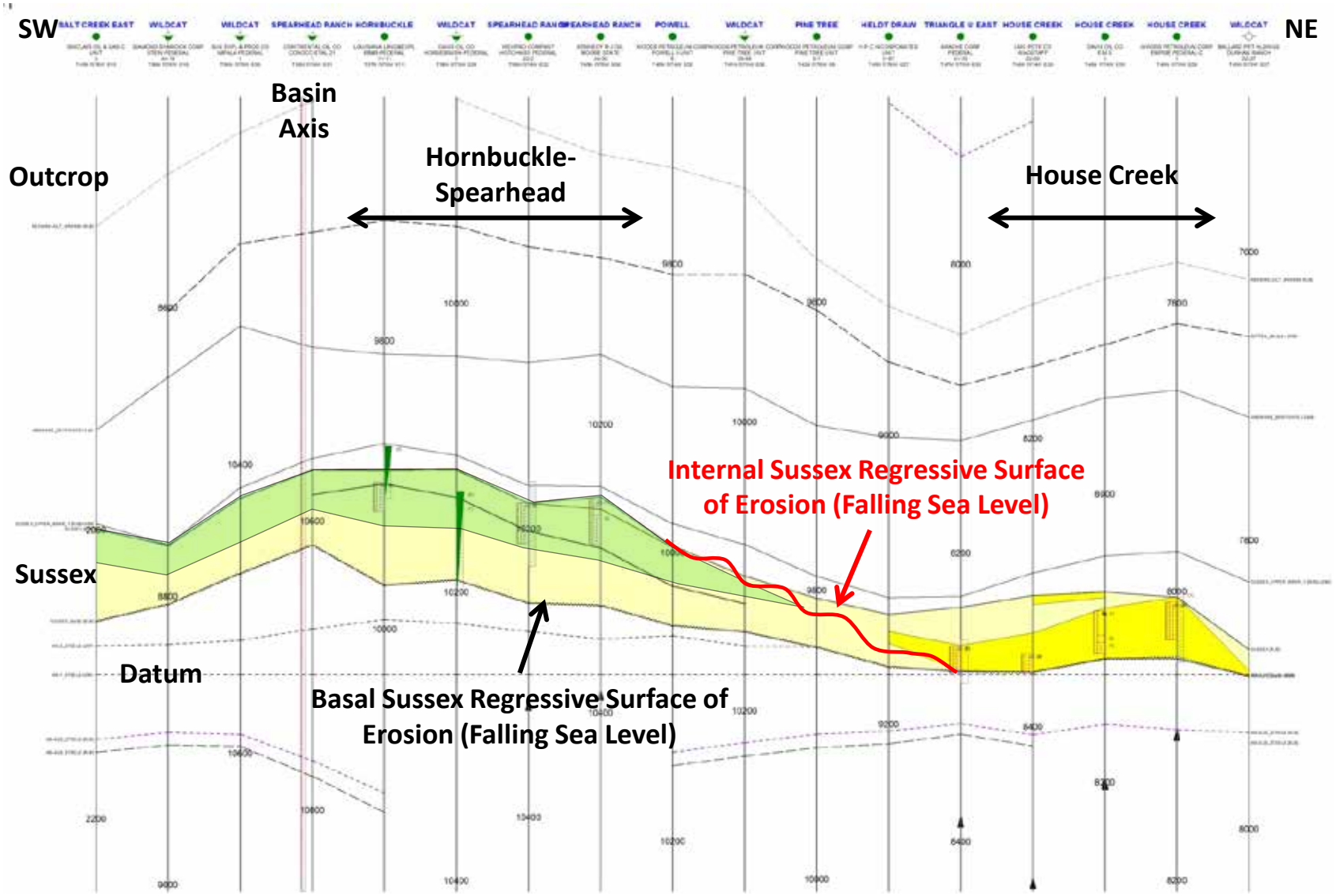
House Creek Waterflood Feasibility Study - 1986

- Depth 8200 ft.
- Avg. Phi 12%
- Avg. Perm. 13.6md
- Avg. Net pay 19 ft.
- Normal Pressure ~ 0.4 psi/ft.

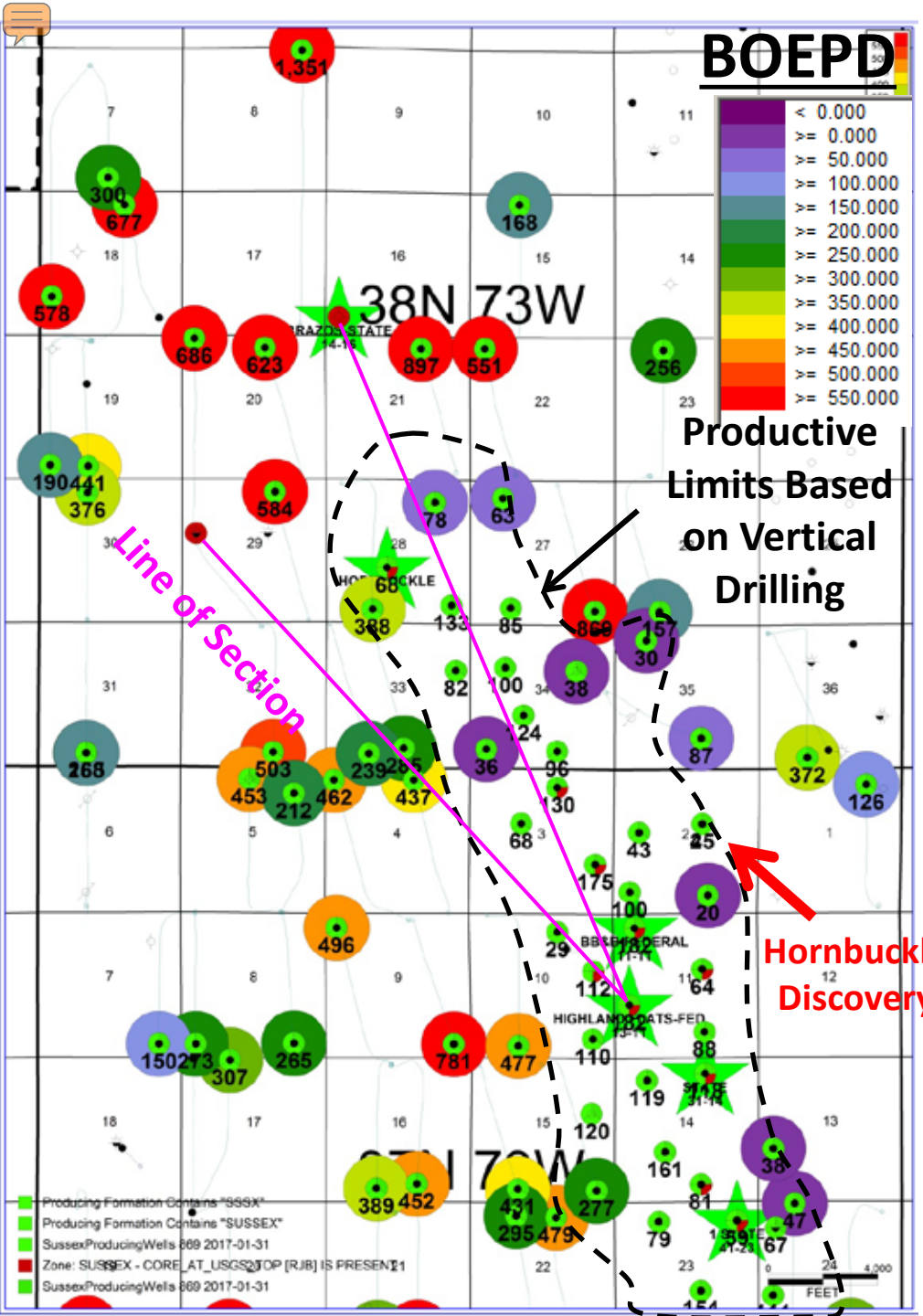
Facies

- Cross-Bedded Sandstone = Main Pay
- Interbedded Sandstone & Shale = Marginal Pay
- Bioturbated Sandstone = Not Pay

Regional Cross Section: Outcrop – Hornbuckle – House Creek



- Sussex Sandstone Climbs Stratigraphically from Outcrops/Salt Creek to Basin Axis
- East of Basin Axis Sussex Sandstone erodes & Truncates underlying Steele Shale Markers



Hornbuckle Field Area Sussex Sandstone Maximum Monthly Production in BOE/day

Wells Drilled After Jan. 1, 2006

Vertical Production Discovered 1984

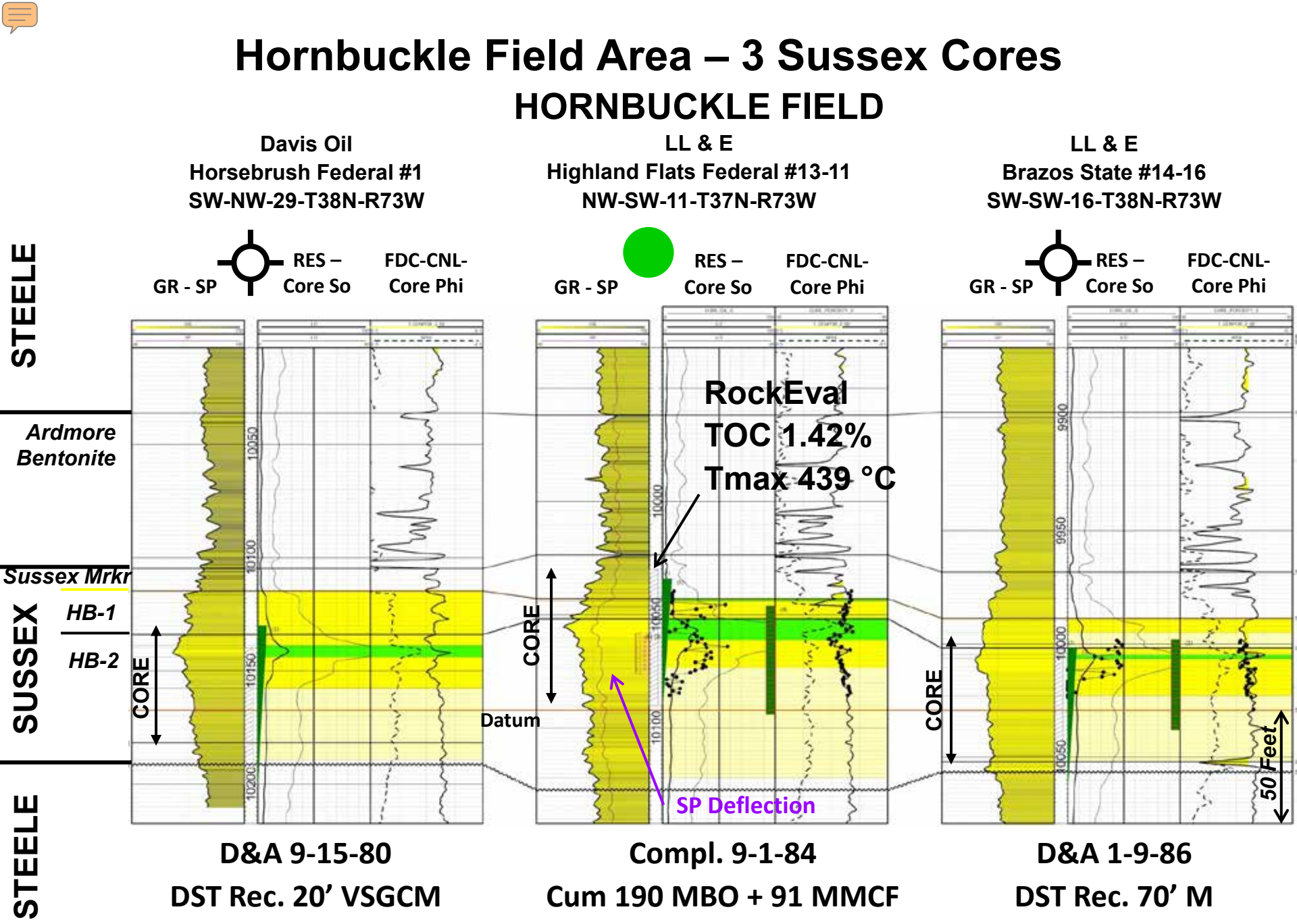
- Depth 10,000 – 10,500 Ft
- 30-Day IPs 30-200 BOPD
- Long Well Life, Long-Term 2-6% Decline
- Overpressured to 0.61 psi/ft (DST)
- 160 Acre Spacing, Wells Not Effectively Draining Spacing Units
- Few Dry Holes At Field Edges

IHS Markit

Well and Production Data From IHS Markit

Hornbuckle Field Area – 3 Sussex Cores

HORNBUCKLE FIELD



D&A 9-15-80
DST Rec. 20’ VSGCM
(Prior to Hornbuckle Discovery)

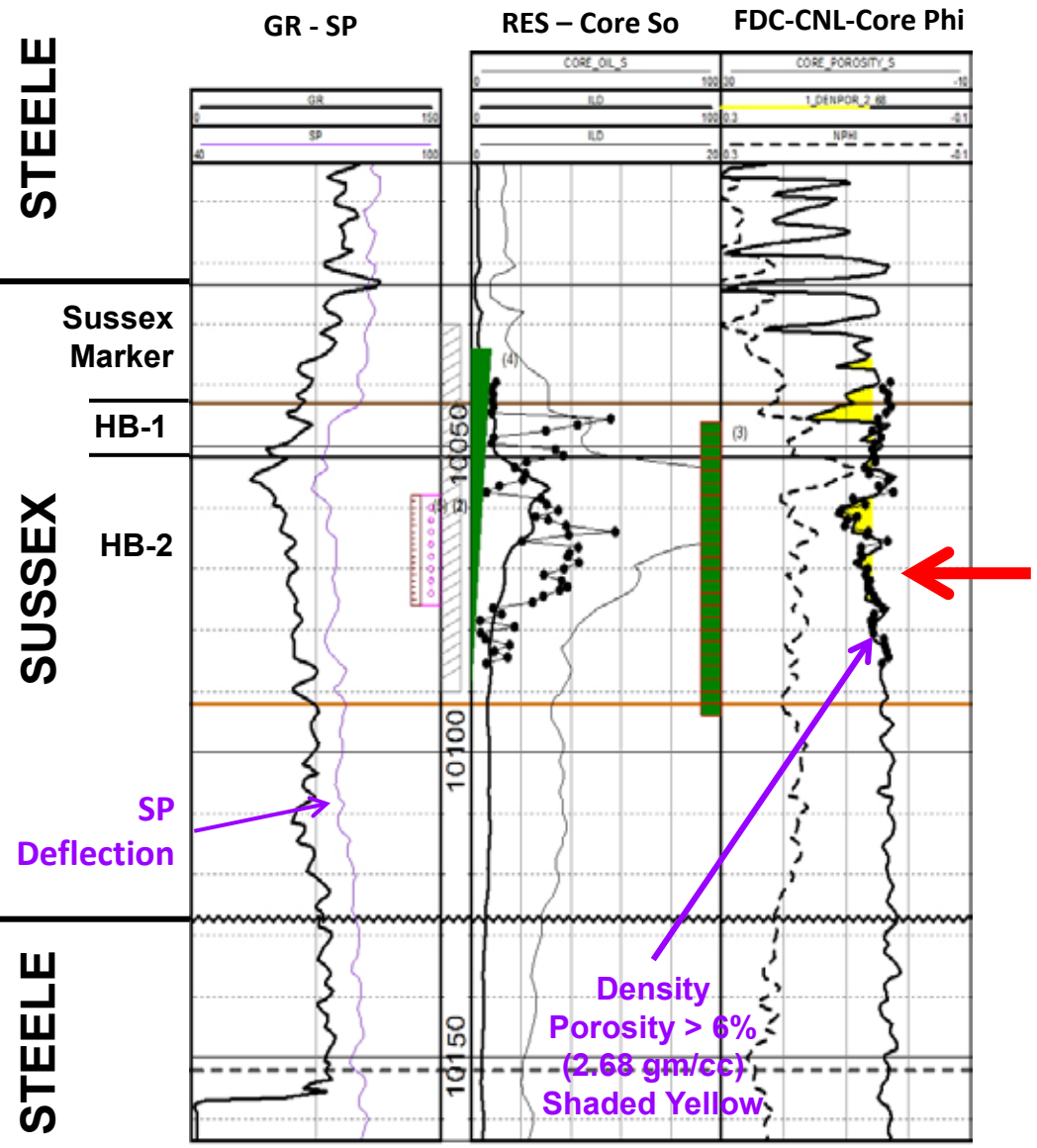
Compl. 9-1-84
Cum 190 MBO + 91 MMCF
+ 3 MBW

D&A 1-9-86
DST Rec. 70’ M

After Bottjer et al (2014)

Hornbuckle Field "Type" Core

HORNBUCKLE FIELD
LL & E
Highland Flats Federal #13-11
NW-SW-11-T37N-R73W



Bioturbated Muddy Sandstone

10,073(Log 10,071)

Sandstone, fine- to very fine-grained, bioturbated (> 75% burrows)

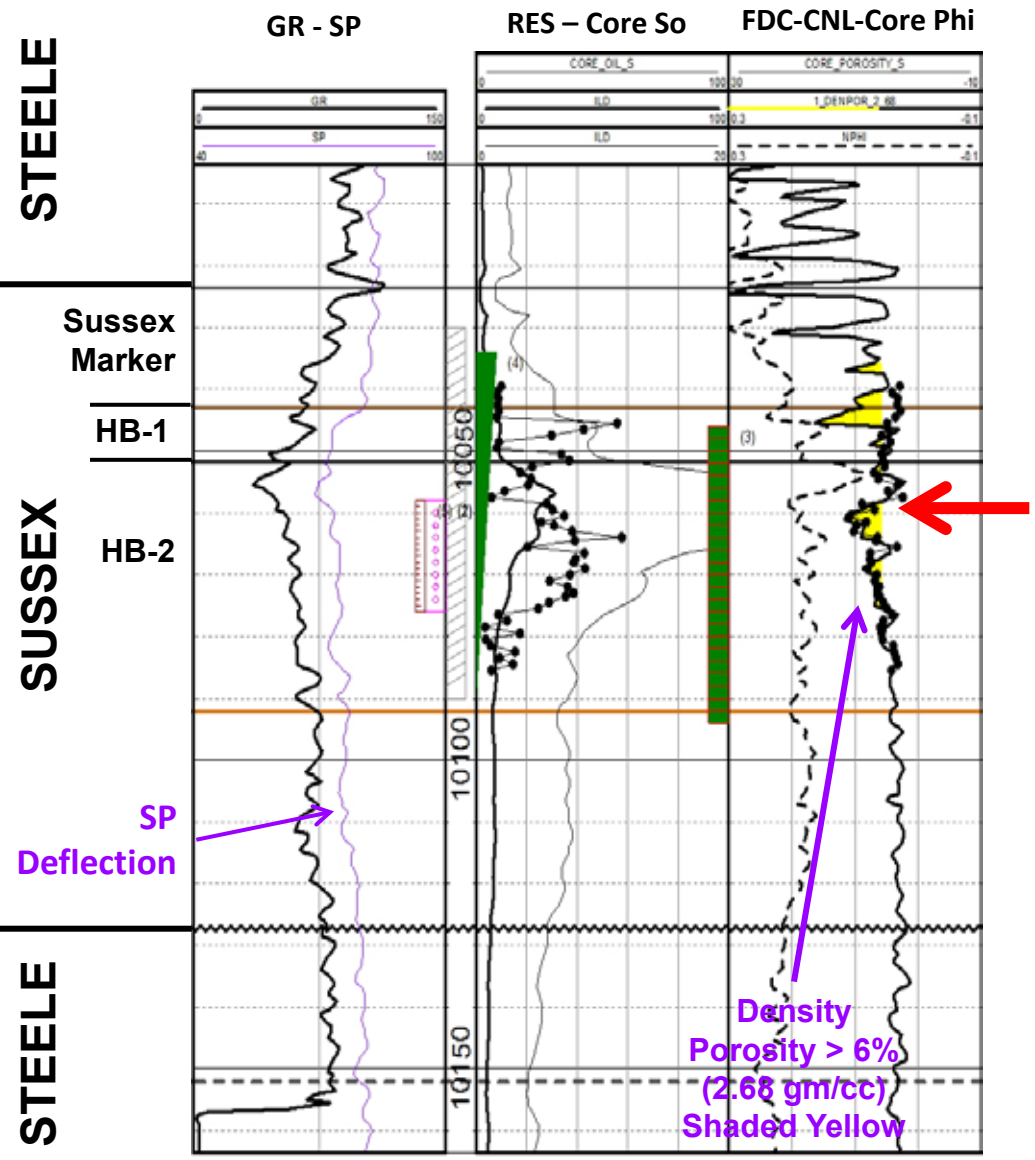
RCA @ 10,072-10,073
Phi 6.9%, k 0.07md
So 29.2%, GD 2.68 gm/cc

Depth Shift Log = Core – 2.0'

After Bottjer et al (2014)

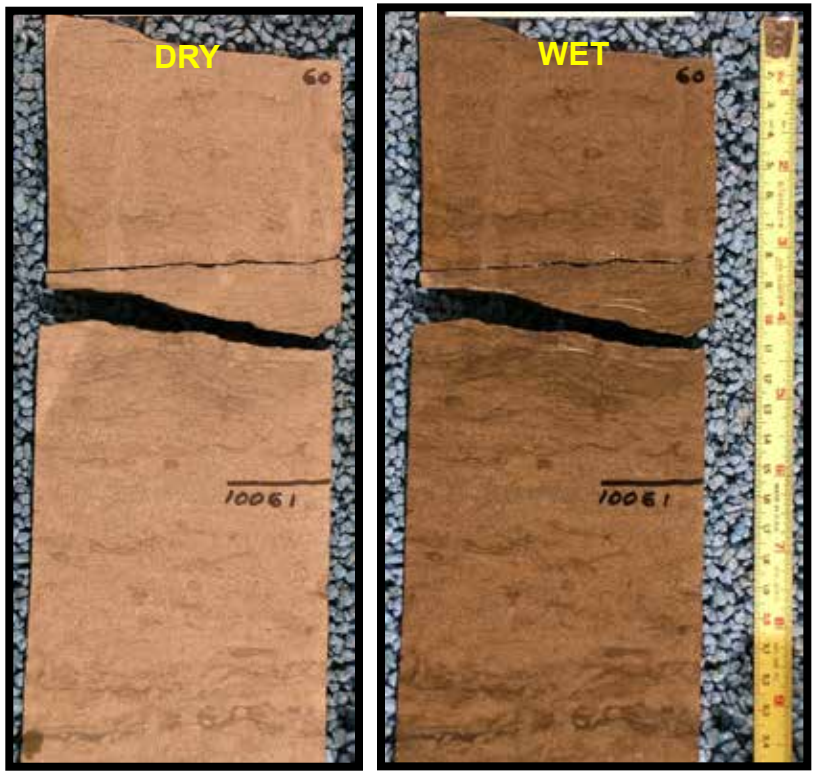
Hornbuckle Field "Type" Core

HORNBUCKLE FIELD
LL & E
Highland Flats Federal #13-11
NW-SW-11-T37N-R73W



Bioturbated Muddy Sandstone

10,060-061 (Log 10,058-059)



Sandstone, fine- to very fine-grained, bioturbated (> 75% burrows), very little primary bedding preserved

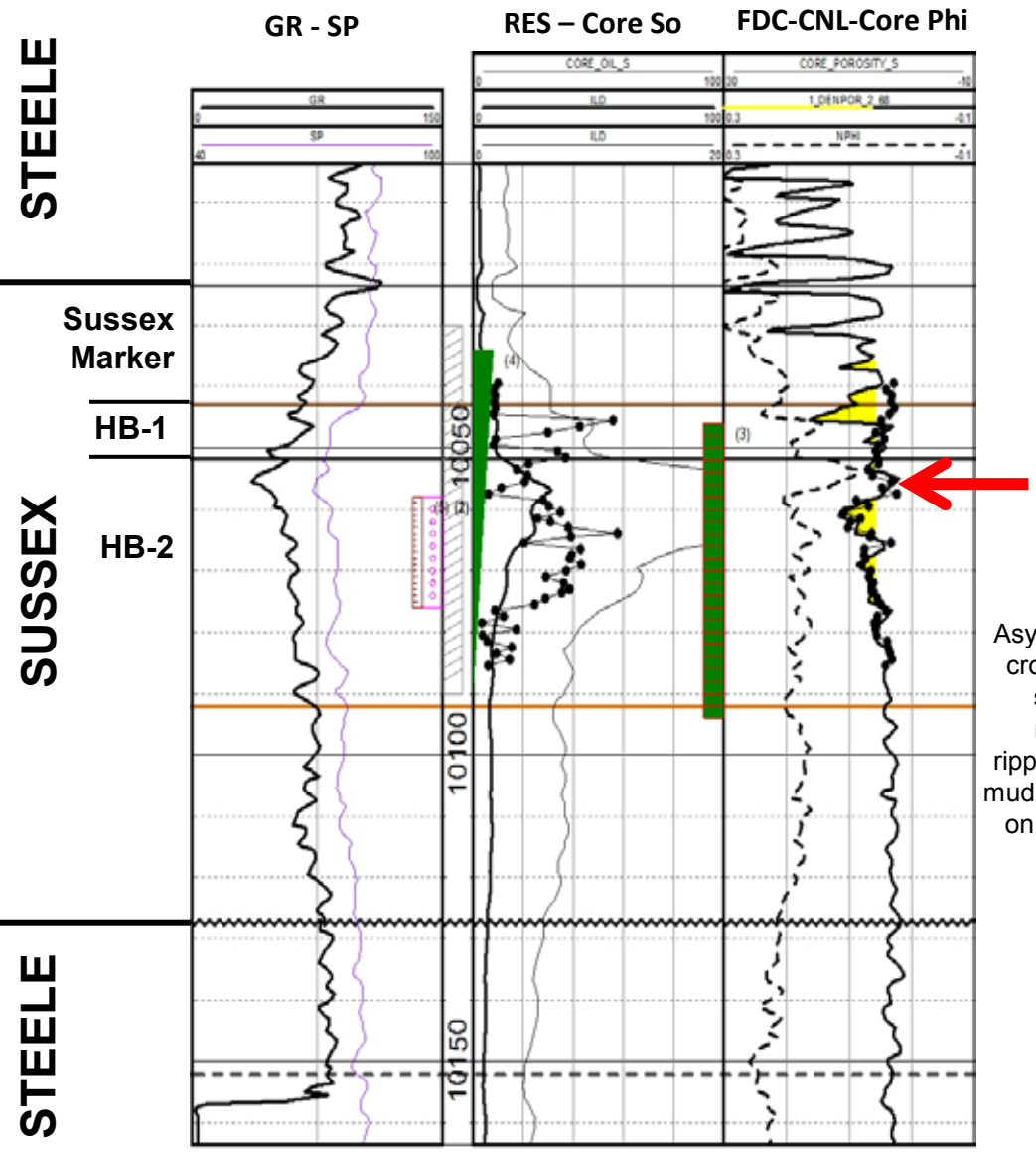
RCA @ 10,060-10,061
Phi 10.8%, k 0.93md
So 34.9%, GD 2.68 gm/cc

Depth Shift Log = Core – 2.0'

After Bottjer et al (2014)

Hornbuckle Field "Type" Core

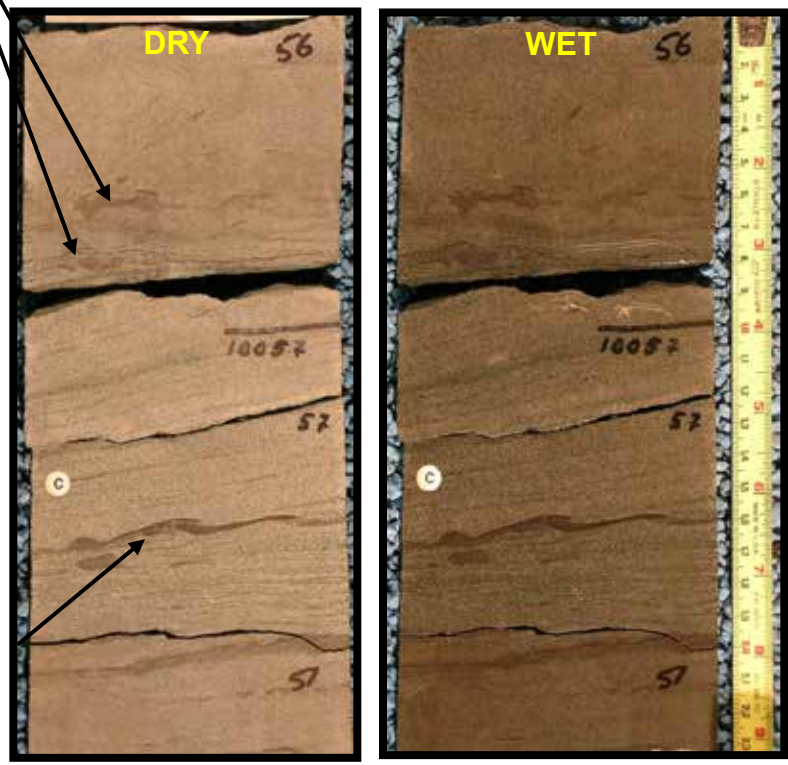
HORNBUCKLE FIELD
LL & E
Highland Flats Federal #13-11
NW-SW-11-T37N-R73W



Mudstone rip-up clasts

Cross-Bedded Sandstone

10,056-057 (Log 10,055-056)



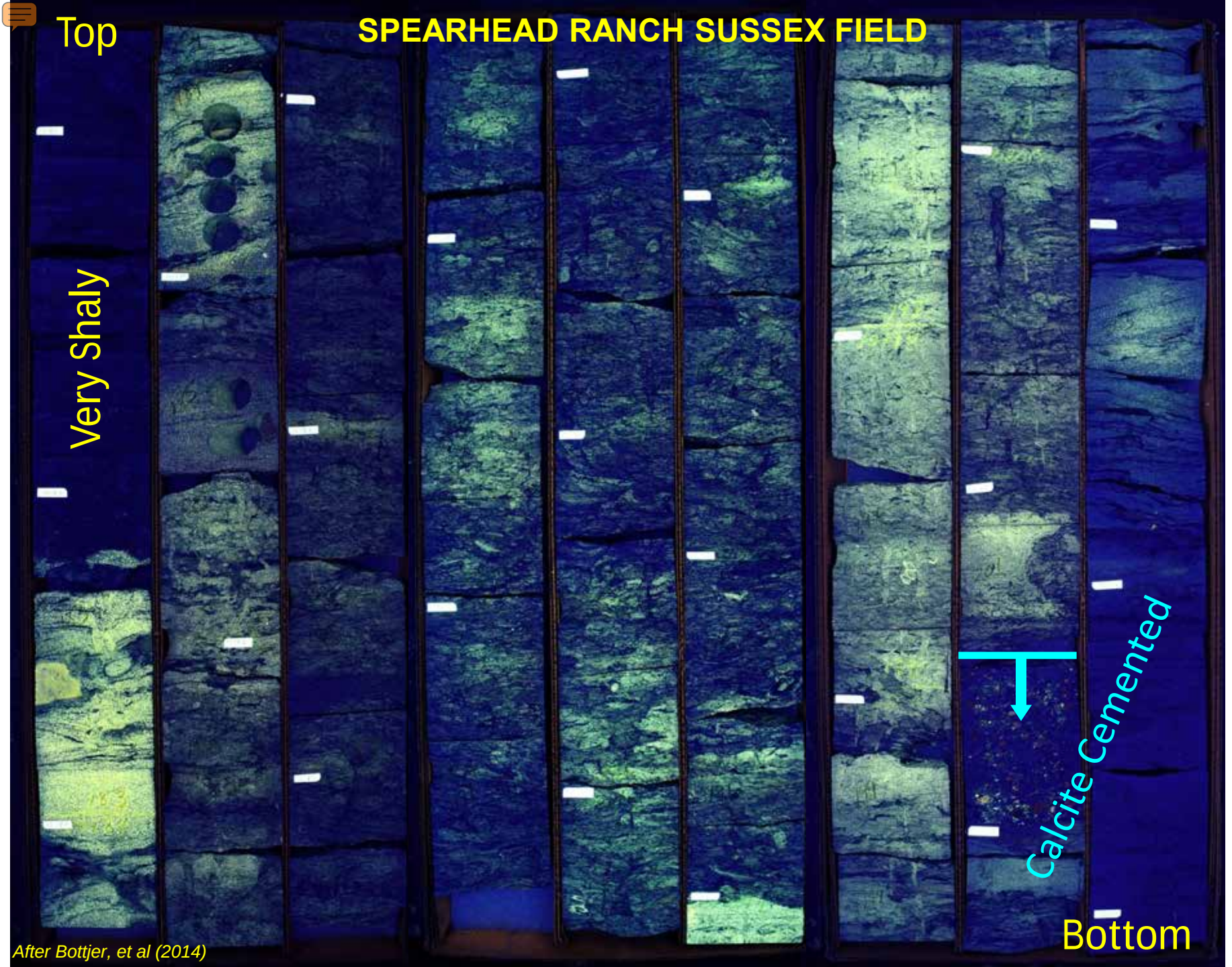
Asymptotic cross-bed set with reverse ripples and mud drapes on foreset

Sandstone, medium to fine grained, cross-bedded, 10-15% glauconite

RCA @ 10,057-10,058
Phi 2.4%, k 0.01md
So 6.1%, GD 2.69 gm/cc

Depth Shift Log = Core – 2.0'

After Bottjer et al (2014)


Top
SPEARHEAD RANCH SUSSEX FIELD
Very Shaly
Calcite Cemented
Bottom
2.5 feet
After Bottjer, et al (2014)

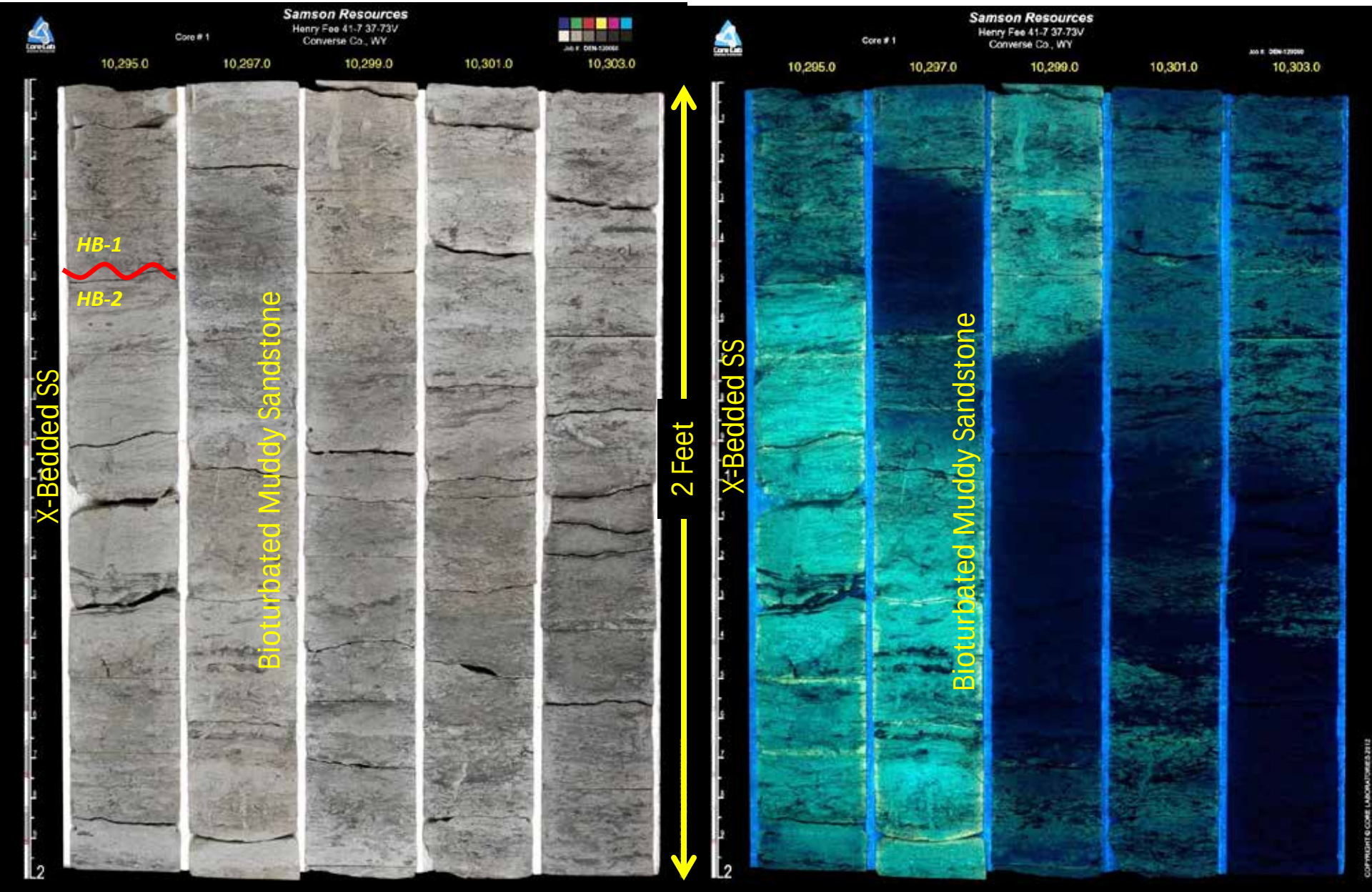
HORNBUCKLE FIELD

Samson Resources Henry Fee #1-7 (T696)

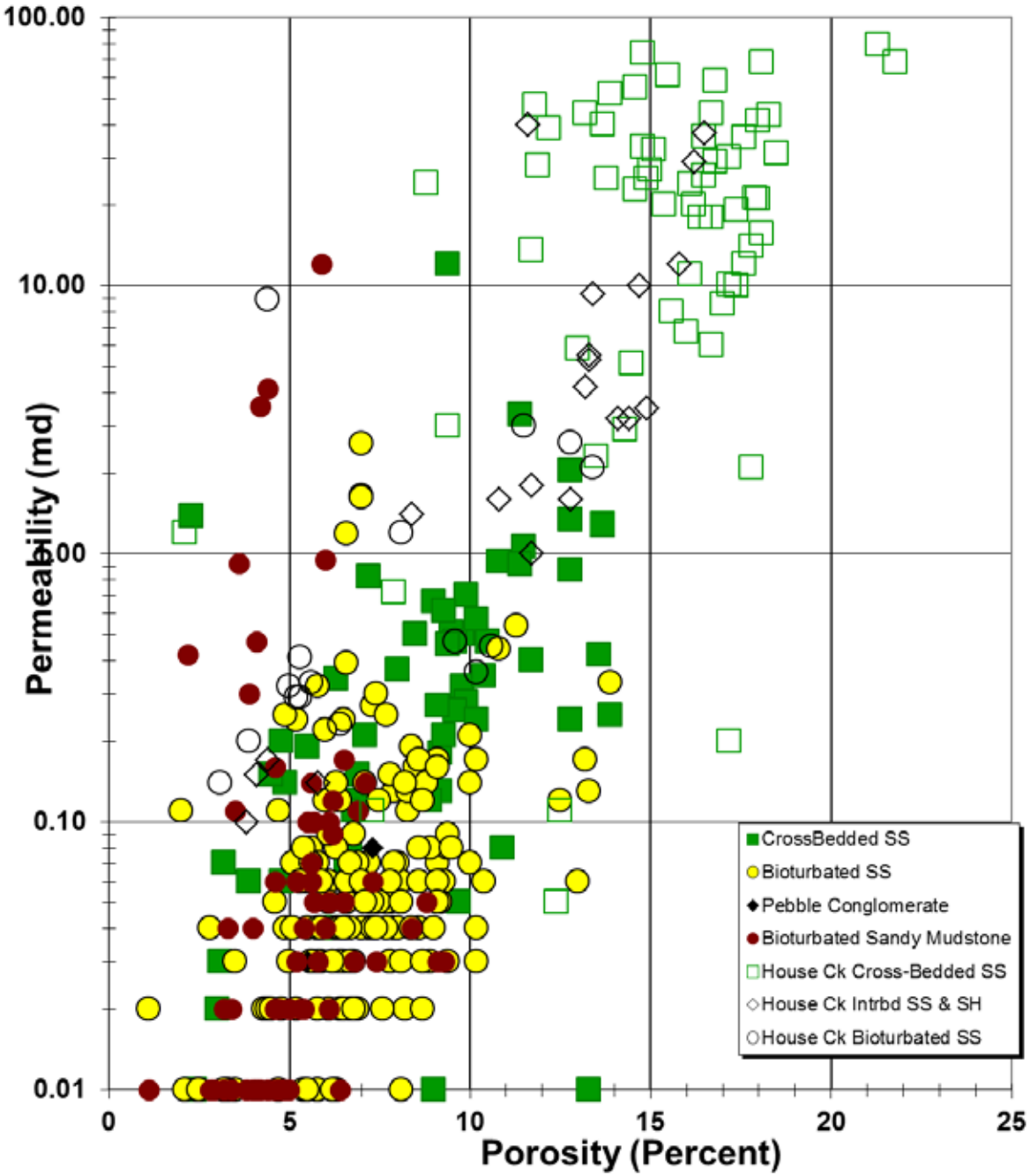
NE-NE-7-T37N-R73W

PLAIN LIGHT

UV LIGHT



Sussex Core Porosity vs Permeability



House Creek

- Unfilled Symbols
- Cross-Bedded Sandstone

Permeability 3-100 md.

- Waterflood

Hornbuckle

- Color-filled Symbols
- "Tight Oil"

<u>Cross-Bedded Sandstone</u>

- Phi 3-14%, Avg 8.8%
- k .01-4.0 md, Avg 0.63md

<u>Bioturbated Sandstone</u>

- Phi 1-14%, Avg 7.1%
- k .01-.60 md, Avg 0.12md

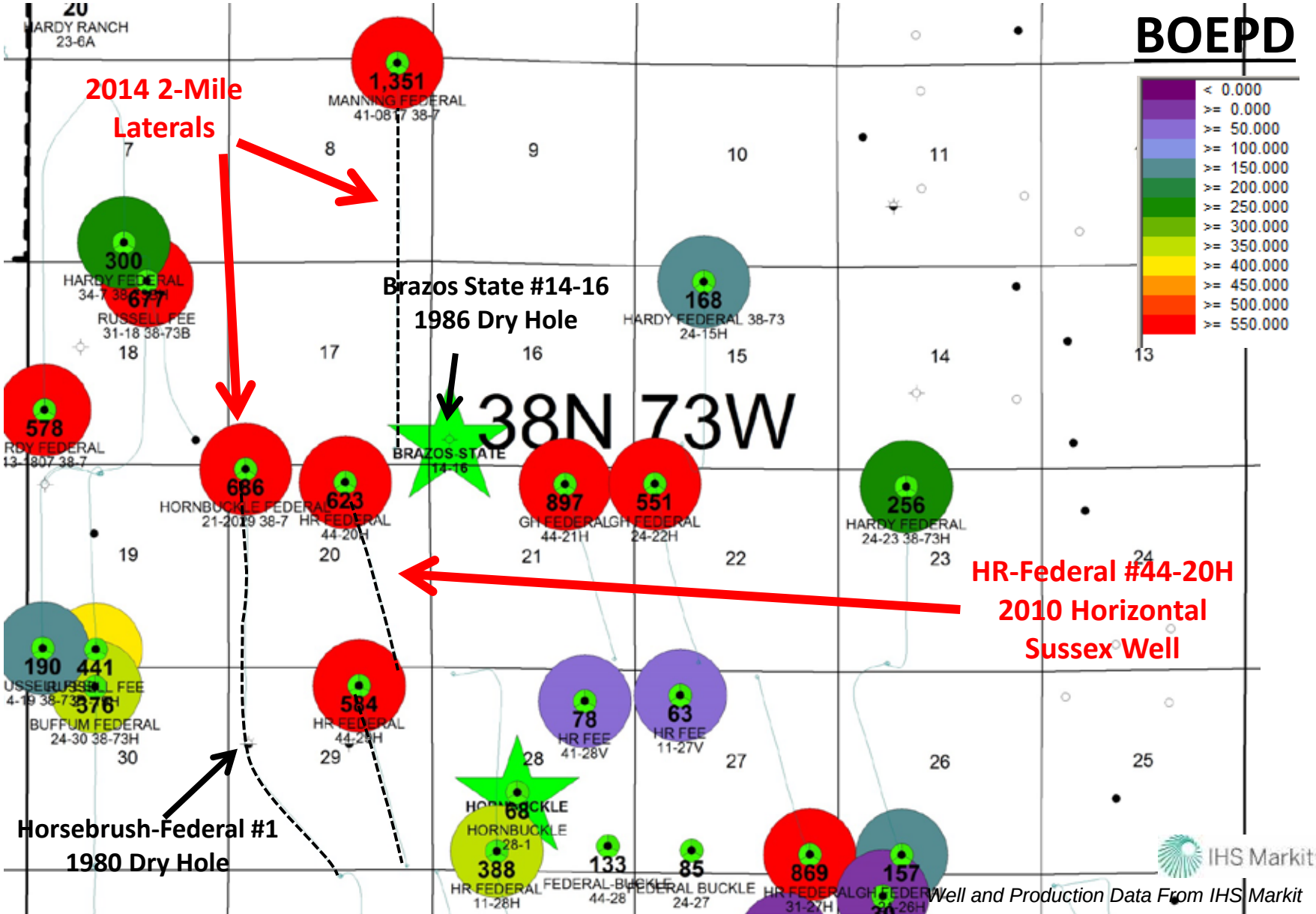
Conclusion

- Sussex Sandstone @ Hornbuckle is Different than Sussex Sandstone @ House Creek

After Bottjer et al (2014)

Recent Horizontal Drilling

Sussex Maximum Month Average Oil in BOEPD



IHS Markit

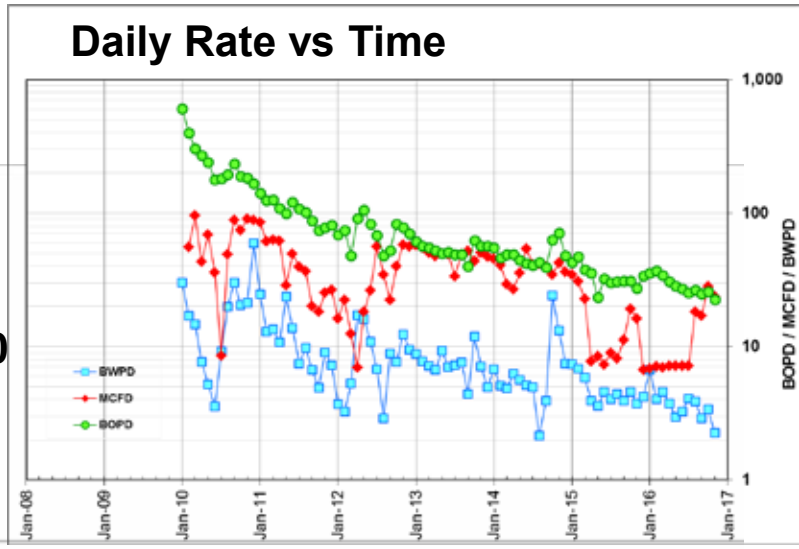
Well and Production Data From IHS Markit

Hornbuckle Field 2010 Horizontal Sussex Well

HR-Federal #44-20H

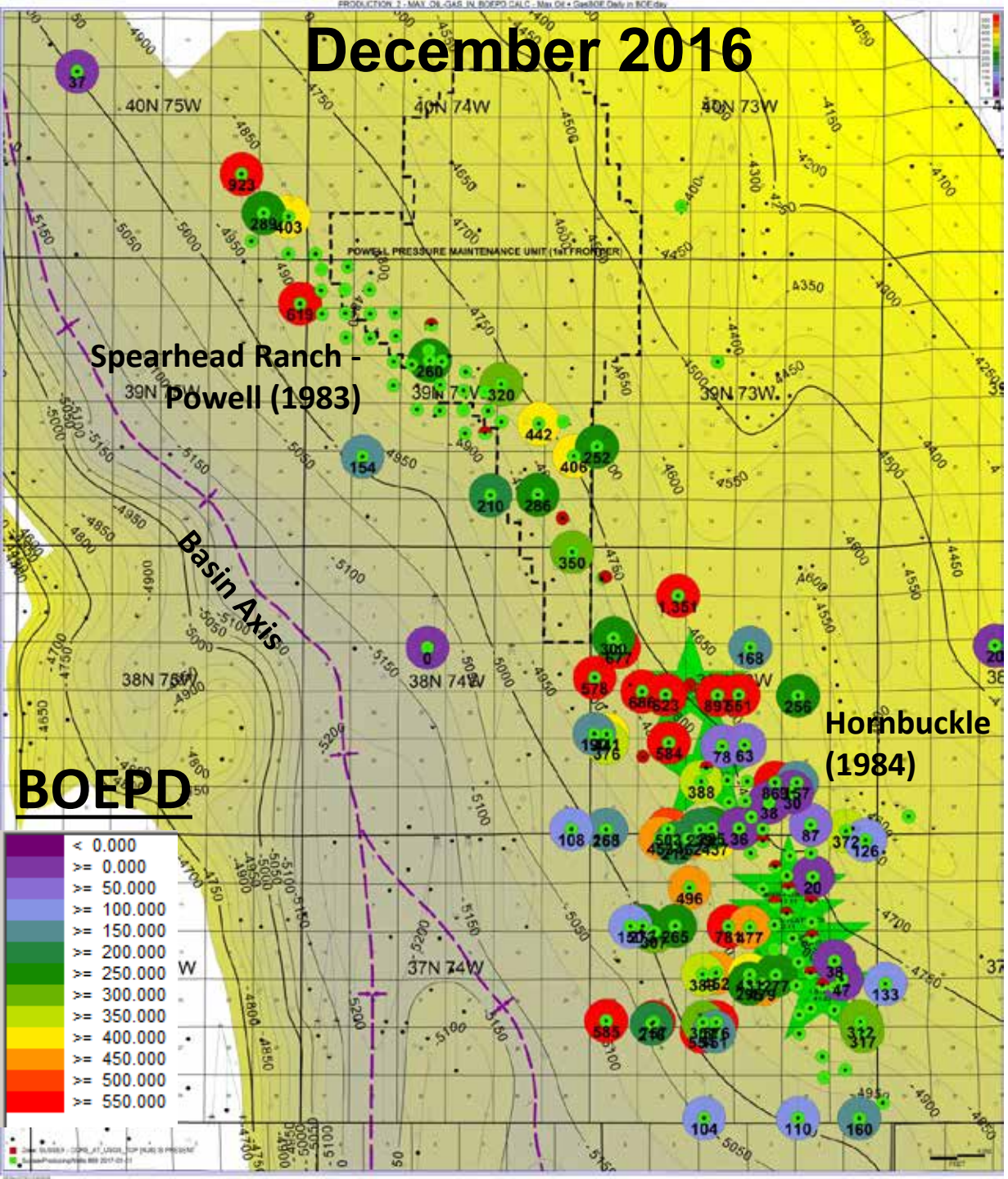
Lateral Length – 4152 Feet
Frac 10 Stages, Packers & Sleeves
Total 2.35 MM lbs Sand + 1.12 MM gals water

IPF 1077 BOPD + 1204 BW, 1100 psi FTP, 14/64" ck
Cum 200 MBO + 82 MMCF + 21 MBW (Nov. 2016)
36.6 API



Production Data From IHS Markit

After Bottjer et al (2014)



SUSSEX MARKER STRUCTURE

CI = 50 Feet

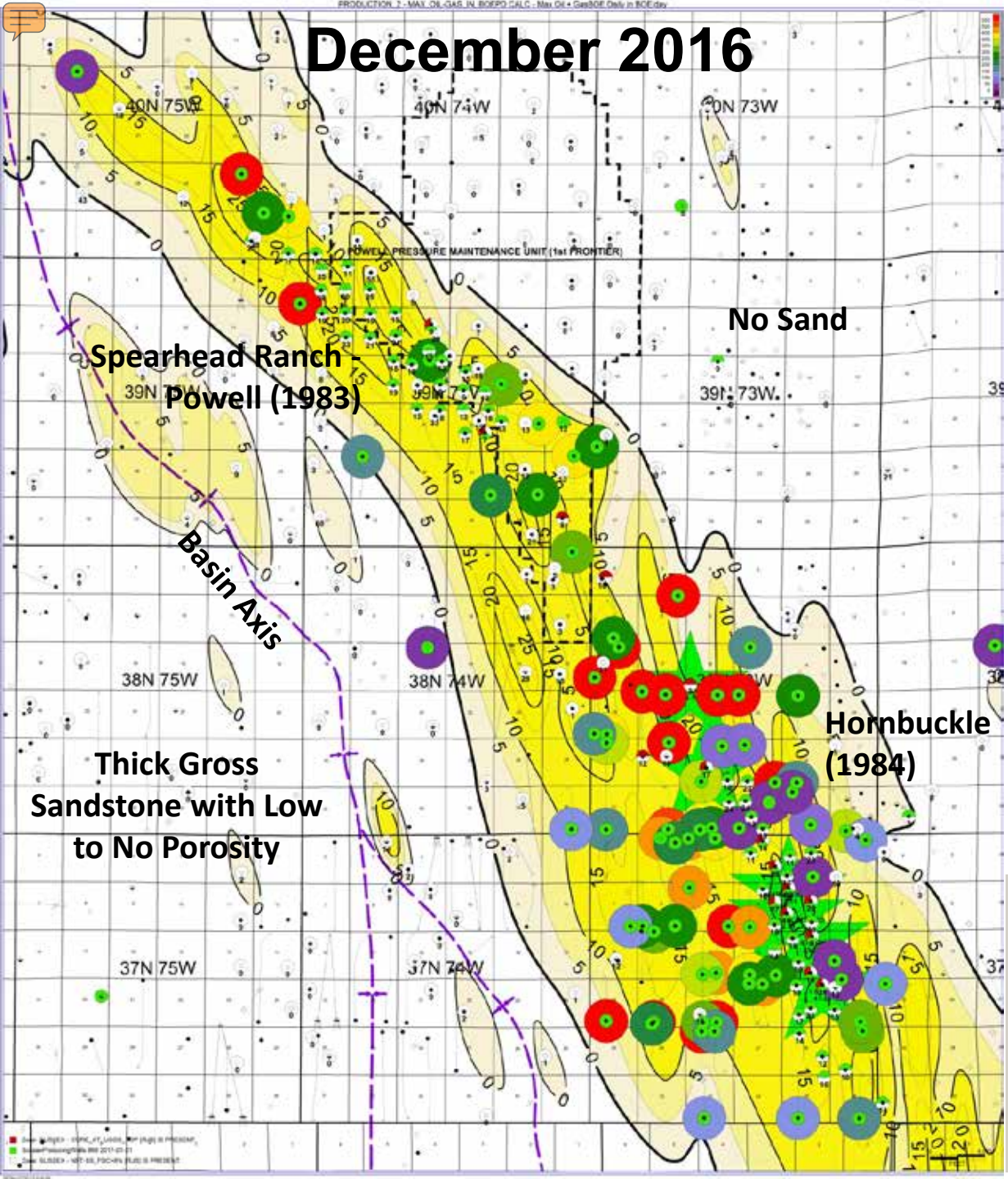
Maximum Monthly Rate Daily Average in BOEPD Bubbles

Red > 500 BOPD

Hornbuckle & Spearhead Ranch - Formerly Separate Fields have Merged Due to Horizontal Drilling

IHS Markit

Well and Production Data From IHS Markit



ISOPACH SUSSEX NET FEET OF POROSITY >8%

CI = 5 Feet

Maximum Monthly Rate Daily Average in BOEPD Bubbles

Red > 500 BOPD

BOEPD

- < 0.000
- >= 0.000
- >= 50.000
- >= 100.000
- >= 150.000
- >= 200.000
- >= 250.000
- >= 300.000
- >= 350.000
- >= 400.000
- >= 450.000
- >= 500.000
- >= 550.000

IHS Markit

Well and Production Data From IHS Markit

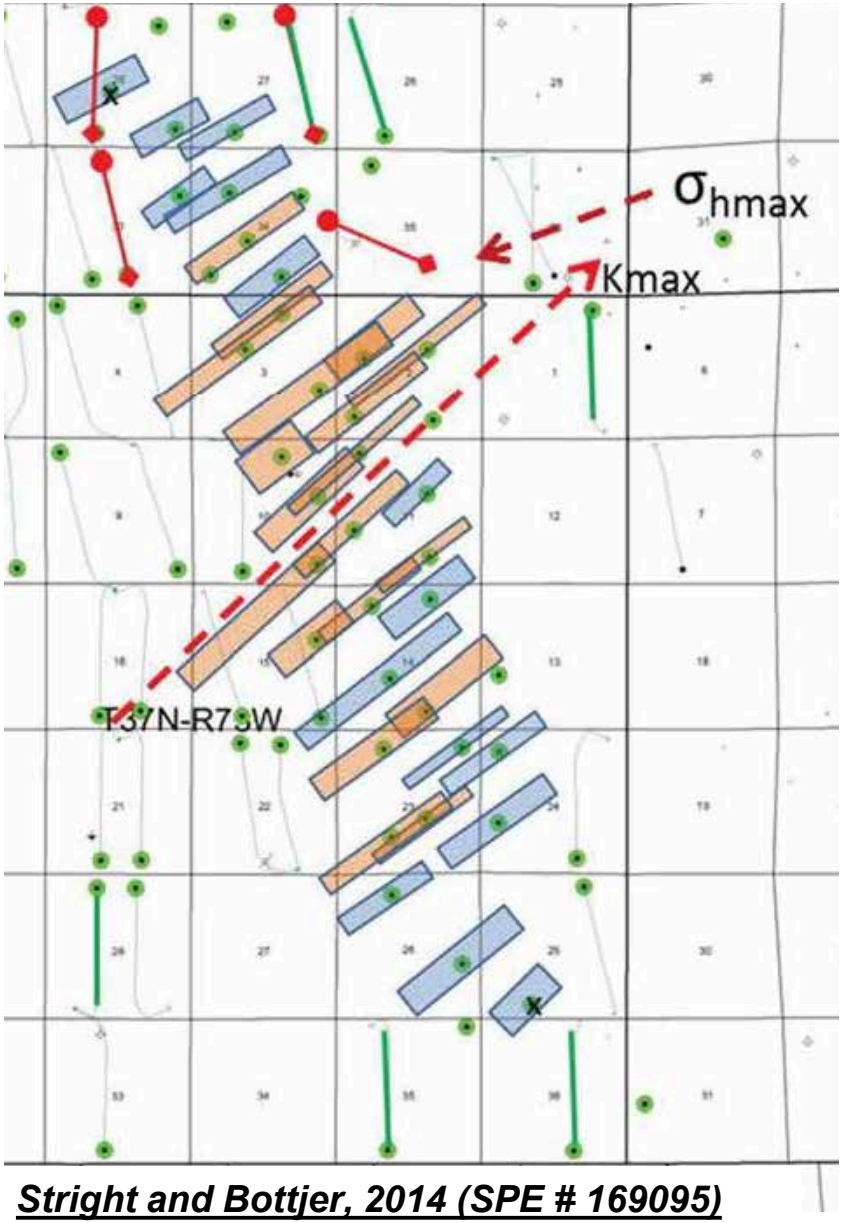
HORNBUCKLE SUSSEX CONCLUSIONS

- **Initial Hornbuckle-Spearhead Sussex Field Development with Vertical Wells Was Based on Distribution of High-Permeability Cross-Bedded Facies**
- **Significant Oil Pay Exists in Bioturbated Sandstone**
- **Integration of Geological and Engineering Analyses Led to Drilling of Horizontal Wells**
- **The Sussex Sandstone in the Hornbuckle-Spearhead Trend is a Tight-Oil Reservoir that is Most Efficiently Developed with Horizontal Drilling & Multi-Stage Fracture Stimulations**
- **So Tight Oil Sandstone Plays are Easy, Right?**

Vertical Wells Drainage Areas

Blue = Single Well per "container"

Orange = Interference

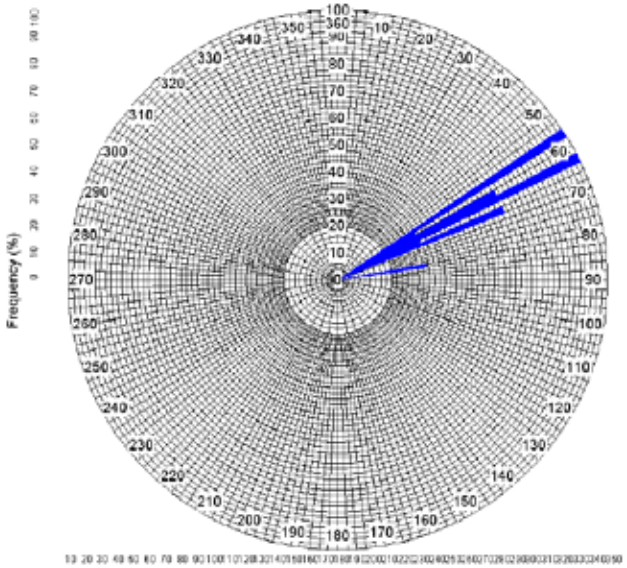


Stright and Bottjer, 2014 (SPE # 169095)

Hornbuckle Field Engineering Production Analysis

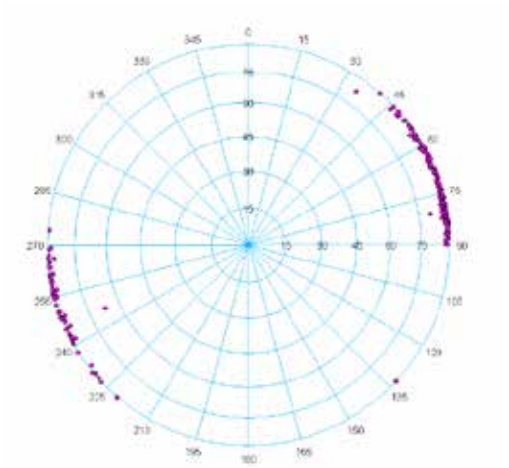
- **Hornbuckle Sussex Producers Exhibit Long-Term (>15 years) Linear Flow**
- **Directional Permeability ~ 10:1; Kmax ~ N45E**
- **High Degree of Permeability Anisotropy in High-Permeability Facies**
- **Interference In Some Cases (Orange Drainage Areas)**
- **Avg. Pay Height = 75 Feet Bioturbated Low-Permeability Facies Contributes to ROIP; Do Not Use Porosity Cutoff for Pay Determination**
- **Anisotropic Reservoir Compartments are Larger than Core-Scale and are Too Small to Resolve with Well Logs**

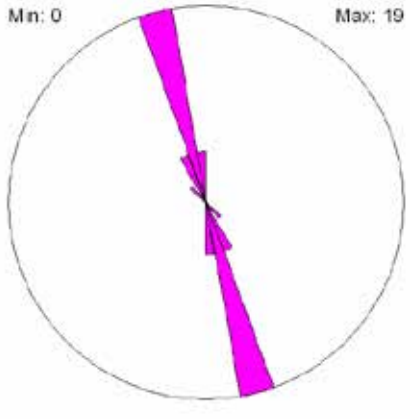
Hornbuckle Field
Southwestern Prod. Corp.
Blaylock Fee #42-34V
NE-34-38N-73W
Spud 9-11-2007



Sonic Scanner

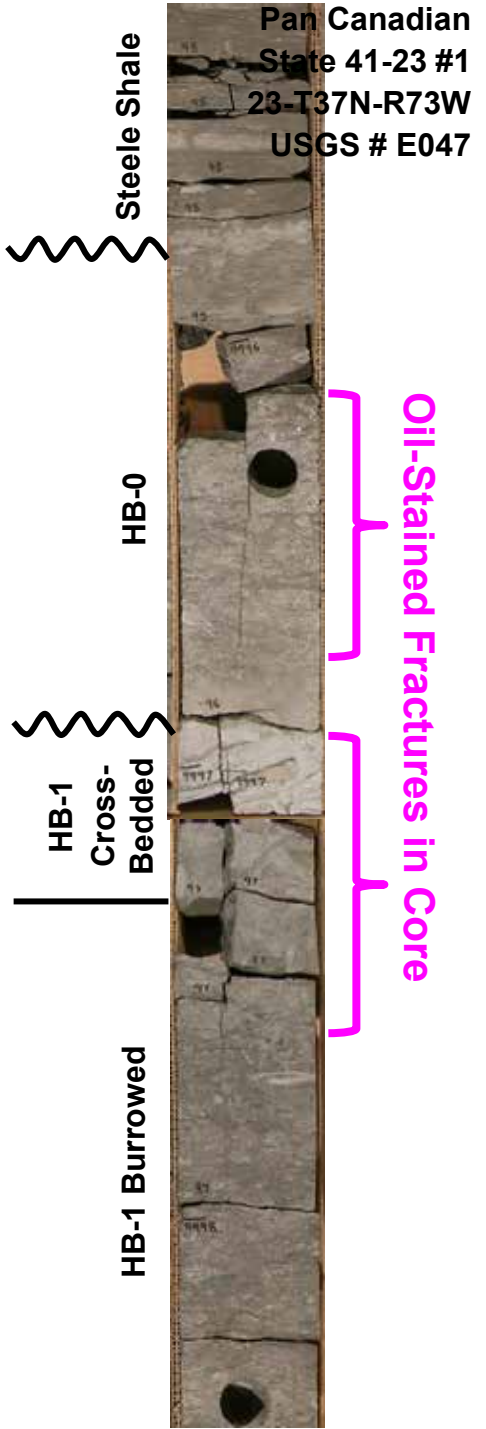
Fast Shear Azimuth
Maximum Stress 60°

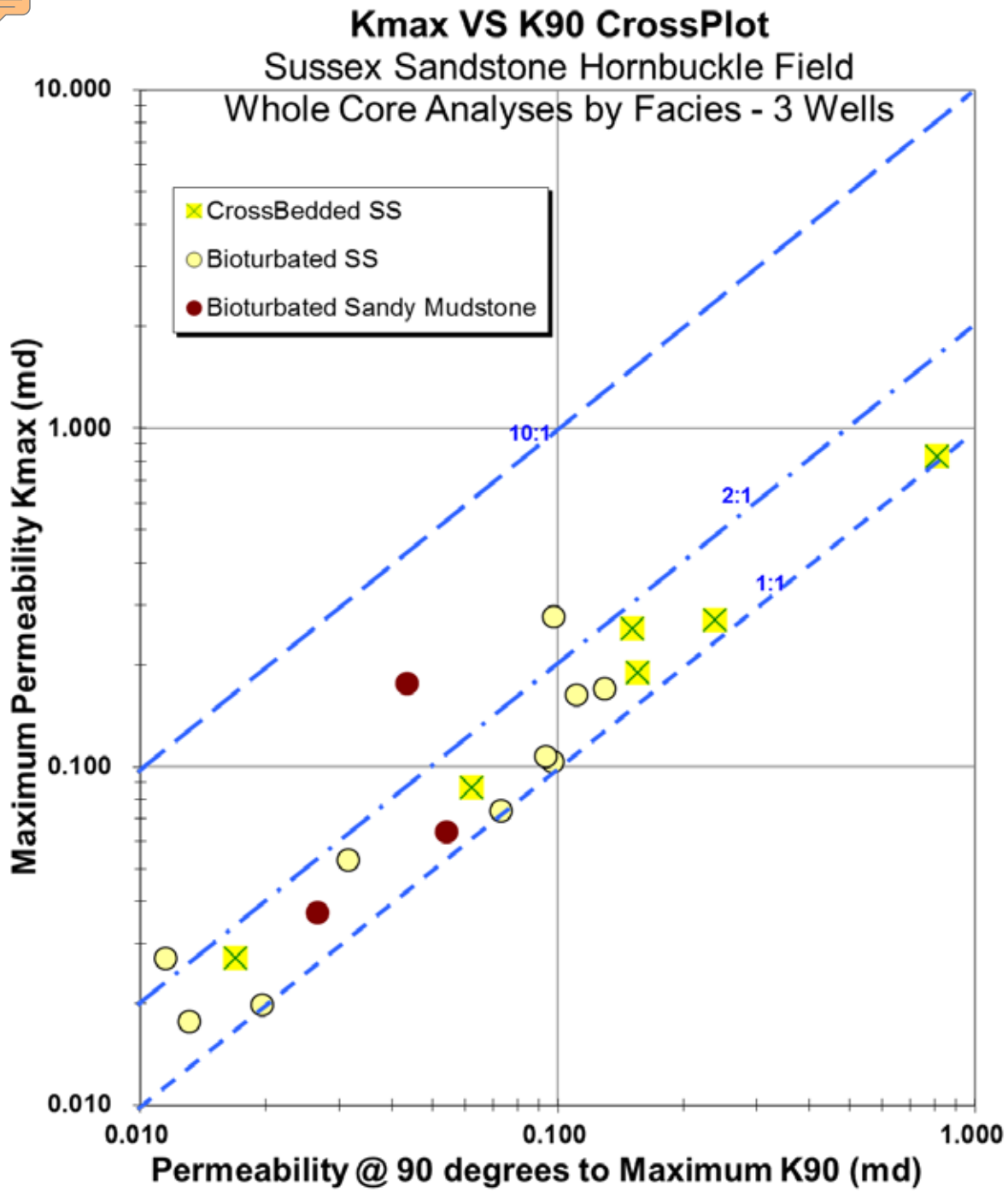




FMI

Borehole Breakouts
Average 165°
Present-Day Maximum Horizontal Stress = 75°
Fractures Rare to Absent

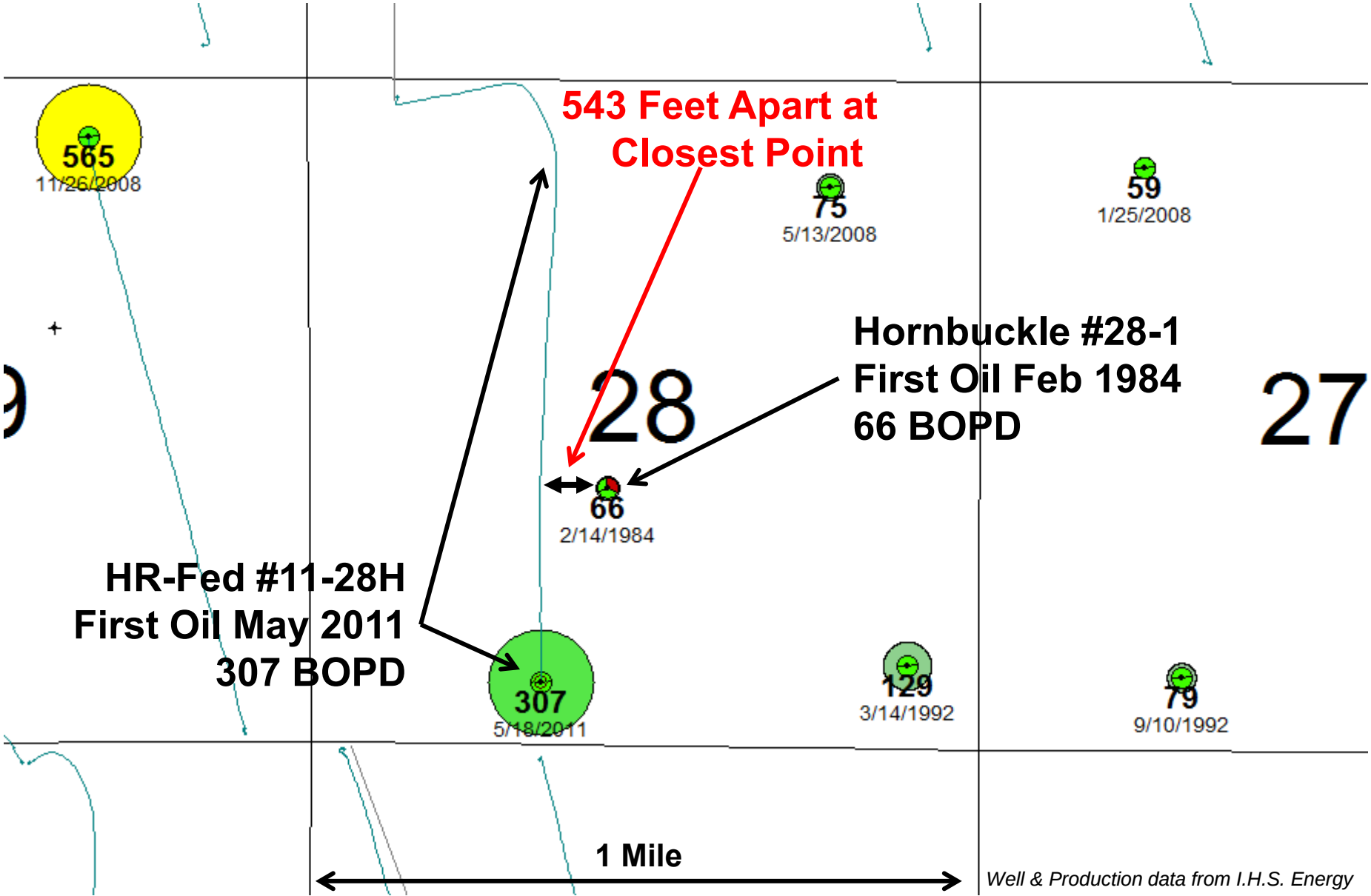




Hornbuckle Field Whole Core Max Permeability vs. K90 Permeability

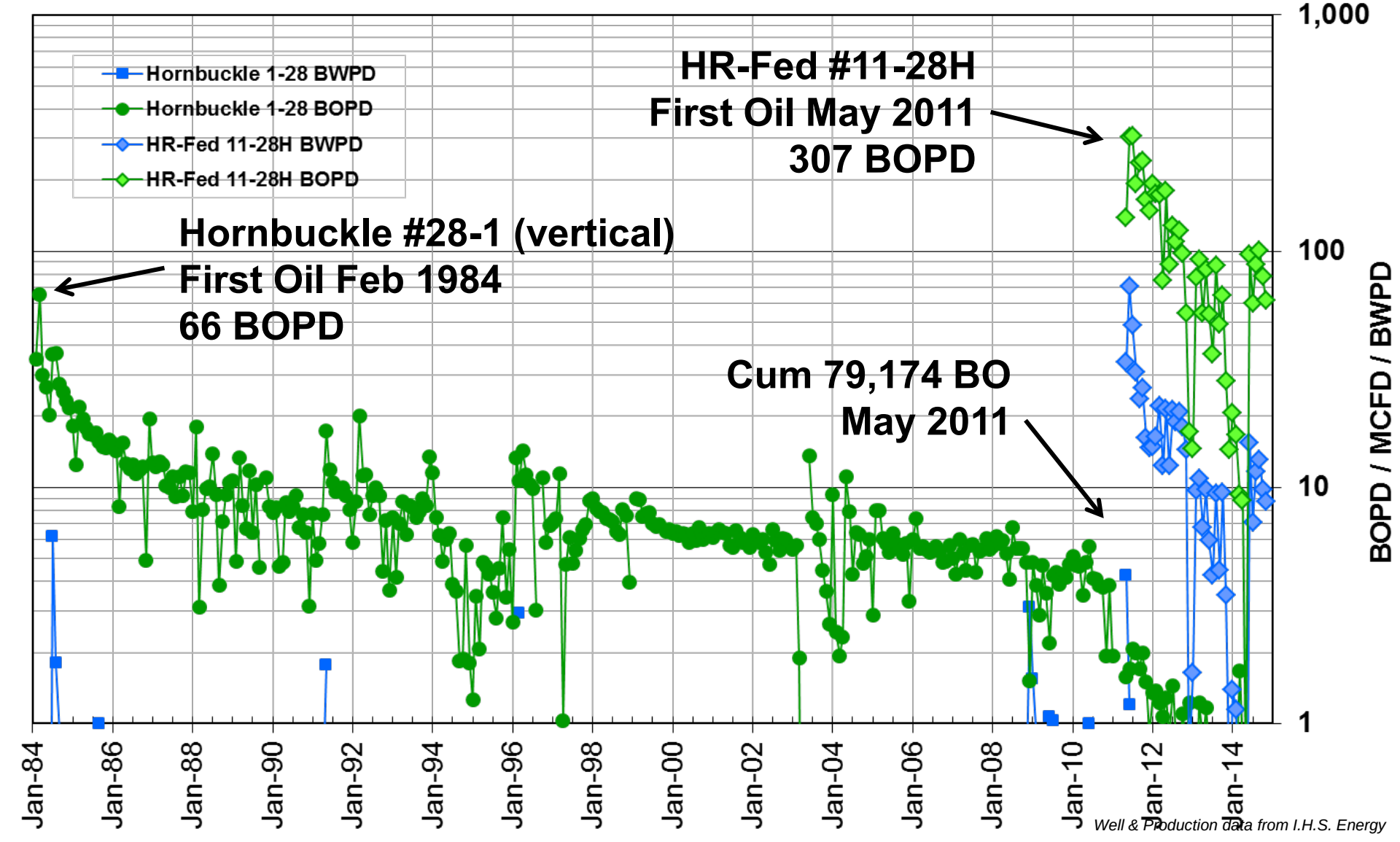
- Minor Directional Permeability at the Core Scale ~ 1.5:1
- Reservoir Modeling Indicates Much Higher Reservoir Anisotropy
- Anisotropic Reservoir Compartments are Larger than Core-Scale and are Too Small to Resolve with Well Logs

New Horizontal Well Drilled Close to Existing Vertical Well



Well & Production data from I.H.S. Energy

HR-Fed #11-28H Horizontal Competes for Oil with Existing Hornbuckle #28-1 Vertical Well



Well & Production data from I.H.S. Energy

Hornbuckle Field 2011 Horizontal Sussex Well

HR-Federal #11-28H

HORNBUCKLE
SUSSEX
132,619
135,729

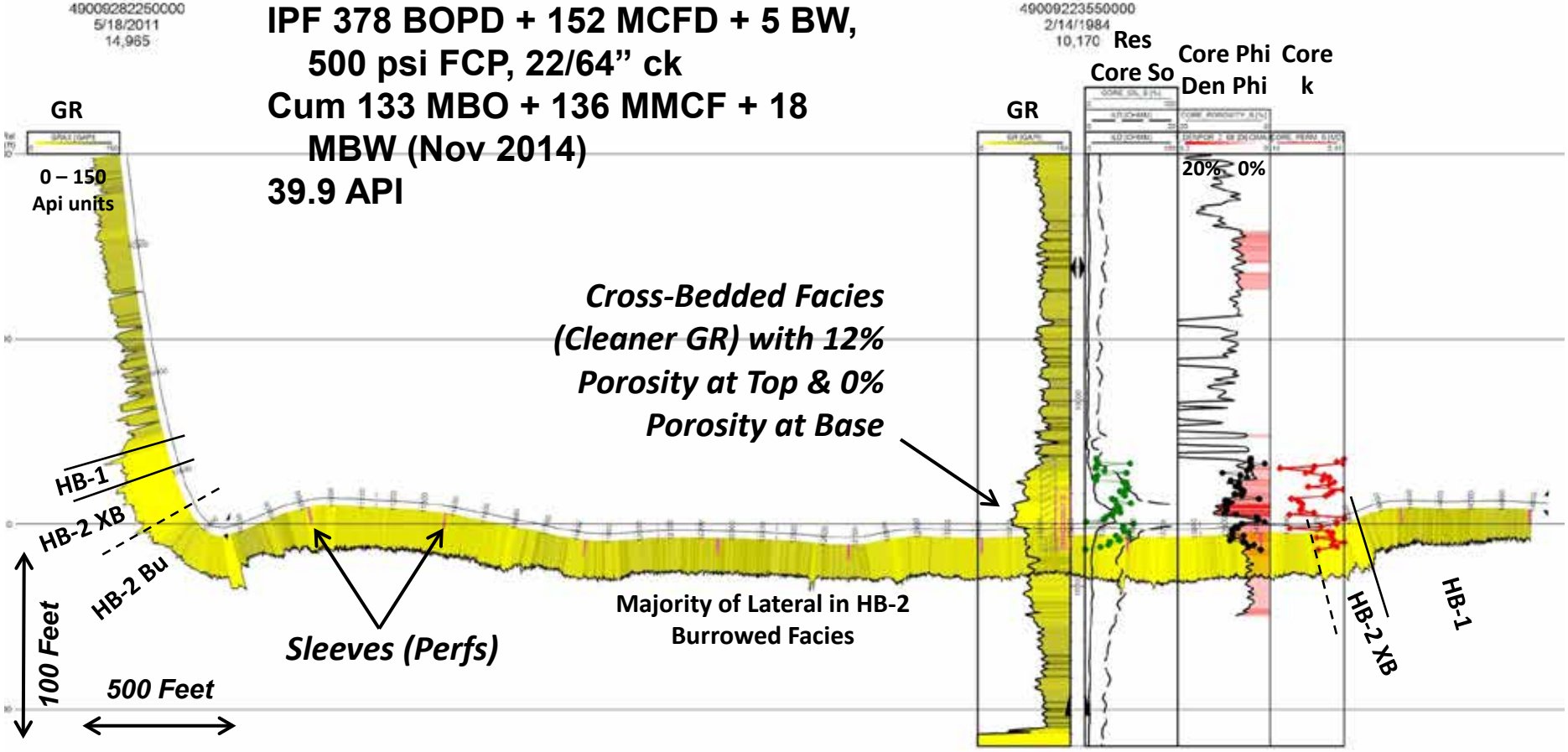
T38N R73W S28
NW NW
SAMSON RESOURCES COMPANY
HR FEDERAL
11-28H
49009282250000
5/18/2011
14,965

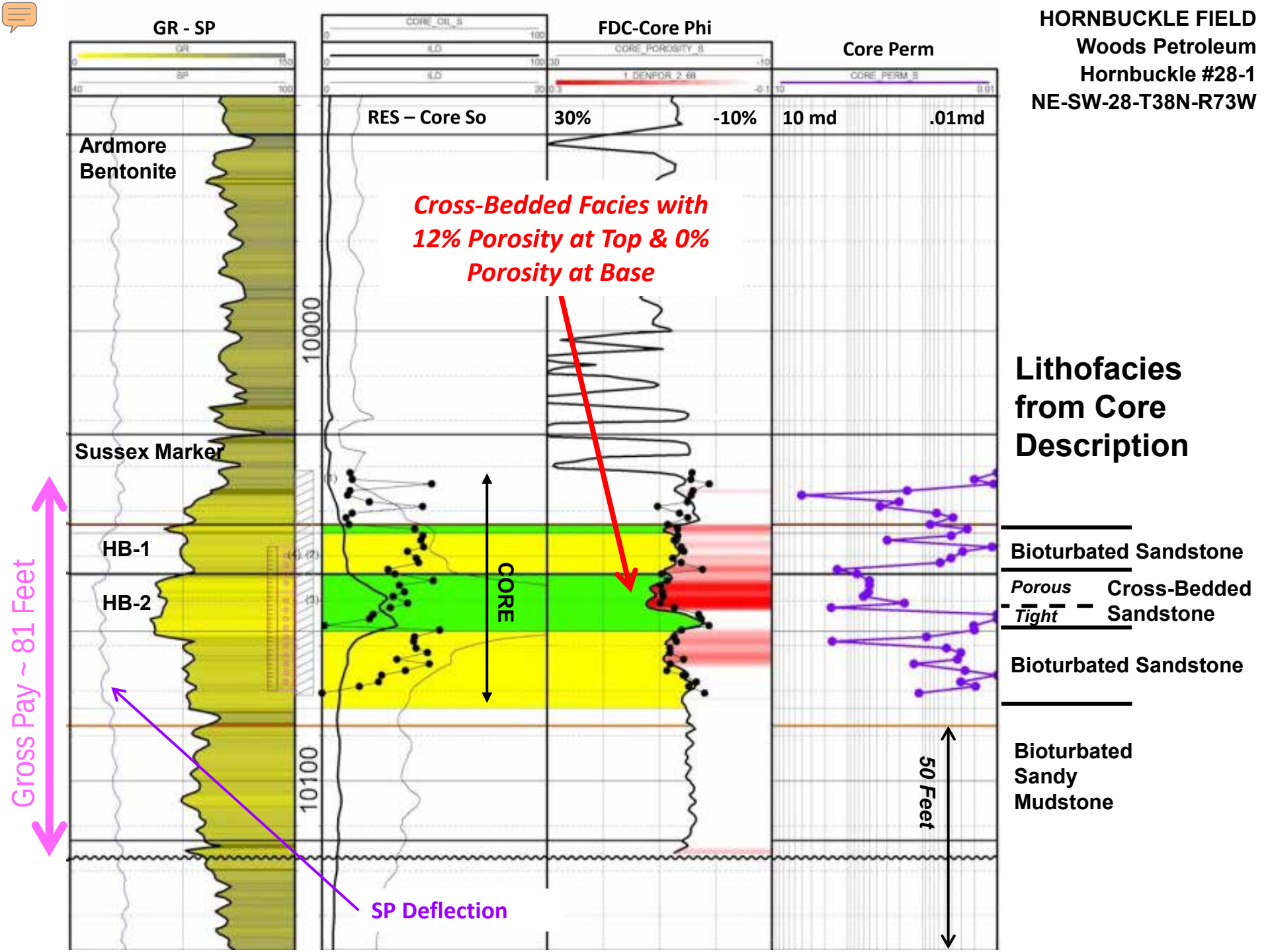
Lateral Length – 4265 Feet
Frac 10 Stages, Packers & Sleeves
Total 2.38 MM lbs Sand + 1.01 MM gals water

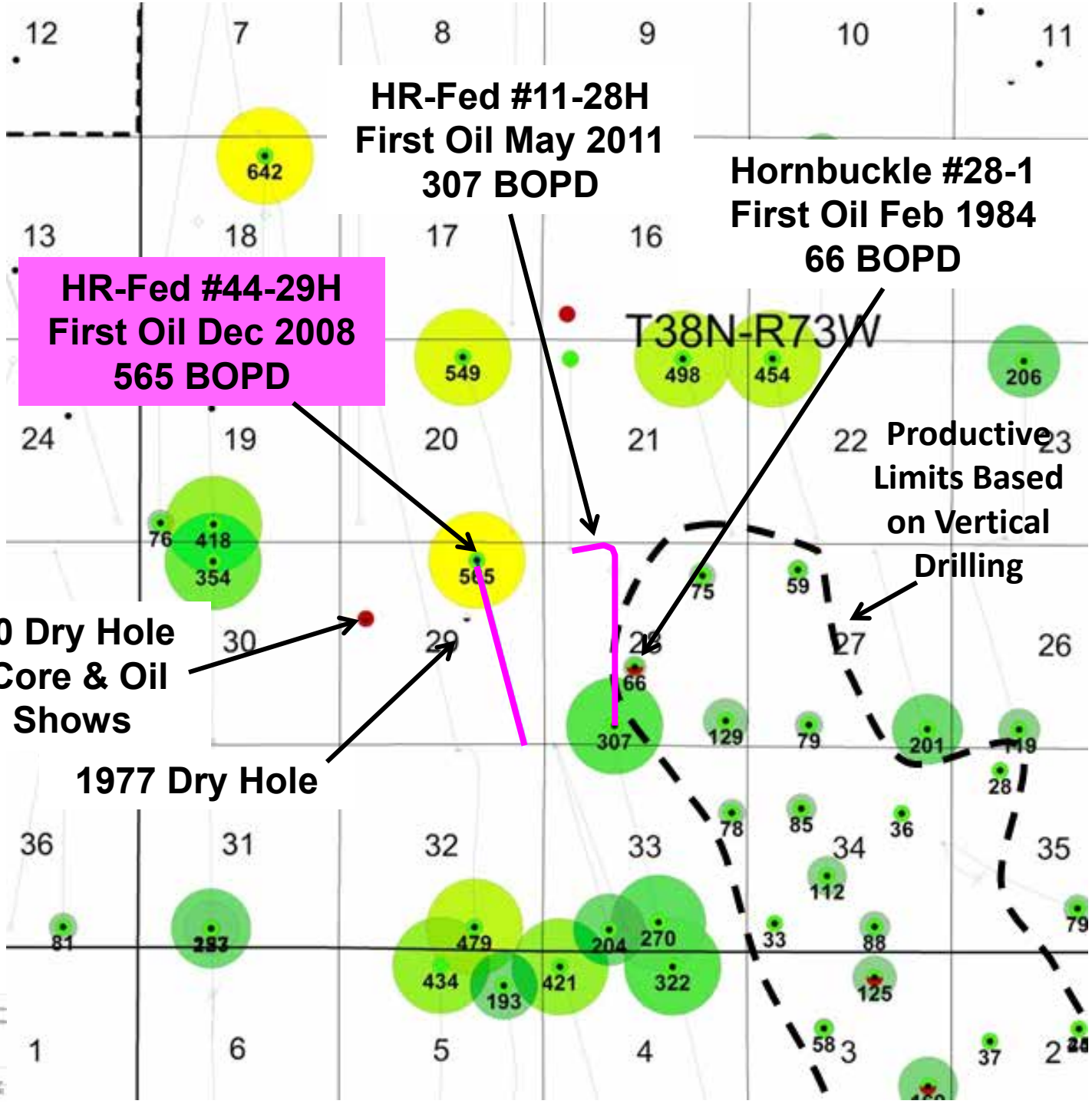
IPF 378 BOPD + 152 MCFD + 5 BW, 500 psi FCP, 22/64" ck
Cum 133 MBO + 136 MMCF + 18 MBW (Nov 2014)
39.9 API

HORNBUCKLE
SUSSEX
80,290
15,826

T38N R73W S28
NE NE SW
WOODS PETROLEUM CORP
HORNBUCKLE
28-1
49009223550000
2/14/1984
10,170




HORNBUCKLE FIELD
Woods Petroleum
Hornbuckle #28-1
NE-SW-28-T38N-R73W
GR - SP
FDC-Core Phi
Core Perm
RES – Core So
30%
-10%
10 md
.01md
Ardmore Bentonite
Cross-Bedded Facies with 12% Porosity at Top & 0% Porosity at Base
Sussex Marker
HB-1
HB-2
CORE
10000
10100
Gross Pay ~ 81 Feet
50 Feet
SP Deflection
Lithofacies from Core Description
Bioturbated Sandstone
Porous
Tight
Cross-Bedded Sandstone
Bioturbated Sandstone
Bioturbated Sandy Mudstone

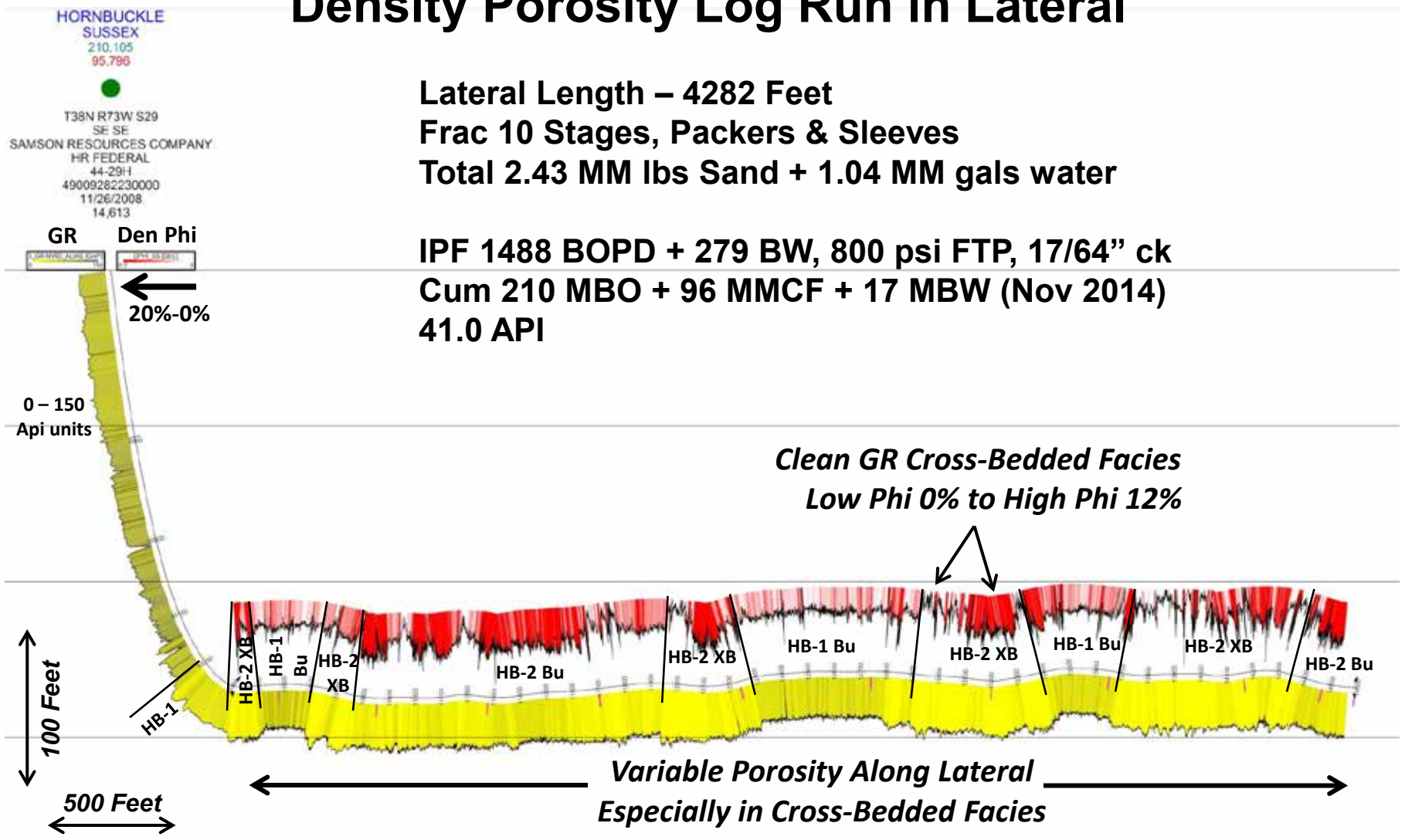


Well & Production data from I.H.S. Energy

Hornbuckle Field 2011 Horizontal Sussex Well

HR-Federal #44-29H

Density Porosity Log Run in Lateral

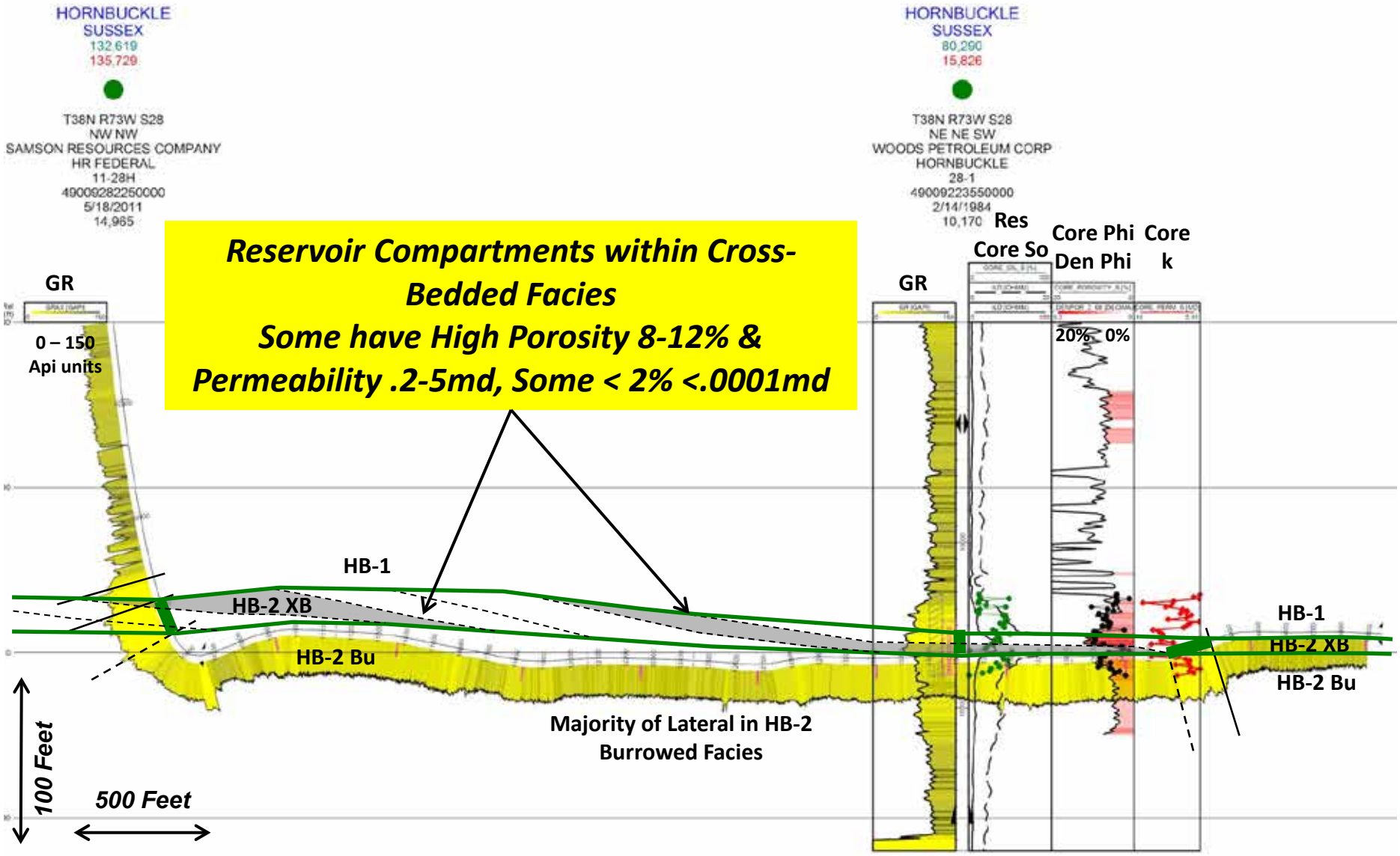


Lateral Length – 4282 Feet
Frac 10 Stages, Packers & Sleeves
Total 2.43 MM lbs Sand + 1.04 MM gals water

IPF 1488 BOPD + 279 BW, 800 psi FTP, 17/64” ck
Cum 210 MBO + 96 MMCF + 17 MBW (Nov 2014)
41.0 API

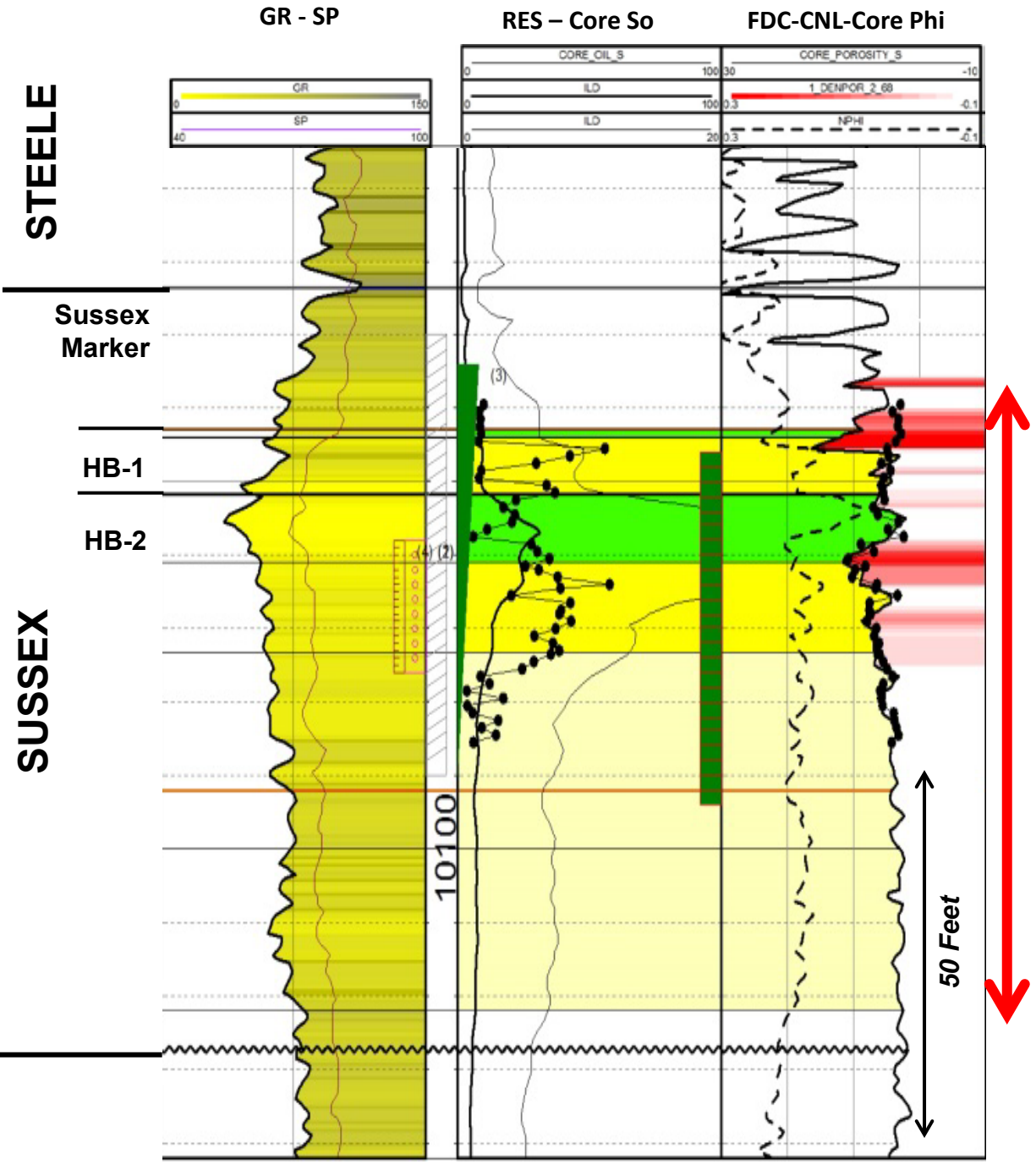
Hornbuckle Field 2011 Horizontal Sussex Well

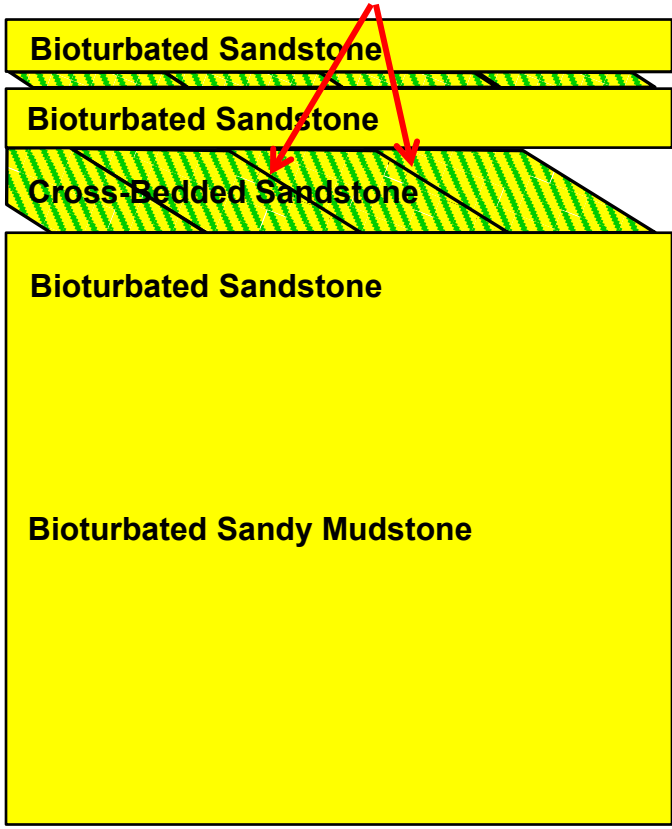
HR-Federal #11-28H



HORNBUCKLE FIELD
LL & E
Highland Flats Federal #13-11
NW-SW-11-T37N-R73W

INTERPRETED RESERVOIR MODEL





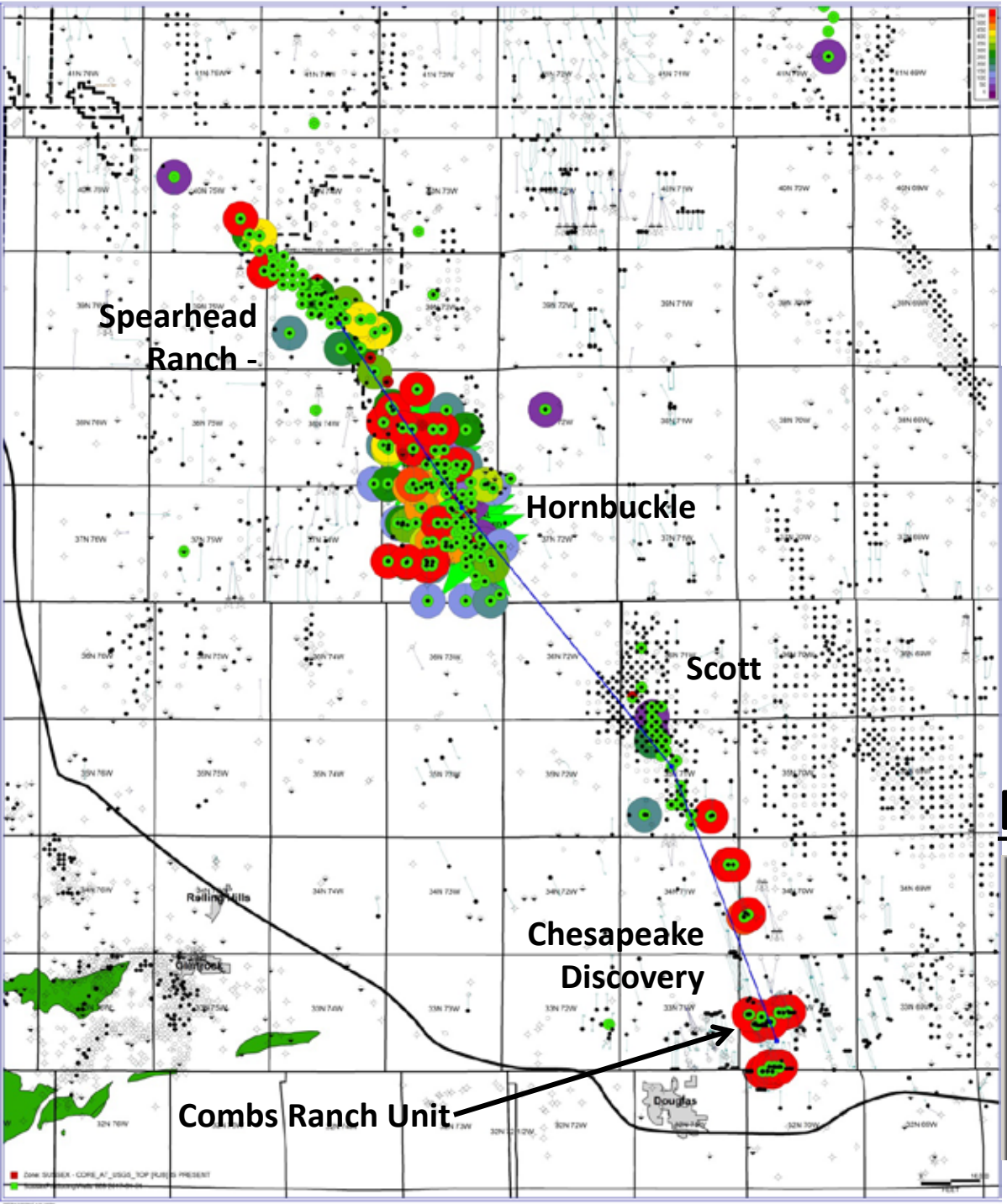
SUSSEX PRODUCTION EXTENSION TO SOUTHERN CONVERSE COUNTY

- **Chesapeake Discovered Sussex Pay When Drilling Horizontal Niobrara Wells**
- **3-12 Miles South of Scott Field, Formerly the Southernmost Sussex Production**
- **High-Volume Oil Wells with High GOR**

Sussex Horizontal Wells Drilled Since Jan. 1, 2006

Maximum Monthly Production in BOE/day for wells after 1-1-2006

- **Sussex Production Extended 15-28 Miles South of Hornbuckle Field**
- **Discovered When Drilling Horizontal Niobrara Wells**



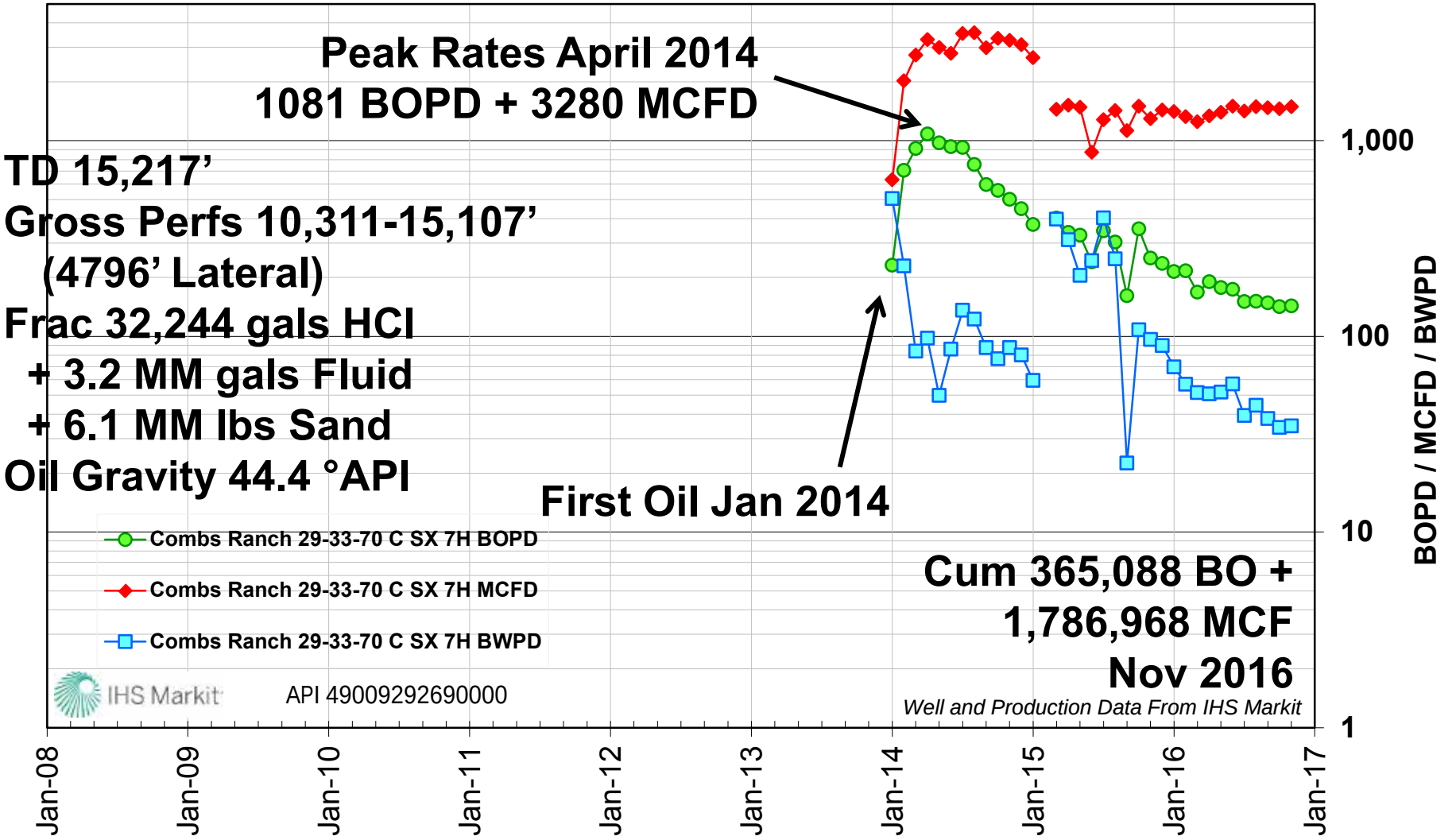
BOEPD

< 0.000
>= 0.000
>= 50.000
>= 100.000
>= 150.000
>= 200.000
>= 250.000
>= 300.000
>= 350.000
>= 400.000
>= 450.000
>= 500.000
>= 550.000

IHS Markit

Well and Production Data From IHS Markit

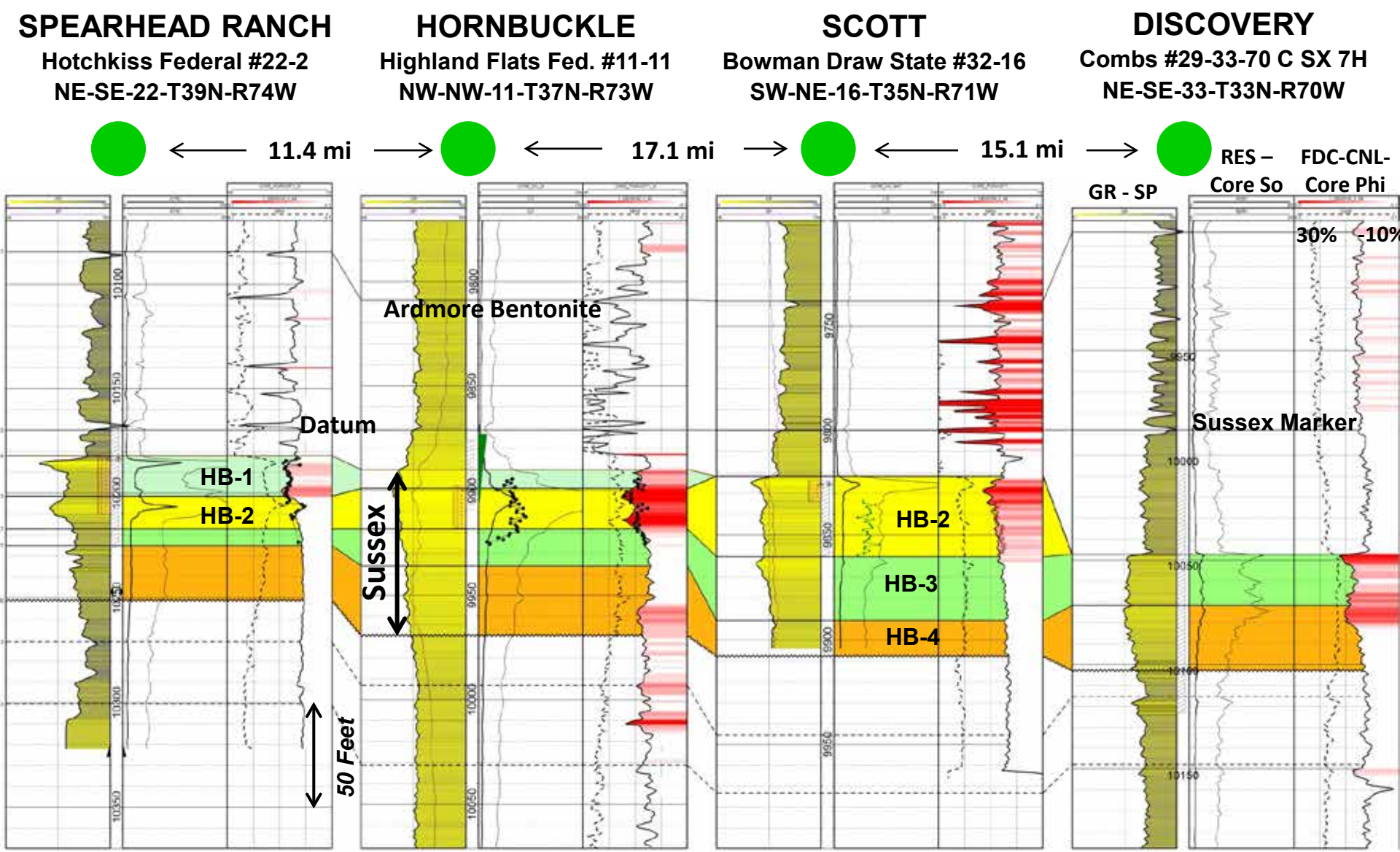
Chesapeake Combs Ranch Unit #29-33-70 C SX
Horizontal Sussex Producer
New Discovery Area, Southern Powder River Basin



HORNBUCKLE TREND SUSSEX STRATIGRAPHIC CROSS-SECTION

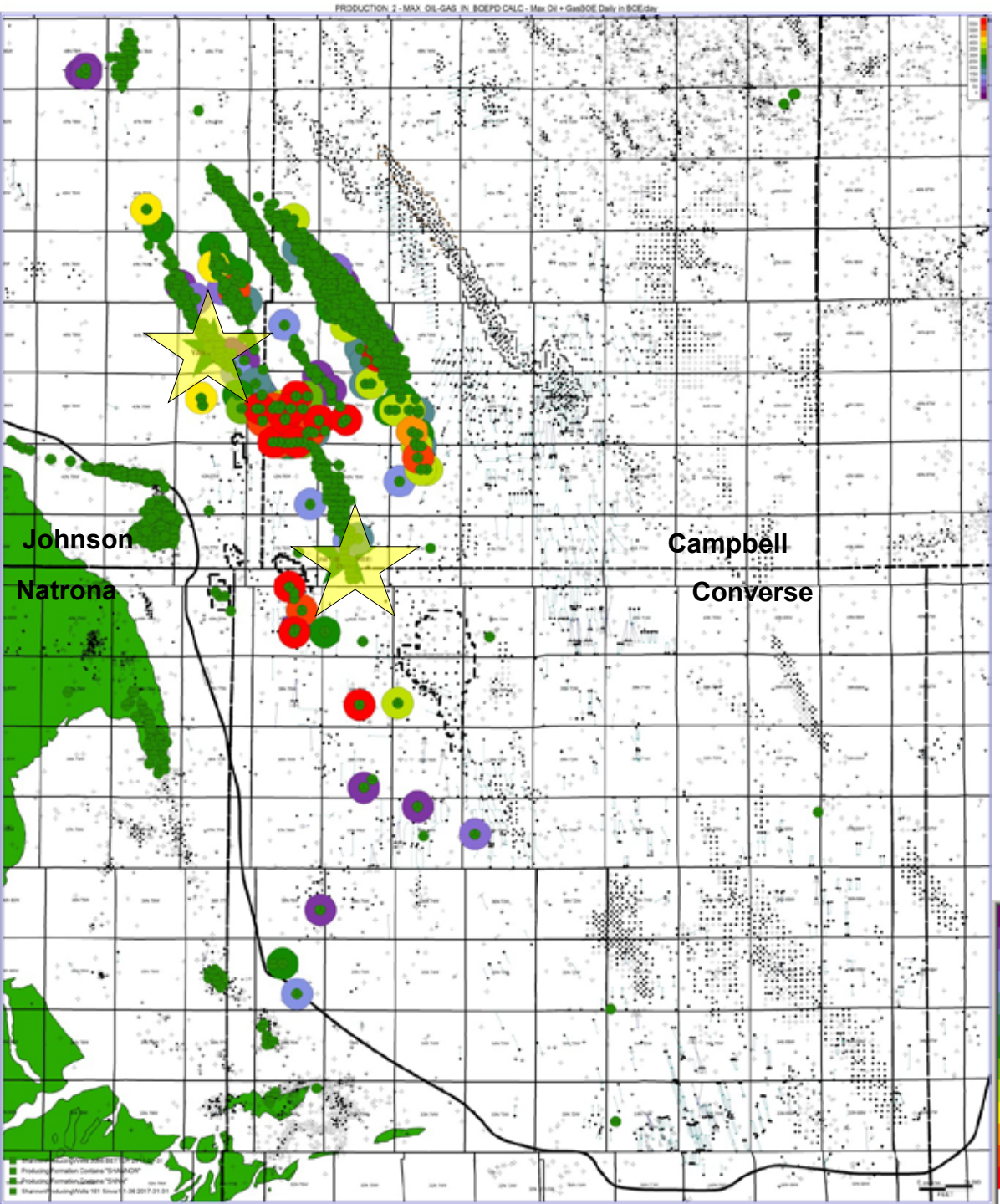
NW SE

SPEARHEAD RANCH TO CHESAPEAKE DISCOVERY



SUSSEX CONCLUSIONS

- **The Sussex Sandstone in the Hornbuckle-Spearhead Trend is a Hybrid Tight-Oil Reservoir that is Most Efficiently Developed with Horizontal Drilling & Multi-Stage Fracture Stimulations**
- **The Sussex Reservoir is Complex**
  - **Large Volume of Lower Permeability "Tight Oil" Bioturbated Sandstones**
  - **Thin-Laminated & Cross-Bedded Sandstones, Some with <0.01md K and Others with >1.0md K**
  - **High-Permeability Zones Enhance IPs and Drainage Areas, But Provide "Channels" for Inter-well Communication and/or Depletion**
- **Our Challenge: Correctly Describe the Reservoir to Optimize Drilling Locations, Azimuths, & Completions**



Shannon Horizontal Wells

Maximum Monthly Production in BOE/day

Wells Drilled After Jan. 1, 2006

- Activity Concentrated in Southwestern Campbell and Southeastern Johnson Counties
- Most Successful Shannon Activity Between and Along Strike With Existing Vertical Fields

BOPD

< 0.000
>= 0.000
>= 50.000
>= 100.000
>= 150.000
>= 200.000
>= 250.000
>= 300.000
>= 350.000
>= 400.000
>= 450.000
>= 500.000
>= 550.000

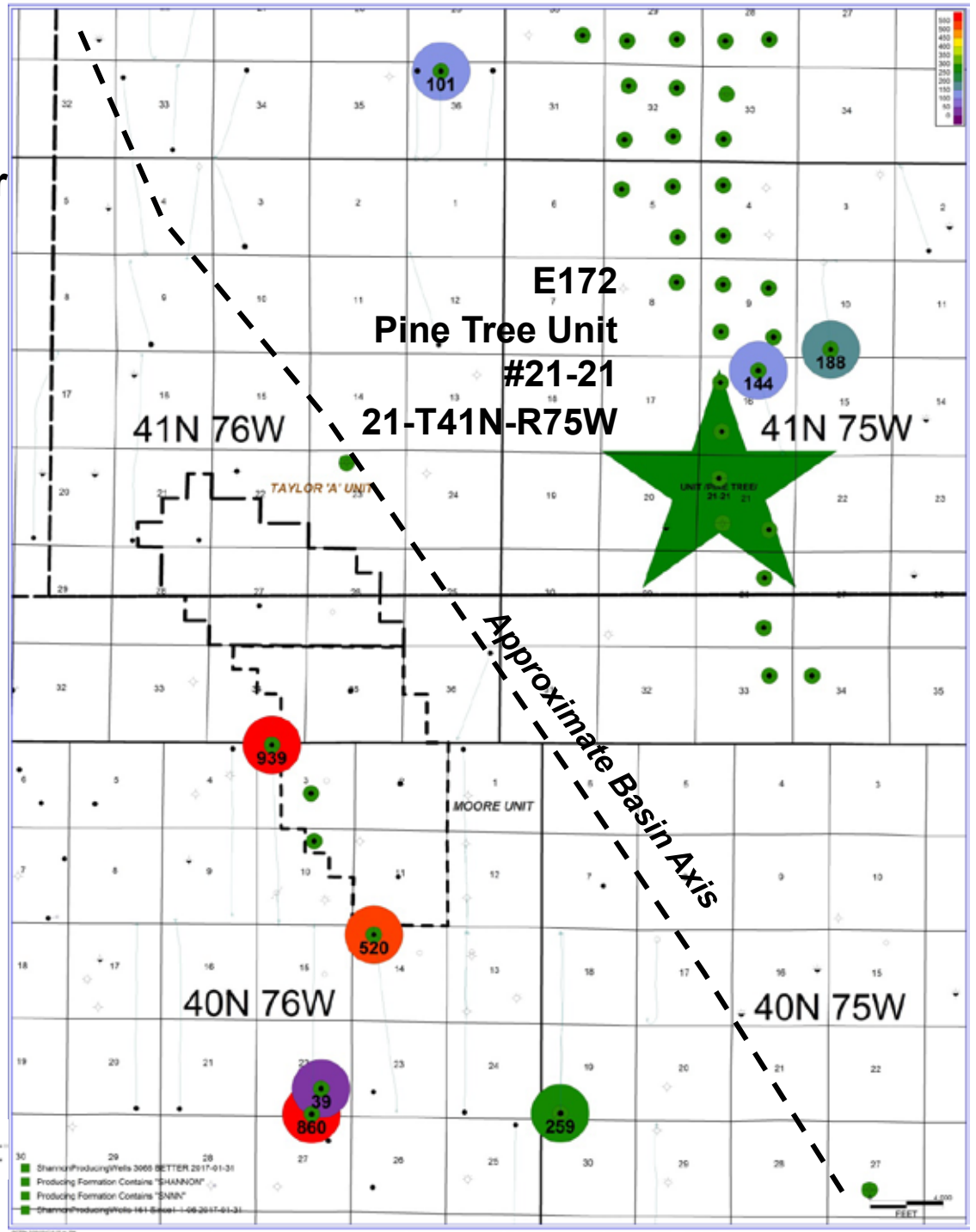
IHS Markit

Well & Production Data From IHS Markit

SHANNON SANDSTONE

Bubbles Max Rate in BOE/day for wells after 1-1-2006

E172
Pine Tree Unit
#21-21
21-T41N-R75W



Well & Production Data From IHS Markit

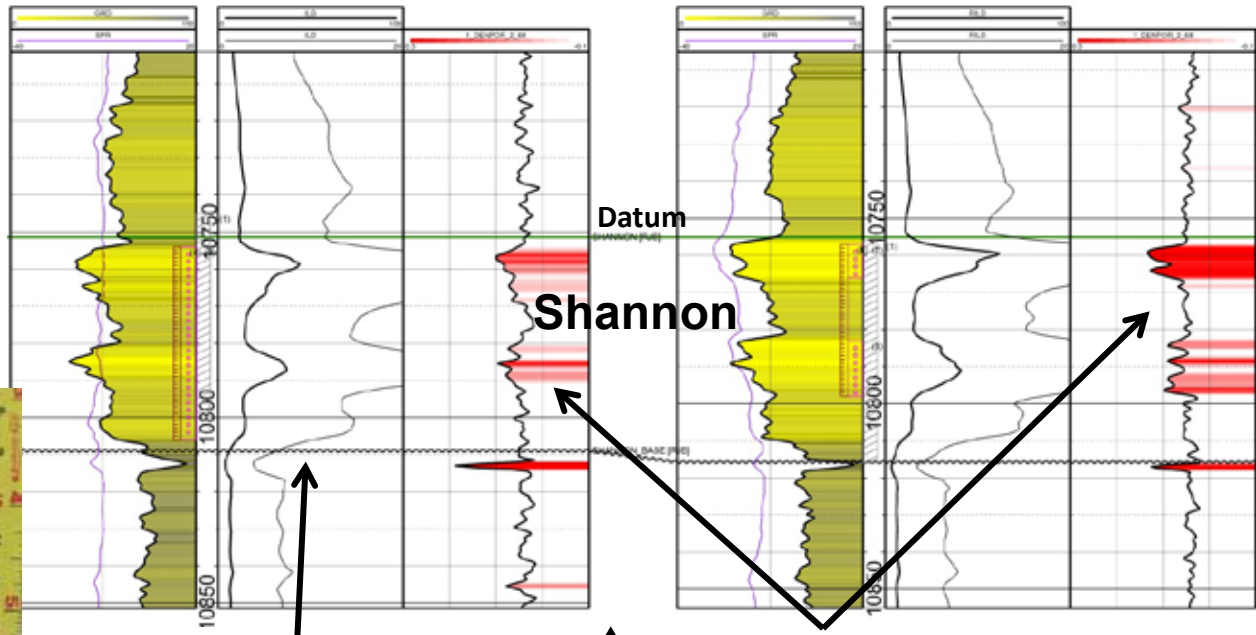
SHANNON SANDSTONE

PINE TREE UNIT AREA, Campbell Co.

- Cross-Bedded Sandstone w/ Shale Rip-up Clasts & Glauconite
- Interlaminated Sandstone & Mudstone
- Burrowed Sandy Mudstone (Bioturbated Facies Rare to Absent)

Pine Tree Unit #21-20
NE-SW-21-T41N-R75W

Pine Tree Unit #21-21
NW-NW-21-T41N-R75W



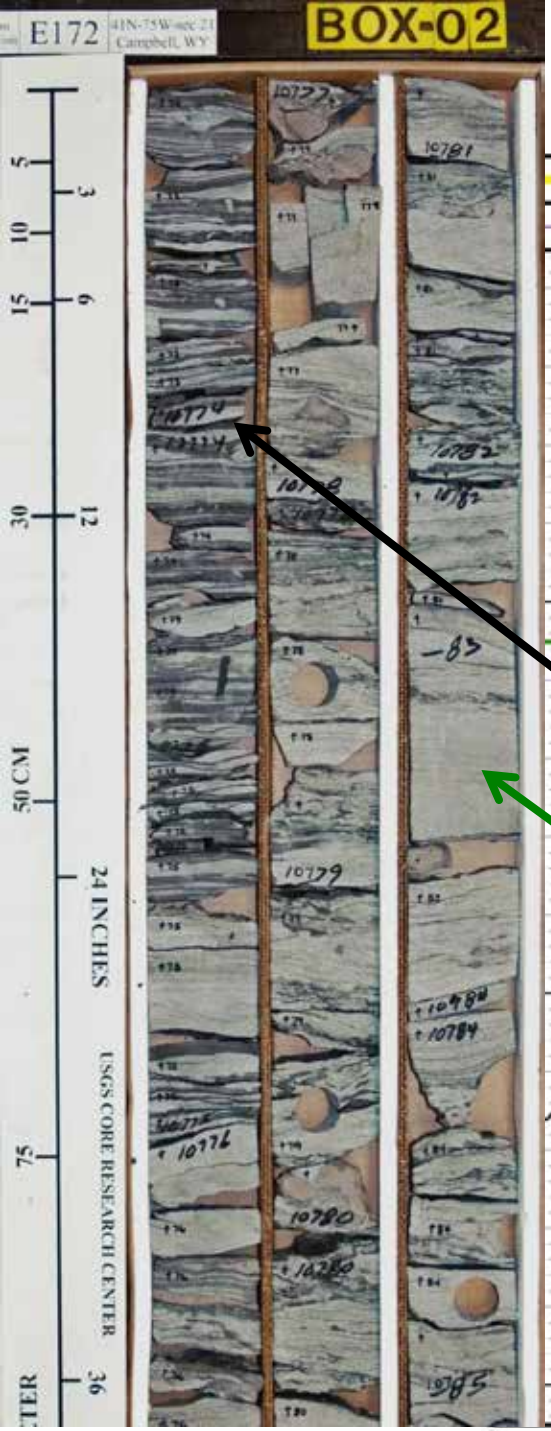
Resistivity 10-50 ohms

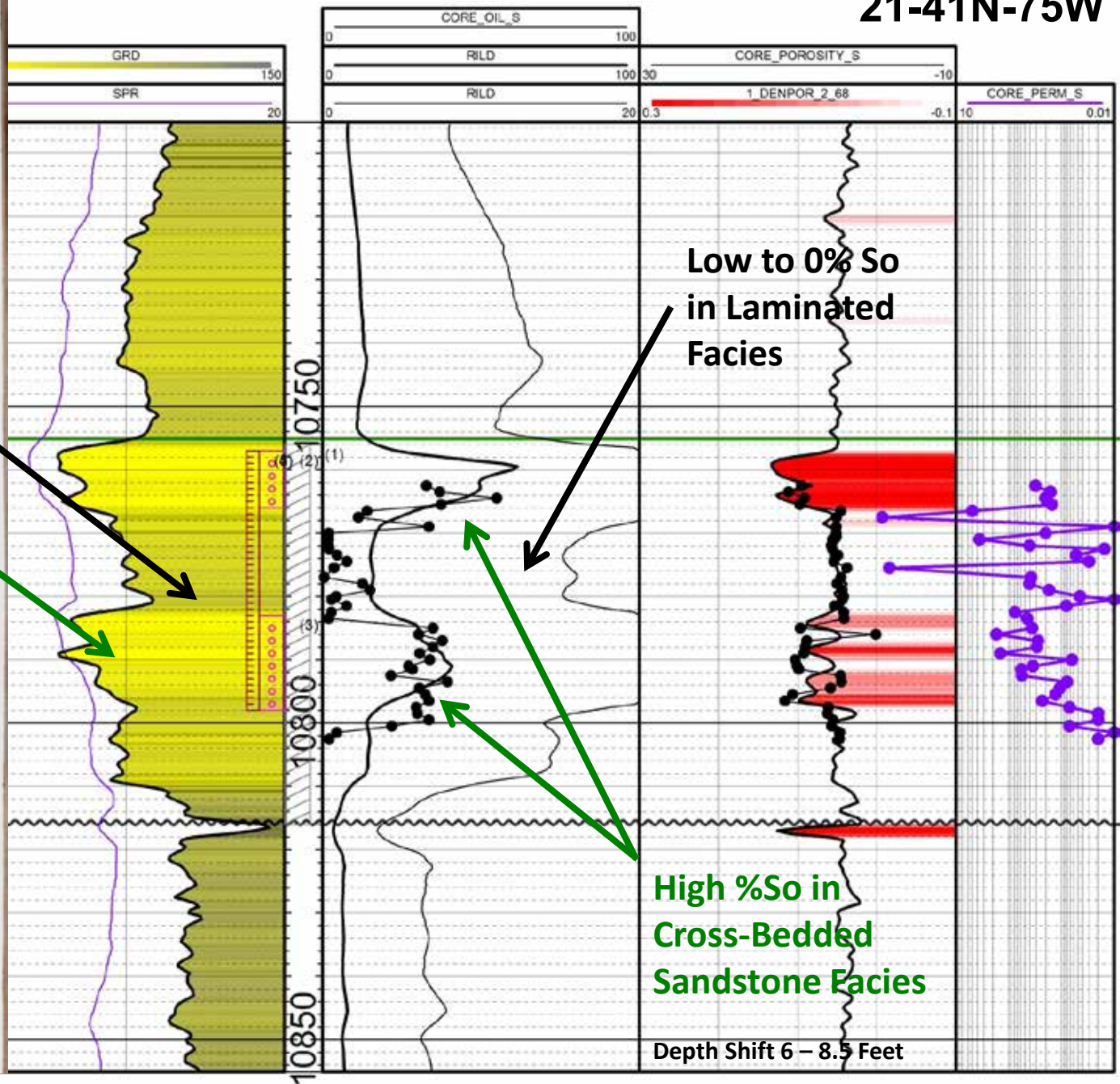
Porosity 4-12%

Vertical Well Cum
83 MBO + 103 MMCF + 3 MBW

Vertical Well Cum
100 MBO + 128 MMCF + 3 MBW

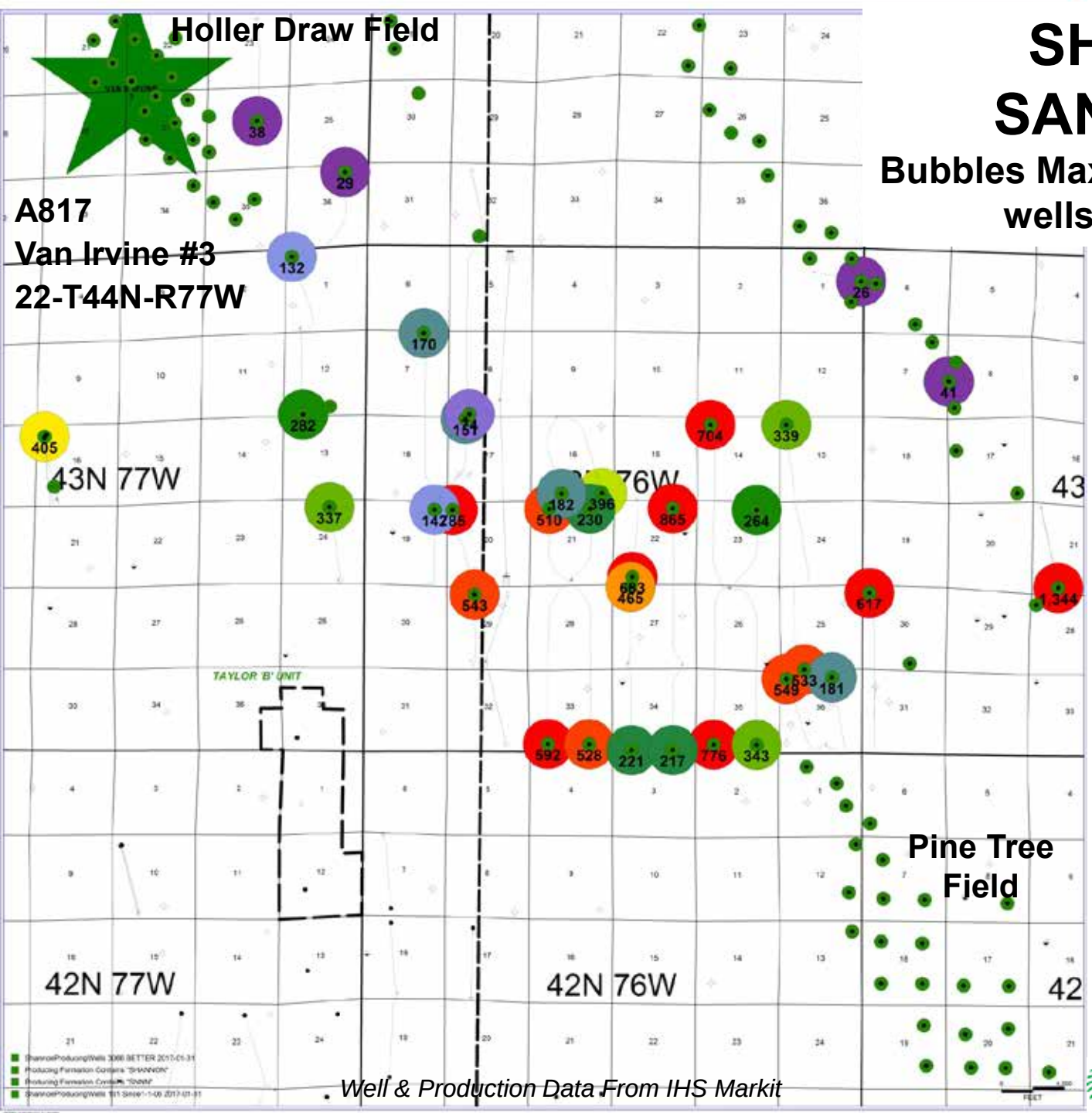
E172 Pine Tree Unit # 21-21
21-41N-75W





SHANNON SANDSTONE

Bubbles Max Rate in BOE/day for wells after 1-1-2006



A817
Van Irvine #3
22-T44N-R77W

BOEPD

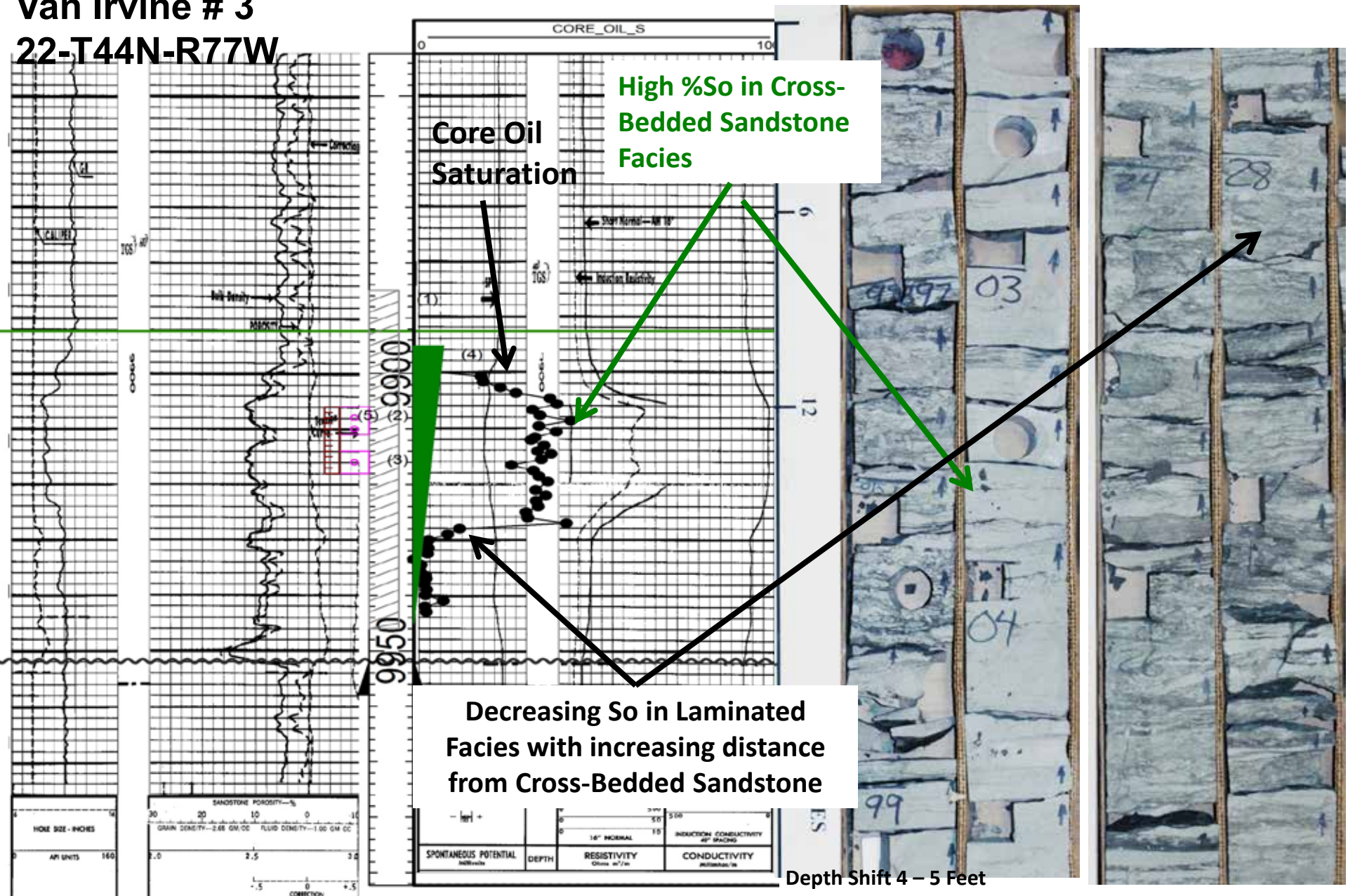
- < 0.000
- >= 0.000
- >= 50.000
- >= 100.000
- >= 150.000
- >= 200.000
- >= 250.000
- >= 300.000
- >= 350.000
- >= 400.000
- >= 450.000
- >= 500.000
- >= 550.000

Well & Production Data From IHS Markit

IHS Markit

A817
Southland Royalty
Van Irvine # 3
22-T44N-R77W

Shannon Sandstone
Conventional Vertical Production

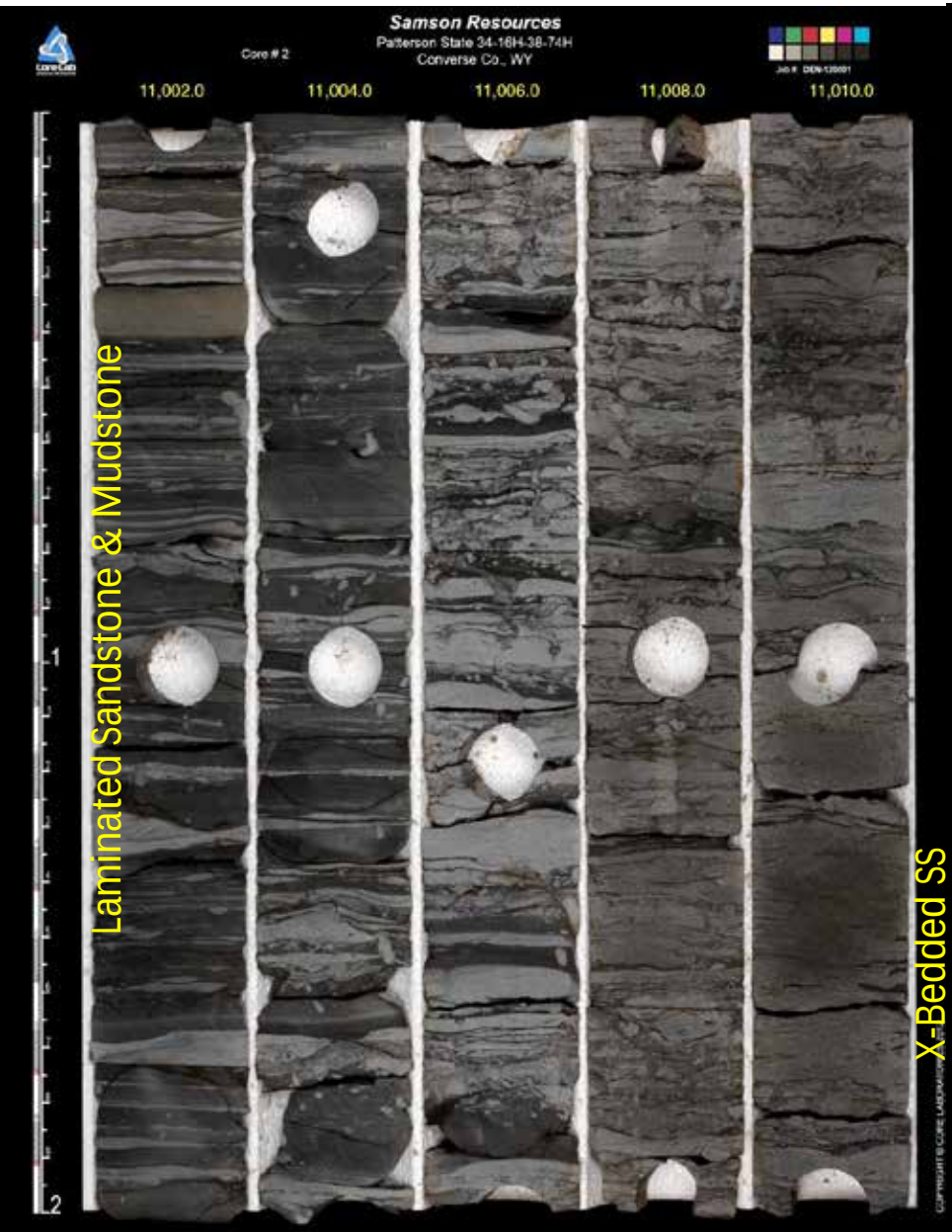


HORNBUCKLE FIELD (WEST)

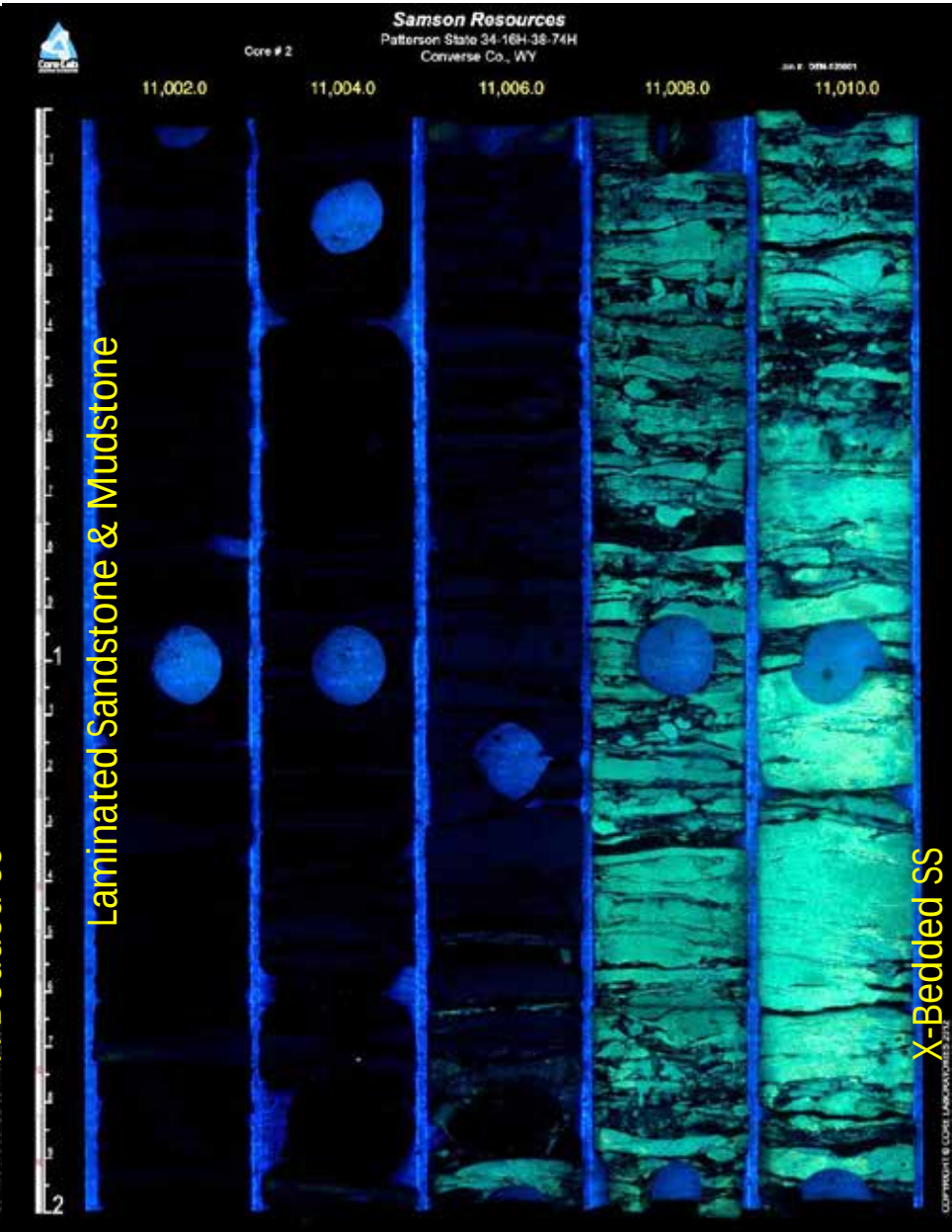
Samson Resources Patterson State #34-16-38-74H (T694)

SW-SE-16-T38N-R73W

PLAIN LIGHT



UV LIGHT

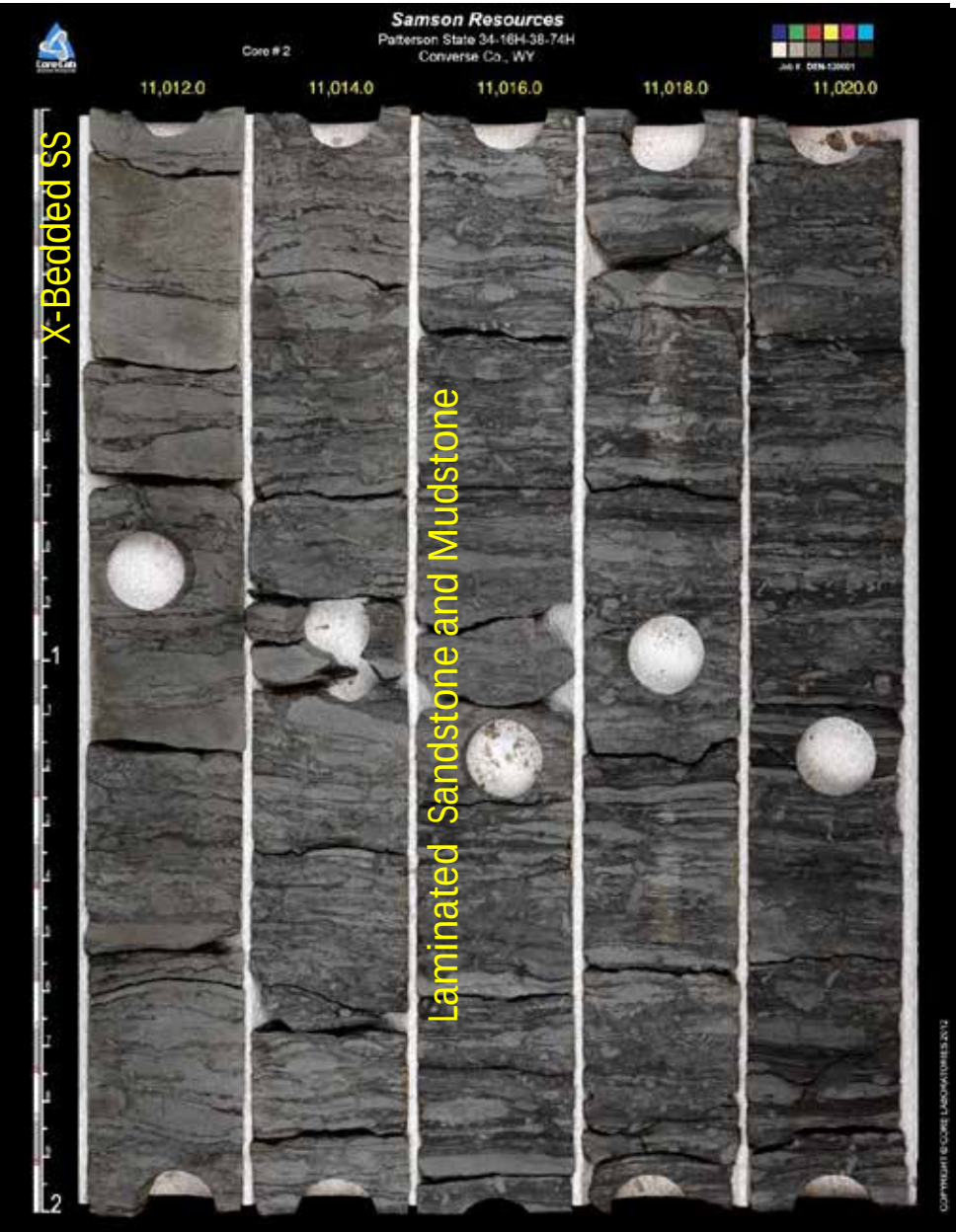


HORNBUCKLE FIELD (WEST)

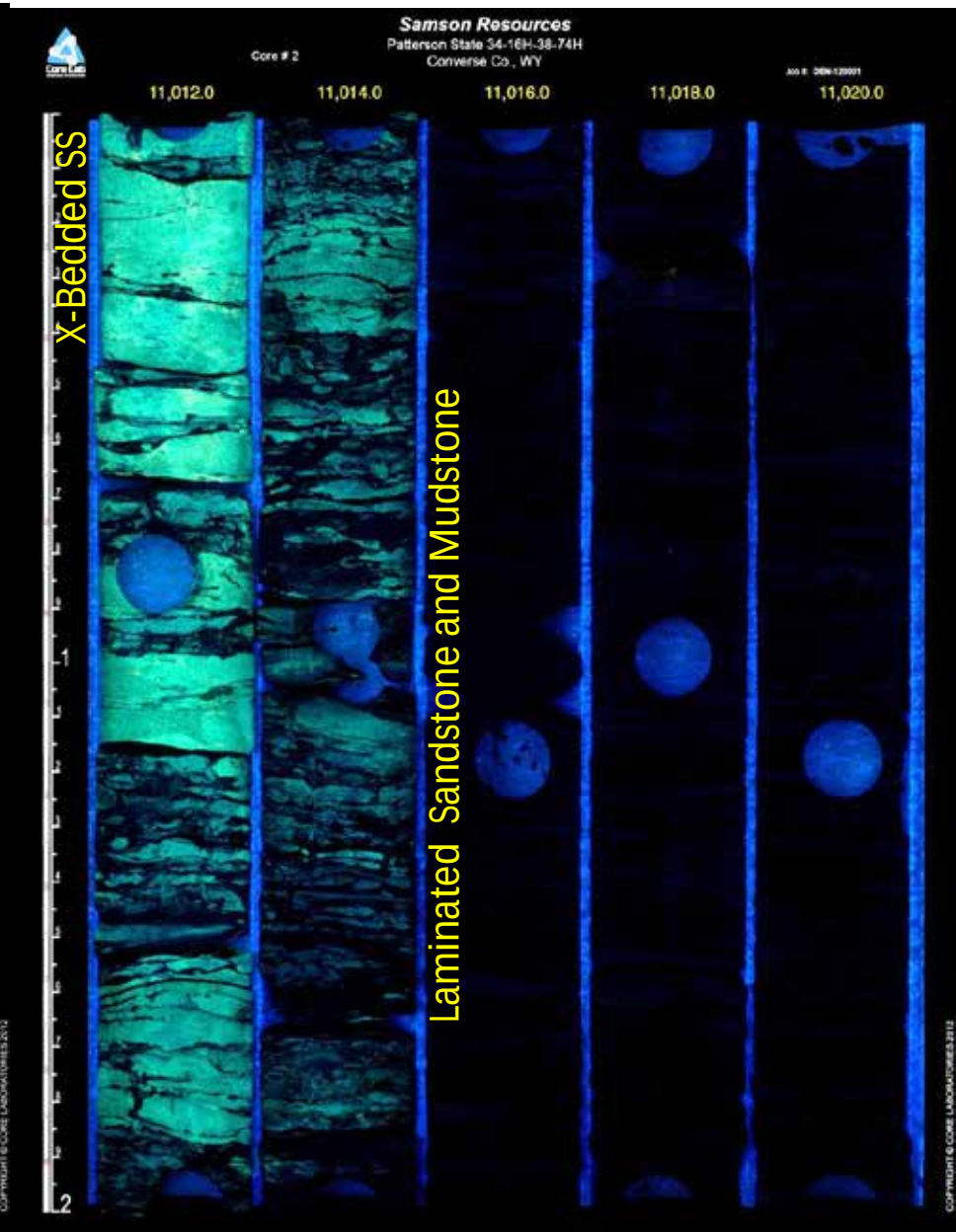
Samson Resources Patterson State #34-16-38-74H (T694)

SW-SE-16-T38N-R73W

PLAIN LIGHT



UV LIGHT



SHANNON OBSERVATIONS

- **The Shannon Sandstone has Lithologic Similarities to the Sussex Sandstone but the Completely Bioturbated Sandstone Facies is Not Well Developed**
- **Higher Porosity, Higher Permeability, Cross-Bedded Sandstones are the Primary Oil-Saturated Reservoirs**
  - **Thinly Interlaminated Sandstones and Mudstones Have Lower Permeability than Cross-Bedded Sandstones and Thicker-Bedded Laminated Sandstones**
  - **Thinly Interlaminated Sandstones Appear to Have Low or Variable Oil Saturations**
- **The Best Horizontal Shannon Wells Appear to be Extending the Better Reservoir Quality Cross-Bedded Sandstone Facies Along Strike with Existing Vertical Fields**

TURNER & FRONTIER SANDSTONES, POWDER RIVER BASIN

Gus Gustason

CODELL SANDSTONE, DJ BASIN

Introduction

Kevin Smith

See Kevin Smith's slides from the 2015 AAPG short course SC-17 at Search and Discovery Article #10760
http://www.searchanddiscovery.com/pdfz/documents/2015/10760smith/ndx_smith.pdf.html

PARKMAN SANDSTONE
POWDER RIVER BASIN

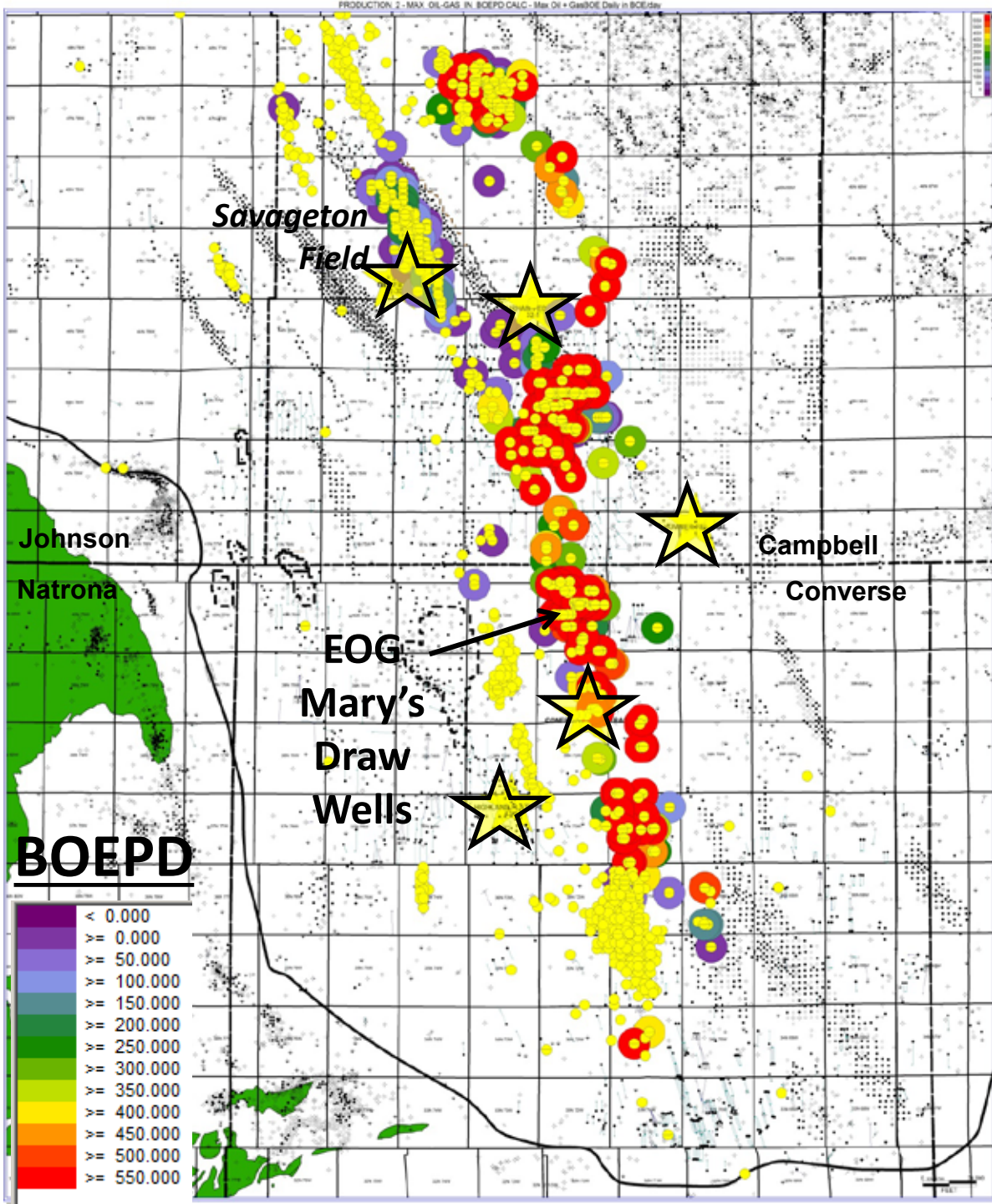
PARKMAN SANDSTONE, POWDER RIVER BASIN

Two Plays (more?), One Formation Name

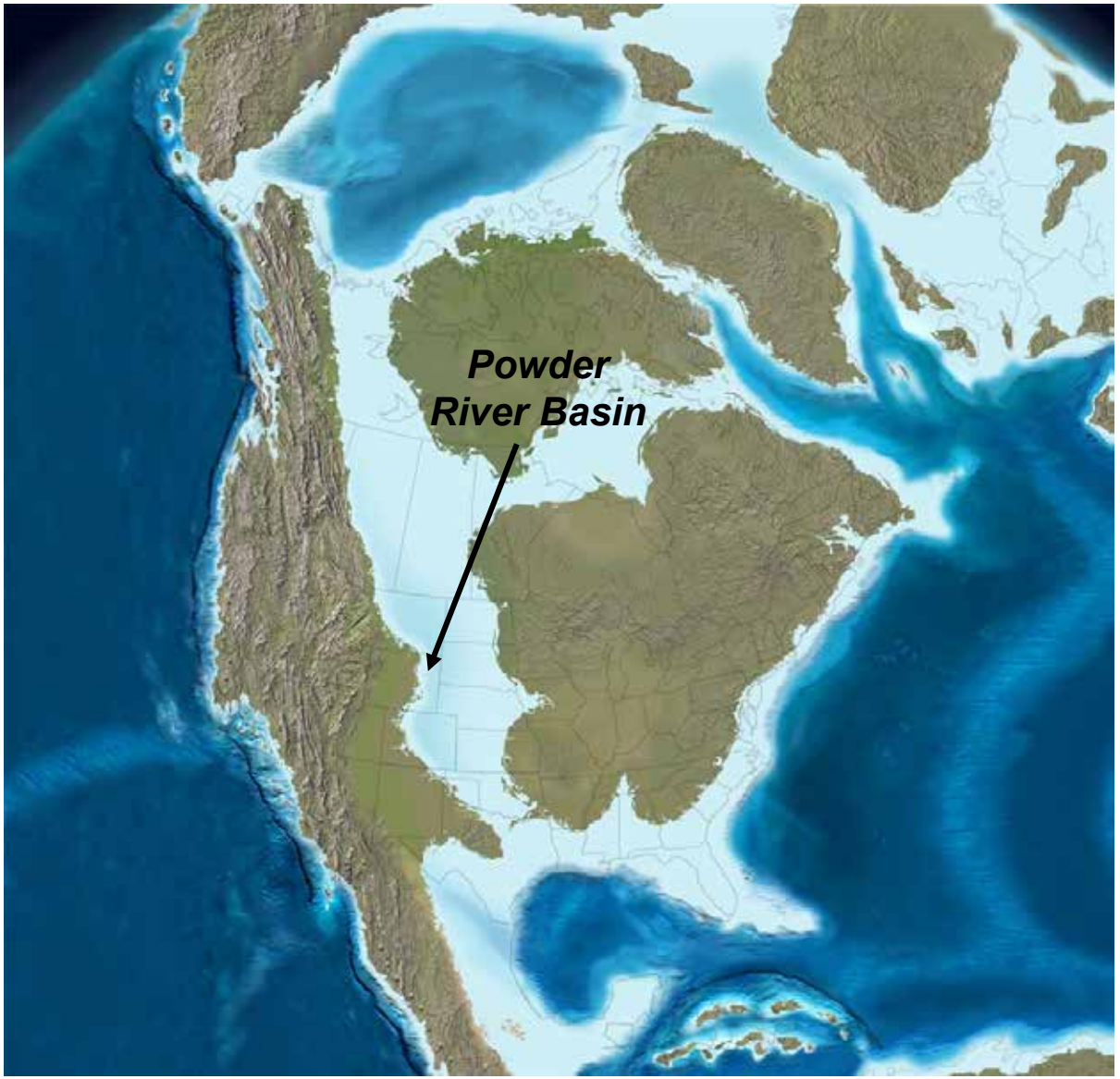
- Progradational Tongue of Mesaverde Delta Complex
- 5 Cores , 2 From Active Drilling Area

Parkman

Historical Wells in Yellow Bubbles for Completions After 1-1-2006



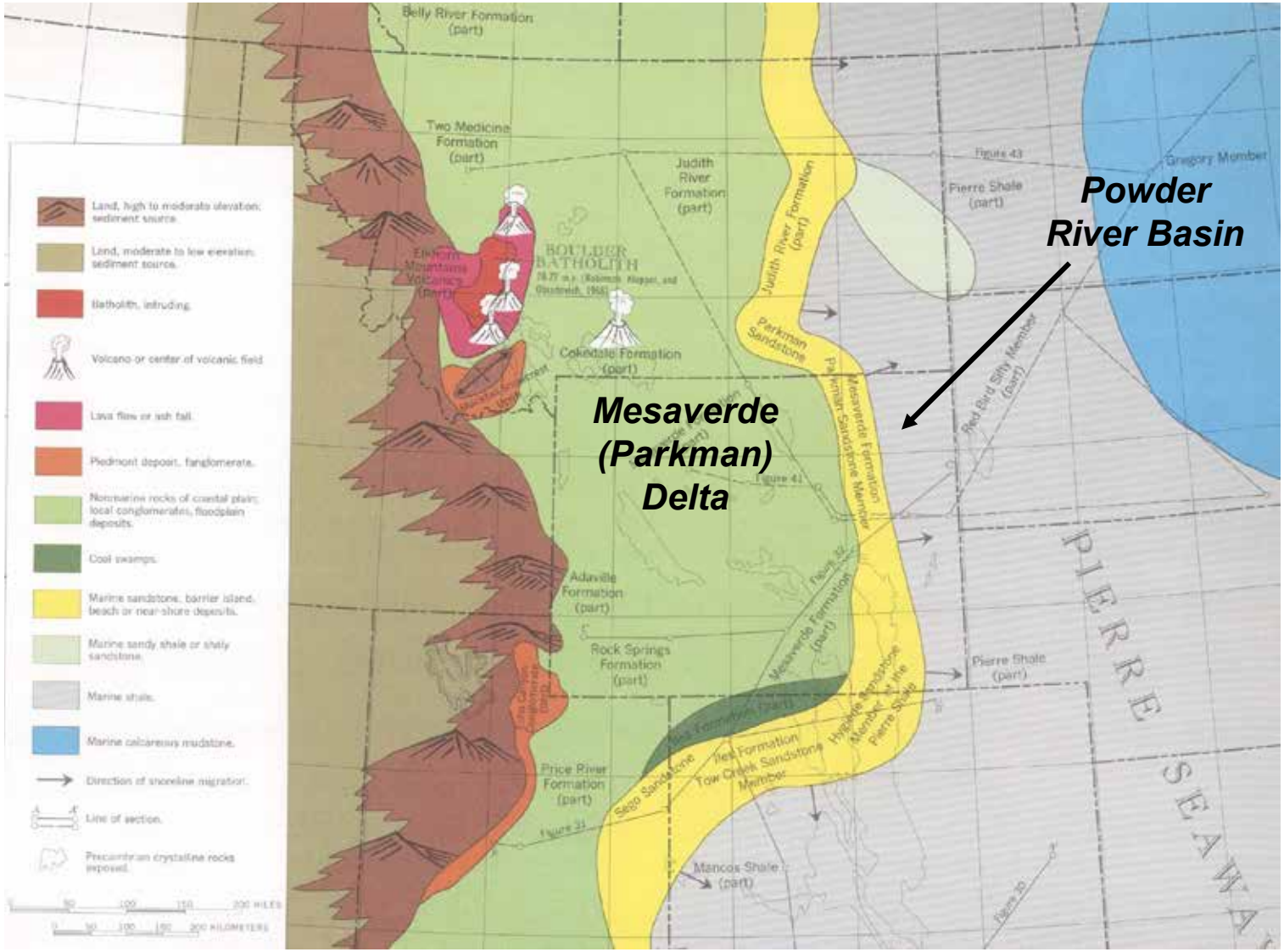
Cretaceous Interior Seaway
75 MA



Ron Blakey

After Wheeler (2010)

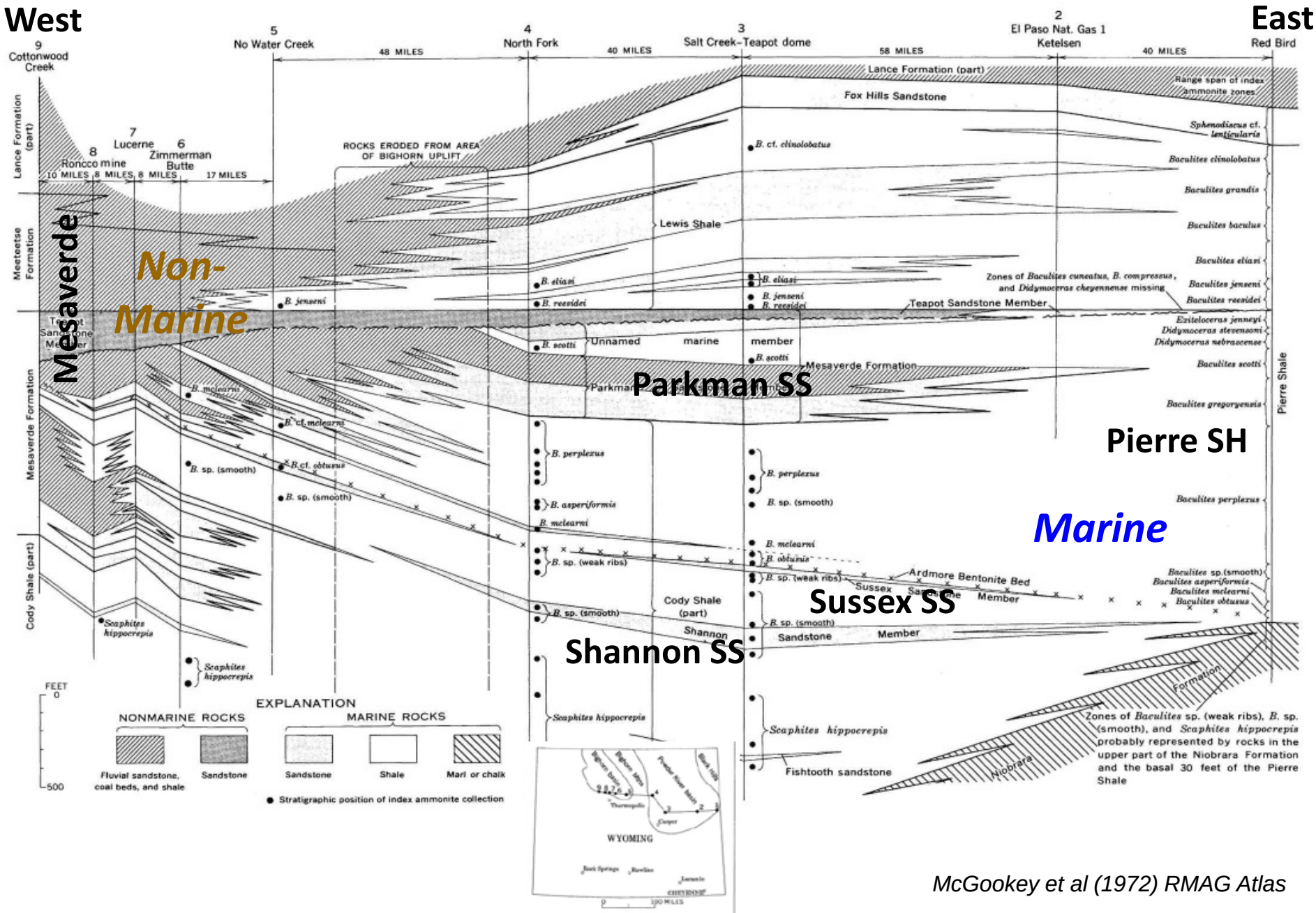
Parkman Paleogeography



RMAG, “the Big Red Book”

After Wheeler (2010)

Big Horn to Powder River Basin Cretaceous Cross Section



McGookey et al (1972) RMAG Atlas

Upper Cretaceous Regional Stratigraphy

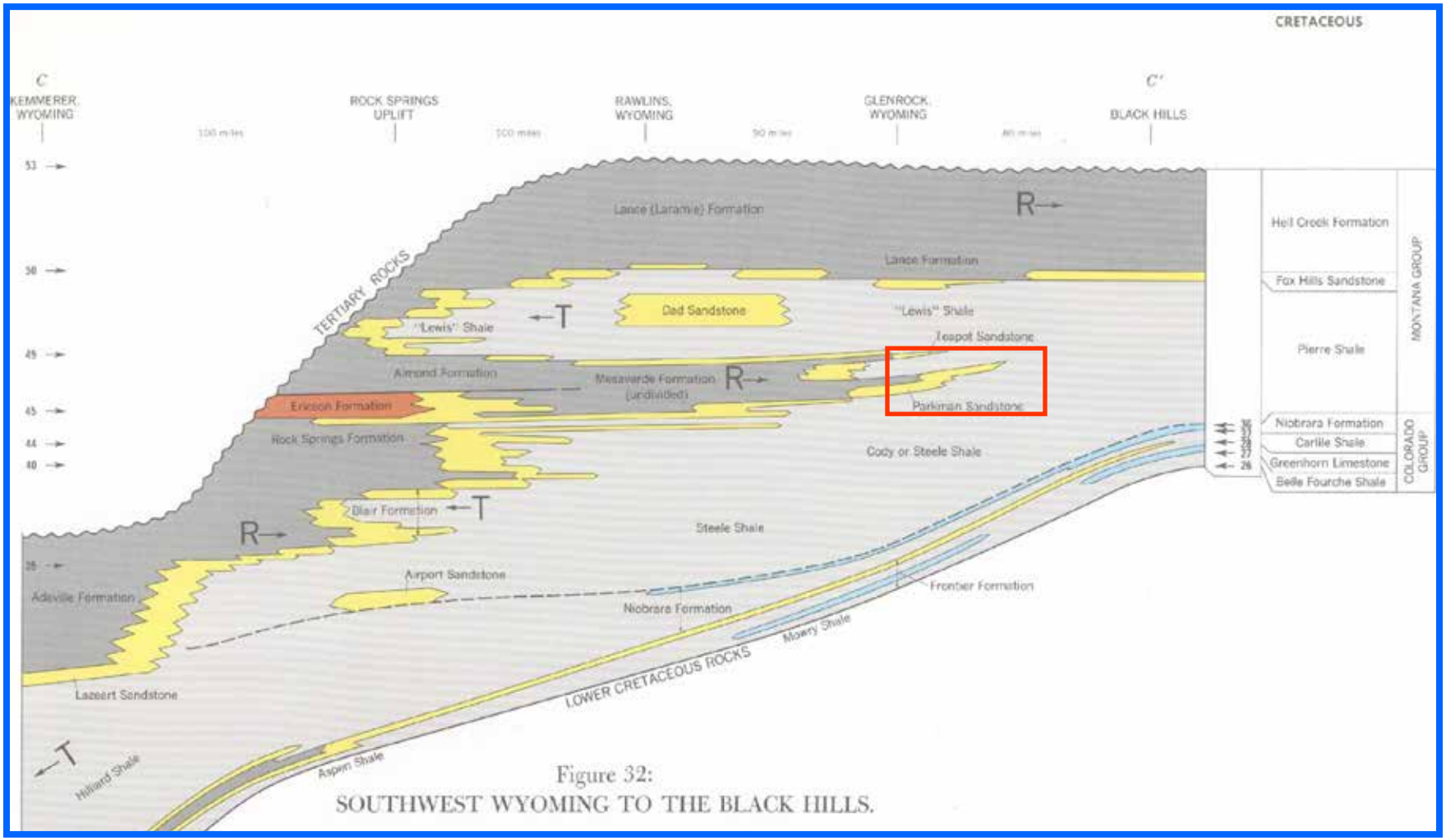
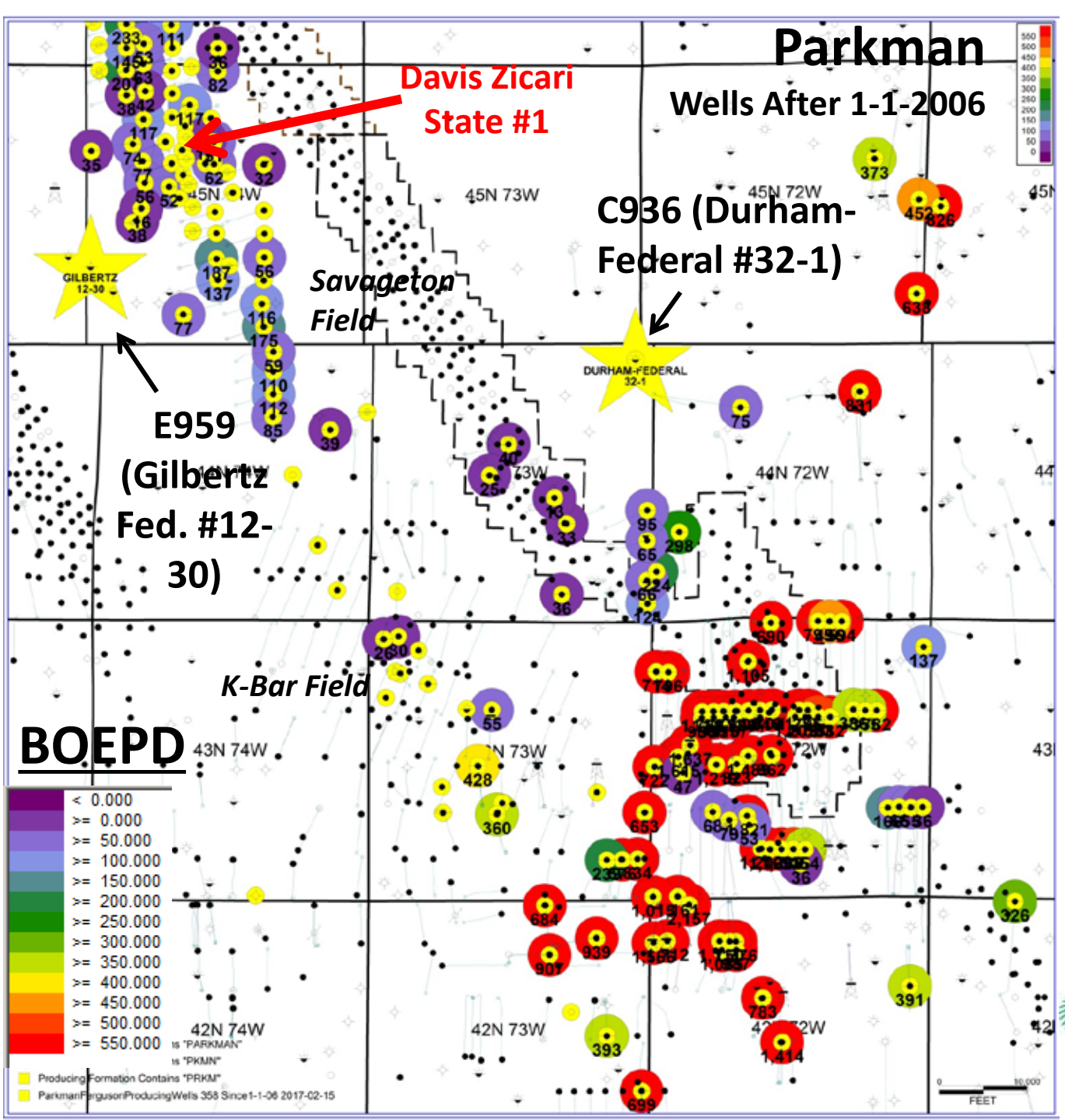


Figure 32:
SOUTHWEST WYOMING TO THE BLACK HILLS.

McGookey et al 1972, after Weimer, 1960; RMAG, "the Big Red Book"

After Wheeler (2010)



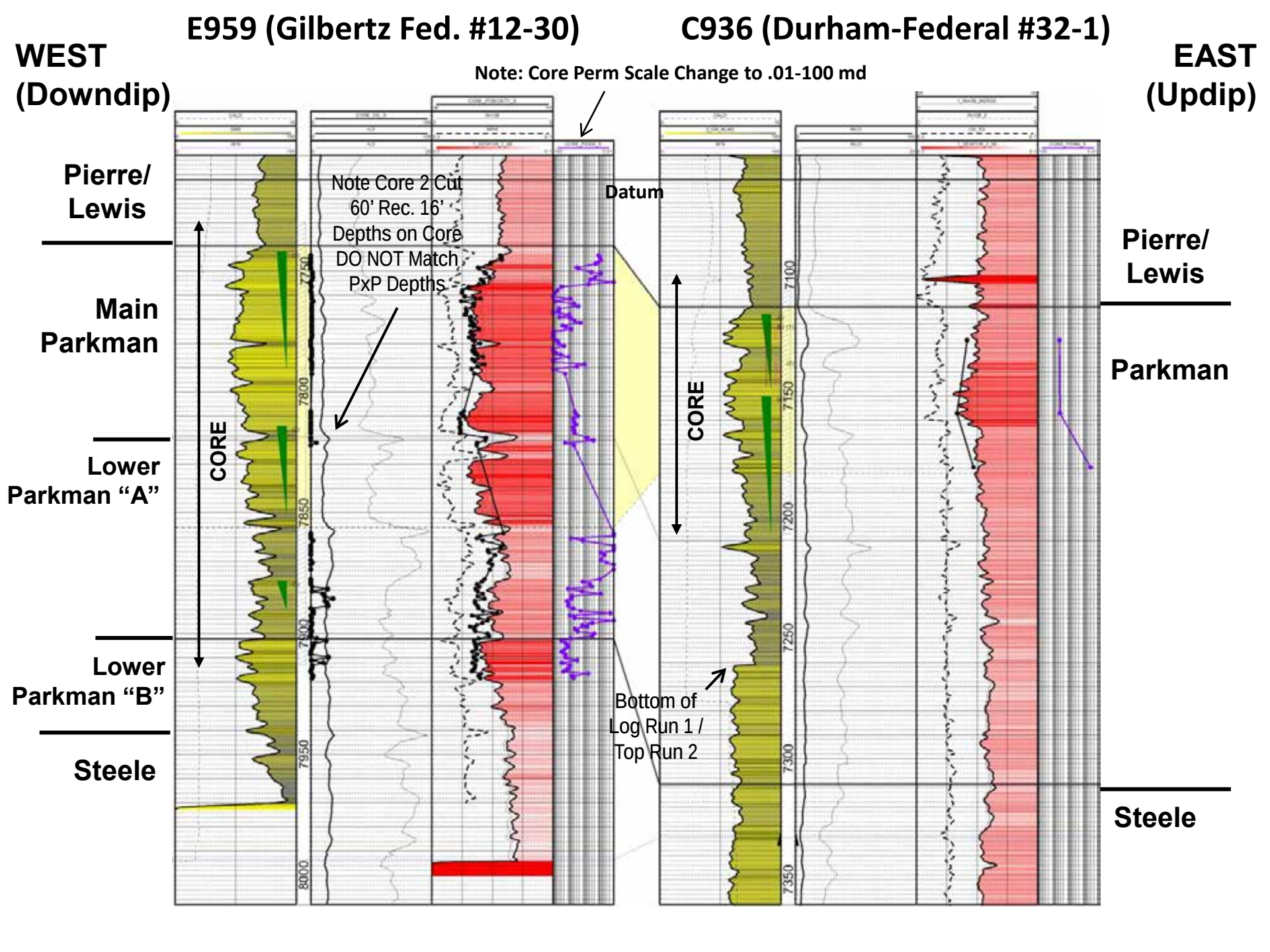
PARKMAN SANDSTONE PLAY

Maximum Daily Oil + Gas Rate in BOE/day for Wells After 1-1-2006

- **Northern Cores**
- **Gilbertz E959 At Downdip Edge of Savageton Field**
- **Durham-Fed C936 on Trend with High-Volume Producers**

IHS Markit

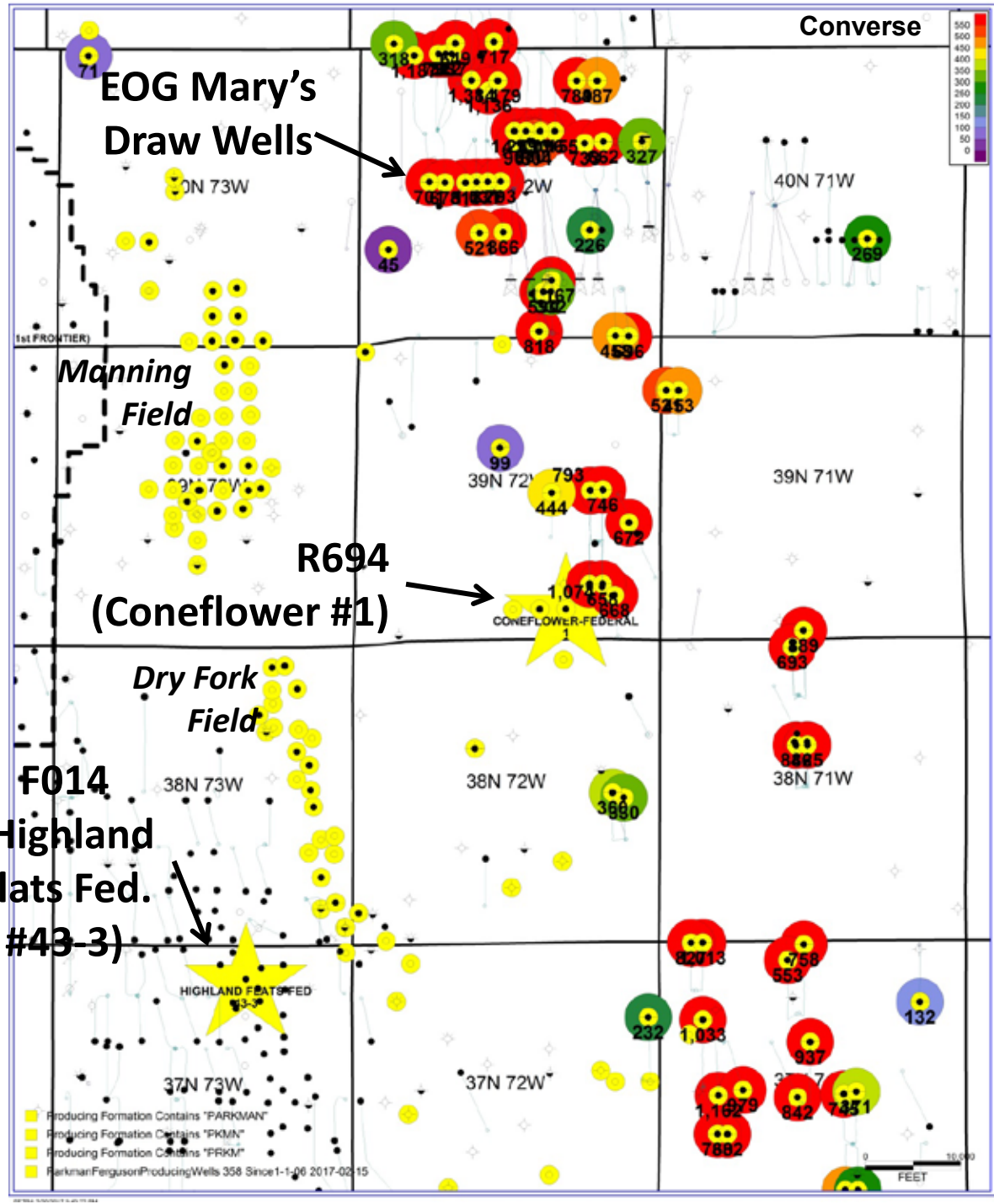
Well and Production Data From IHS Markit


E959 (Gilbertz Fed. #12-30)
C936 (Durham-Federal #32-1)
WEST
(Downdip)
EAST
(Updip)
Note: Core Perm Scale Change to .01-100 md
Pierre/
Lewis
Main
Parkman
Lower
Parkman "A"
Lower
Parkman "B"
Steele
Note Core 2 Cut
60' Rec. 16'
Depths on Core
DO NOT Match
PxP Depths
Datum
CORE
CORE
Bottom of
Log Run 1 /
Top Run 2
Pierre/
Lewis
Parkman
Steele
7250
7800
7850
7900
7950
8000
7100
7150
7200
7250
7300
7350

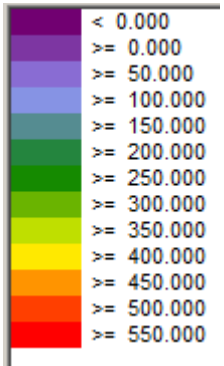
PARKMAN SANDSTONE PLAY

Maximum Daily Oil + Gas Rate in BOE/day for Wells After 1-1-2006

- **Southern Cores**
- **Davis Oil Coneflower #1 R694 is on Trend with EOG Mary's Draw Wells**

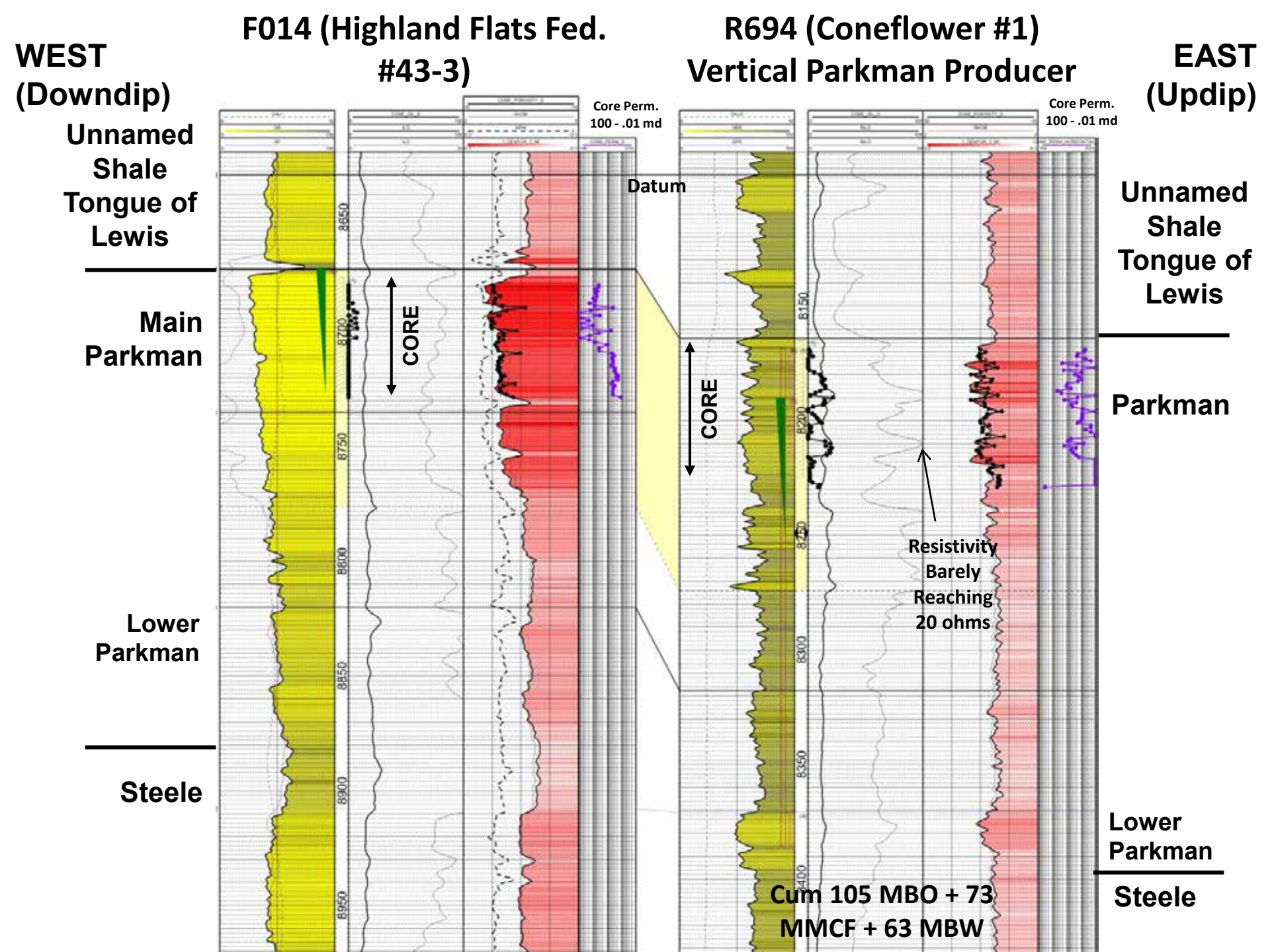


BOEPD

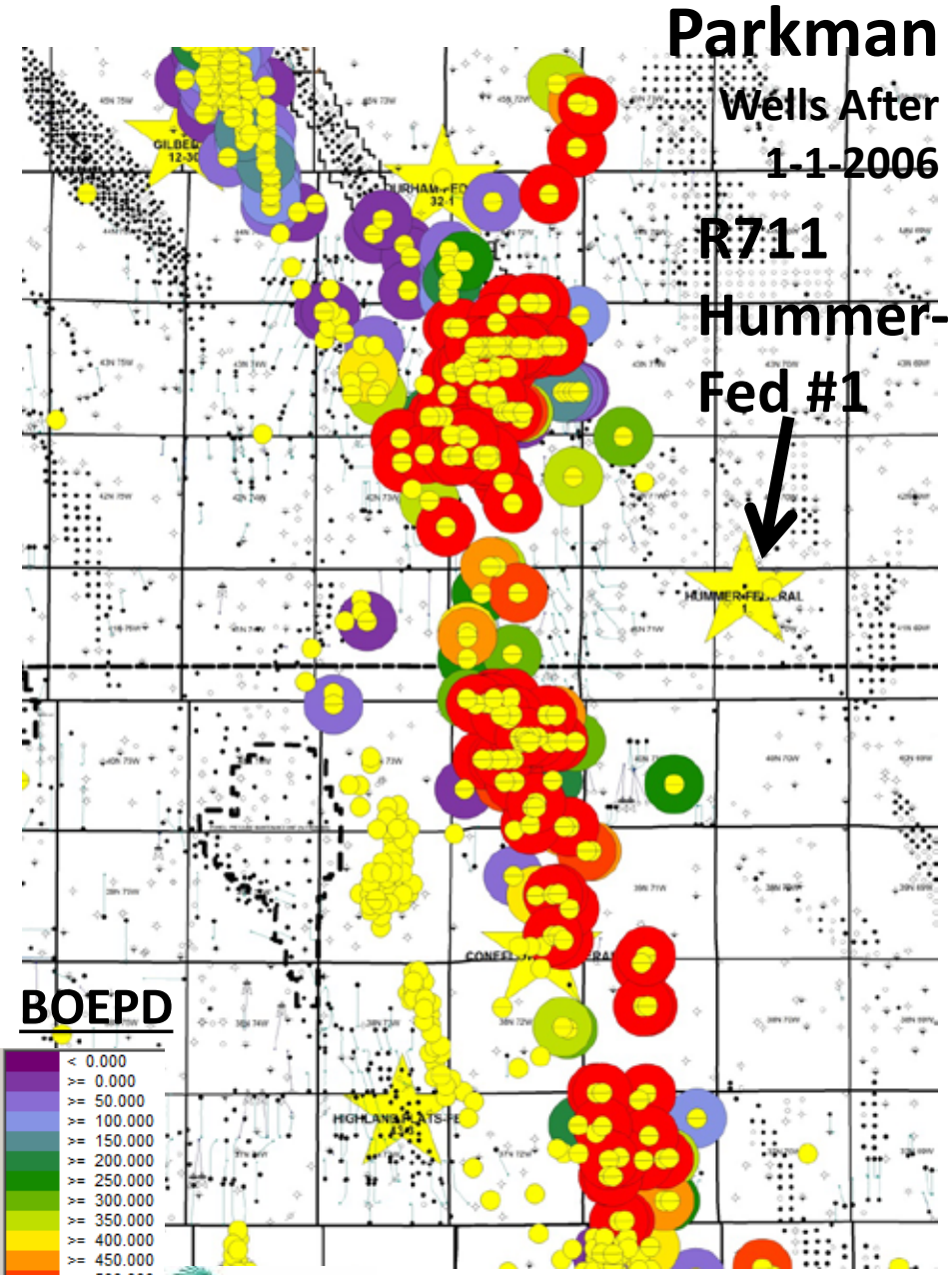


IHS Markit

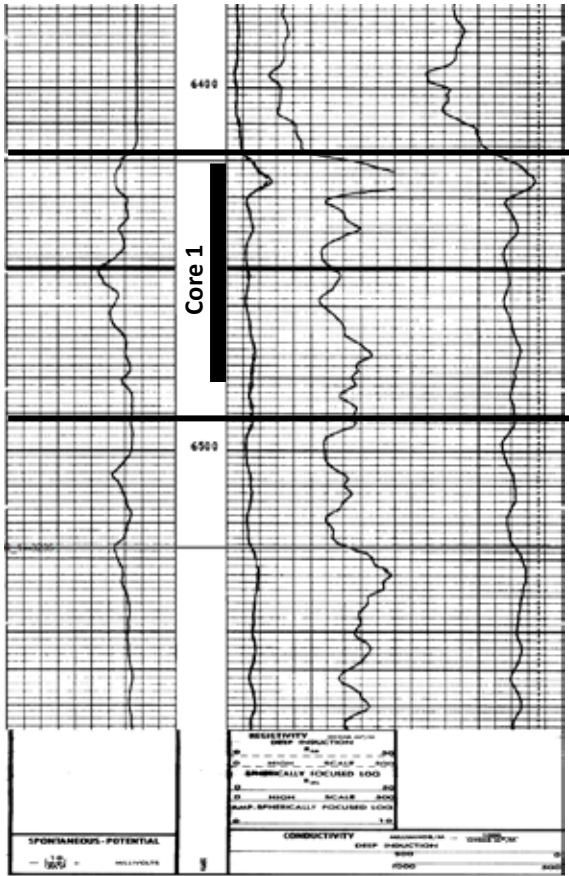
Well and Production Data From IHS Markit


WEST
(Downdip)
F014 (Highland Flats Fed.
#43-3)
R694 (Coneflower #1)
Vertical Parkman Producer
EAST
(Updip)
Core Perm.
100 - .01 md
Core Perm.
100 - .01 md
Datum
Unnamed
Shale
Tongue of
Lewis
Unnamed
Shale
Tongue of
Lewis
Main
Parkman
Parkman
CORE
CORE
Resistivity
Barely
Reaching
20 ohms
Lower
Parkman
Lower
Parkman
Steele
Steele
Cum 105 MBO + 73
MMCF + 63 MBW

R711 Davis Oil Hummer-Federal #1 Parkman Sandstone



- **Eastern Core**
- **Hummer-Fed #1 R711 is 6-8 Miles East of Historical Parkman Production & Active Horizontal Plays**



PARKMAN CORES
What Should I Look For?

- **Sedimentary Structures & Facies – What Lithologies Have Porosity & Oil Saturation?**
- **How do these Change From West to East?**
- **WHAT WOULD BE THE MAIN HORIZONTAL TARGET RESERVOIR?**
- **What is the trap? Is it the same for all of the Parkman?**

Break into 2 Groups to Look at Cores

PARKMAN CORES

- Start at F014 Highland Flats Federal #43-3
- E959 Gilbertz Federal #12-30
- Compare with Eastern Cores R694 & C936
- Compare Easternmost Core R711 Hummer-Federal #1 to Other Parkman Cores and to Facies Observed in Other Reservoirs

CODELL CORES

- Start at Berry Unit #13-09
- Compare Northern DJ Codell with Wattenberg Codell
- Note Changes in Fort Hays Limestone

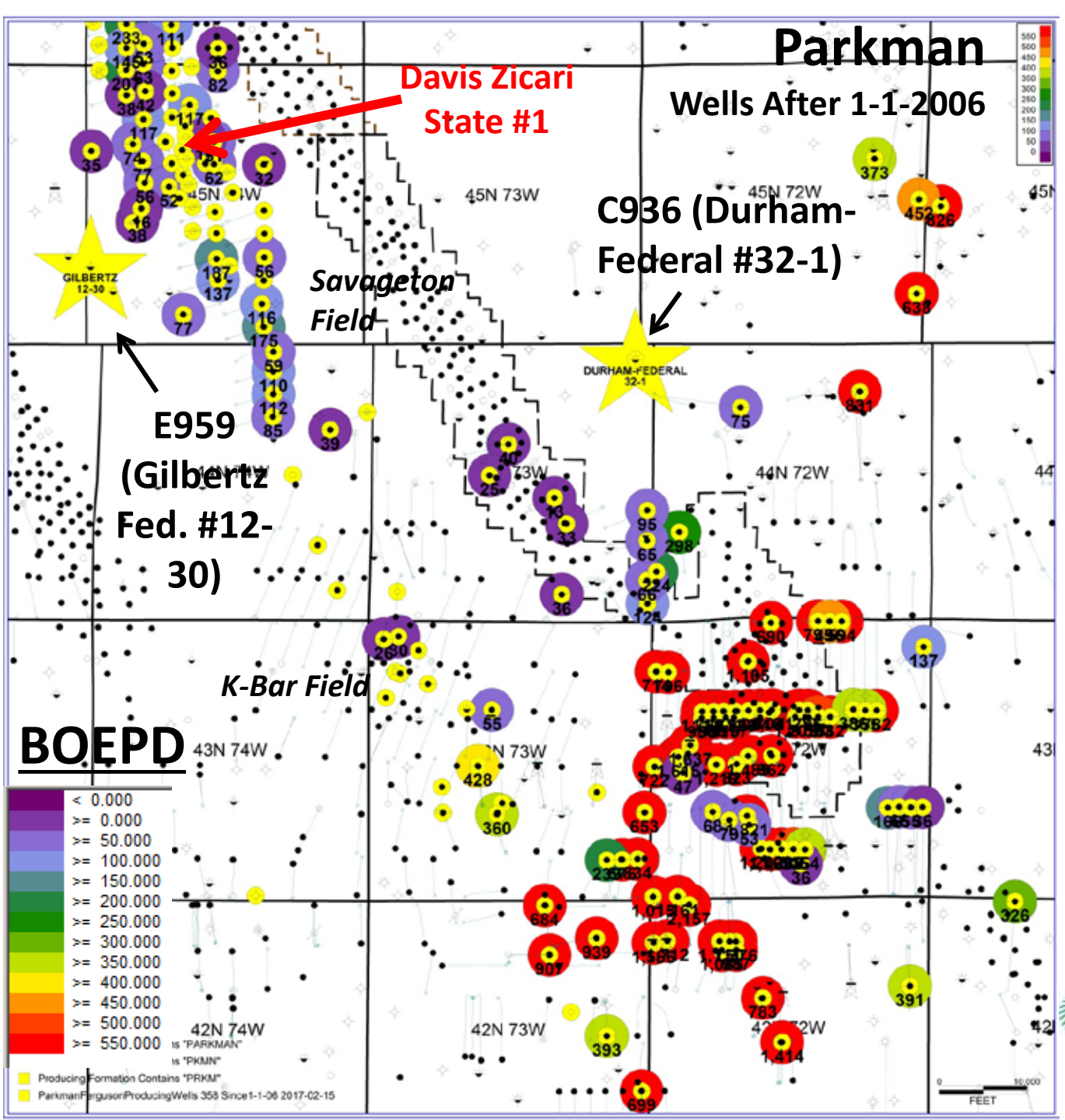
CODELL SANDSTONE, DJ BASIN

Kevin Smith

See Kevin Smith's slides from the 2015 AAPG short course SC-17 at Search and Discovery Article #10760
http://www.searchanddiscovery.com/pdfz/documents/2015/10760smith/ndx_smith.pdf.html

PARKMAN SANDSTONE
Conclusions

- Where is the Oil?
- What is the best Horizontal Drilling Target?
- Regional Facies Changes?
- Is it the Same at each Core Location?



PARKMAN SANDSTONE PLAY

Maximum Daily Oil + Gas Rate in BOE/day for Wells After 1-1-2006

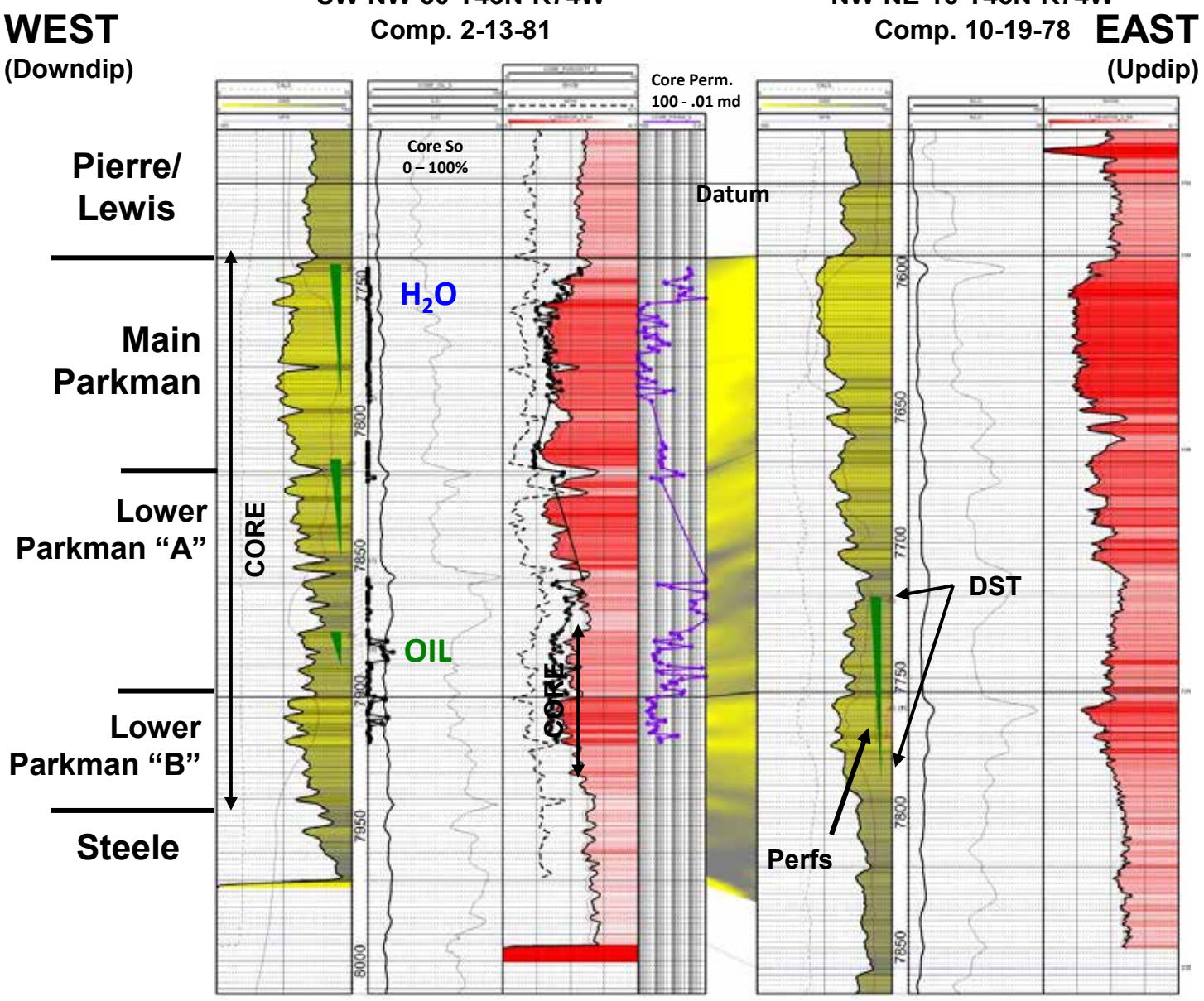
Savageton Field Discovery "*SMOKING GUN*" Well Zicari State #1

IHS Markit

Well and Production Data From IHS Markit

Savageton Field Discovery

"SMOKING GUN" Well



DST Rec. 570' GCO + 270' HO & SOCM + 100' WCM

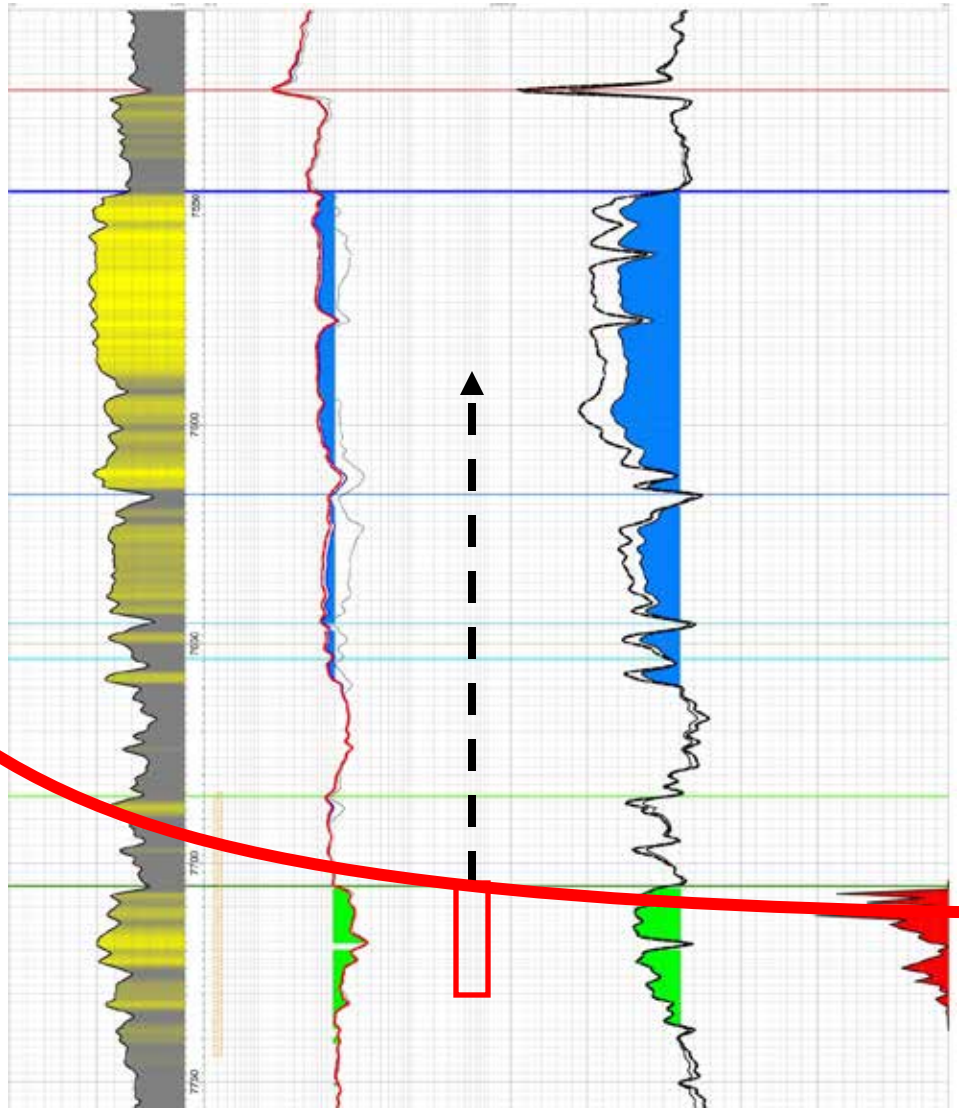
<u>NO FREE WATER!</u>

Perf & Frac
50,000 LBS X 18,000 GALS

IP 18 BO + + 30 mcfd
+350 BW
Compl. 2-14-84

Cum 86 MBO + 6 MMCF + 674 MBW

Water over Oil



PROBLEM:

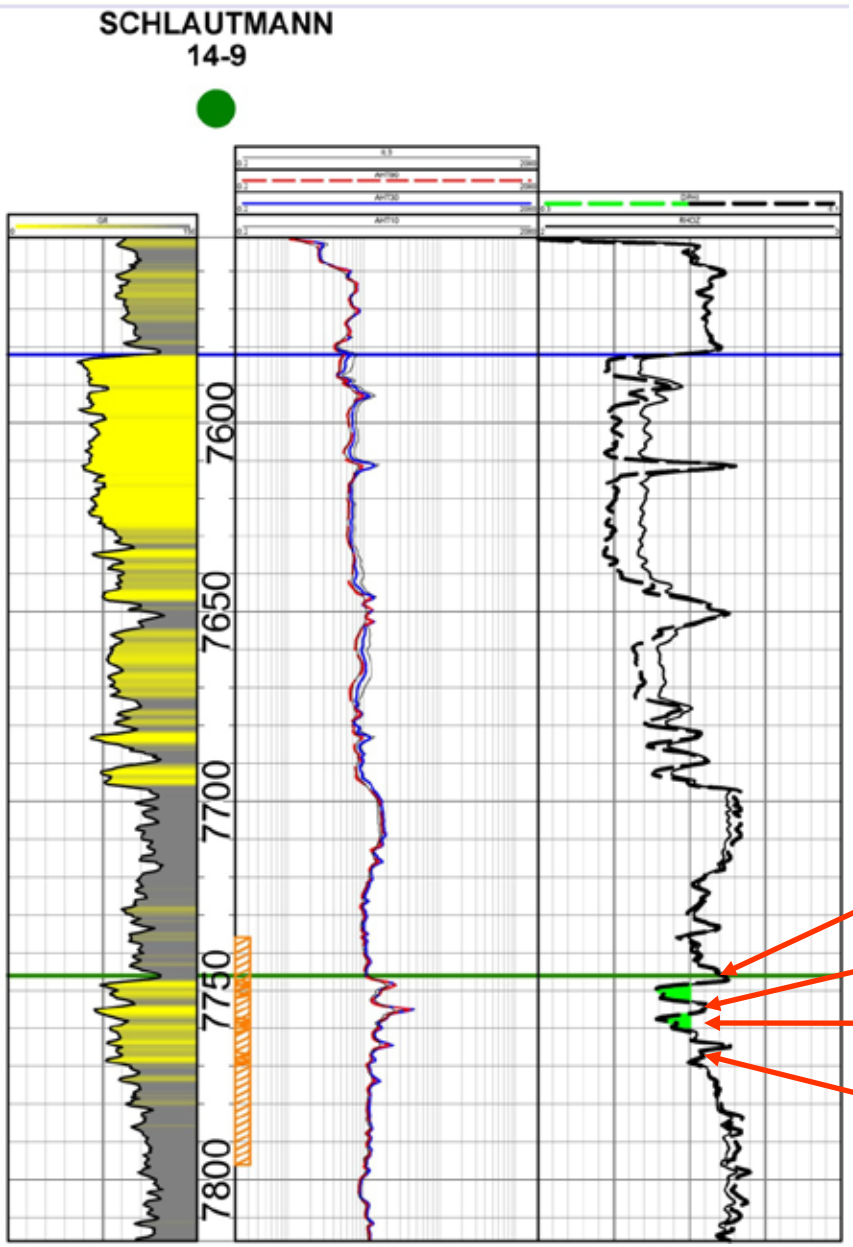
FRAC jobs communicate with Upper Parkman yielding 350 BWPD

SOLUTION:

Horizontal Wells

After Wheeler (2010)

Core Photos



Vertical Well

Primary EUR 177 MBO

Top Seal, Central Bar

Tight Streak

Bar Margin

Bottom Seal

After Wheeler (2010)

Core Photos

Plain UV Plain UV Plain UV

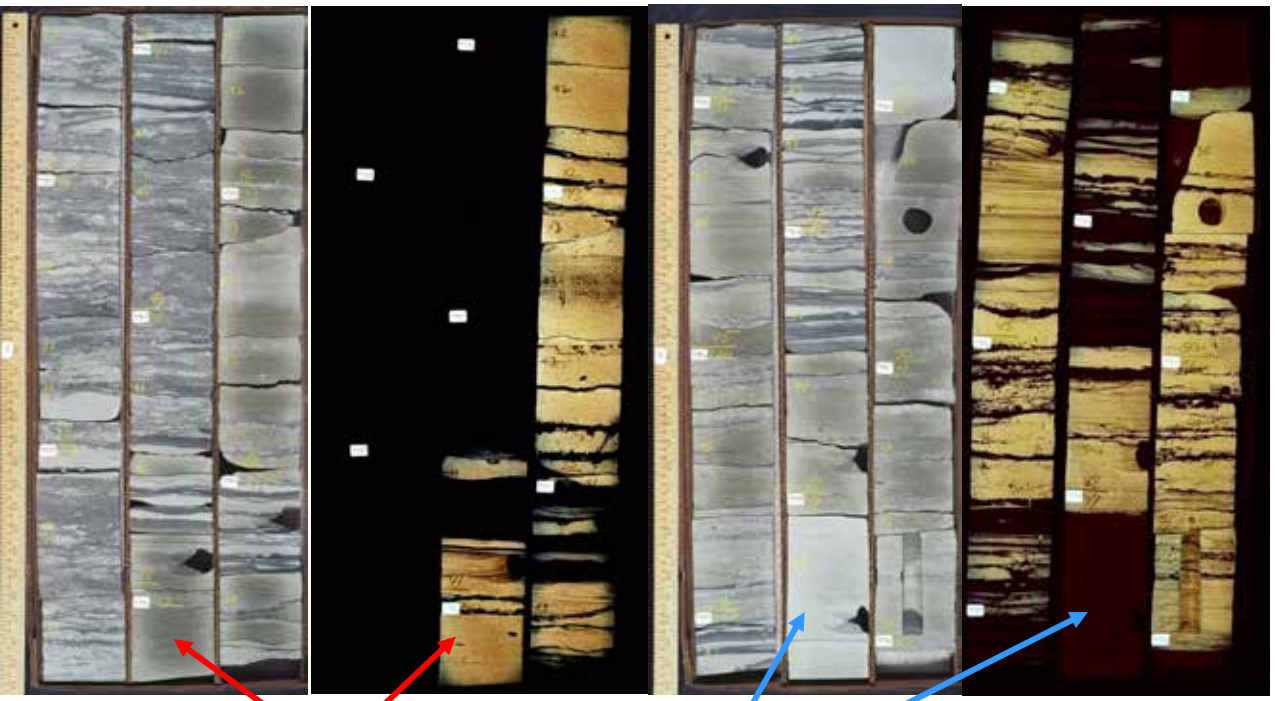
Bright UV Fluorescence & Oil Stain in Laminated Facies

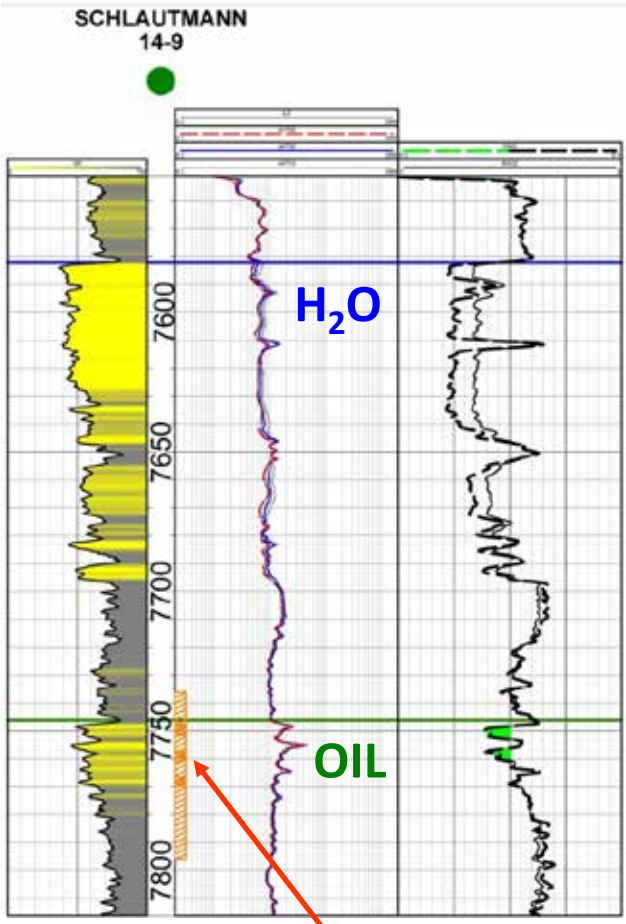
Calcite Cement

After Wheeler (2010)

Parkman Sandstone Savageton Field Core Photos

Water in Overlying Upper Shoreface Means Horizontal Wells Are Not Fracture-Stimulated





Bright UV Fluorescence & Oil Stain in Laminated Sandstones

Calcite Cement

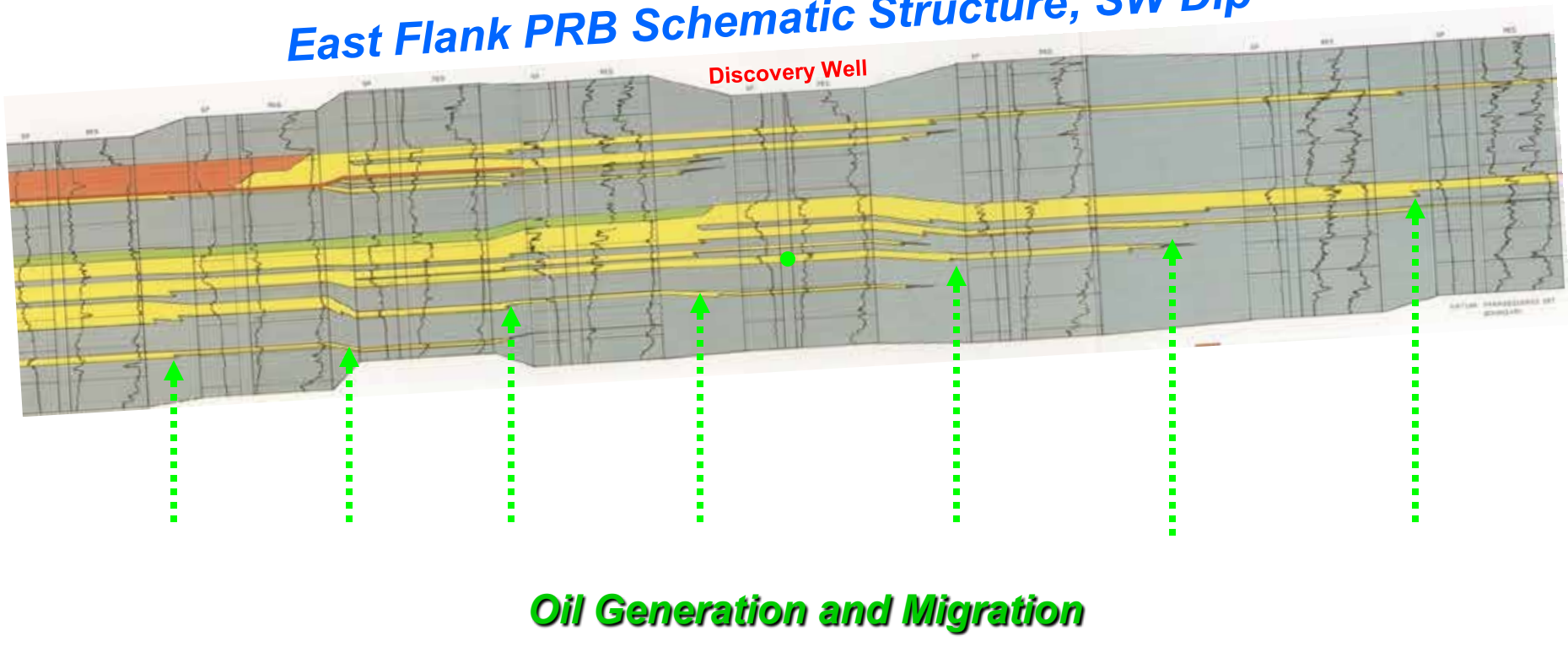
No Fluorescence or Oil Stain in Thinly Interlaminated Sandstones & Mudstones

Oil-Saturated Sandstones

After Wheeler (2010)

Parkman Stacking Pattern
Migration and Trapping

West East

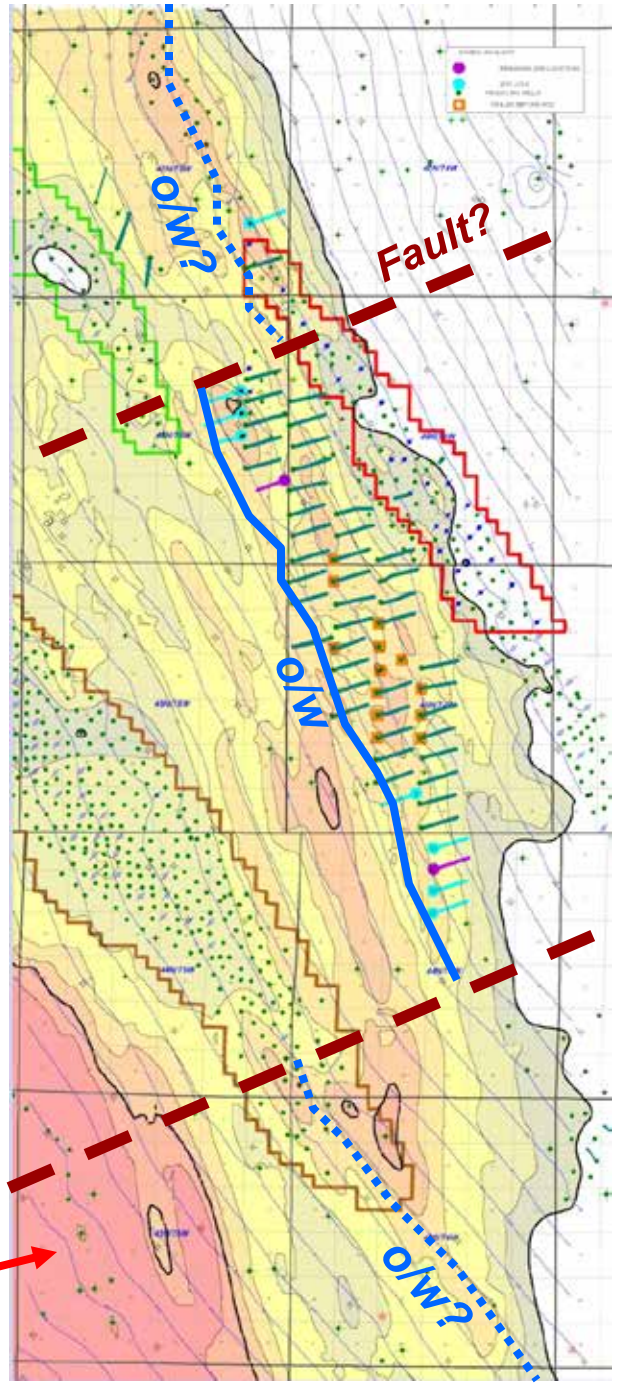


Van Wagoner et al., 1990, Siliciclastic sequence stratigraphy

After Wheeler (2010)

Savageton Field

Net (>10%) SS Isopach & Structure



Shoreface Thick

- Stratigraphic Trap
- Updip Pinchout of Lower Parkman Sandstone
- Downdip Water Leg
- Water in Main Parkman Above Pay – No Fracs!

After Wheeler (2010)

PARKMAN SANDSTONE

Savageton Field (Gilbertz #12-30 E959)

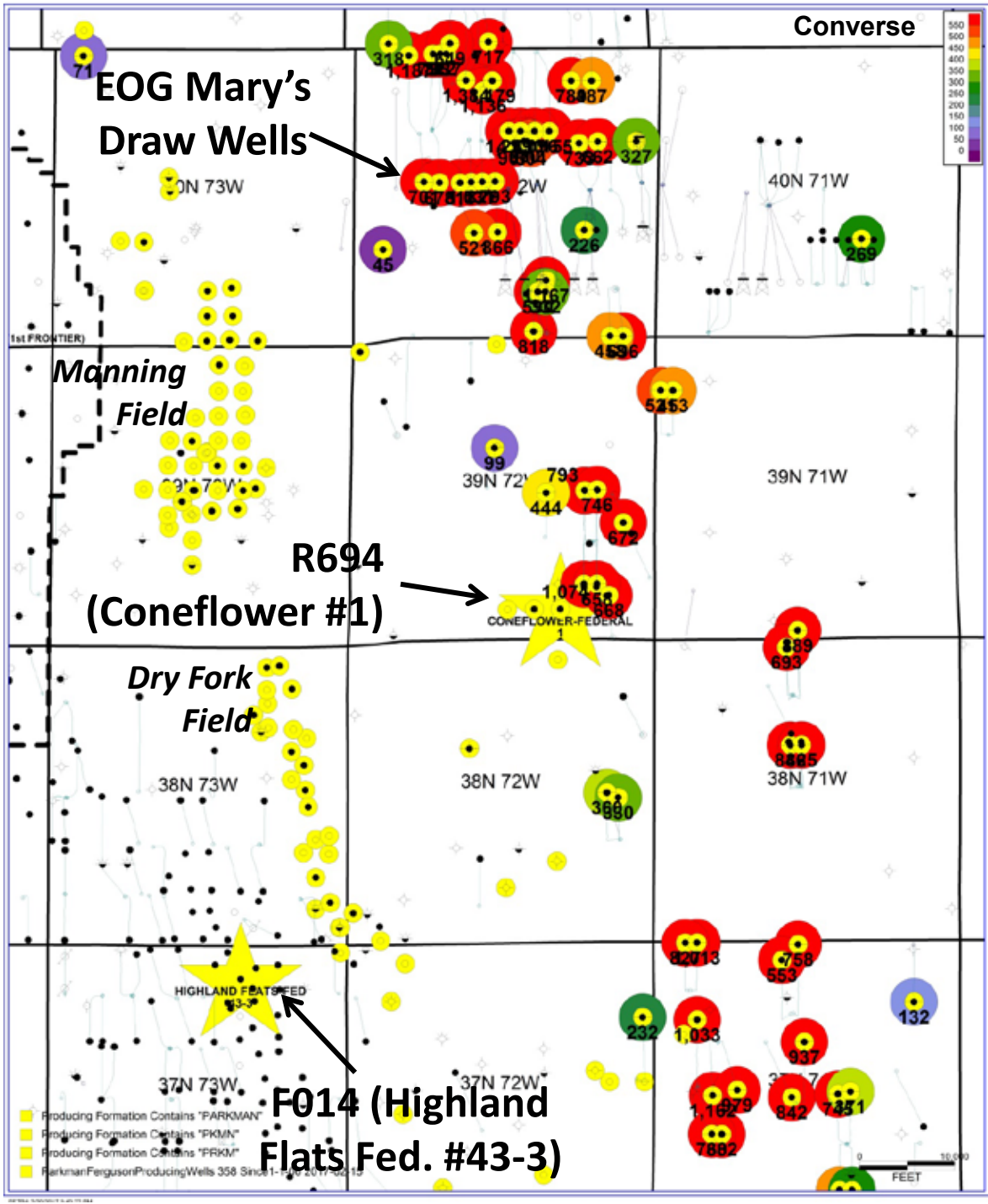
- Ø Upper Parkman SS Wet, High Permeability
- Ø Lower Parkman Stratigraphic Trap – Updip Pinchout of Distal Delta Front or Lower Shoreface Sandstone
- Ø No Frac Barrier Between the Two Reservoirs
- Ø Oil Saturation in High-Porosity, Higher Permeability Laminated Beds
- Ø Burrowed Facies has No to Low So% - Migrated Oil?

WHAT ABOUT THE EASTERN PARKMAN PLAY?

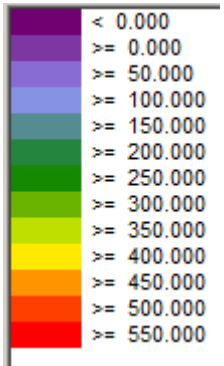
PARKMAN SANDSTONE PLAY

Maximum Daily Oil + Gas Rate in BOE/day for Wells After 1-1-2006

- **Southern Cores**
- **Manning Field, Discovered 1970, Cum 2.8 MMBO + 5.7 BCFG + 4.5 MMBW**
- **Dry Fork Field Discovered 1970 Cum 1.6 MMBO + 1.1 BCFG + 1.8 MMBW**
- **Davis Oil Coneflower #1 R694 is on Trend with EOG Mary's Draw Wells**



BOEPD



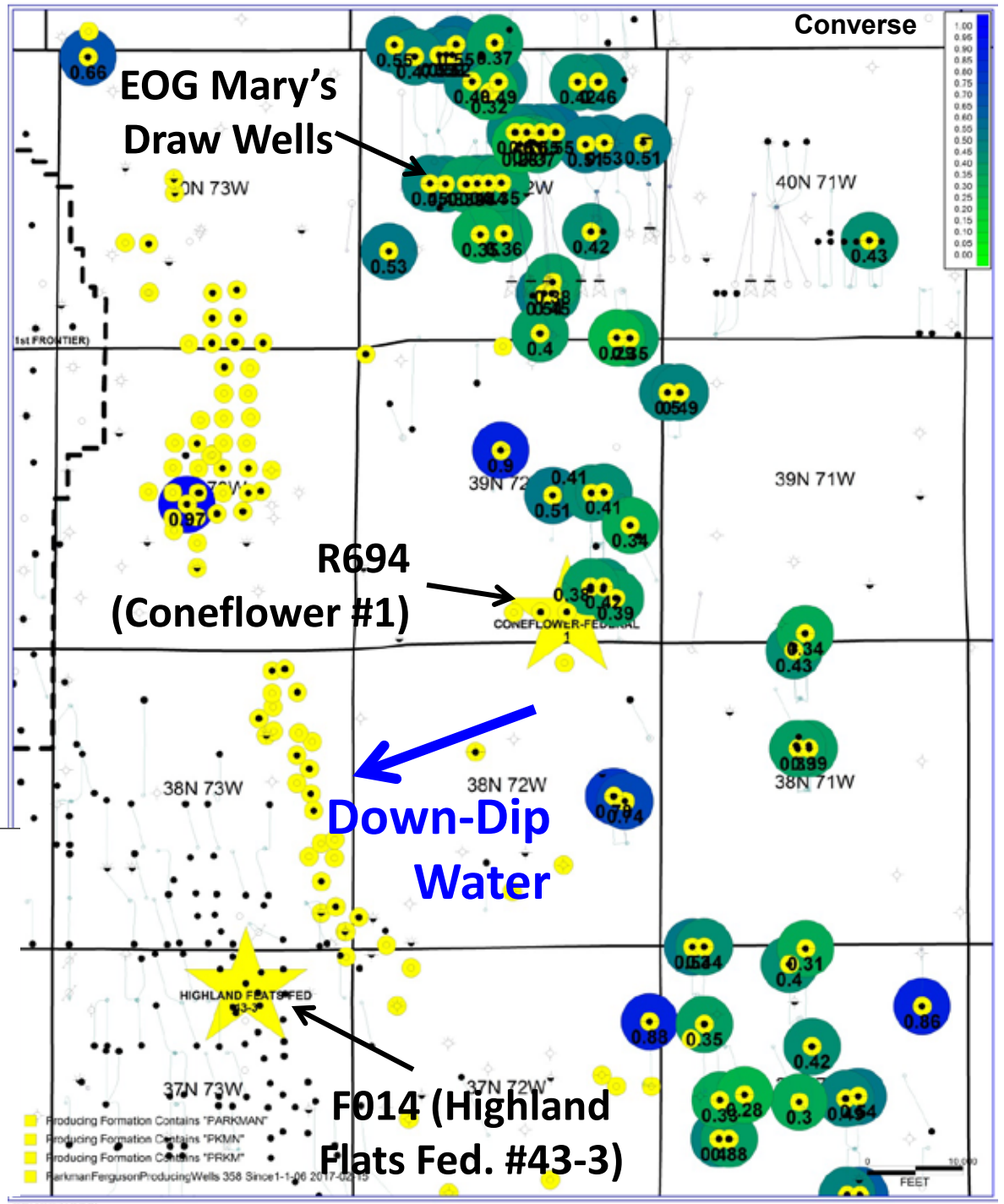
IHS Markit

Well and Production Data From IHS Markit

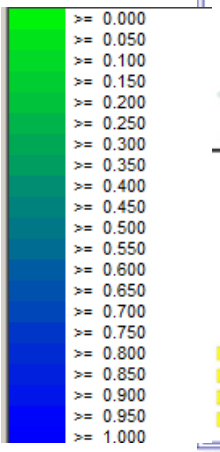
PARKMAN SANDSTONE PLAY

Water Cut (Decimal) from Cum Production for Wells After 1-1-06

- **Moderate Water Cut in Active Area, Generally < 30-50%**
- **Water Cut Increases Downdip (west)**
- **Apparent Water Cut Increases Updip (East) Due to Low-Volume Wells**

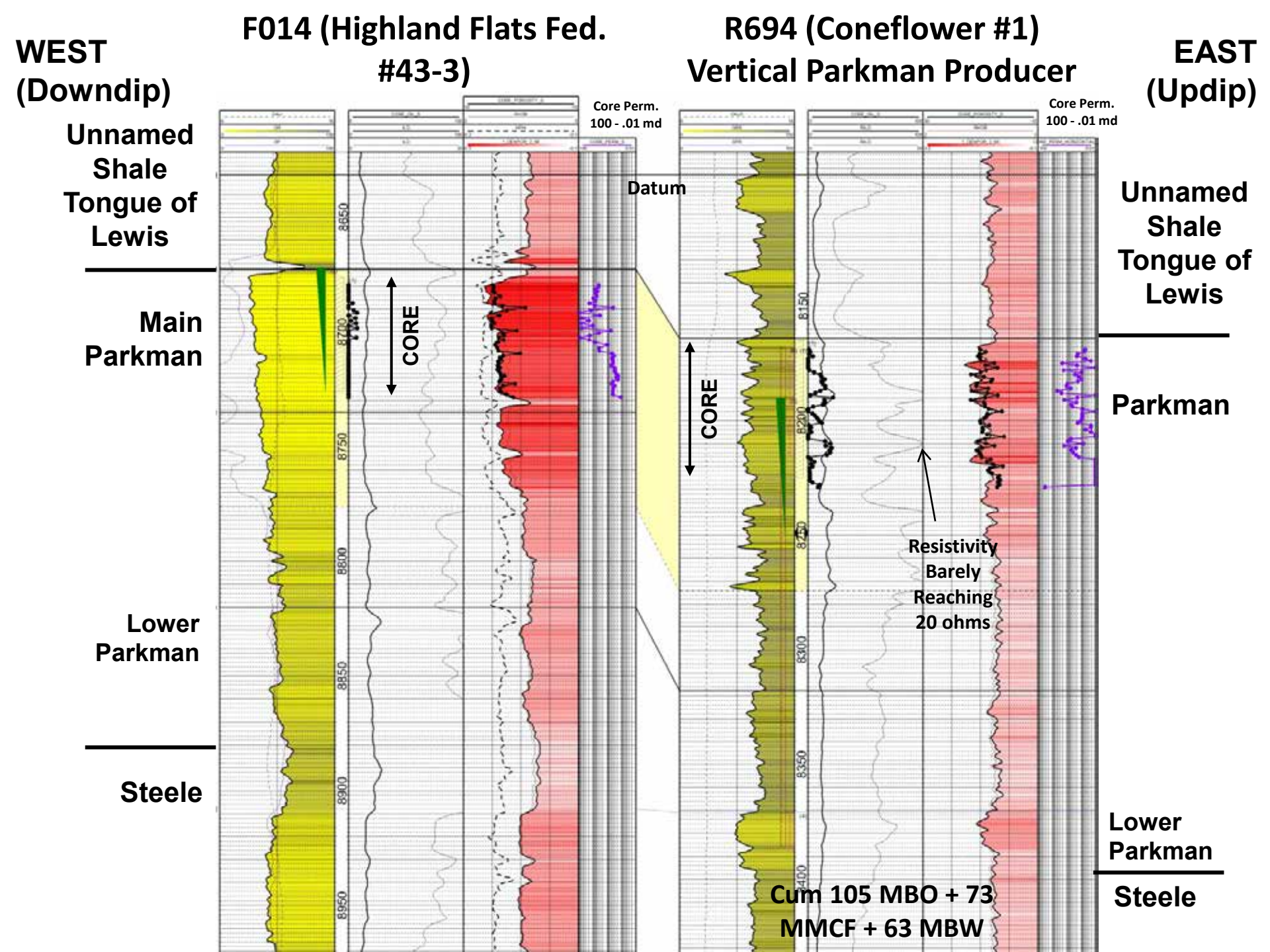


Water Cut (Decimal)



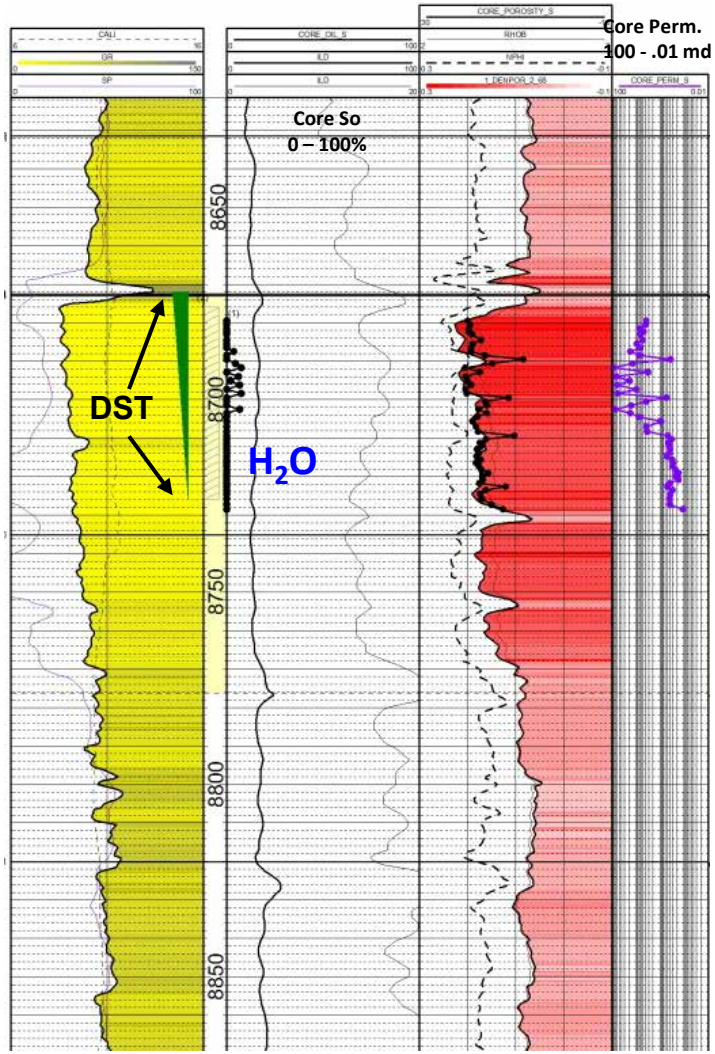
IHS Markit

Well and Production Data From IHS Markit


WEST
(Downdip)
F014 (Highland Flats Fed.
#43-3)
R694 (Coneflower #1)
Vertical Parkman Producer
EAST
(Updip)
Core Perm.
100 - .01 md
Core Perm.
100 - .01 md
Datum
Unnamed
Shale
Tongue of
Lewis
Unnamed
Shale
Tongue of
Lewis
Main
Parkman
Parkman
CORE
CORE
Resistivity
Barely
Reaching
20 ohms
Lower
Parkman
Lower
Parkman
Steele
Steele
Cum 105 MBO + 73
MMCF + 63 MBW

F014

LL&E
Highland Flats-Fed #43-3
NE-SE-3-T37N-R73W
Comp. 8-6-84



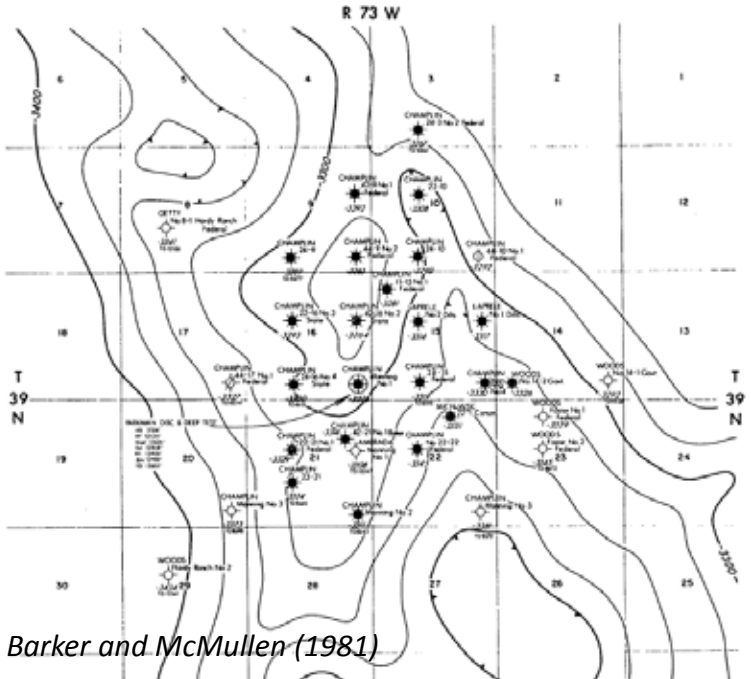
Cored 50’ Parkman SS – Average 17.2%
Porosity & 2.3 md Perm.
DST Rec. 50’ SM&WCO + 1500’ SO&GCW

PARKMAN SANDSTONE

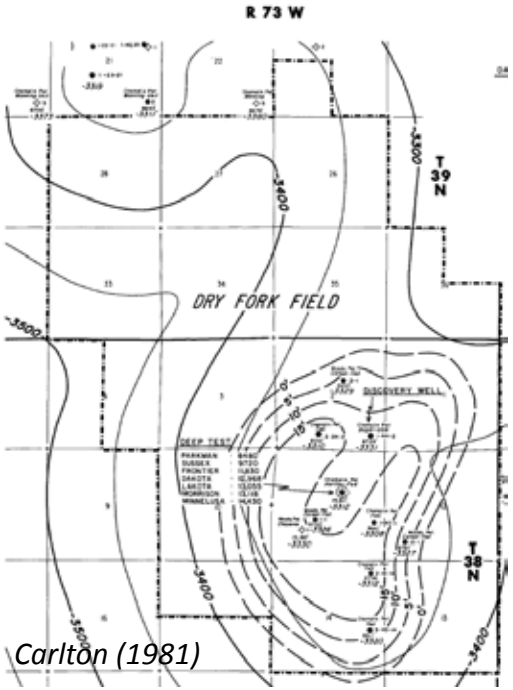
Manning & Dry Fork Fields (Highland Flats Federal #43-3 F014)

- Ø Upper Parkman SS High Permeability, High Porosity, Produces on "Structure"
- Ø Upper Shoreface to Foreshore
- Ø Productive Limits Beyond Limit of 4-Way Closure – Stratigraphic Component to Trap?

WHAT ABOUT THE EASTERN PARKMAN PLAY?



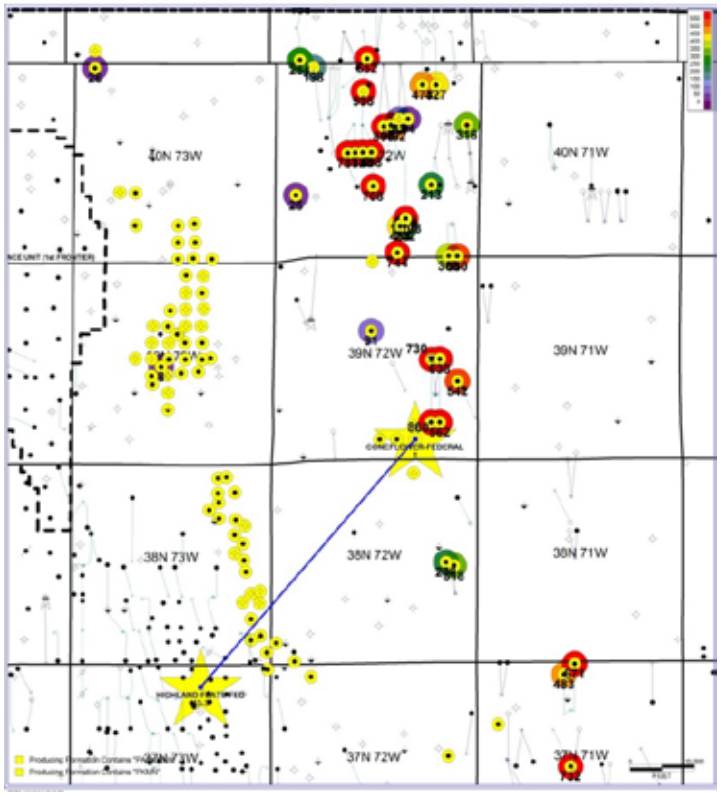
Barker and McMullen (1981)



Carlton (1981)

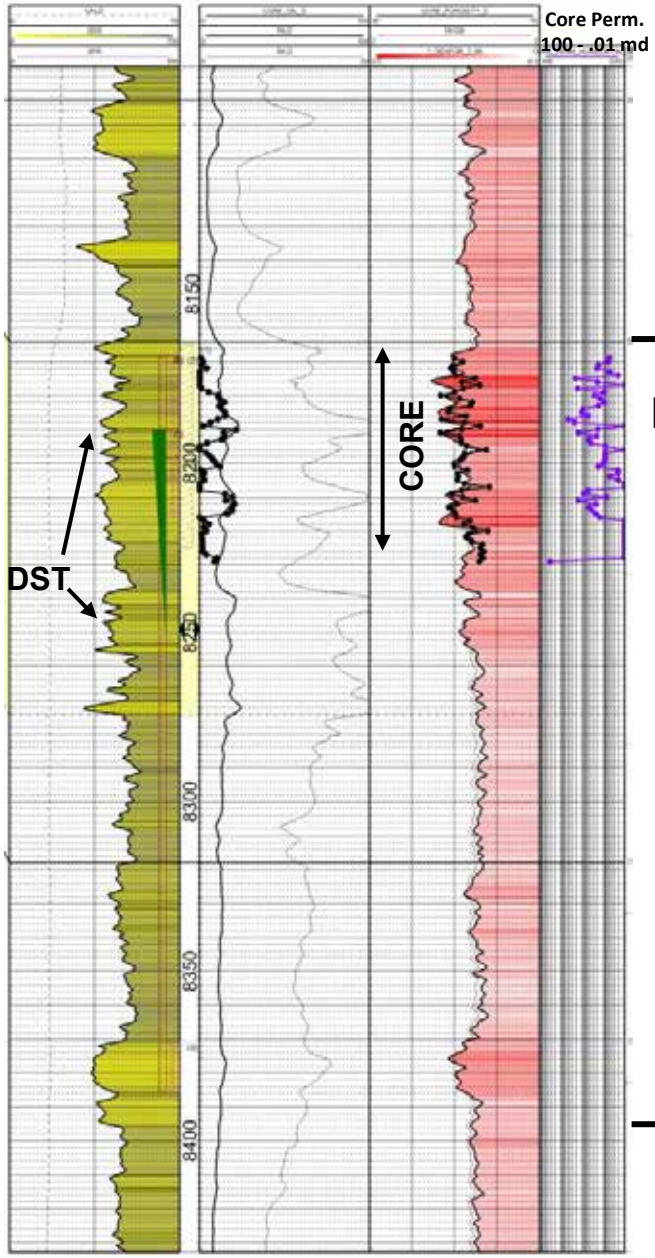
R694 (Coneflower #1) Vertical Parkman Producer

- Cored 60’ Parkman SS – Average 6.7% Porosity & 0.86 md Perm.
- DST Rec. 100’ SOCM w/ 900 CFG + 350cc O + 750cc M in Sample Chamber
- NO WATER!



Davis Oil
Coneflower-Federal #1
SW-NW-35-T39N-R72W
Comp. 7-30-80

Cum 105 MBO + 73 MMCF + 63 MBW



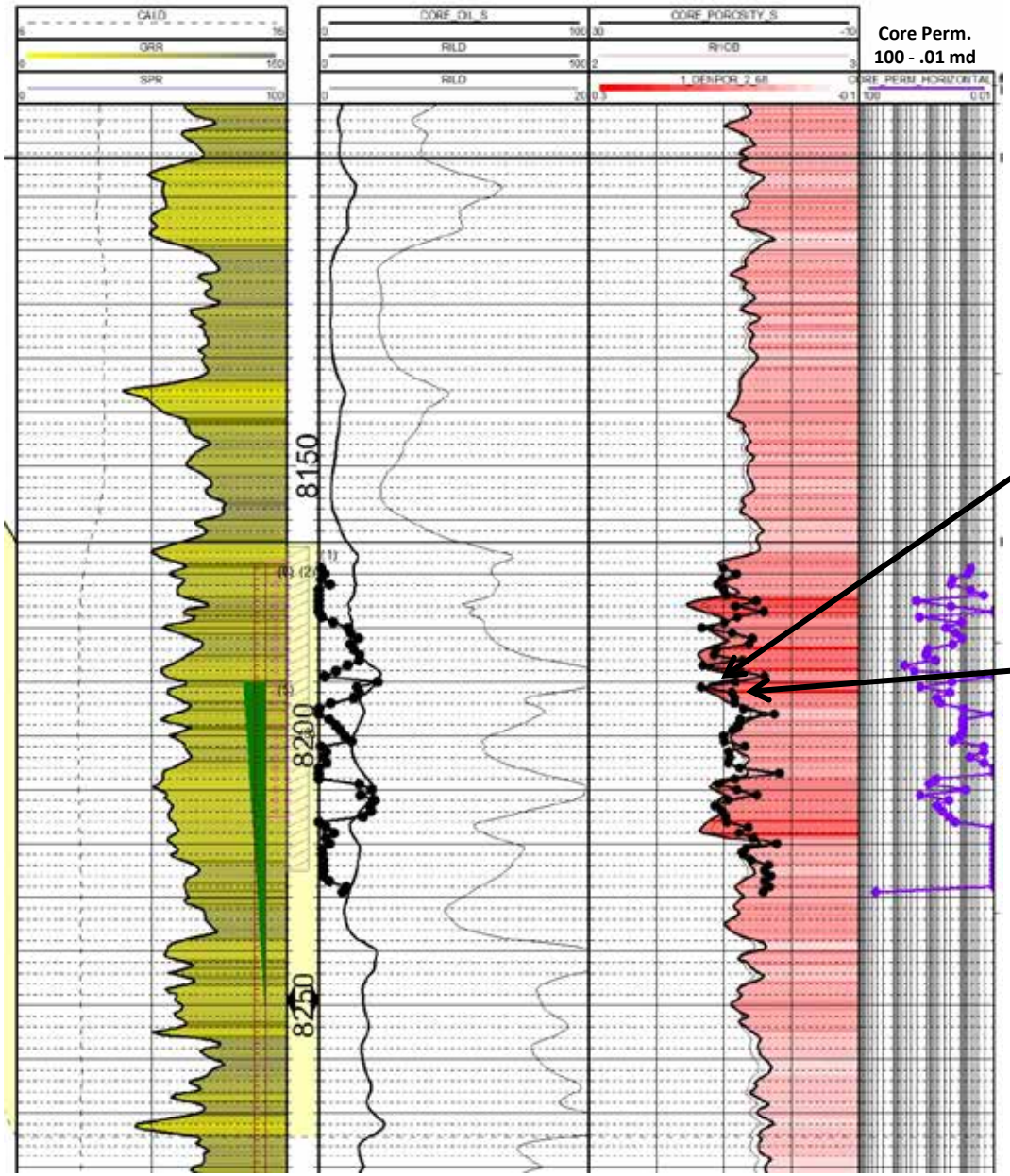
Unnamed Shale Tongue of Lewis

Parkman

Lower Parkman

Steele

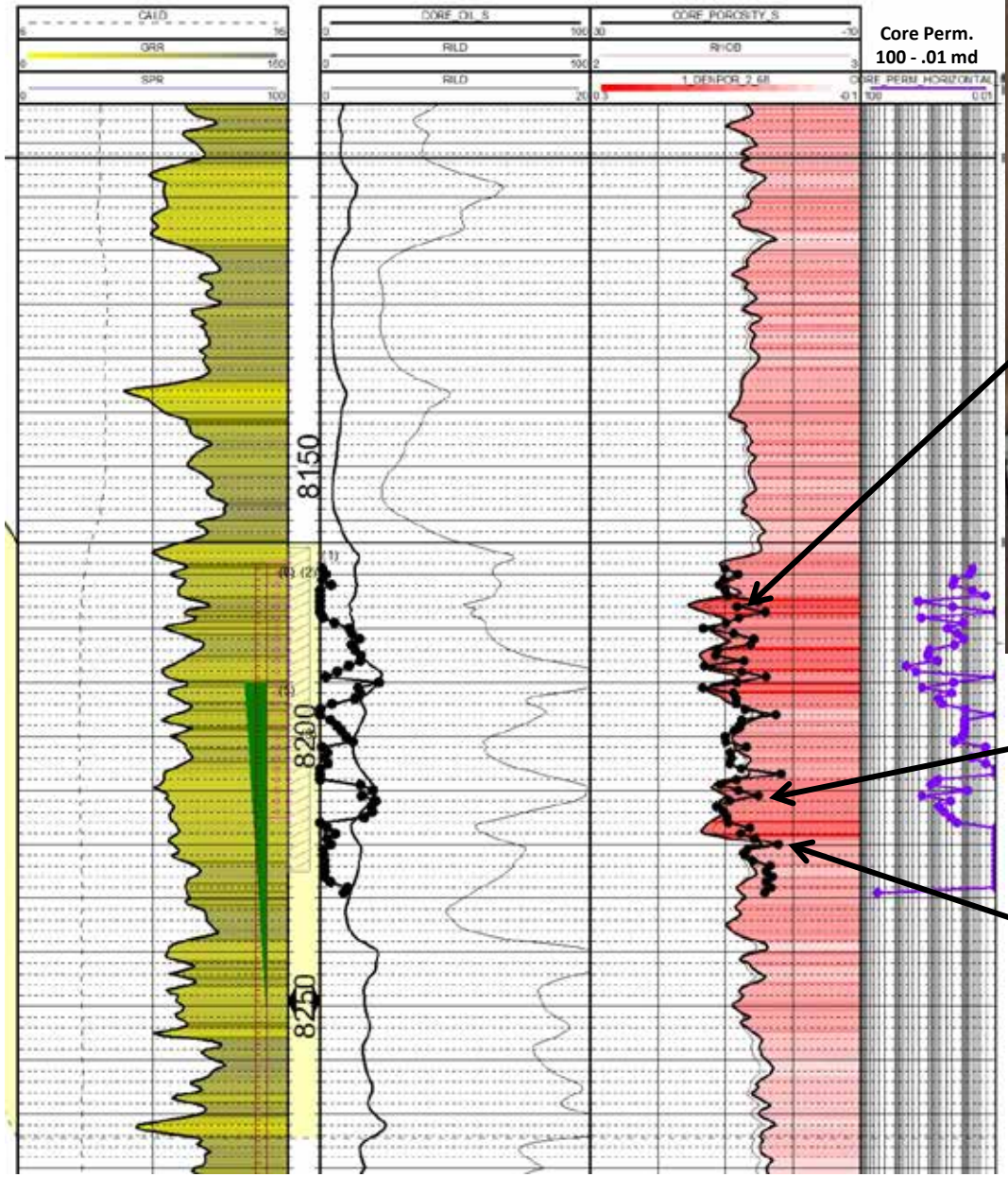
R694 (Coneflower #1)



RCA @ 8,212 Core =
8,191 Log
Phi 13.4%,
k 1.5md,
So 14.1%
Interlaminated SS &
SH

RCA @ 8,213 Core =
8,192 Log
Phi 9.4%,
k 0.3md,
So 14.1%
Interlaminated SS &
SH

R694 (Coneflower #1)

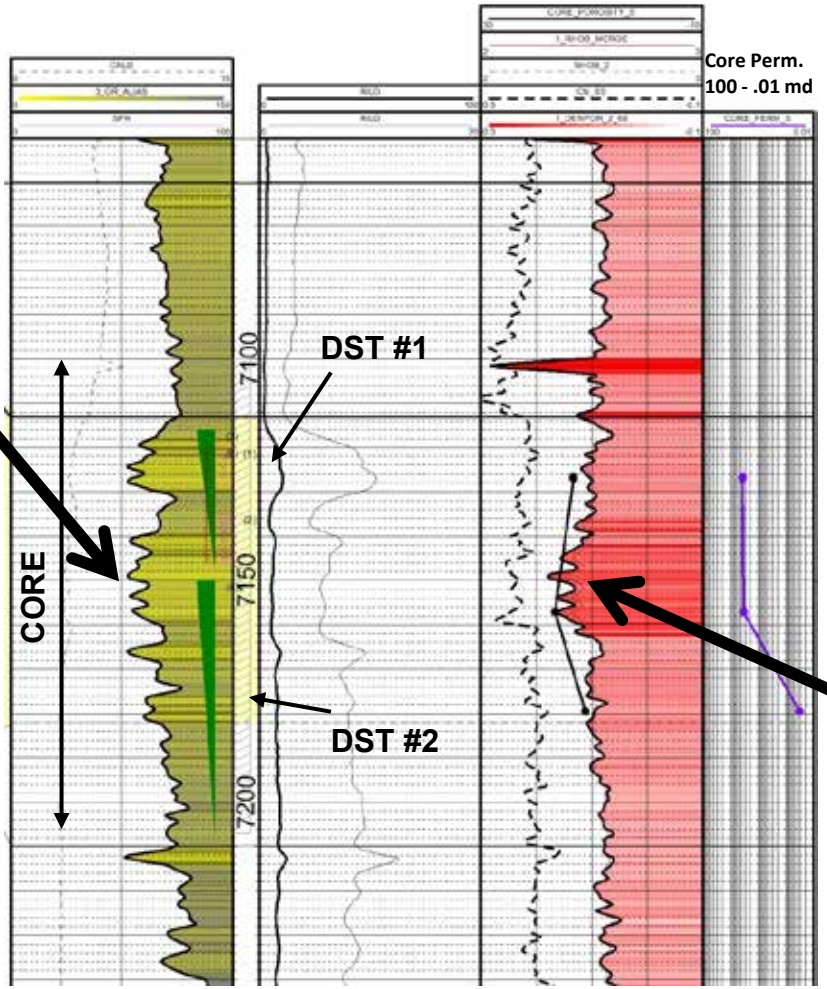


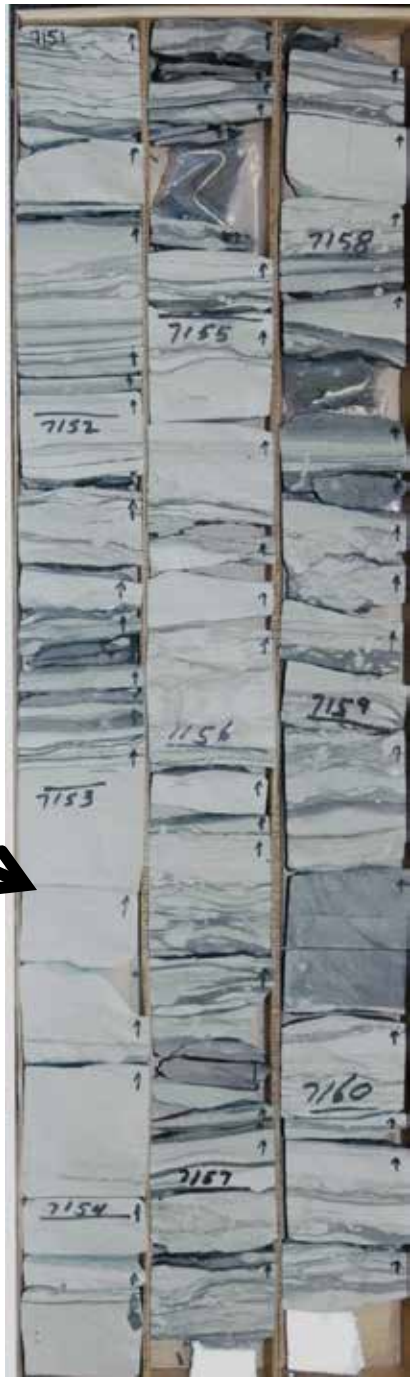
RCA @ 8,196 Core = 8,174 Log
Phi 9.7%, k 0.02 md, So 0.0%
Bioturbated Muddy SS
Note Separation Between Density Porosity & Core Porosity

RCA @ 8,234 Core = 8,213 Log
Phi 11.4%, k 0.48 md, So 18.8%
Laminated SS

RCA @ 8,241 Core = 8,220 Log
Phi 2.2%, k 0.01 md, So 4.0%
Burrowed Muddy SS

C936 (Durham Federal #32-1)





Thin Mudstone Beds

- Transgressive/Flooding Events
- Decrease Vertical Permeability
- Suppressed Resistivity in Sandstone Beds Due to Thin-Bed Resolution Problems with Logs

- Cored 107’ Parkman SS –
- DST #1 Rec. 660’ G + 31’ G&MCO + 245’ O&GCW
- DST #2 Rec. 100’ MCW

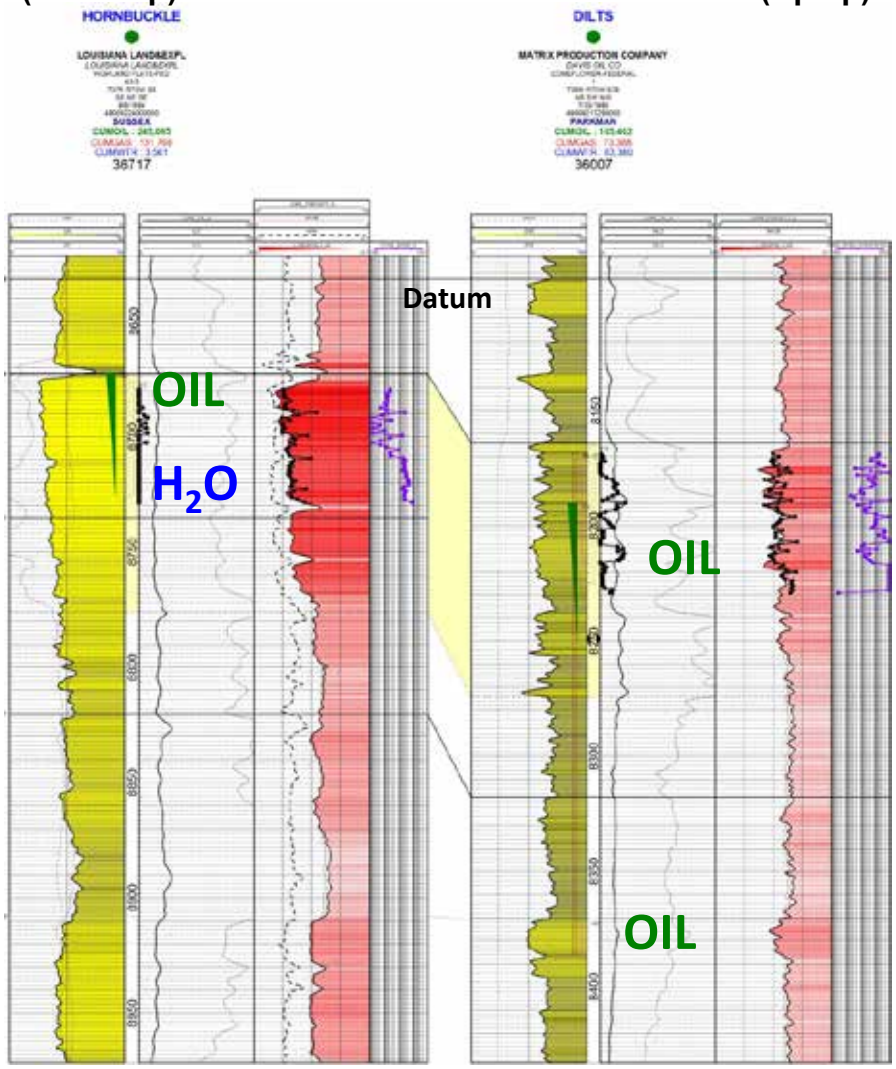
2 Southern Cores

F014 (Highland Flats Fed. #43-3)

WEST
(Downdip)

R694 (Coneflower #1)

EAST
(Updip)



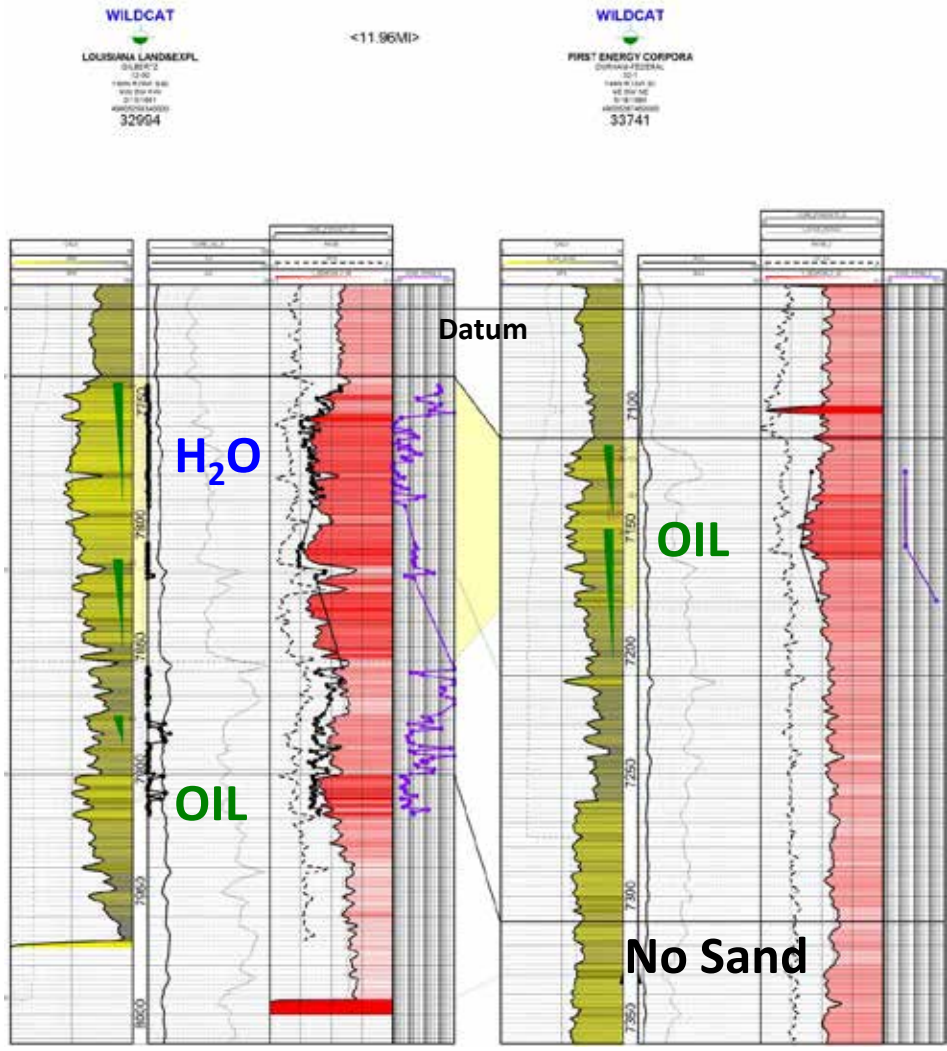
2 Northern Cores

E959 (Gilbertz Fed. #12-30)

WEST
(Downdip)

C936 (Durham-Federal #32-1)

EAST
(Updip)



Stratigraphic Cross Sections, Datum Pierre Shale Marker Above Top Parkman

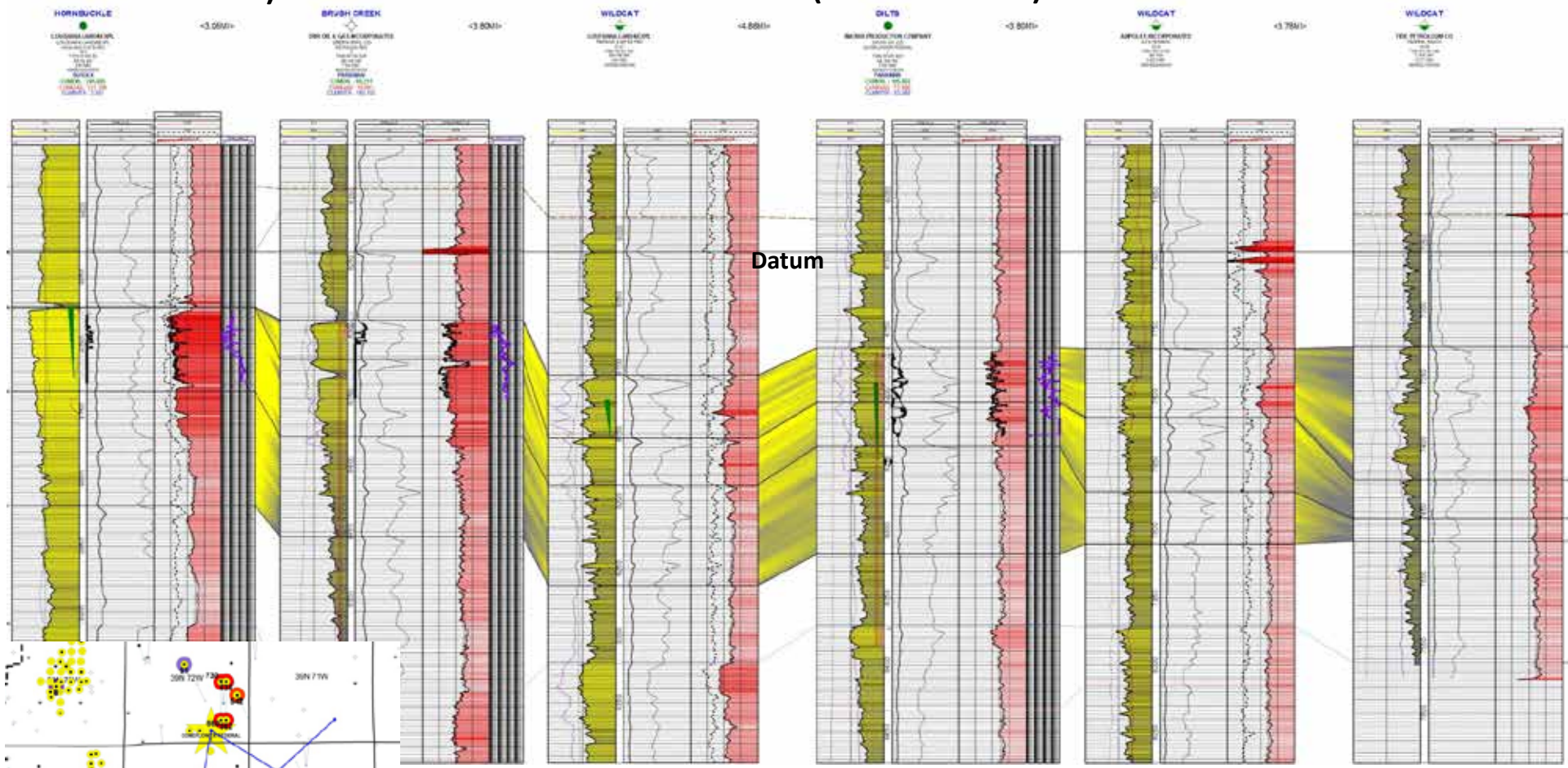
Parkman Sandstone Stratigraphic Cross-Section
Southern Cores

WEST
(Downdip)

EAST
(Updip)

F014 (Highland Flats Fed. #43-3)

R694 (Coneflower #1)



Updip / Eastward Pinchout of Parkman Shoreface Facies

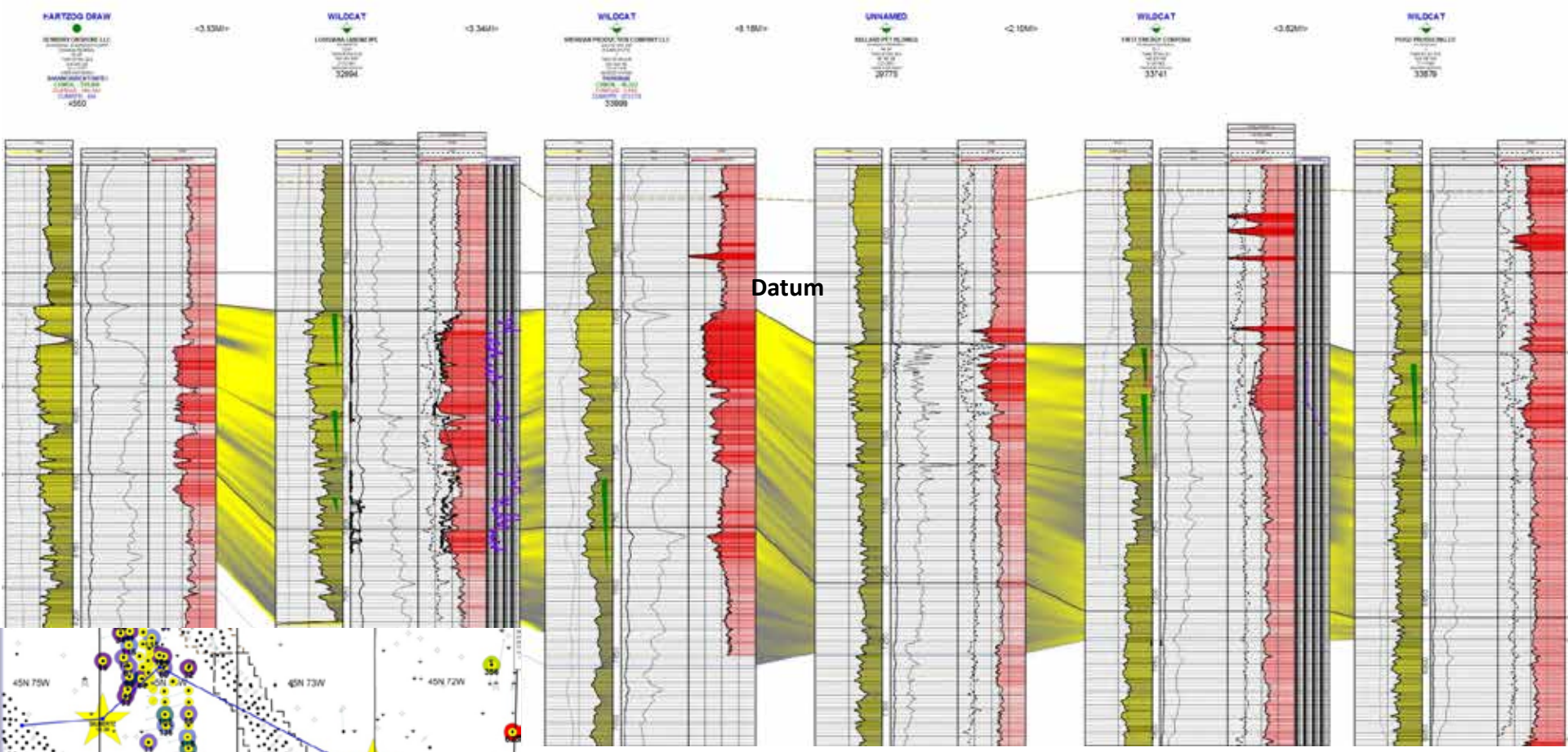
Parkman Sandstone Stratigraphic Cross-Section
Northern Cores

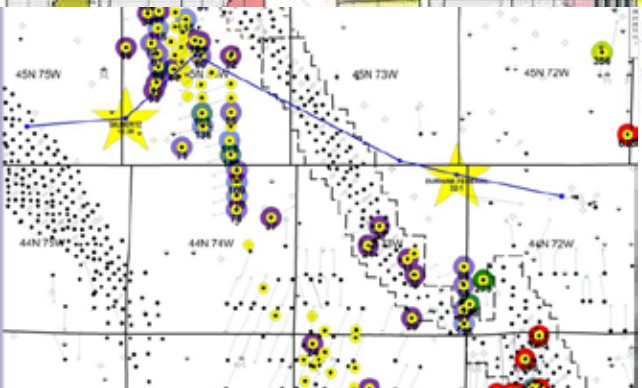
WEST
(Downdip)

E959 (Gilbertz-Fed. #12-30)

C936 (Durham-Fed #32-1)

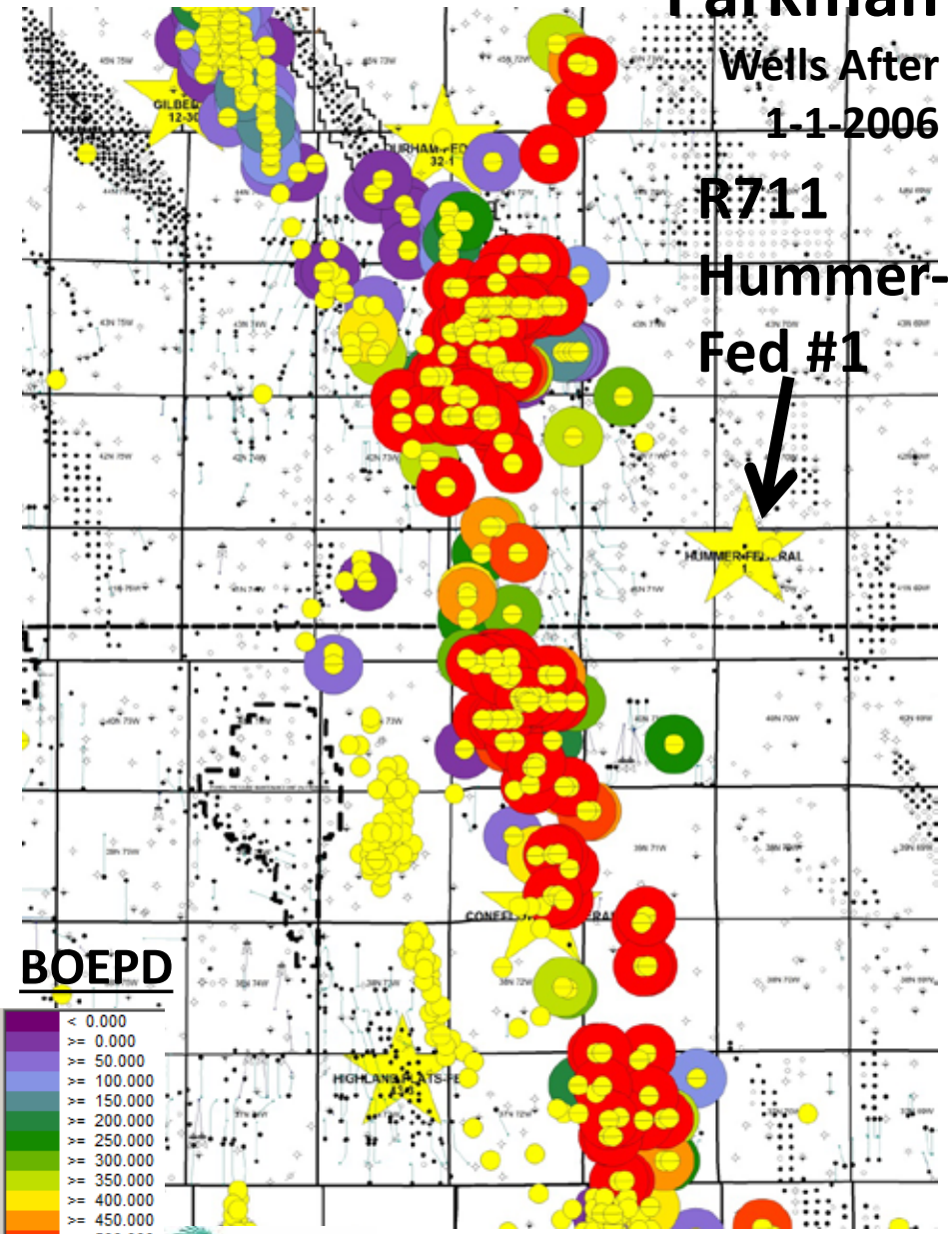
EAST
(Updip)



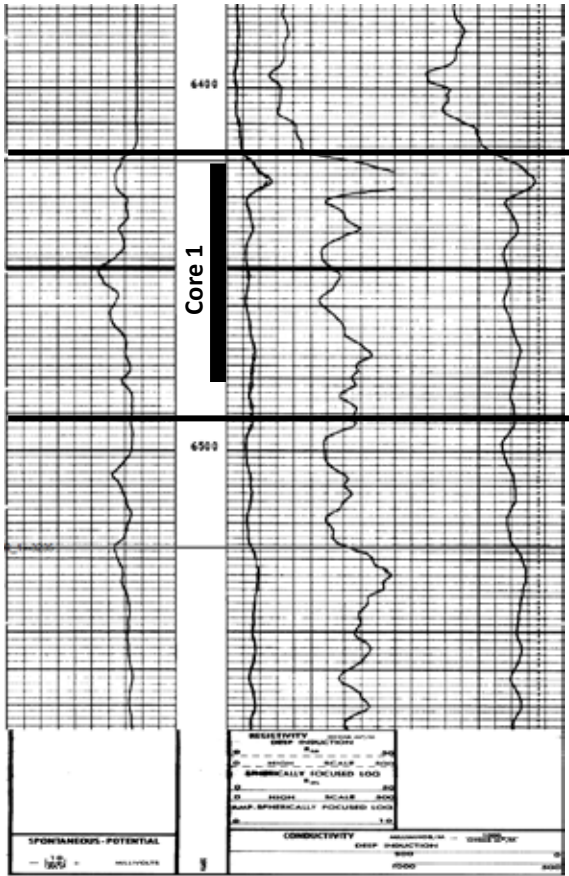


Updip / Eastward Pinchout of Parkman Shoreface Facies

R711 Davis Oil Hummer-Federal #1 Parkman Sandstone



- **Eastern Core**
- **Hummer-Fed #1 R711 is 6-8 Miles East of Historical Parkman Production & Active Horizontal Plays**



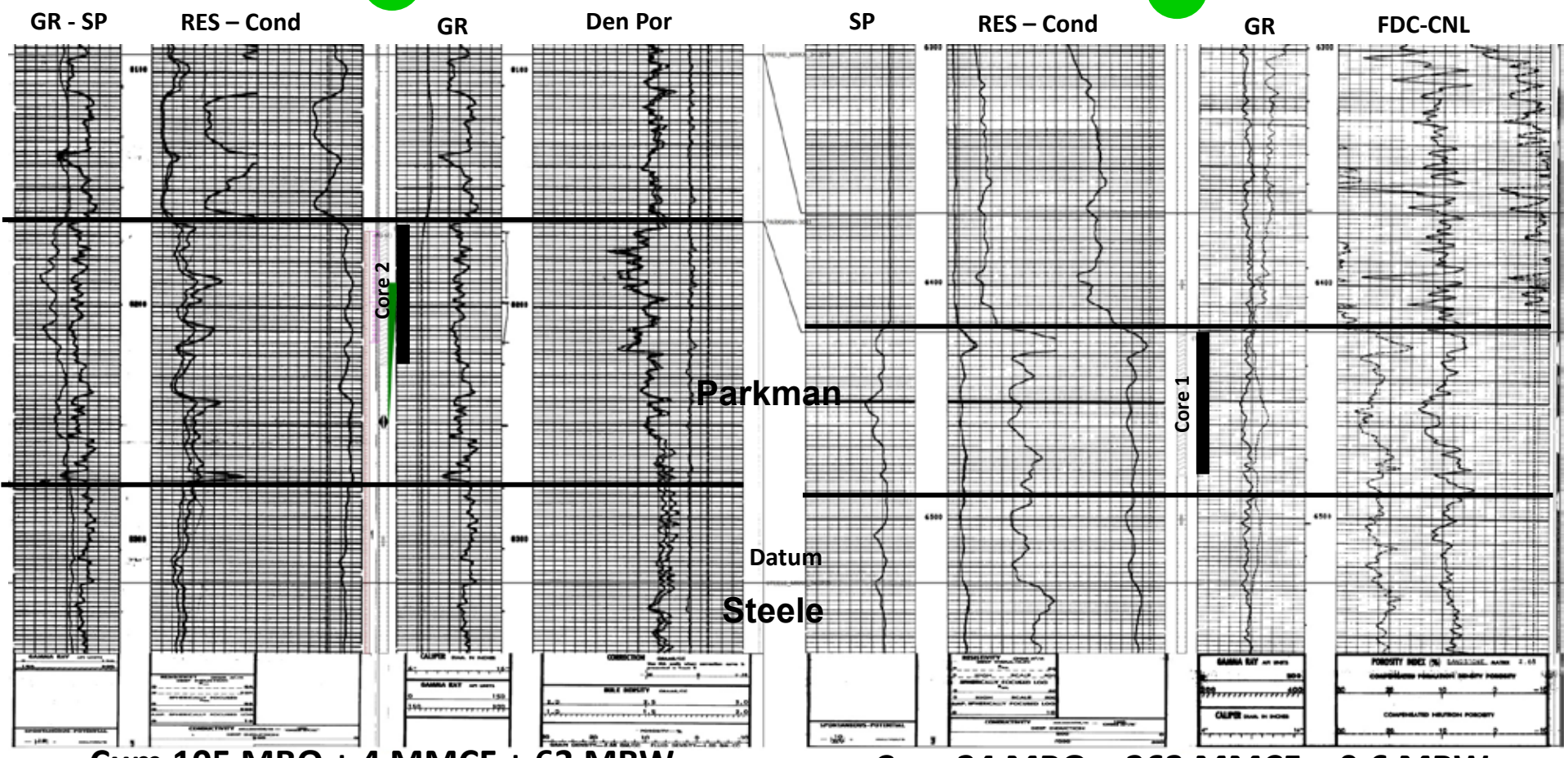
R694 Coneflower #1 to R711 Hummer-Federal #1

WEST
(Downdip)

EAST
(Updip)

R694 Davis Oil
Coneflower-Federal #1
SW-NW-35-T39N-R72W
Comp. 7-30-80

R711 Davis Oil
Hummer-Federal #1
SW-5-T41N-R70W
Comp. 3-5-81



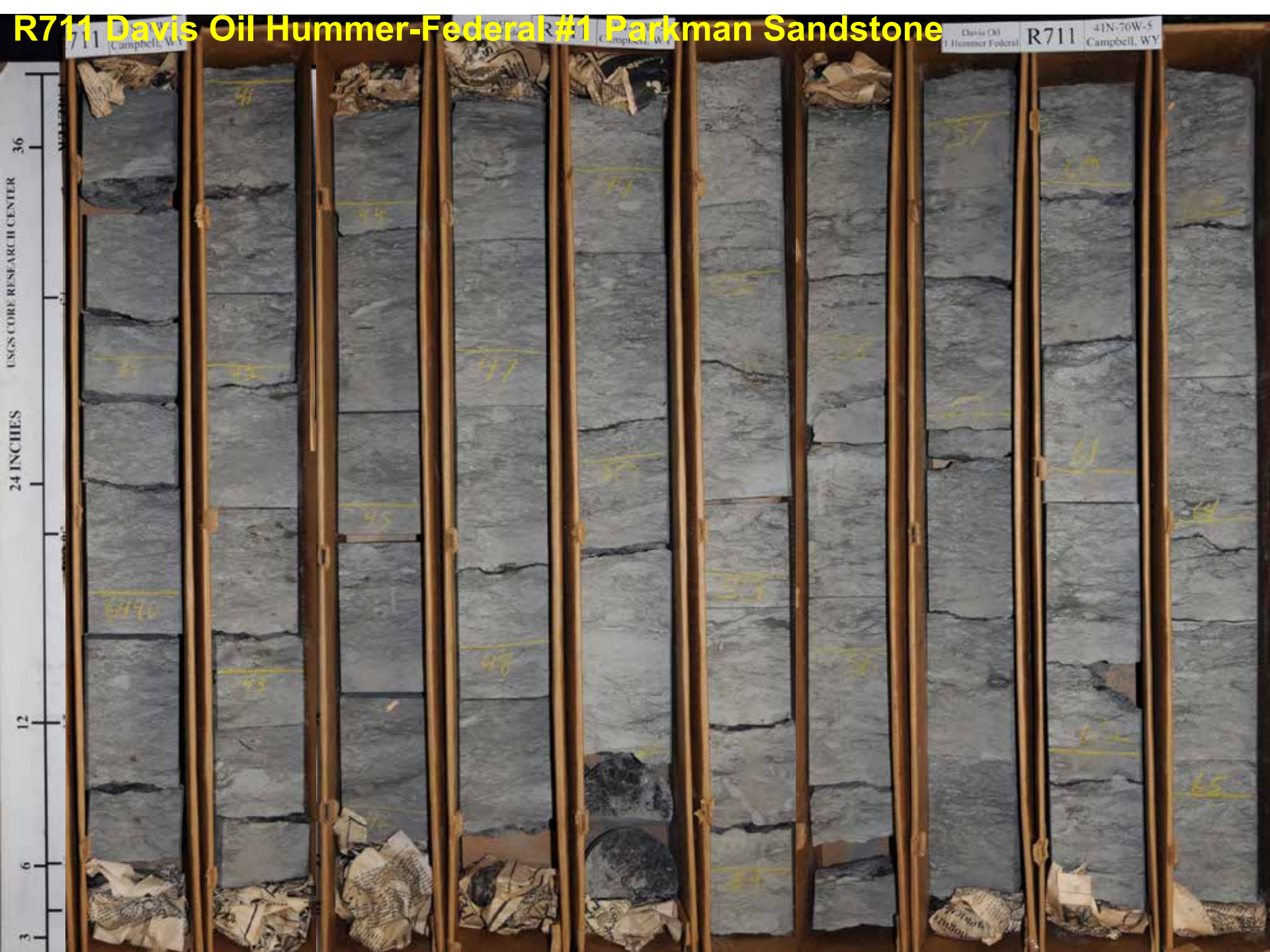
Cum 105 MBO + 4 MMCF + 63 MBW

Parkman

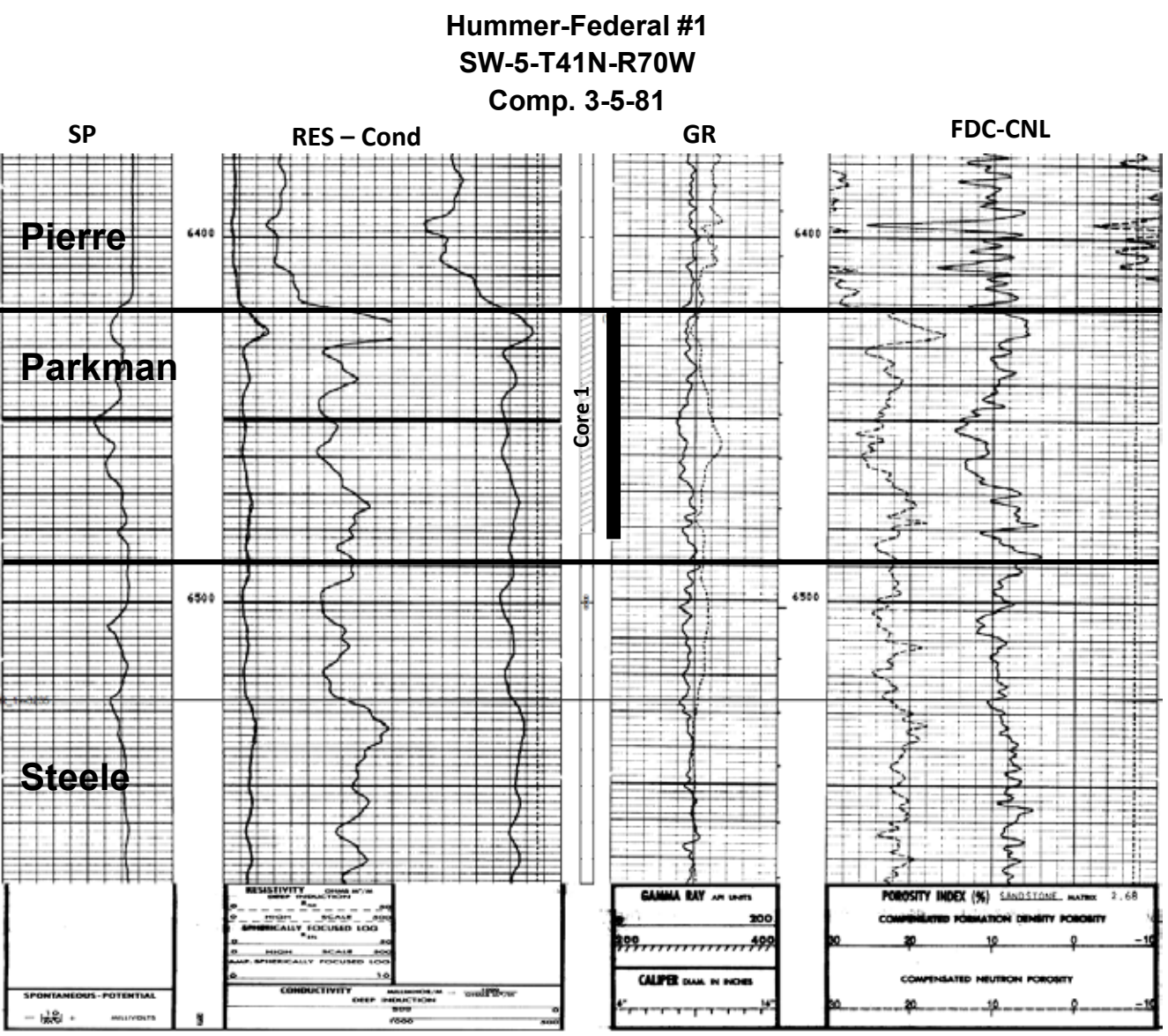
Cum 24 MBO + 263 MMCF + 0.6 MBW

Muddy

R711 Davis Oil Hummer-Federal #1 Parkman Sandstone



R711 Davis Hummer-Federal #1



- **Eastern Core**
- **Hummer-Fed #1 R711 is 6-8 Miles East of Historical Parkman Production & Active Horizontal Plays**
- **Resistivity Decreases When Porosity Increases & SP Indicates Permeability**
- **Completely Bioturbated**
- **Low Permeability, Small Pore-Throats – Requires High Injection Pressure for Oil Saturation**
- **Shallow Depth, Probably Not Thermally Mature – TRAP! (Waste Zone)**

PARKMAN SANDSTONE PLAY

- Ø Regional Updip Pinchout of Parkman Sandstone
- Ø Multiple Sandstone Pinchouts – Complex System of Traps
- Ø Short Distance Facies Change from Clean Upper Shoreface to "Lam-Scram" Lower Shoreface
- Ø Oil Saturation in High-Porosity, Higher Permeability Laminated Beds
- Ø Bioturbated Facies has No to Low So%
- Ø Hummer Core/Well is East of Active Oil Play
- Ø Migrated Oil?

IS THE PARKMAN A "TIGHT" OIL RESERVOIR?

RMAG Tight Oil Sandstones

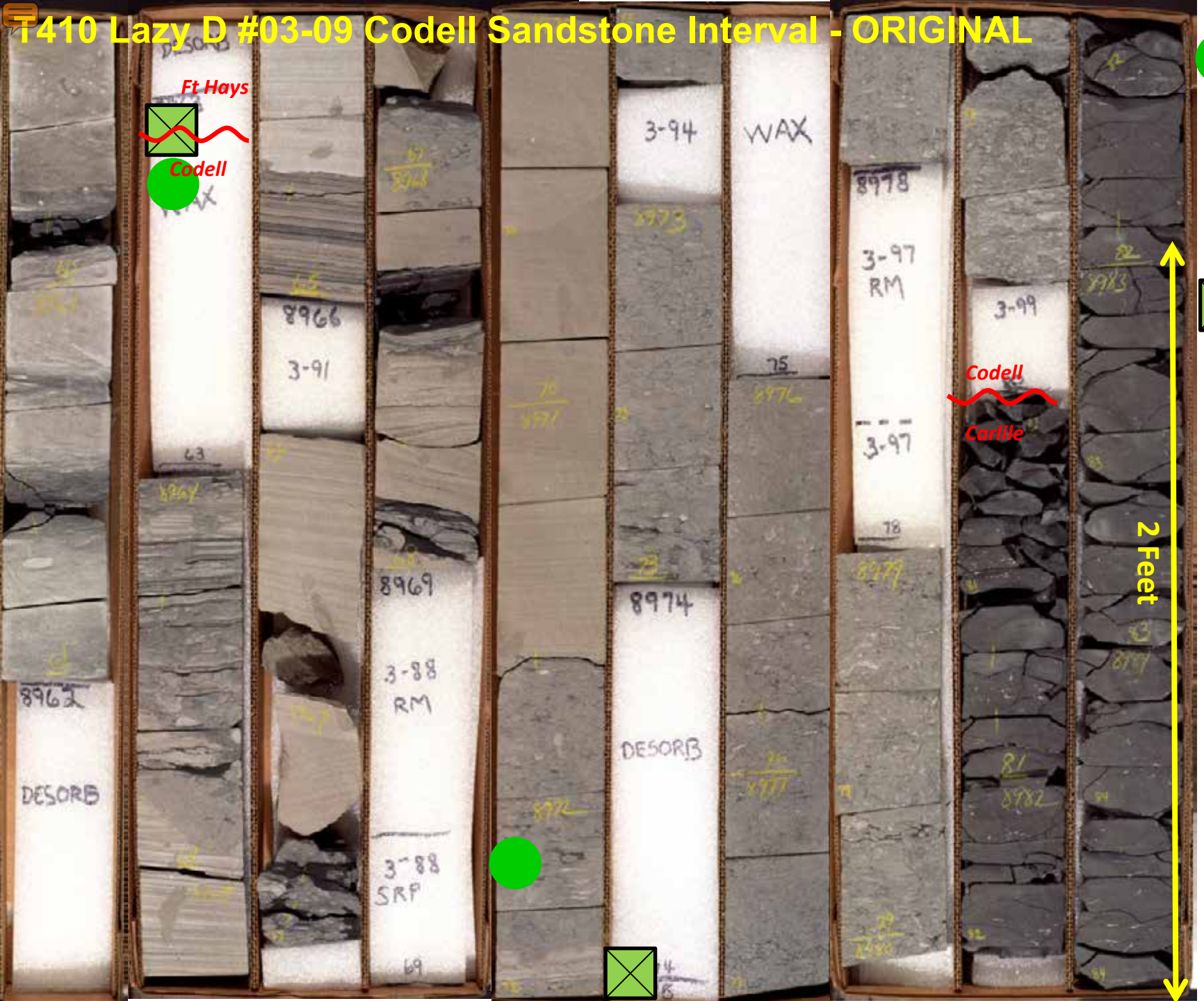
Core Sampling Comments & Recommendations

CORE SAMPLING

- **New Cores Provide a Once-In-A-Lifetime Opportunity to Collect Key Data**
  - **UV Photos, Fluid Saturations, CT Scans**
- **Tight Oil Sandstone Reservoirs Can Be Very Heterogeneous – Sample Interval Should be NO LESS THAN 1-Per-Foot**
- **Key Stratigraphic Surfaces Can Be Missing if Pieces of Core are "Preserved" in Wrapped Samples**

BUILD THESE ANALYSES INTO YOUR ORIGINAL CORE BUDGET

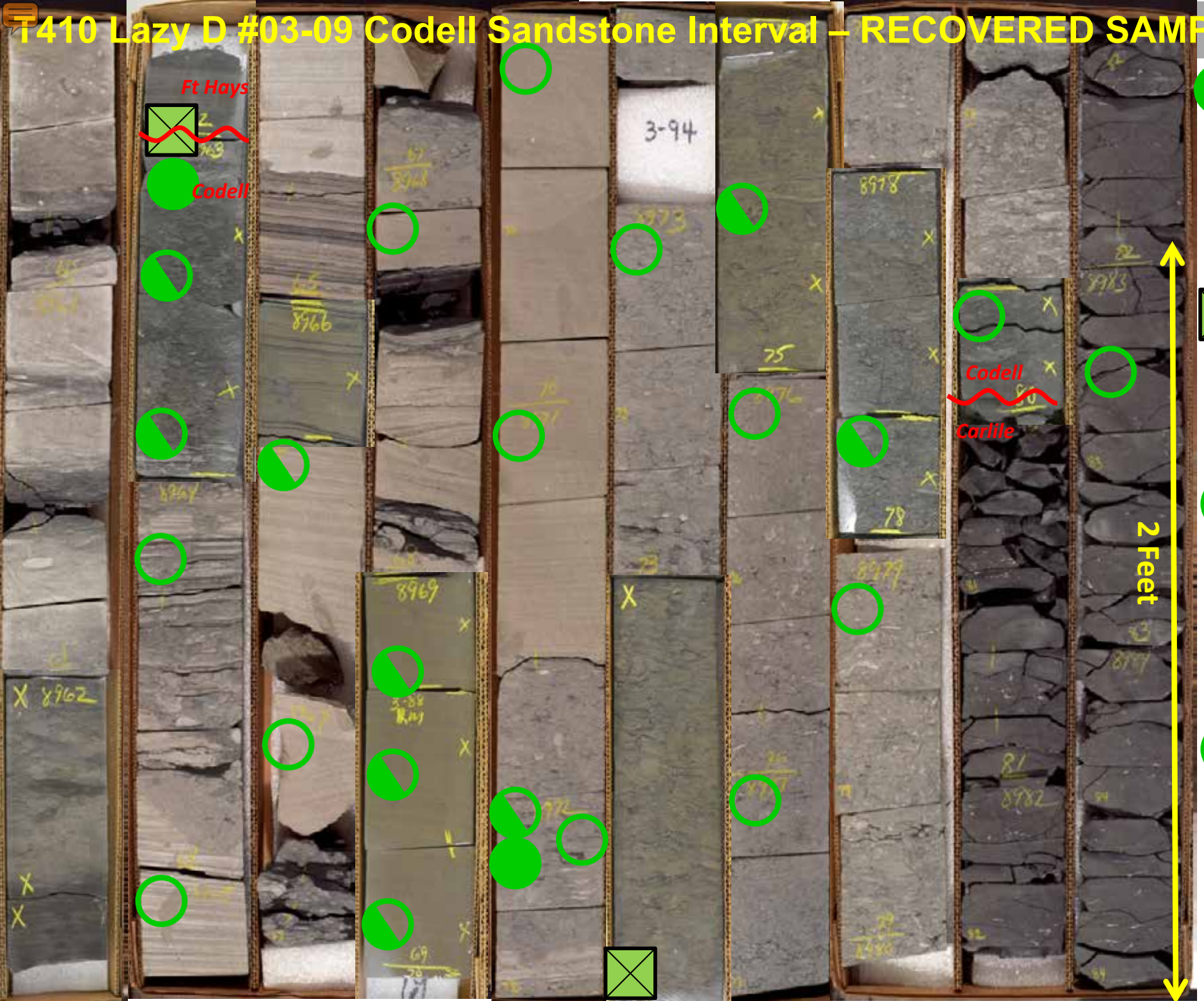
T410 Lazy D #03-09 Codell Sandstone Interval - ORIGINAL



2011 Routine Core Analysis Plug w/ Saturations

2011 Crushed Rock Analysis w/ Saturations

T410 Lazy D #03-09 Codell Sandstone Interval – RECOVERED SAMPLES



2011 Routine Core Analysis Plug w/ Saturations

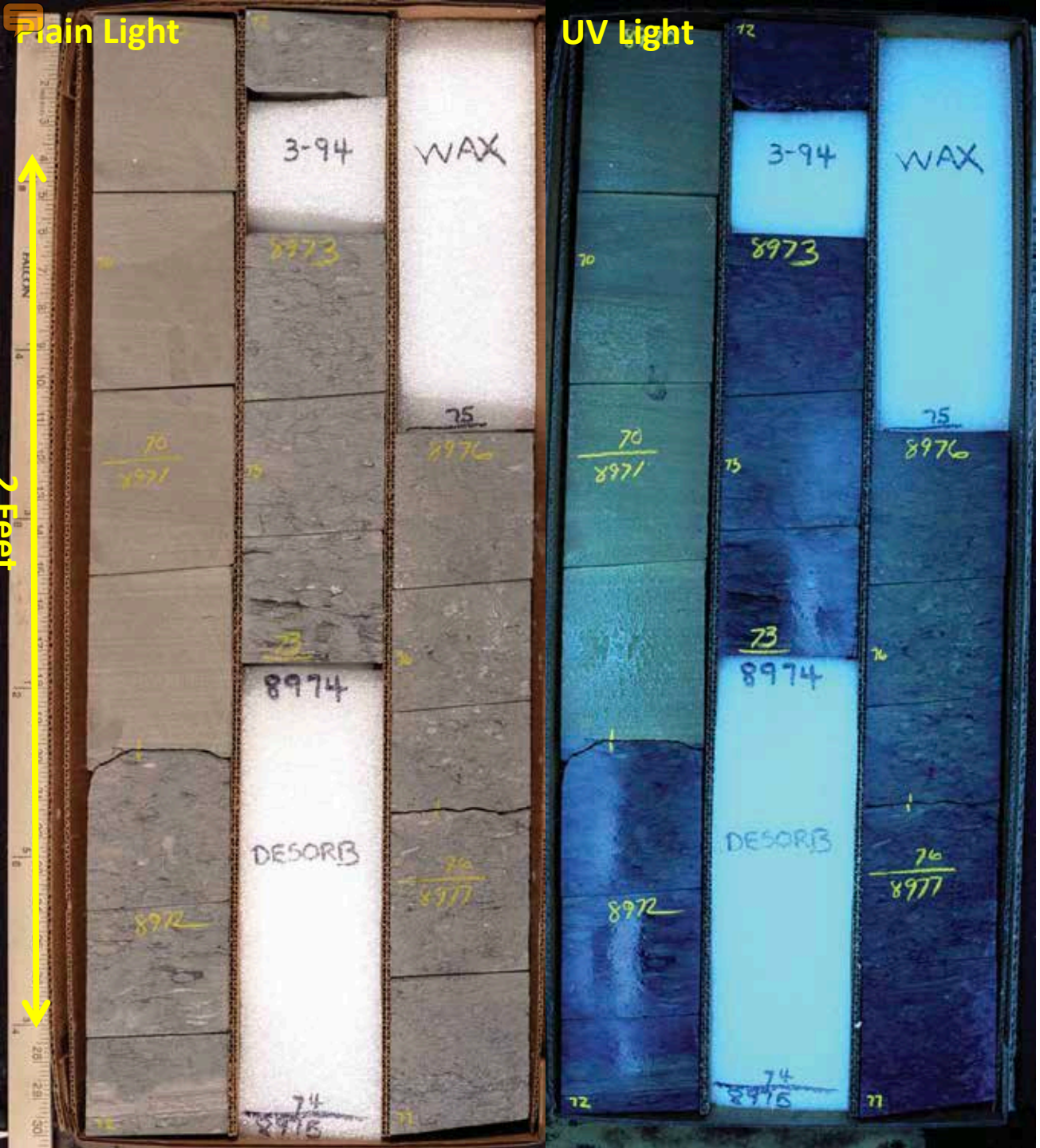
2011 Crushed Rock Analysis w/ Saturations

2013 Routine Core Analysis Plug w/ No Saturations

2014 Routine Core Analysis Plug w/ Partially Evaporated Saturations

LAZY D CODELL Original Core Sampling

- **Original Core Analysis – *Corporate Policy* – *Preserved 1-Foot Samples Every 10 Feet***
  - Left Large Gaps in Core – Ft Hays/Codell & Codell/Carlile Contacts in “Preserved Samples”
  - ONLY One Fluid Saturation from a Plug (Bioturbated Sandstone) in entire Codell SS – No Representative Samples from Laminated or Upper Bioturbated Facies
  - Plugs Taken From Samples that were Wax Preserved – Cannot Determine Lithofacies!
  - One Plug from 2” Below Ft Hays Contact – Calcite Cemented, Not Representative of Codell Reservoir
- **Initial Evaluation of Codell Sandstone Reservoir was Incomplete**
- **Supplemented with Later Plug Analyses of Evaporated and Wax-Preserved (Partially Evaporated?) Samples**

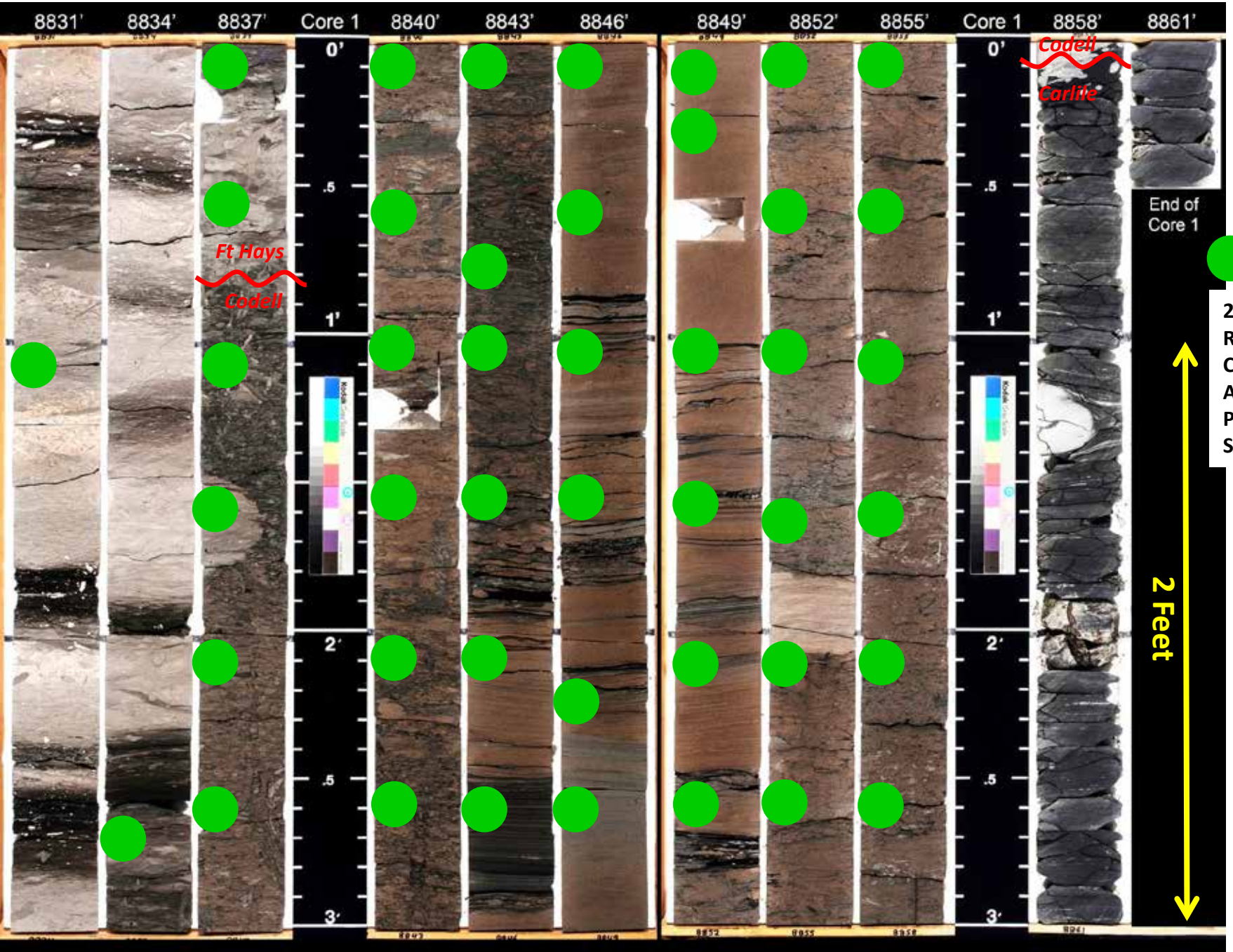


T410 Lazy D #03-09 Codell Sandstone Interval

UV PHOTOS

- Core Remained Unslabbed and Unphotographed more than 2 Months After Extraction from Tubes due to Backlog & Low Priority
- Allowed Oil Evaporation and Loss of Fluorescence

Laguna #8-8-2-CH Codell Sandstone Interval – ORIGINAL



LAGUNA CODELL Original Core Sampling

- Ø One P & P & So/Sw Sample Every 6 Inches
- Ø Whole Core UV Photos within Hours of Extraction
- Ø Slabbing & Slabbed Core UV Photos within 1-2 Days of Extraction

Other Things to Consider

- Ø If Source – Reservoir Relationships are in Question, Get Reservoir Fluid/Oil Extracts Immediately (for Oil Typing)
- Ø Consider UV Photos of P & P Plugs
- Ø XRD Mineralogy Should be Done When Core is Fresh – Clays Desiccate over Time!

BUILD THESE ANALYSES INTO YOUR ORIGINAL CORE BUDGET

RMAG Tight Oil Sandstones Core Workshop Summary

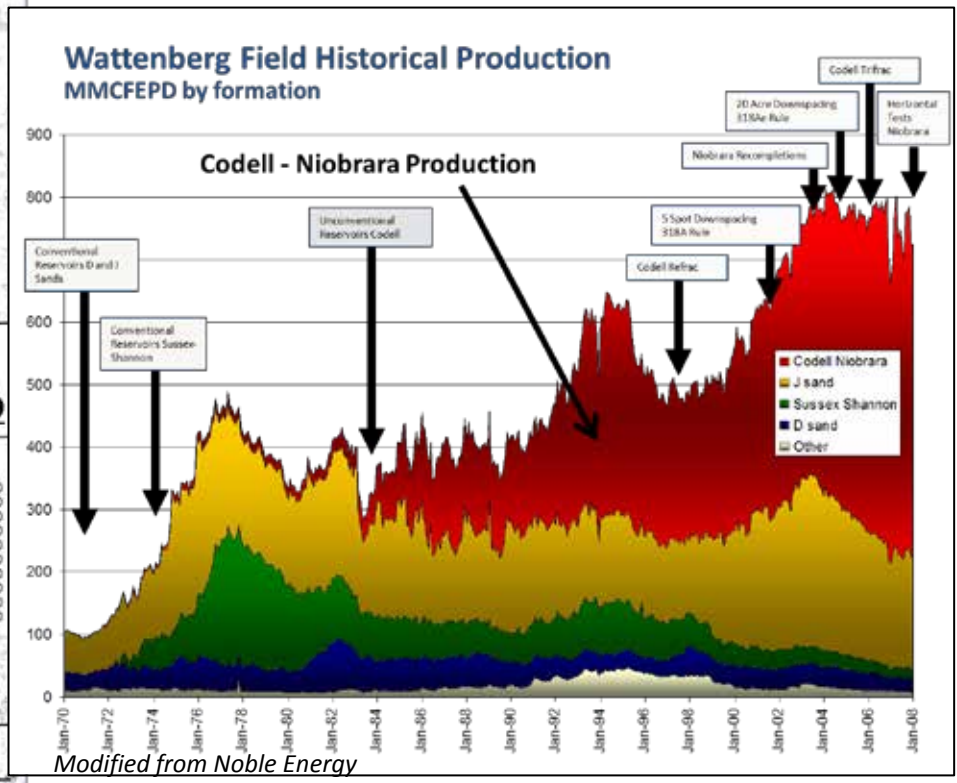
CODELL SANDSTONE CORES, DJ BASIN

Banner
Silo
Kimball
Brennsee
Fairway
Wyoming | Nebraska
Colorado
Hereford
Northeast Extension
Wattenberg
WELD
BOEPD
Codell SS Producer Max Daily Rate
Codell Core (8)
IHS Markit

Well & Production Data From IHS Markit

Codell Sandstone – Where it all Started?

- **Tight Oil / Wet Gas Play Started with Vertical Wells in 1980s**
- **Expanding into Oil Window with Horizontal Drilling & Completion Technology**



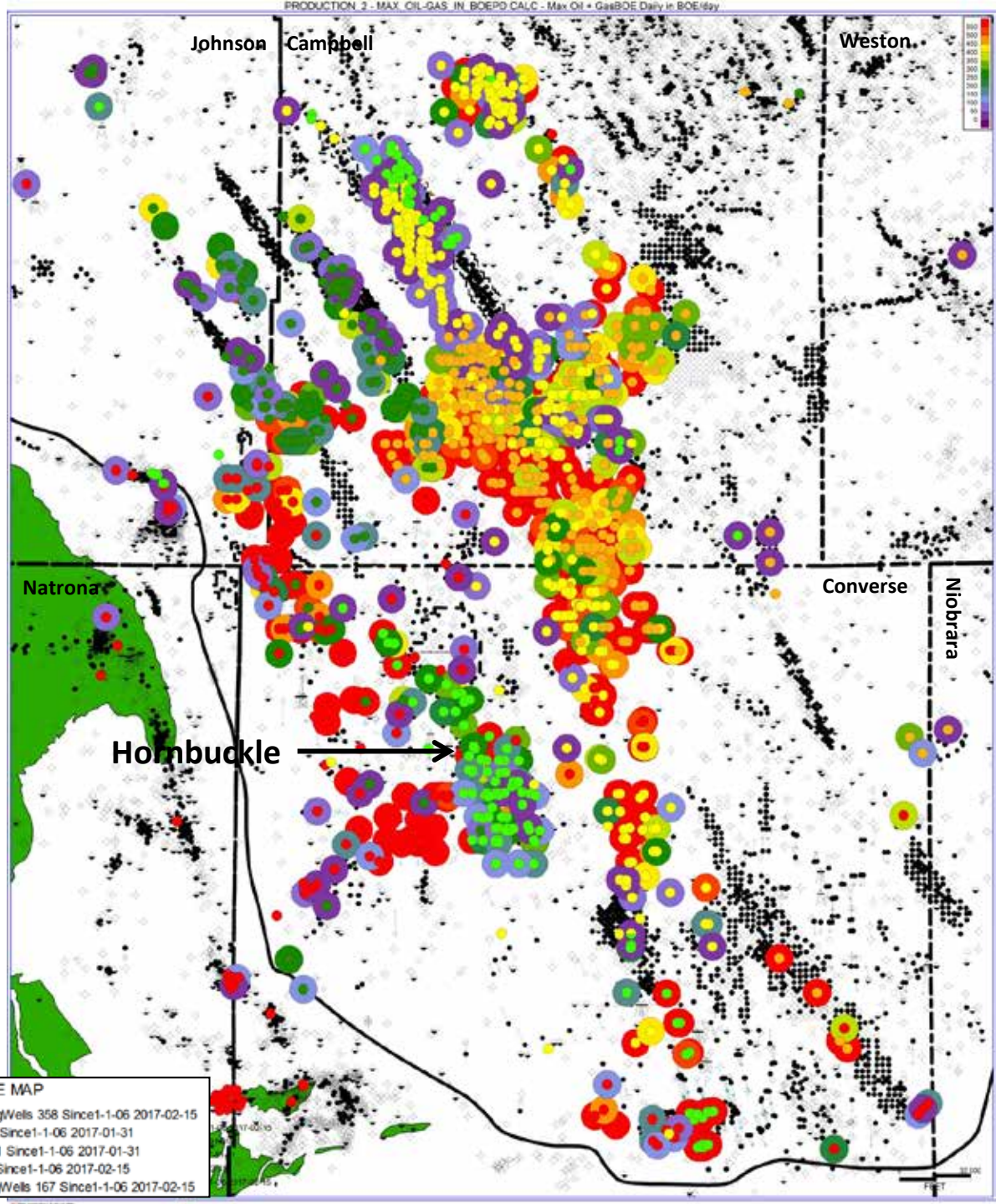
Modified from Noble Energy

POWDER RIVER BASIN TIGHT OIL

Wells Drilled After 1-1-06

Max Oil Month Avg. Daily Rate

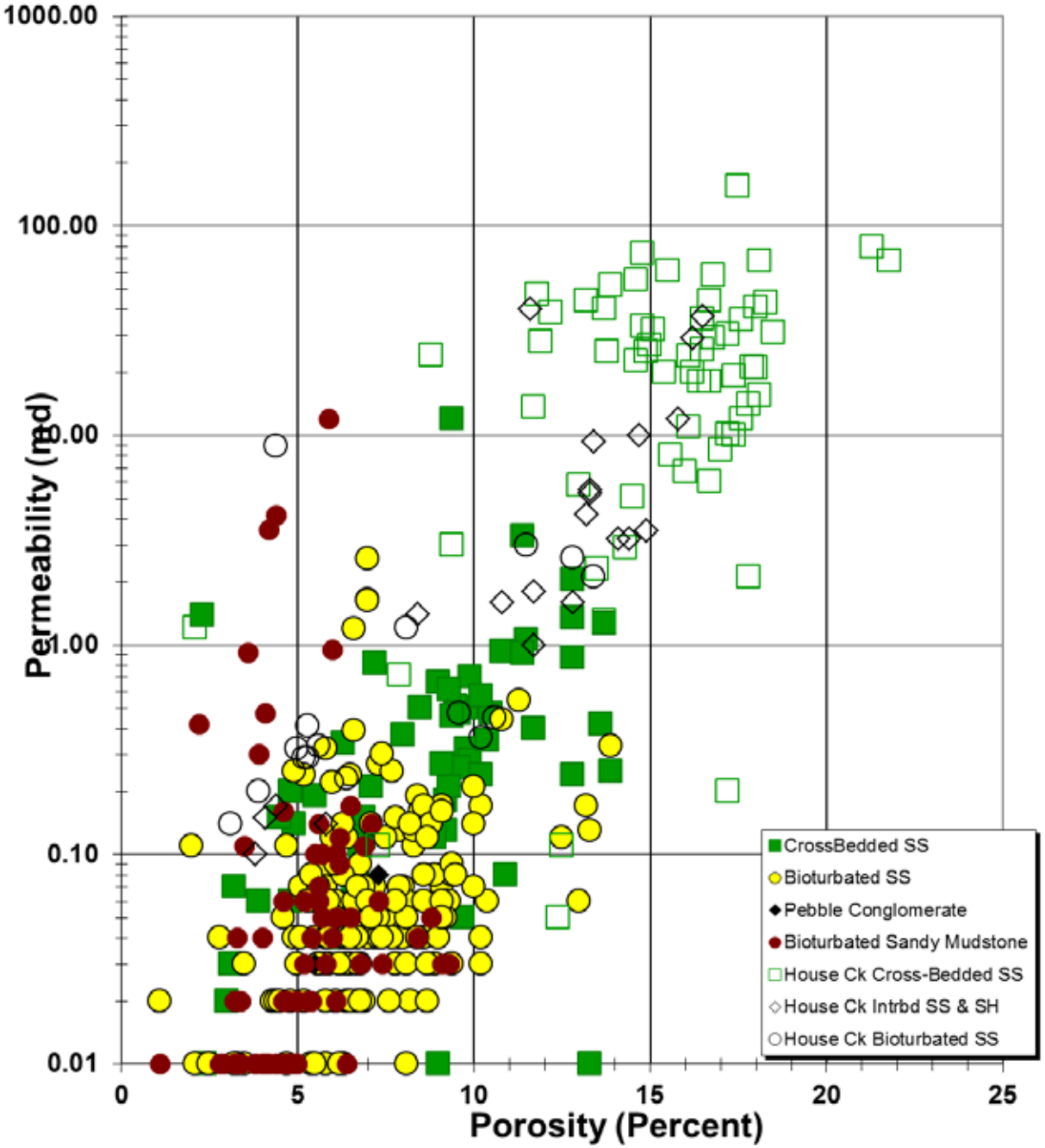
- **Parkman (355)**
- **Sussex (150)**
- **Shannon (161)**
- **Turner (338)**
- **Frontier (167)**



Well & Production Data From IHS Markit

IHS Markit

Sussex Core Porosity vs Permeability



House Creek

- Unfilled Symbols
- Cross-Bedded Sandstone

Permeability 3-100 md.

- Waterflood

Hornbuckle

- Color-filled Symbols
- "Tight Oil"

<u>Cross-Bedded Sandstone</u>

- Phi 3-14%, Avg 8.8%
- k .01-4.0 md, Avg 0.63md

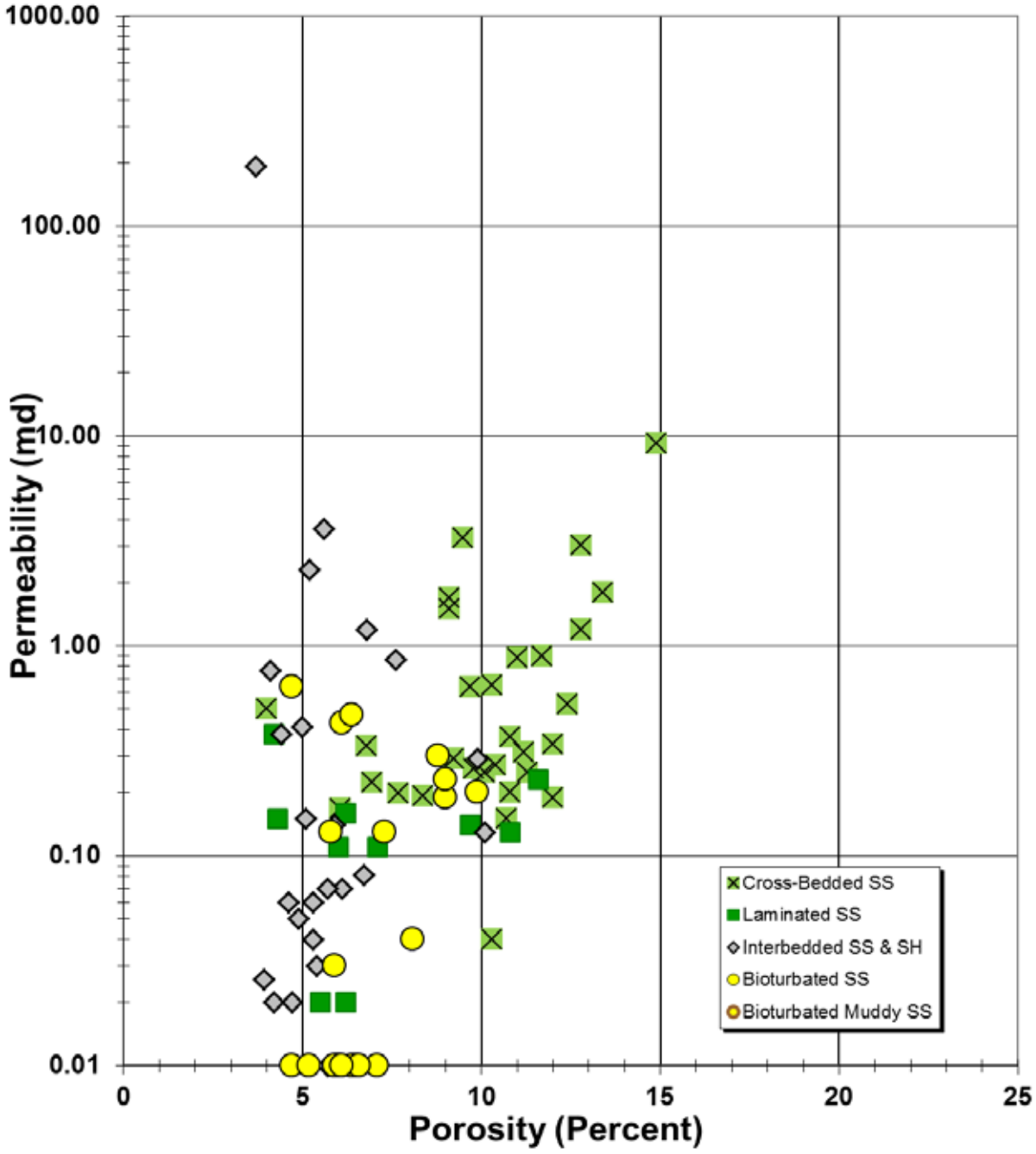
<u>Bioturbated Sandstone</u>

- Phi 1-14%, Avg 7.1%
- k .01-.60 md, Avg 0.12md

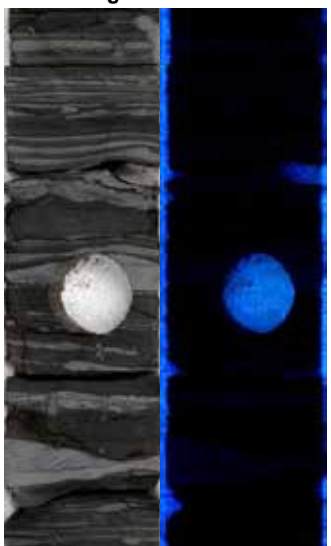
Conclusion

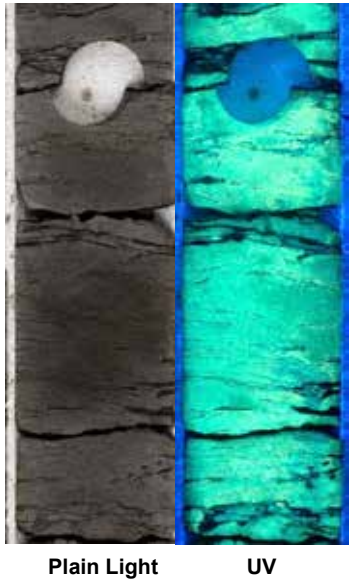
- Sussex Sandstone @ Hornbuckle is Different than Sussex Sandstone @ House Creek

Shannon Core Porosity vs Permeability

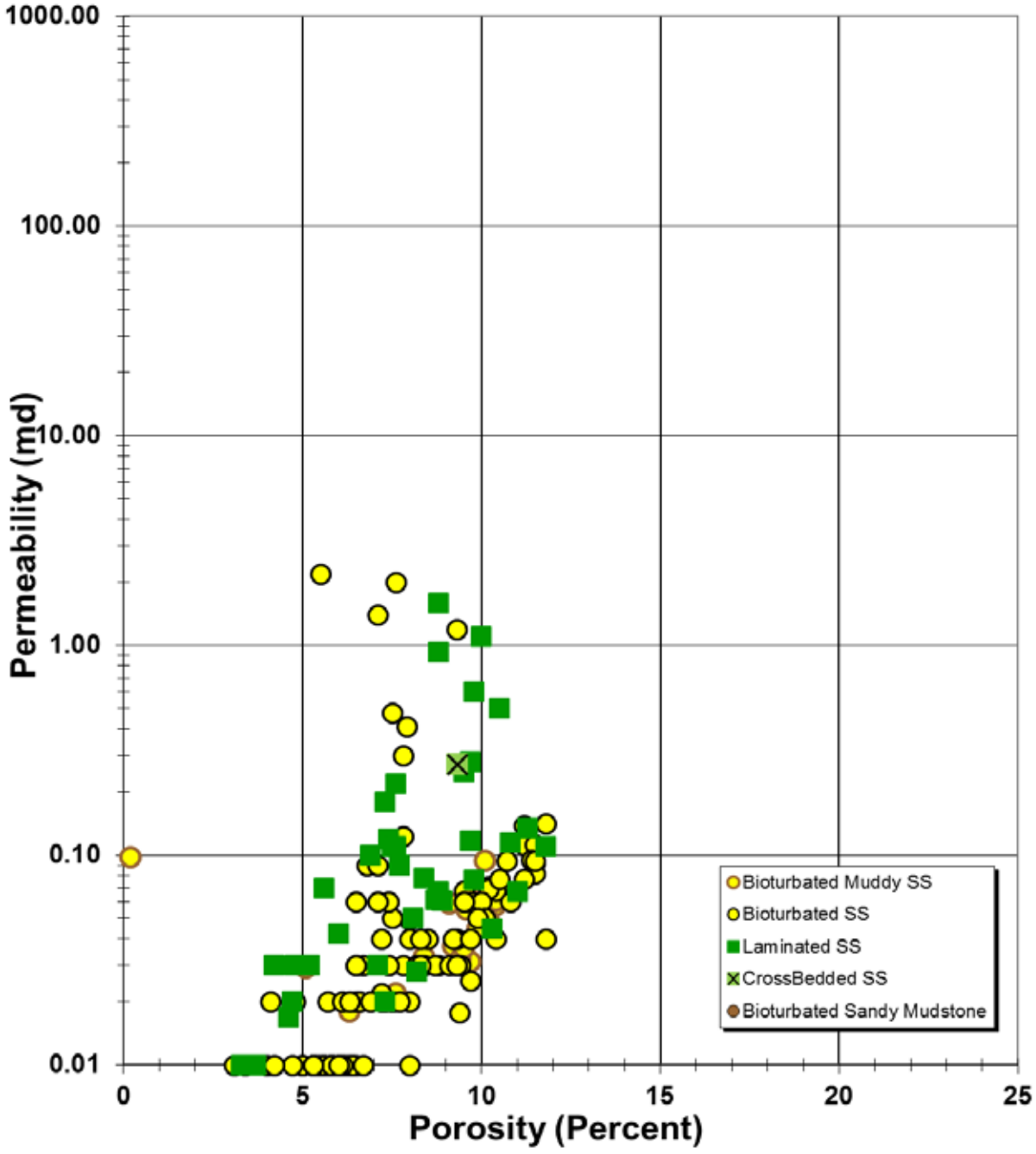


- Note – Most Analyses on These Plots are Original (1970s-1980s) Vintage Data with Permeability Measurements Less Than .01md Not Resolved.
- Modern Analyses Have Better Permeability Resolution.



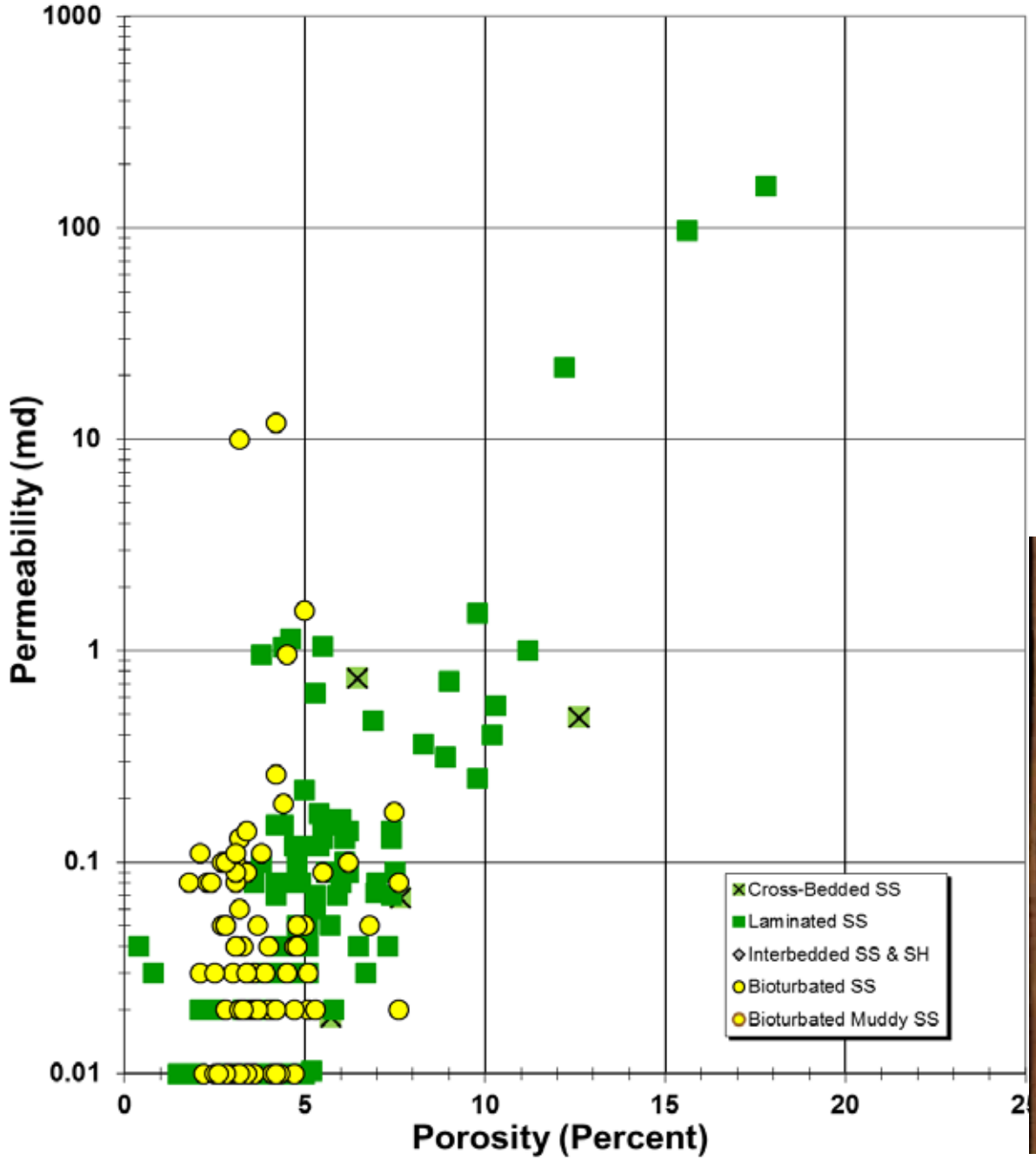


Turner Core Porosity vs Permeability



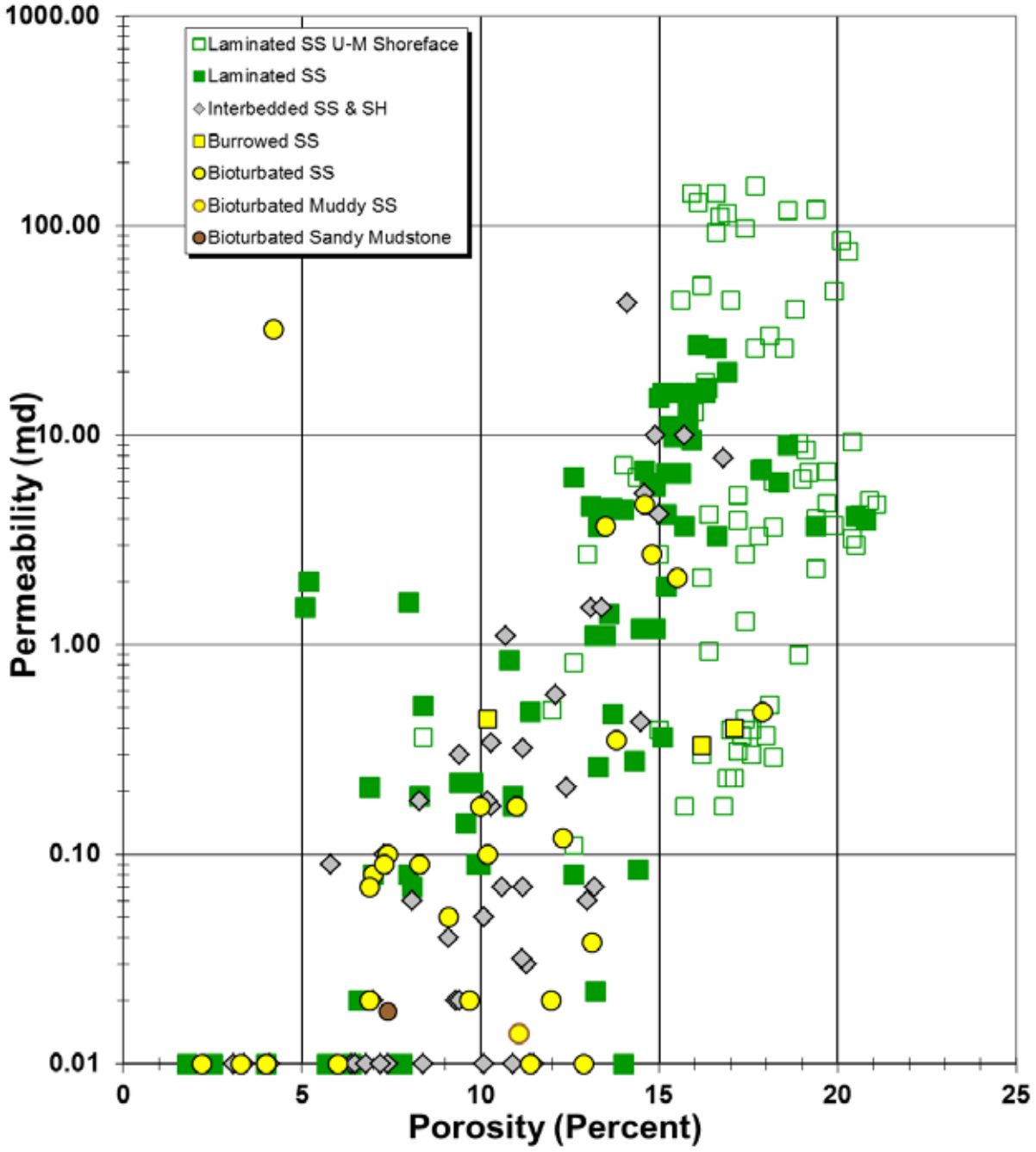
Plain Light

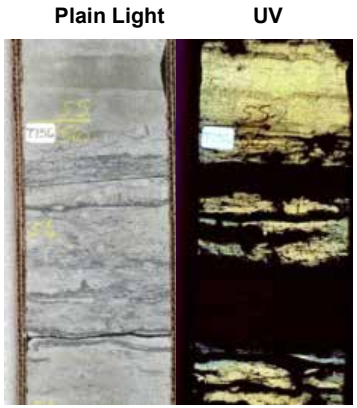
Frontier Core Porosity vs Permeability



Plain Light

Parkman Core Porosity vs Permeability

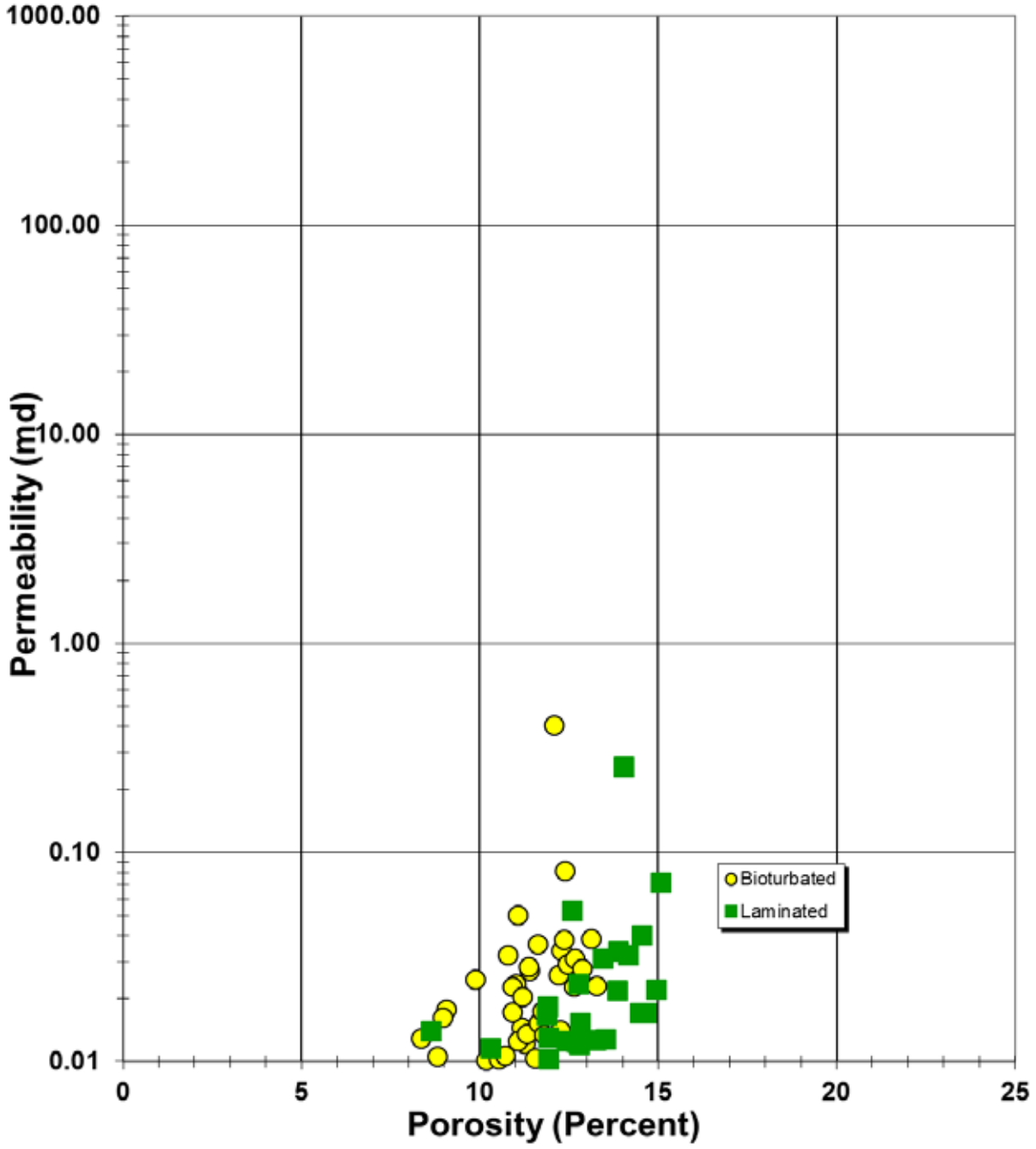




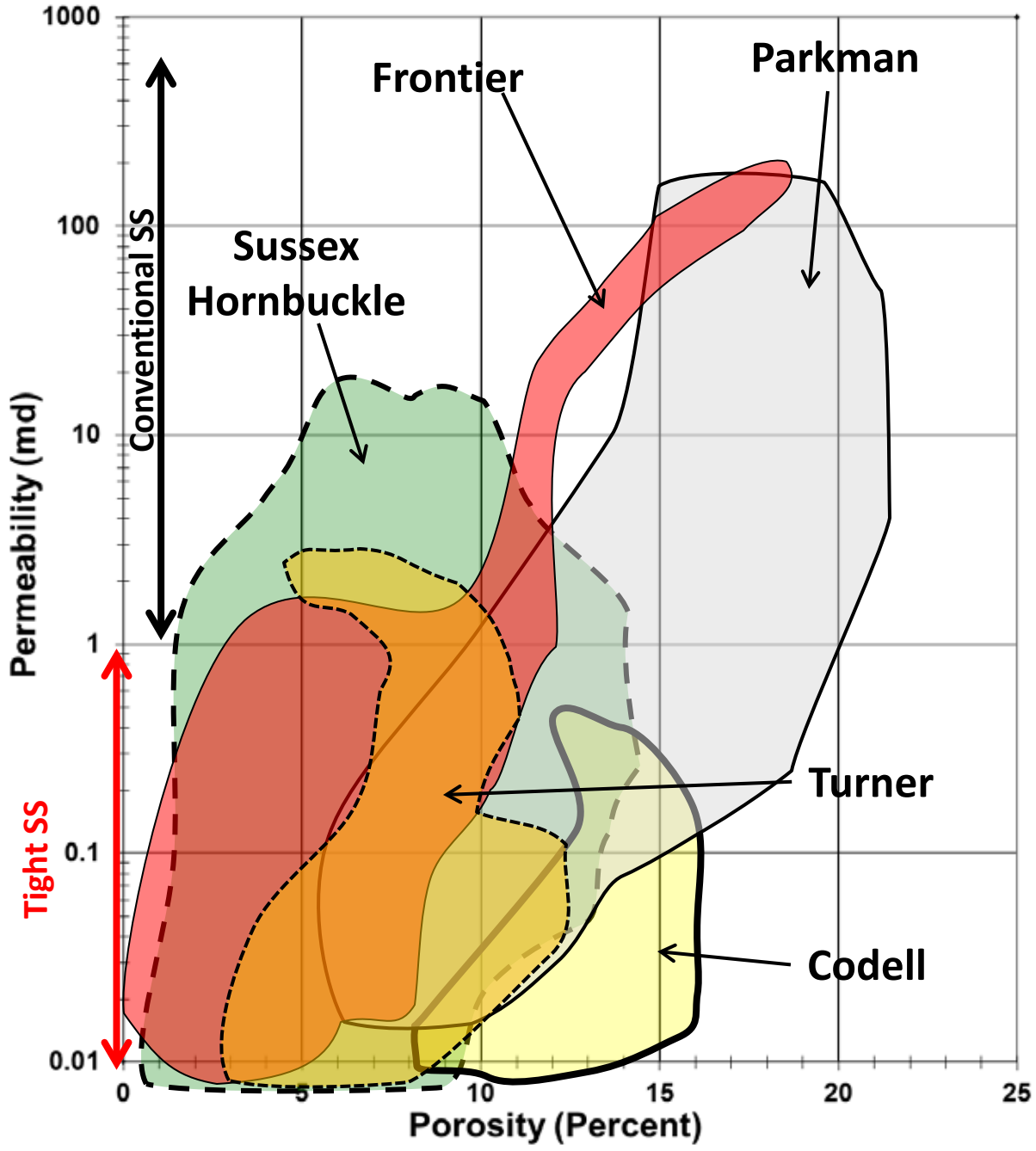
Laminated

Burrowed

Codell Core Porosity vs Permeability



Core Porosity vs Permeability



True "Tight Oil"

- Codell
- Turner

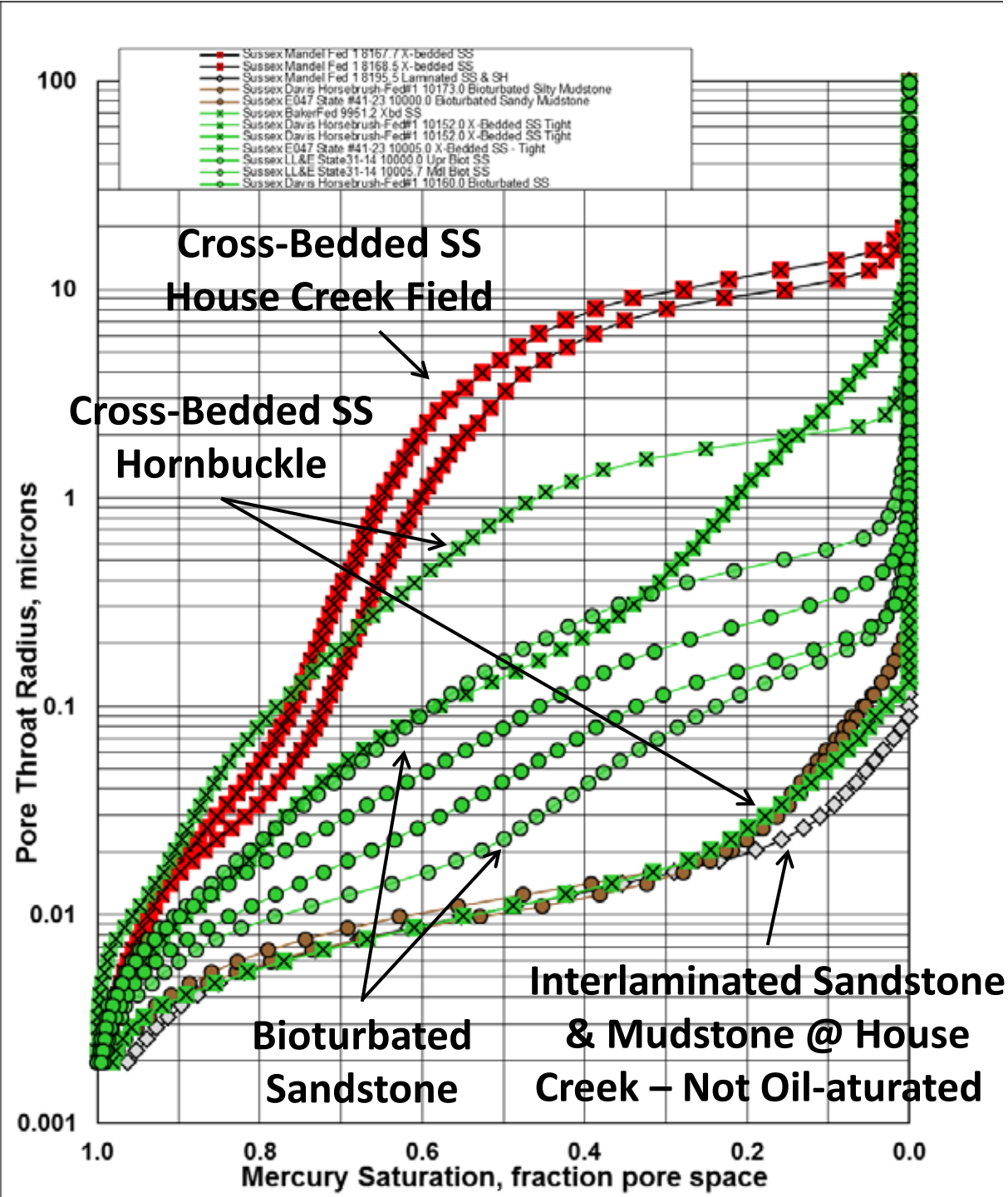
Hybrid "Tight" Oil with Conventional Component

- Frontier
- Hornbuckle Sussex

Mostly Conventional Reservoir with "Tight Oil" Component

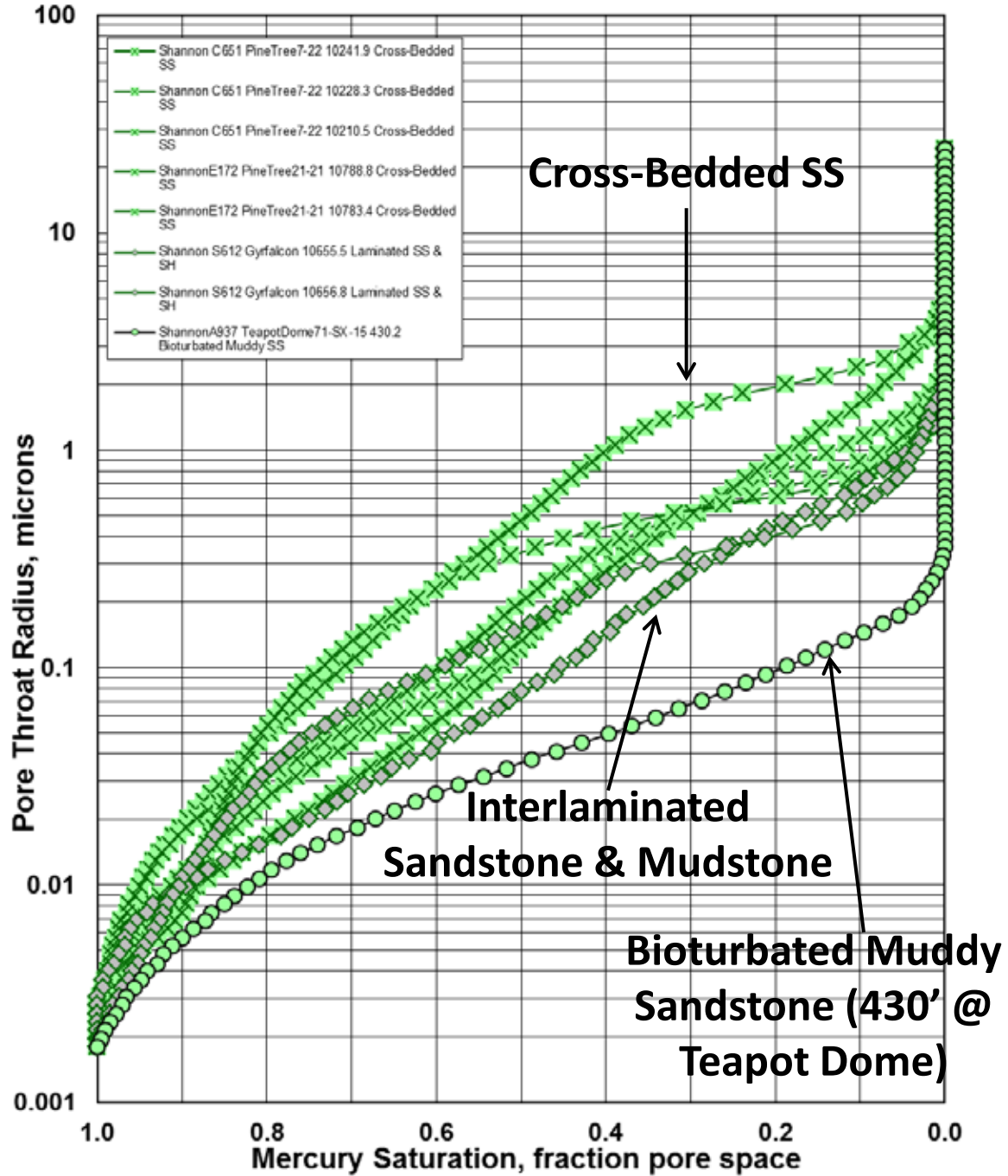
- Parkman

Sussex
Pore-Throat Radii vs Hg Saturation



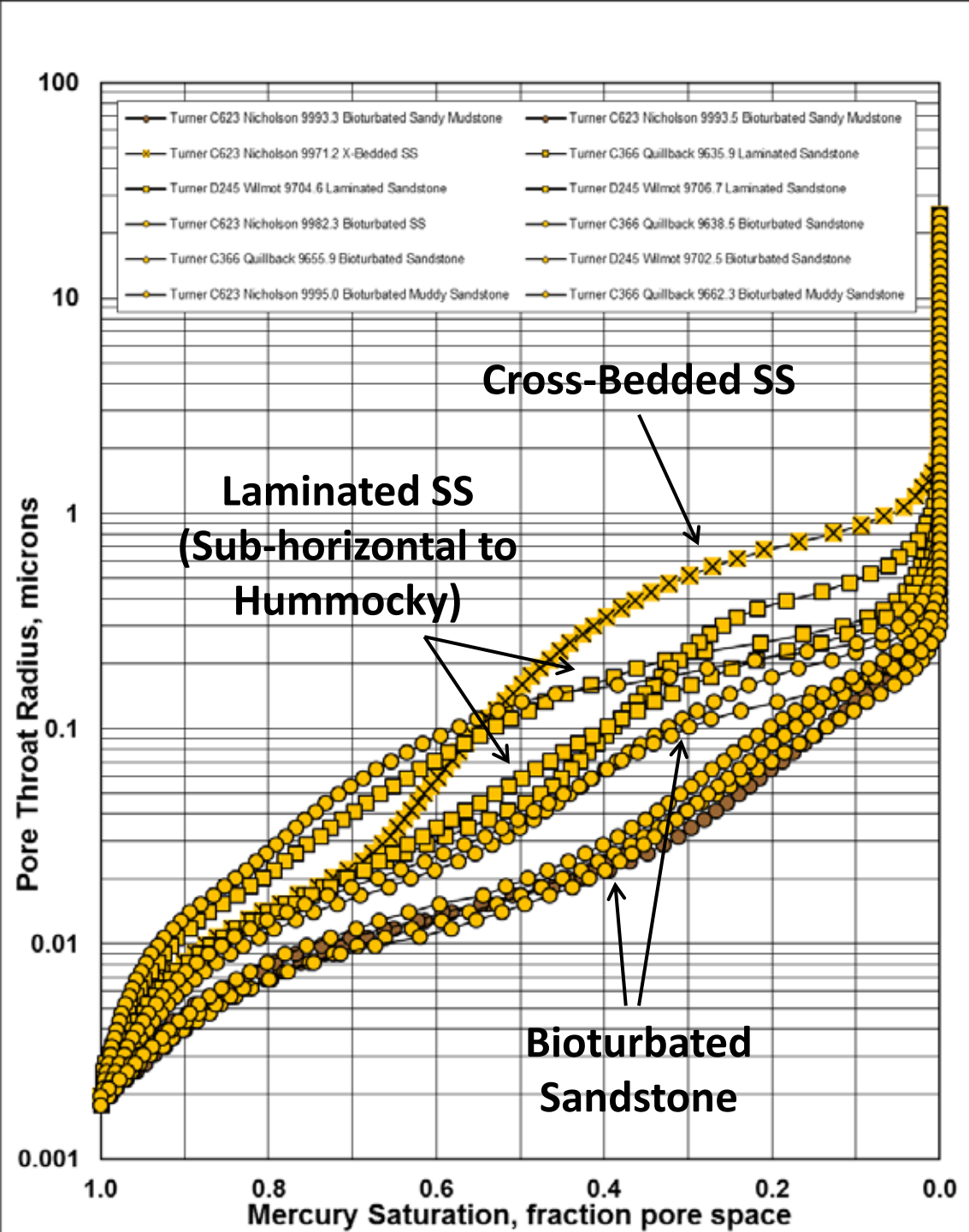
- Large Pore Throats in Cross-Bedded Sandstones @ House Creek = Waterflood
- Hornbuckle (Unconventional) Cross-Bedded Sandstones have Wide Range of Pore Throats
- Unconventional R35 range ~ .015 – 1.5u; Conventional R35 ~ 6-10u
- Significant Pay Contribution from Bioturbated Sandstone Facies @ Hornbuckle
- Complex Reservoir
- Heterogeneities Can Lead to Mixed Results & Inter-Well Interference

Shannon Pore-Throat Radii vs Hg Saturation



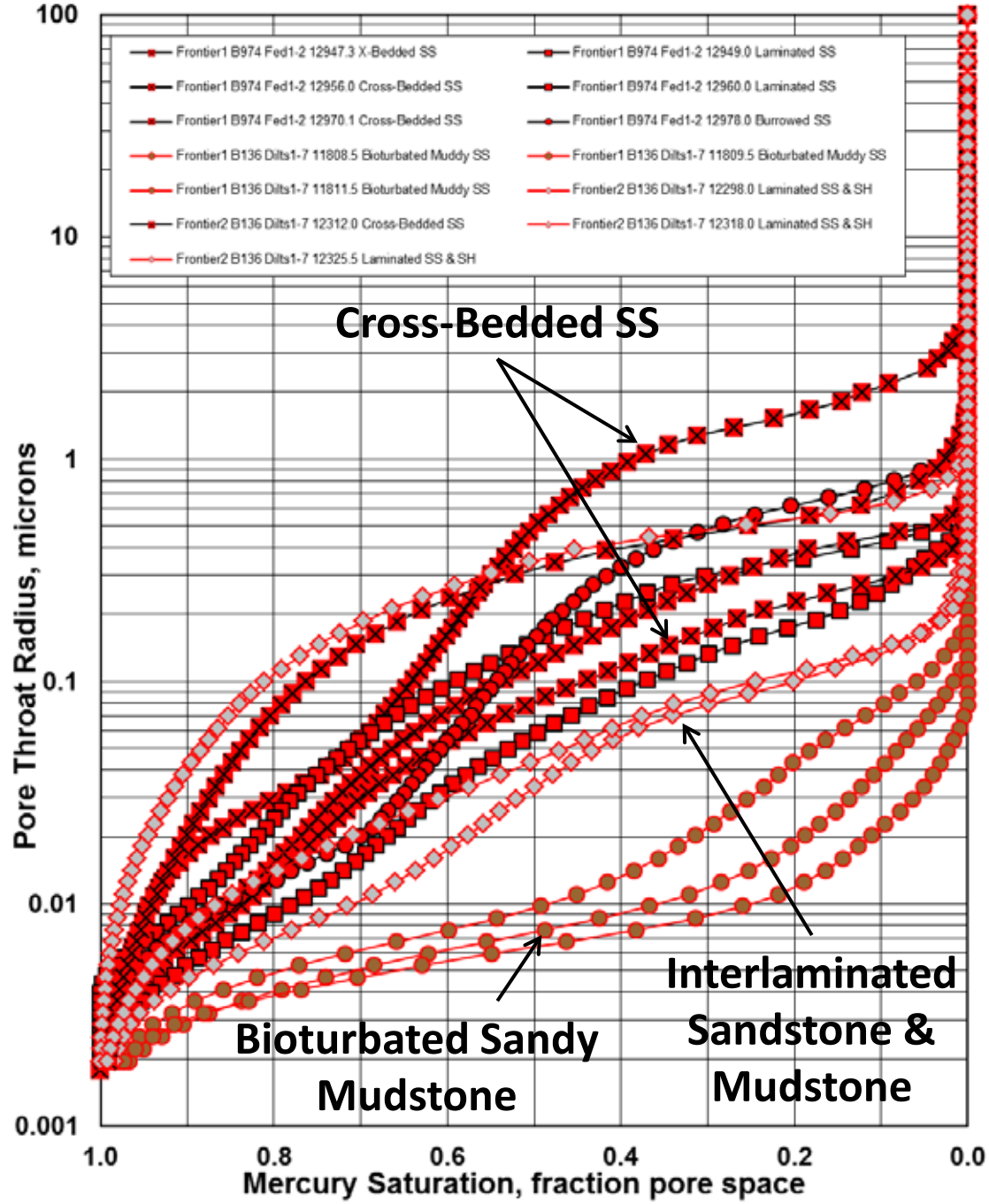
- Relatively Large Pore Throats (sample bias?)
- Bioturbated Sandstone Facies Rare to Absent in Cores Available (see Teapot Dome/Outcrop?)
- Relatively Homogeneous Pore-Throat Sizes
- R35 range ~ .2 – 1.5u
- Most Pay Contribution from Cross-Bedded Sandstone Facies
- Sample Bias? Plugs from Interlaminated Facies Break?

Turner
Pore-Throat Radii vs Hg Saturation



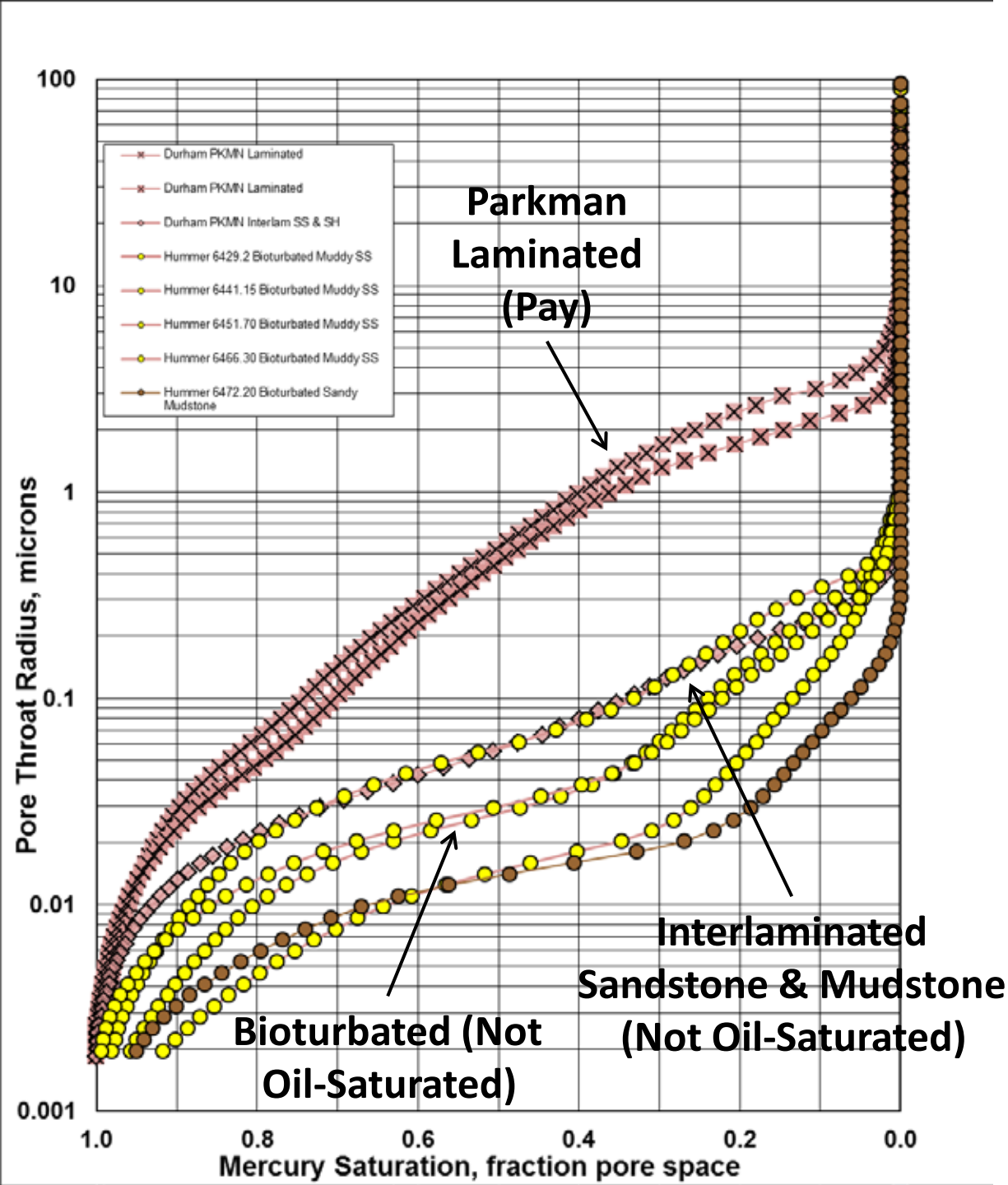
- Largest Pore Throats in Cross-Bedded and Laminated Sandstones
- Relative Homogeneous Pore-Throat Sizes
- R35 range ~ .025 – 0.4u
- Significant Pay Contribution from Bioturbated Sandstone Facies

Frontier
Pore-Throat Radii vs Hg Saturation

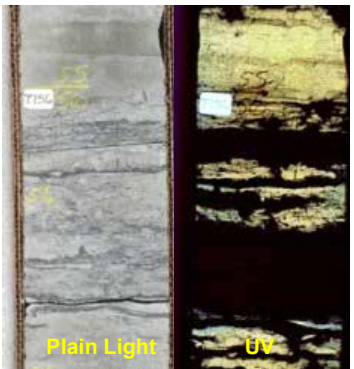


- Some Cross-Bedded and Laminated Sandstones have large pore throats – Can Result in High-Volume Wells (best reservoir rocks not sampled!
- Wide Range of Pore-Throat Sizes
- R35 range ~ .008 – 1.5u
- High Level of Thermal Maturity – All Pores are Oil-Saturated
- Complex Reservoir
- Heterogeneities Can Lead to Mixed Results

Parkman Pore-Throat Radii vs Hg Saturation



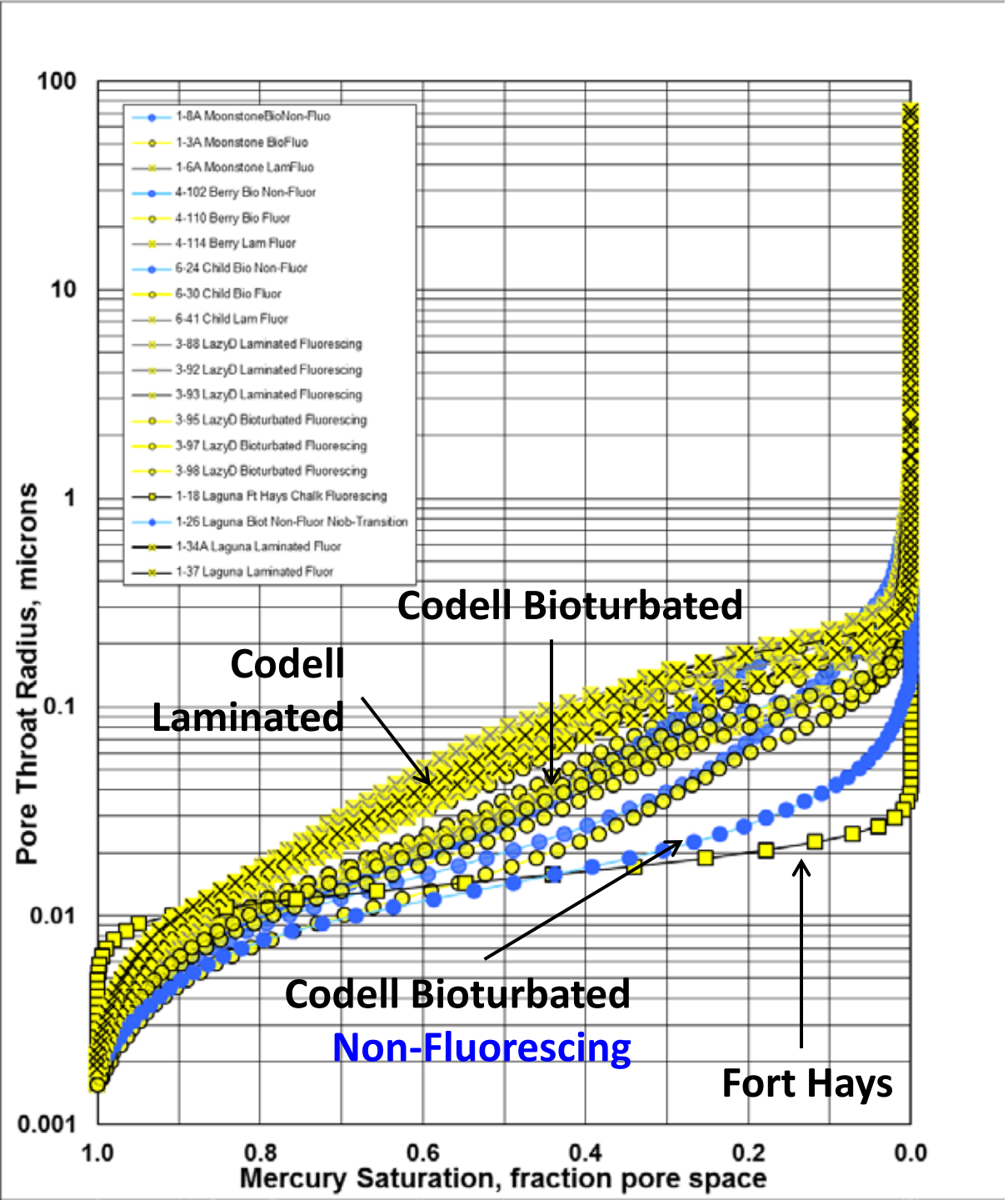
- Laminated Sandstones have larger pore throats than other Facies
- Wide Range of Pore Throat Sizes
- R35 range ~ .02 – 1.5u
- Fluorescing vs Non-Fluorescing Related to Ability of Migrating Oil to Enter Pores – Need Large Pores for Oil Saturation



Laminated

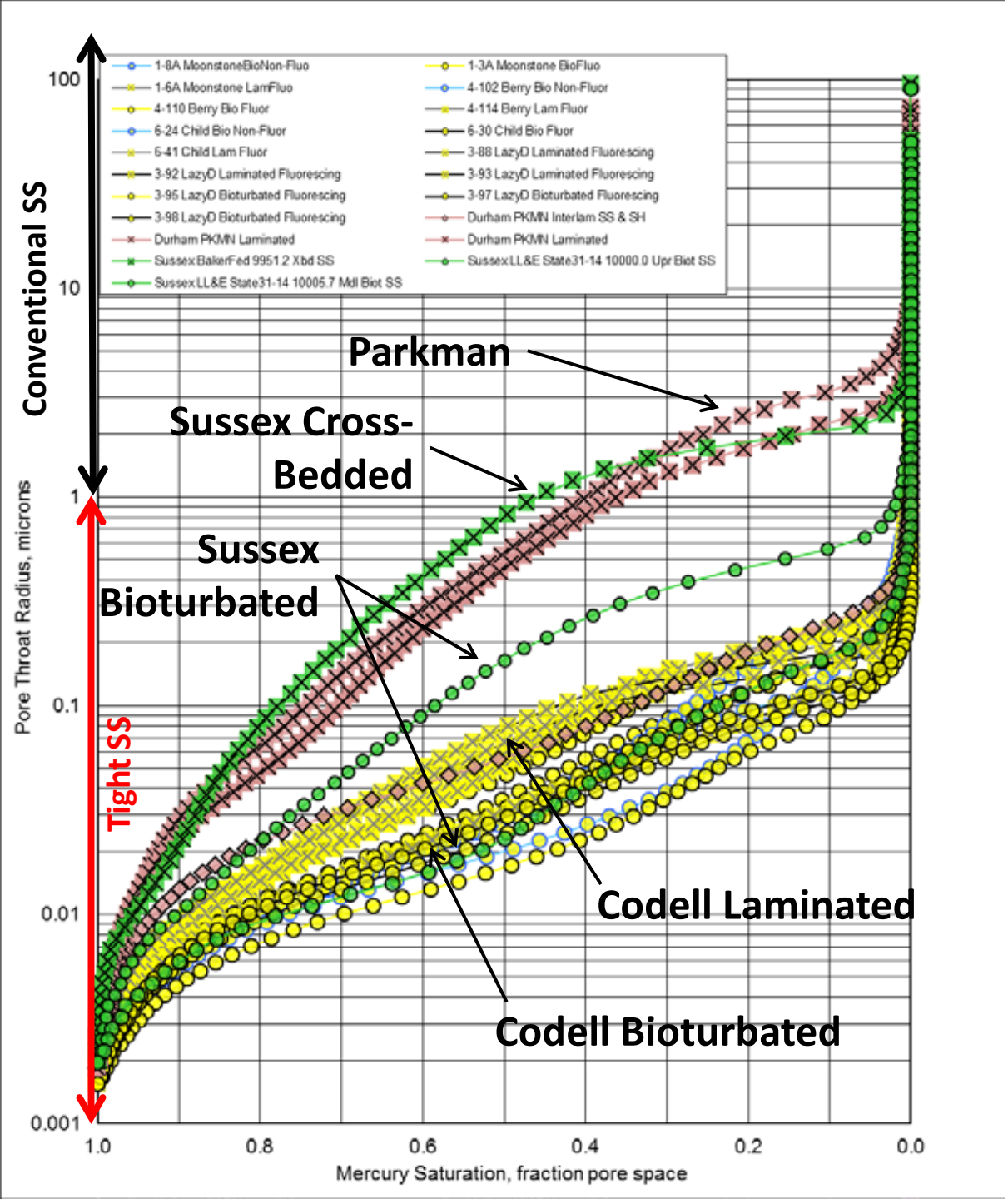
Burrowed

Codell
Pore-Throat Radii vs Hg Saturation



- Laminated Sandstones have slightly larger pore throats than Bioturbated Sandstones
- Codell Pore Throats are Fairly Homogeneous
- R35 range ~ .03 - .15u
- Fluorescing vs Non-Fluorescing Related to Thermal Maturity

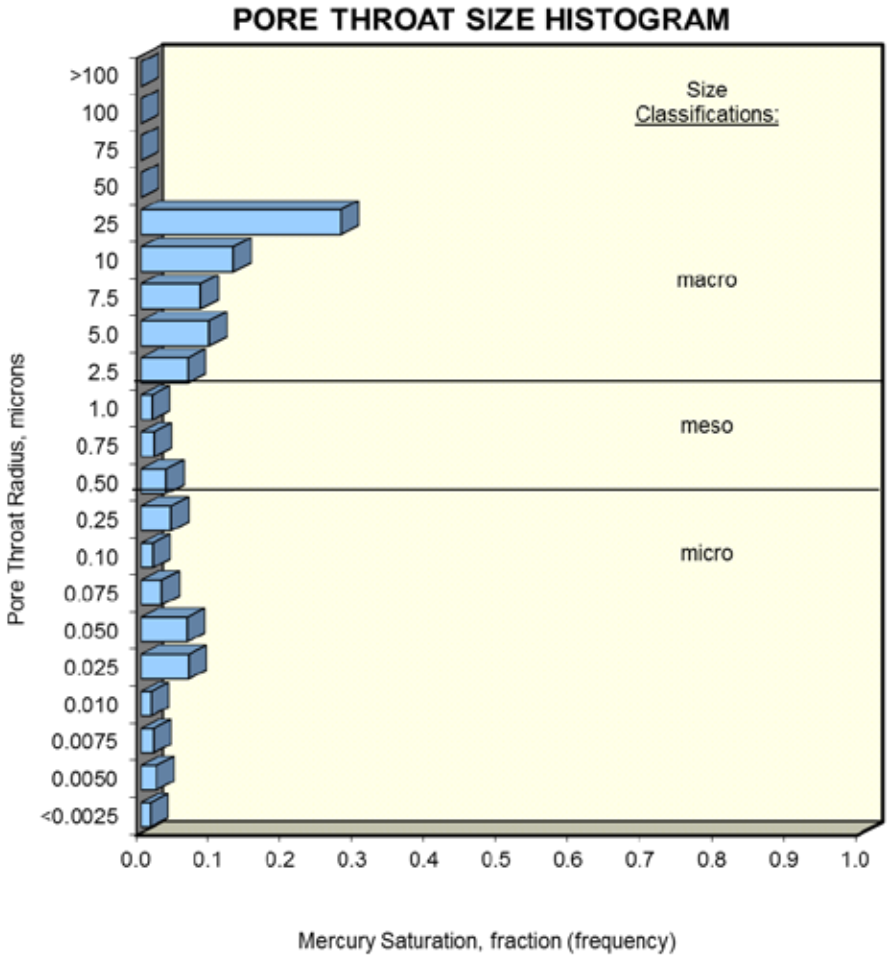
Pore-Throat Sizes from Mercury Injection-Capillary Pressure Data – Multiple Reservoirs



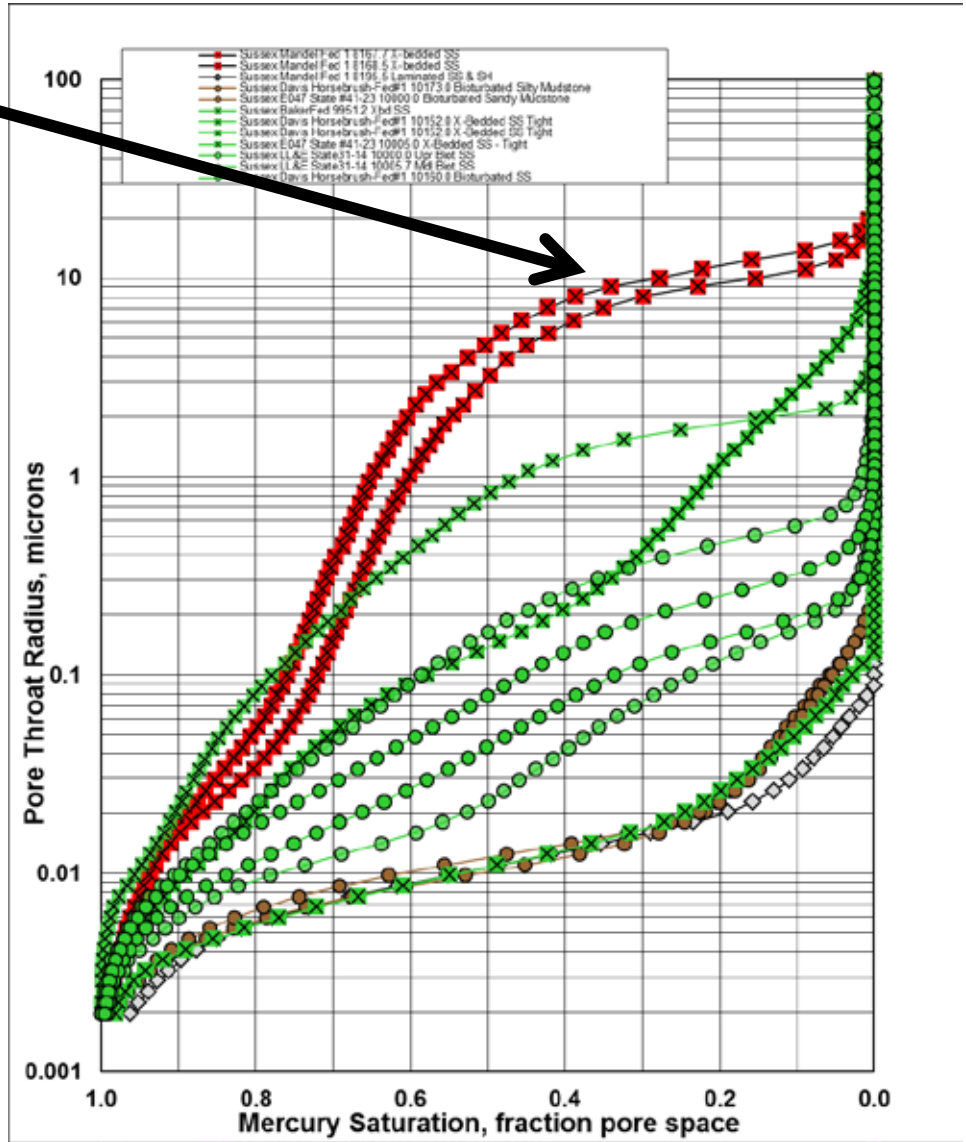
Pore-Throat Sizes from Hg Injection-Cap. Pressure

Sussex Conventional – Pay

A422 Mandell-Federal #1
Cross-Bedded Sandstone
8167.7', Phi 18.5%, k = 138.0 md
R35 = 8.87 microns



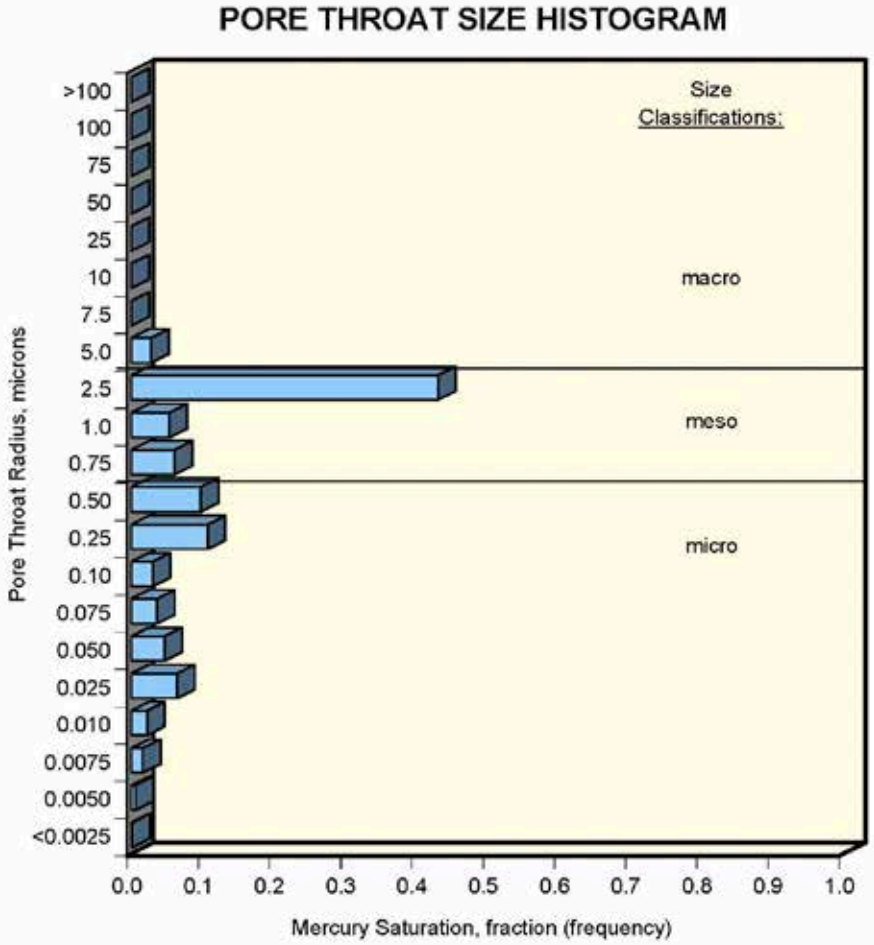
Sussex Conventional Reservoirs Have Large Pore Throats (Parkman)



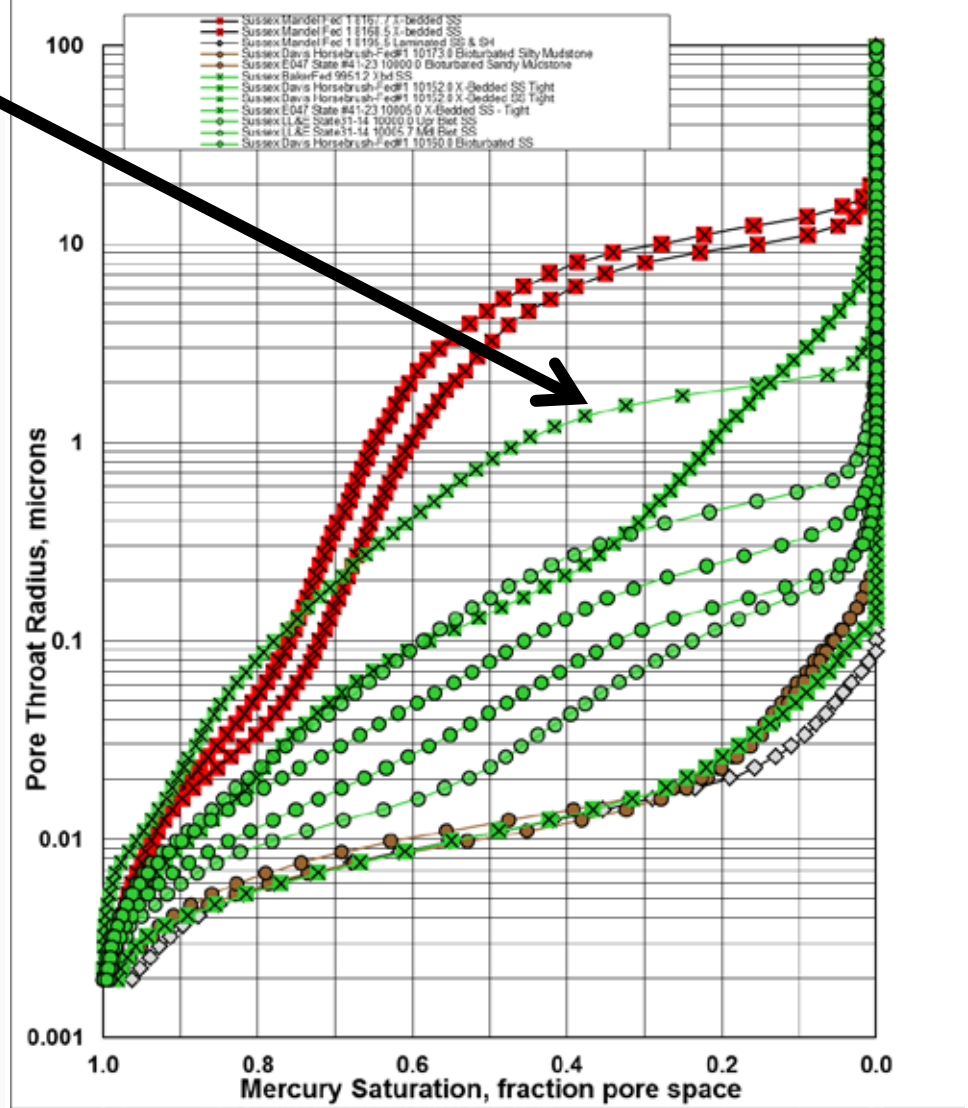
Pore-Throat Sizes from Hg Injection-Cap. Pressure

Sussex Unconventional – Cross-Bedded Sandstone Pay

A422 Baker-Federal #11-7
Cross-Bedded Sandstone
9951.2', Phi 9.9%, k = 1.29 md
R35 = 1.44 microns



Sussex Unconventional Reservoirs Have Facies that can have Moderately Large Pore Throats – HETEROGENEITY (see also Frontier & Shannon)

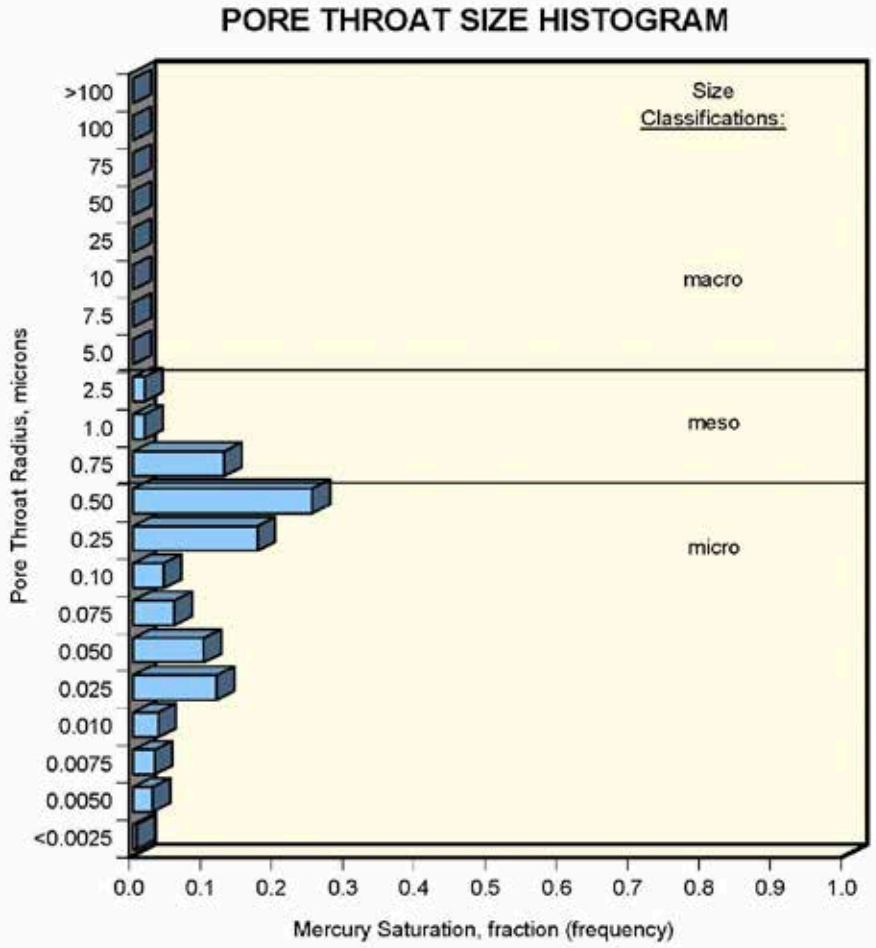


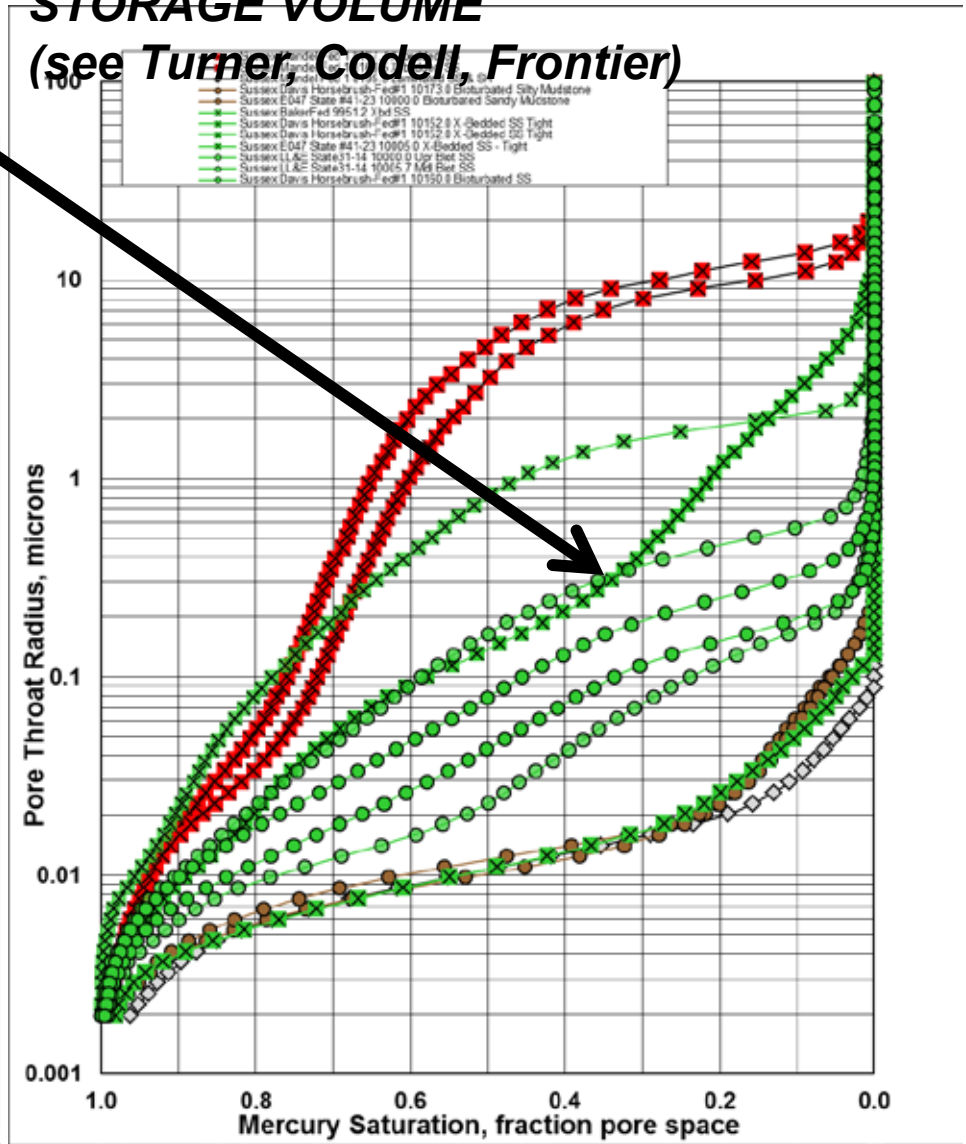
Pore-Throat Sizes from Hg Injection-Cap. Pressure

Sussex Unconventional – Bioturbated Sandstone Pay

F010 State #31-14
Upper Bioturbated Sandstone
10000.0', Phi 7.7%, k = 0.103 md
R35 = 0.314 microns

Sussex Unconventional Reservoirs Bioturbated Facies have Moderately Small Pore Throats – SIGNIFICANT OIL STORAGE VOLUME
(see Turner, Codell, Frontier)

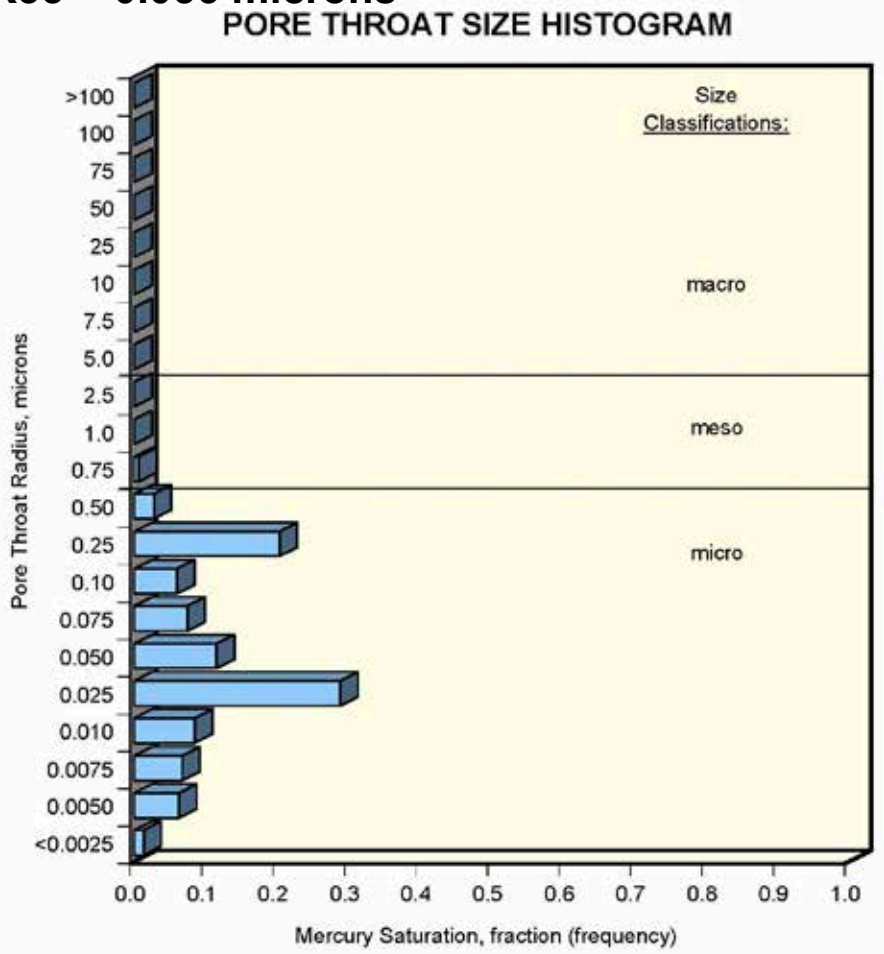




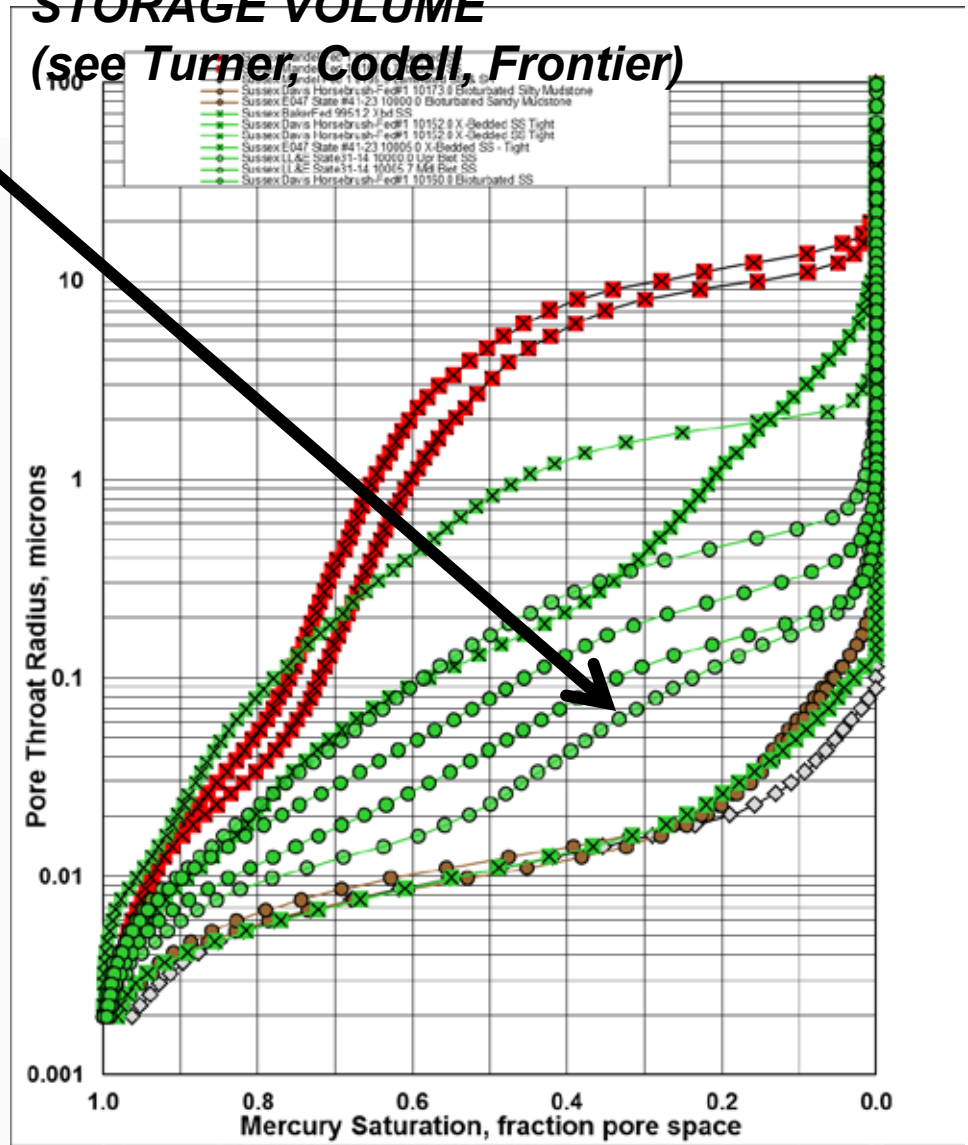
Pore-Throat Sizes from Hg Injection-Cap. Pressure

Sussex Unconventional – Bioturbated Muddy Sandstone Pay

F010 State #31-14
Middle Bioturbated Sandstone
10005.7', Phi 7.7%, k = 0.044 md
R35 = 0.056 microns



Sussex Unconventional Reservoirs Muddier Bioturbated Facies have Small Pore Throats – SIGNIFICANT OIL STORAGE VOLUME
(see Turner, Codell, Frontier)



TIGHT OIL SANDSTONE PLAYS COMMON ATTRIBUTES

- **Proximity to Marginal or Uneconomic Vertical Producers**
- **Muddy Sandstones– Low-Resistivity Pay**
- **Significant Oil Pay Exists in Bioturbated Facies – Moderate Porosity & Low Permeability**
- **Some are "Hybrid" Tight Oil Reservoirs, with Contribution From Locally Developed High-Permeability Reservoirs**
- **Pore-Throat Size & Thermal Maturity-Control Oil Saturations, Flow Rates, & Prospectivity**
- **Larger Areal Extent than Typical "Stratigraphic" Traps (e.g., Sussex "Bars" vs Horizontal Play)**
- **All of these Tight Sandstone Reservoirs & Plays are DIFFERENT in Subtle Ways**

TIGHT OIL SANDSTONE PLAYS
HOW DO WE EXPLORE FOR THEM?

- **Look for Marginal or Uneconomic Vertical Producers**
- **Collaborate with Engineers – Vertical Wells with Anomalous Production Declines**
- **Shows on Mudlogs & DSTs (look for NO WATER RECOVERY)**
- **Geological Interpretation & Mapping – Use Cores to Understand Facies Distribution, Using Current Plays as Analogs**
- **Search for Low-Resistivity Pay Zones Near Mature Source Rocks or at Stratigraphic/Facies Pinchouts**
- **Map Thermal Maturity – OIL HAS NOT MIGRATED VERY FAR! (in most cases)**

CONCLUSIONS

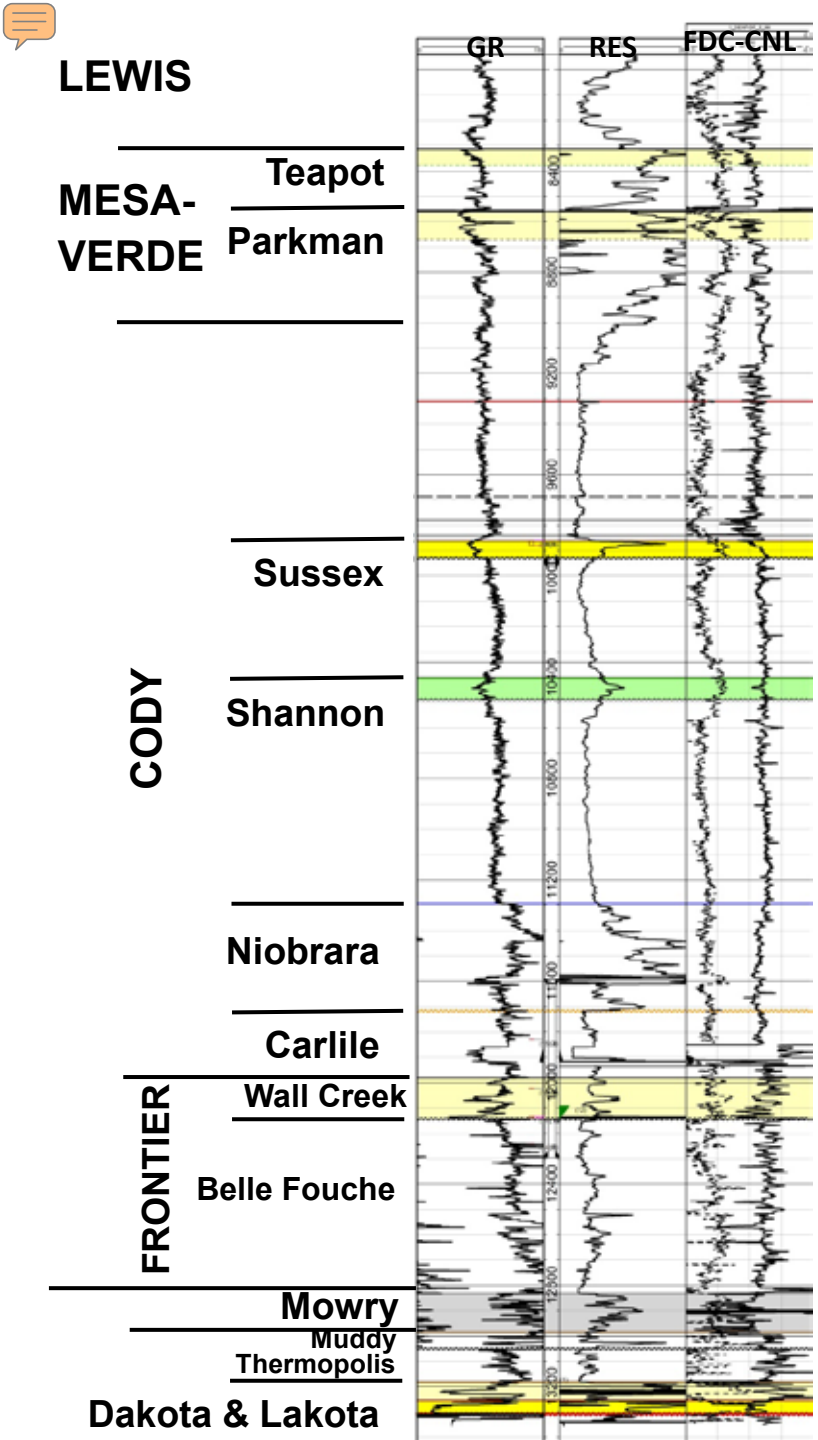
- Tremendous Oil Resource in “Tight” Reservoirs
- Parkman SS is NOT Tight – Complex Stratigraphic Play
- Exploitation Has Led to > 100,000 BOPD of New Production in the Powder River Basin
  - DJ Basin Codell
  - San Juan Basin Gallup
  - Anadarko Basin Tonkawa, Cottage Grove, Cleveland
- Challenges
  - Understand Distribution of High-Permeability Compartments (Cores, FMIs in Laterals, Tracers in Fracs)
  - Optimize Lateral Azimuth & Length, Density of Increased Density Wells
  - Stimulations – Maximize Sand in Pay Zone
  - Find New Tight Oil Plays

Thank You


Southwestern Production Corp.
Blaylock #13-35A
34 & 35-T38N-R73W
A GEOLOGICAL SUCCESS!

SUPPLEMENT

A few slides removed from the primary presentation due to time constraints, but pertinent and of interest to the Sussex presentation.



TYPE LOG
HORNBUCKLE FIELD
Sussex Pool Discovery Well

LL & E
Federal #32-2
SW-NE-2-T37N-R73W
Converse Co., WY
Compl. 1-8-84

MUDLOG SHOWS

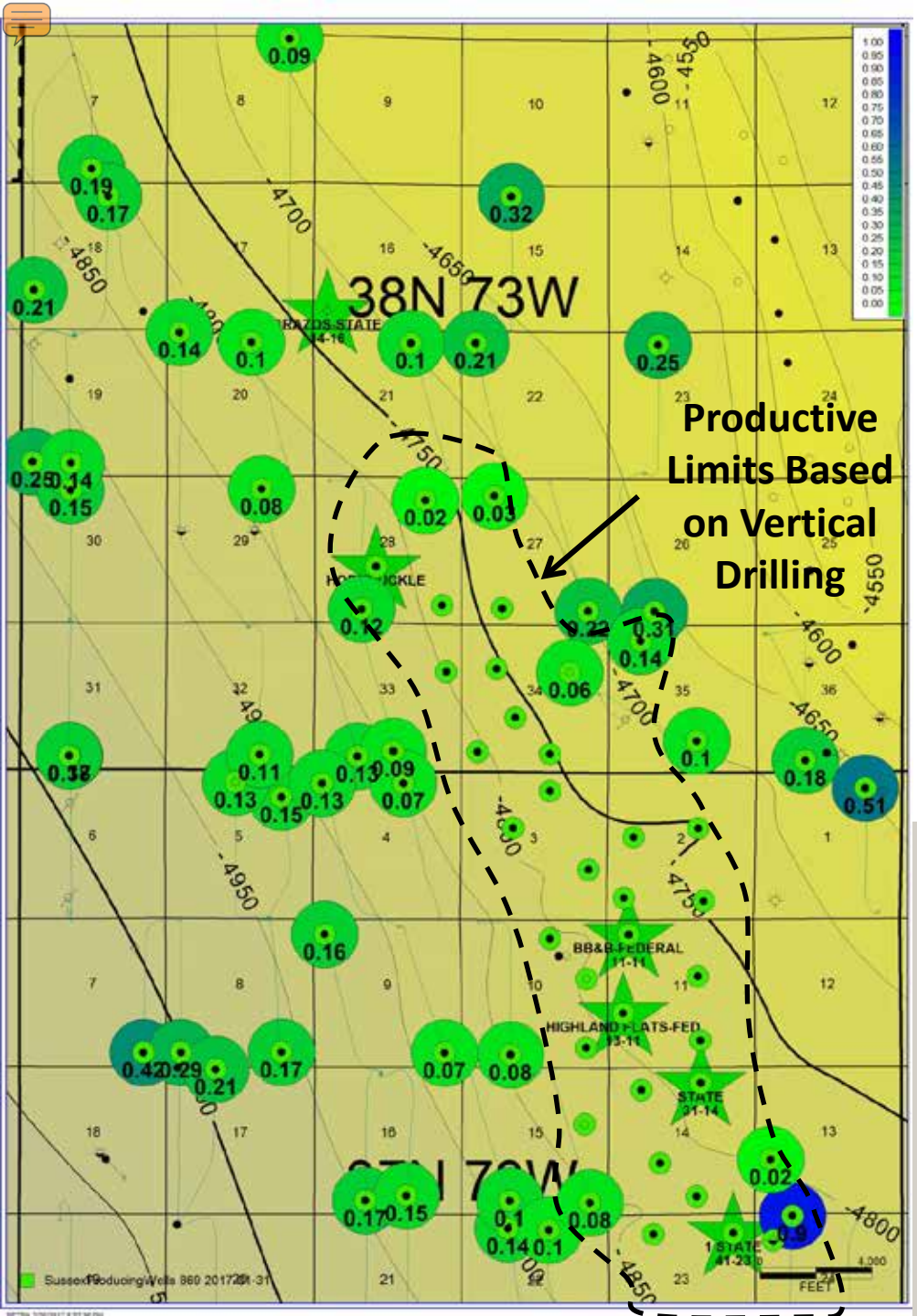
- **5000+ Units Gas Show @ MW 9.0ppg**
- **OIL ON PITS**
- **Bri Gold Fluor & Slow Streaming Cut & Tr. Lt. Brown Oil Stain**

COMPLETION

- **Perf Sussex**
- **Frac w/ 135,000 # Sd**
- **IPP 55 BOPD + 49 MCFD**
- **CUM 115 MBO + 11 MCF + 2MBW**

Hornbuckle Field Area
Sussex Water Cut
Structure Top Sussex Marker
Contour Interval = 50’

- **Low Water Cut, Generally < 15%**
- **Not a Water-Drive Reservoir**



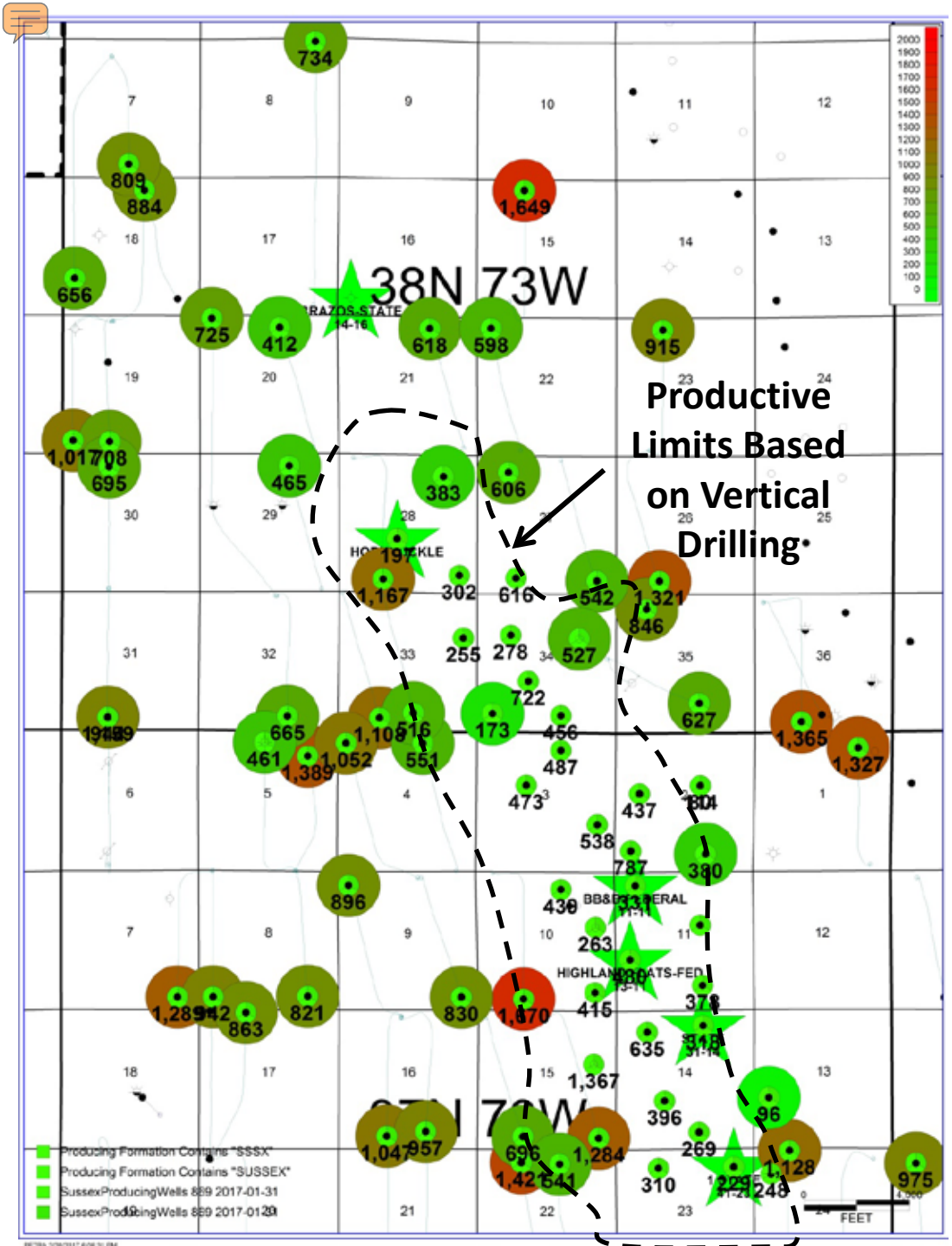
Water Cut (Decimal)

- >= 0.000
- >= 0.050
- >= 0.100
- >= 0.150
- >= 0.200
- >= 0.250
- >= 0.300
- >= 0.350
- >= 0.400
- >= 0.450
- >= 0.500
- >= 0.550
- >= 0.600
- >= 0.650
- >= 0.700
- >= 0.750
- >= 0.800
- >= 0.850
- >= 0.900
- >= 0.950
- >= 1.000

IHS Markit

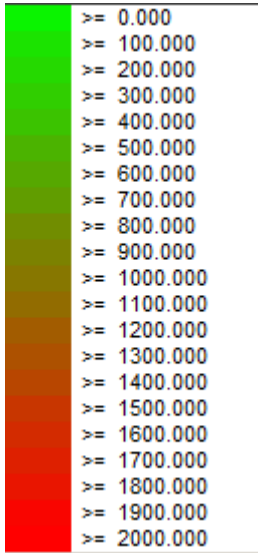
Well and Production Data From IHS Markit

Hornbuckle Field Area Sussex Gas-Oil Ratio In SCF/BBl



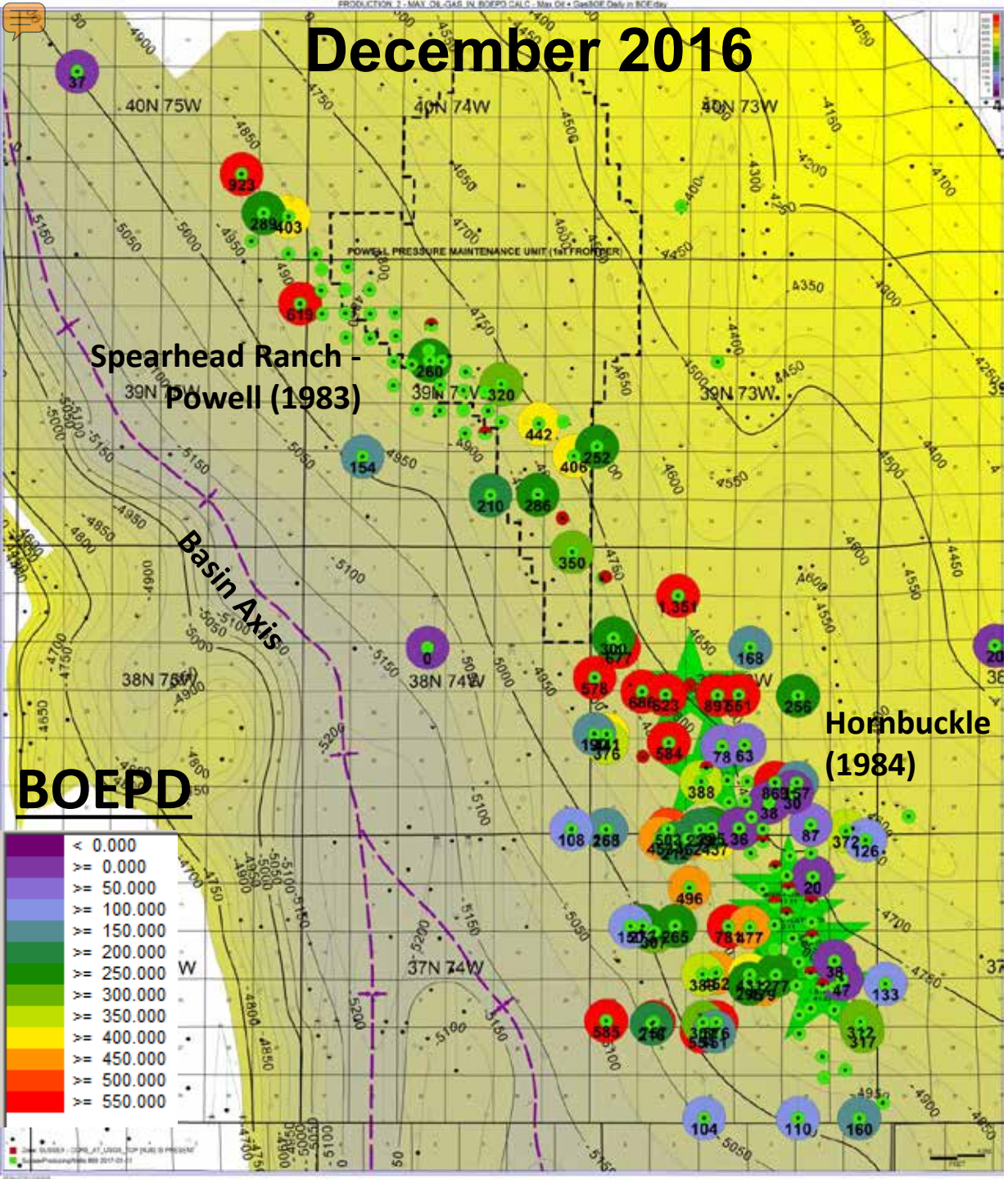
- Most Sussex Wells have GOR < 1000 SCF/Bbl
- Slightly Higher GOR in Updip Edge Wells & Downdip (western) Deeper Wells

GOR SCF/Bbl



IHS Markit

Well and Production Data From IHS Markit



SUSSEX MARKER STRUCTURE

CI = 50 Feet

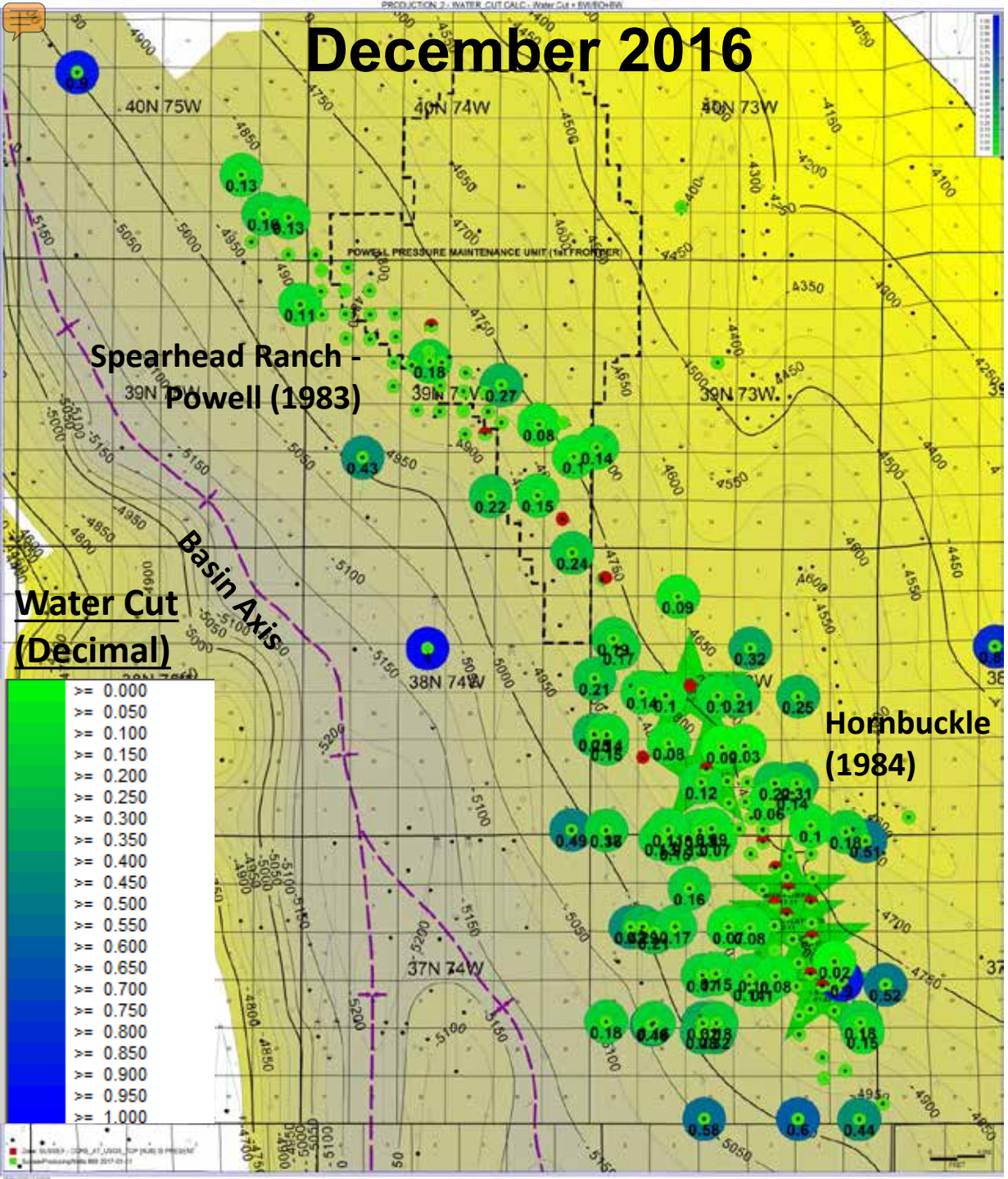
Maximum Monthly Rate Daily Average in BOEPD Bubbles

Red > 500 BOPD

Hornbuckle & Spearhead Ranch - Formerly Separate Fields have Merged Due to Horizontal Drilling

IHS Markit

Well and Production Data From IHS Markit



SUSSEX MARKER STRUCTURE

CI = 50 Feet

Sussex Water Cut (Decimal)

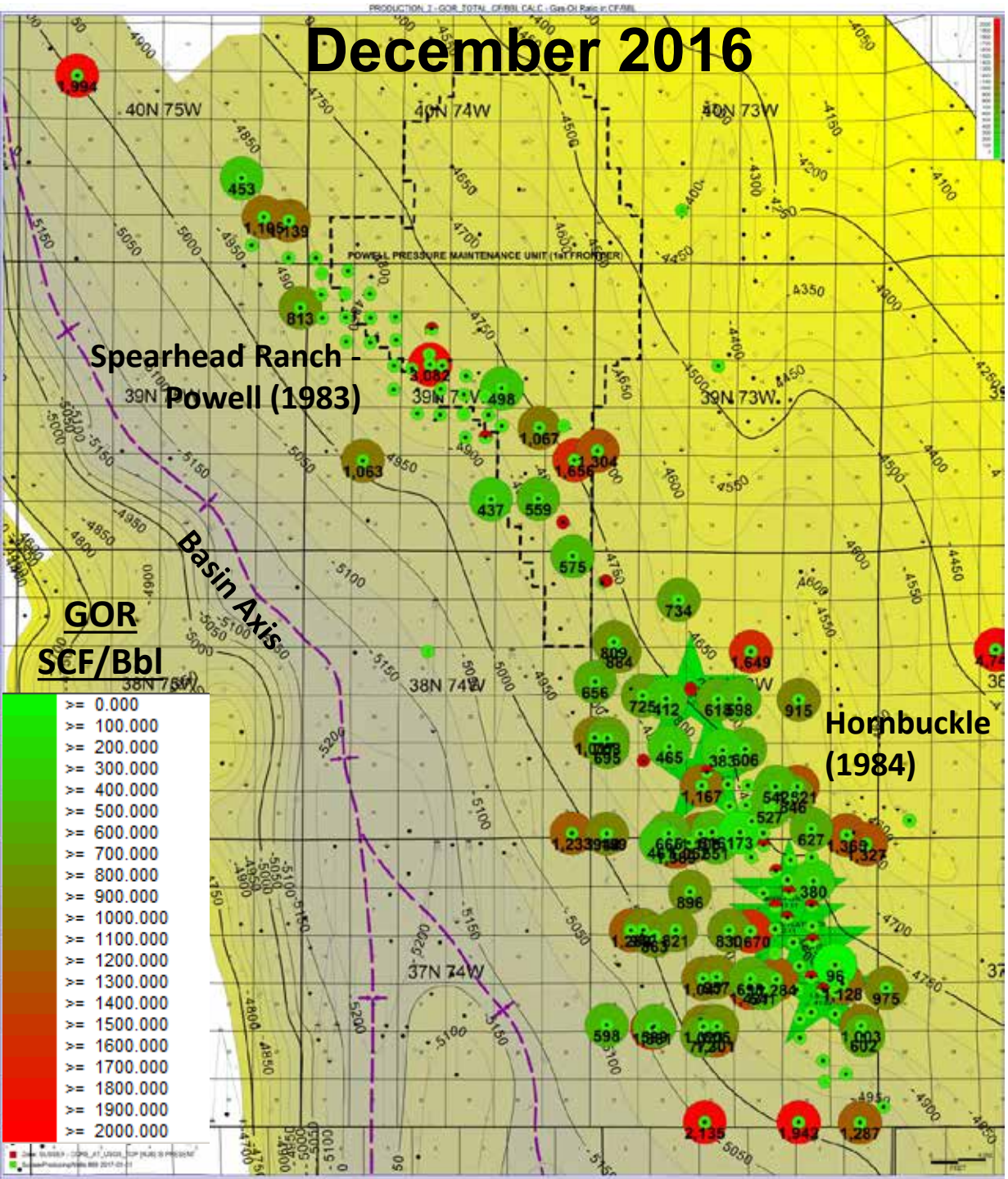
0% = Green

100% = Blue

- ***Low-Volume Wells Have Higher Water Cuts***
- ***Most Sussex Wells Water Cut < 20%***

IHS Markit

Well and Production Data From IHS Markit



SUSSEX MARKER STRUCTURE

CI = 50 Feet

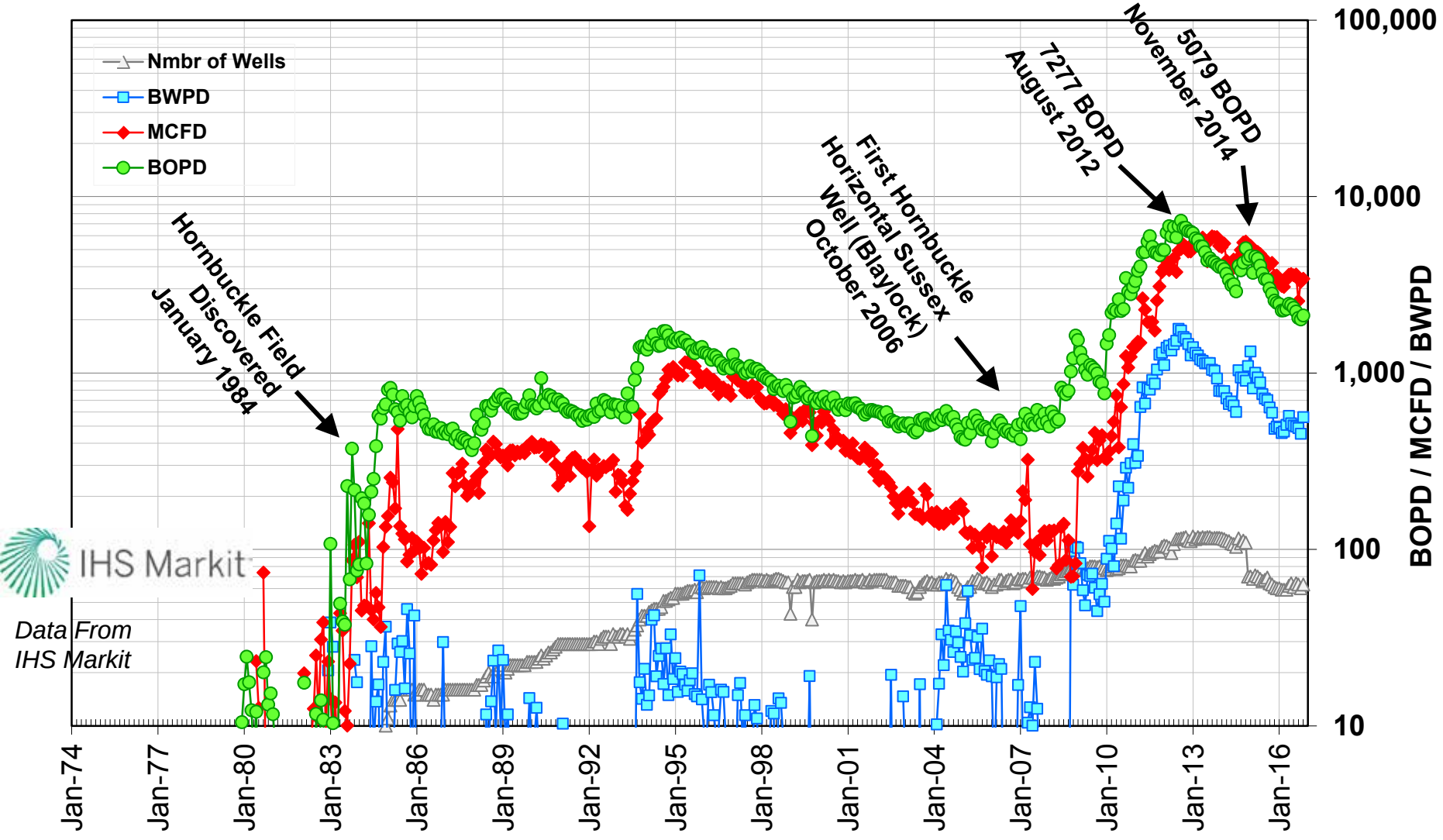
Sussex Gas-Oil Ratio (from Cum)

- Most Sussex Wells have GOR < 1000 SCF/Bbl
- Slightly Higher GOR in Updip Edge Wells & Downdip (western) Deeper Wells

IHS Markit

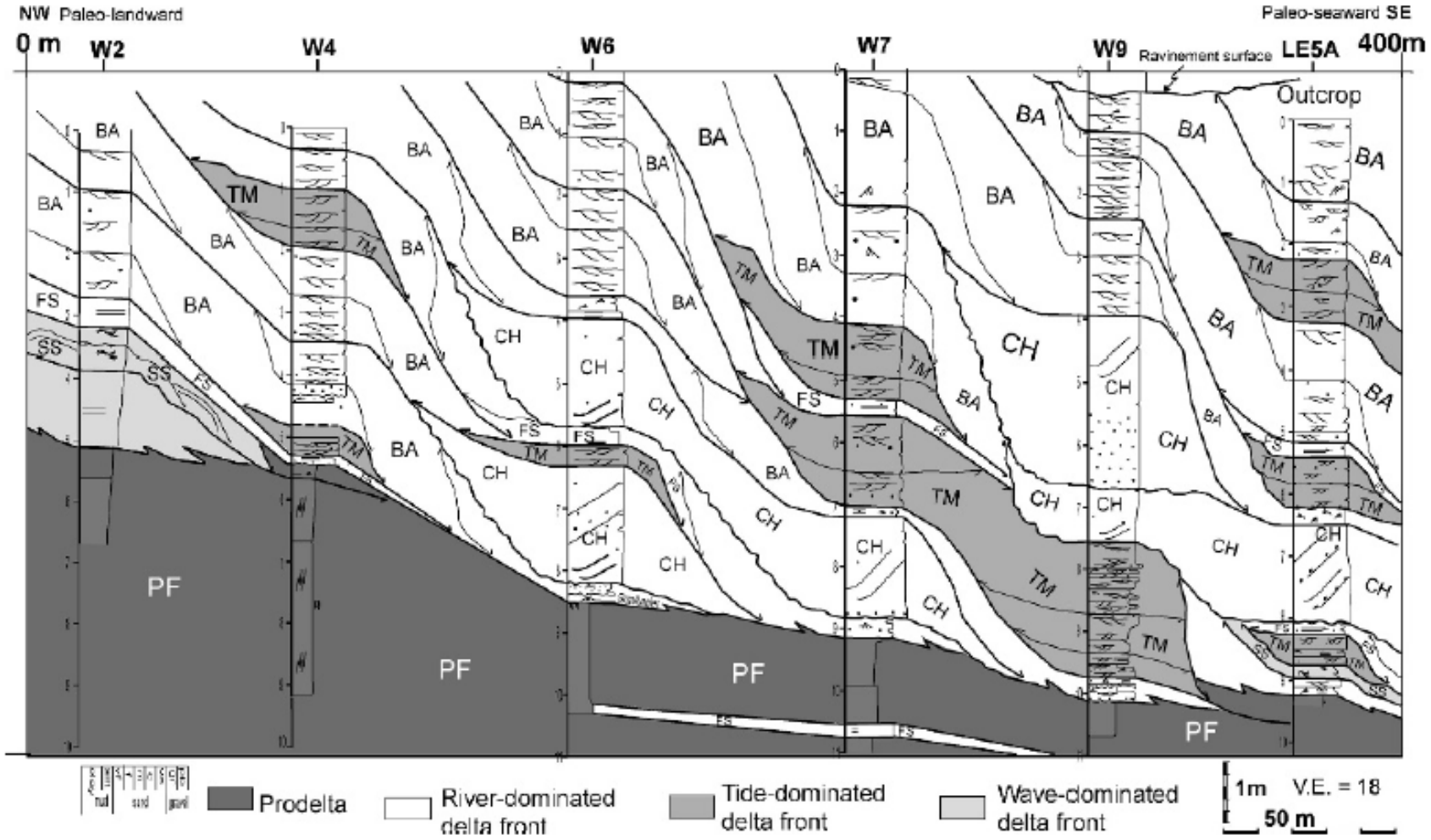
Well and Production Data From IHS Markit

SUSSEX SANDSTONE PRODUCTION
HORNBUCKLE - SPEARHEAD RANCH TREND
Powder River Basin, Wyoming, 1974 - 2017



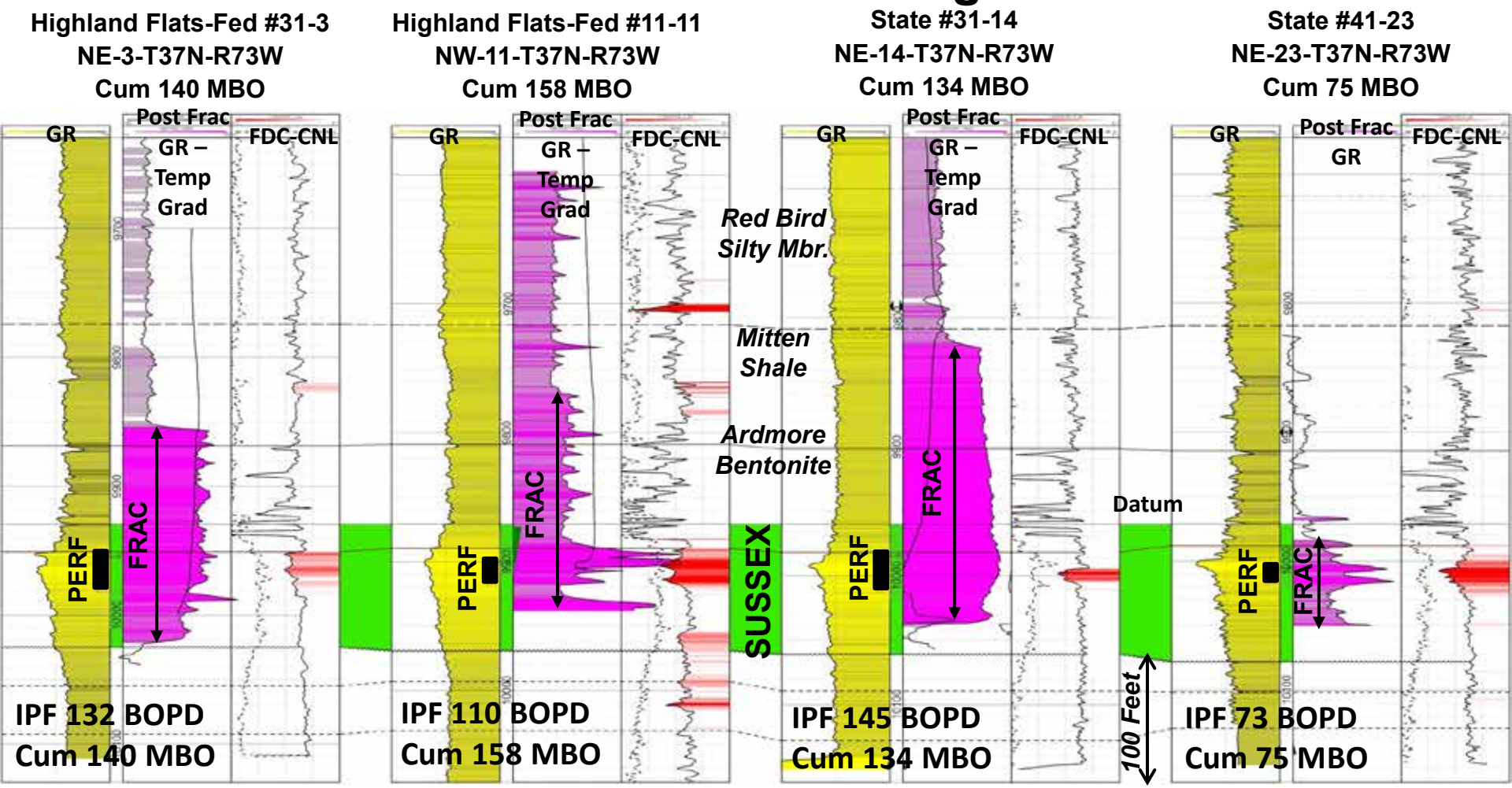
Architectural Elements – Frontier Sandstone, Raptor Ridge Outcrops, Natrona County, Wyoming

Northwest **Southeast**



Gani and Bhattacharya (2007), JSR v77, P284-302

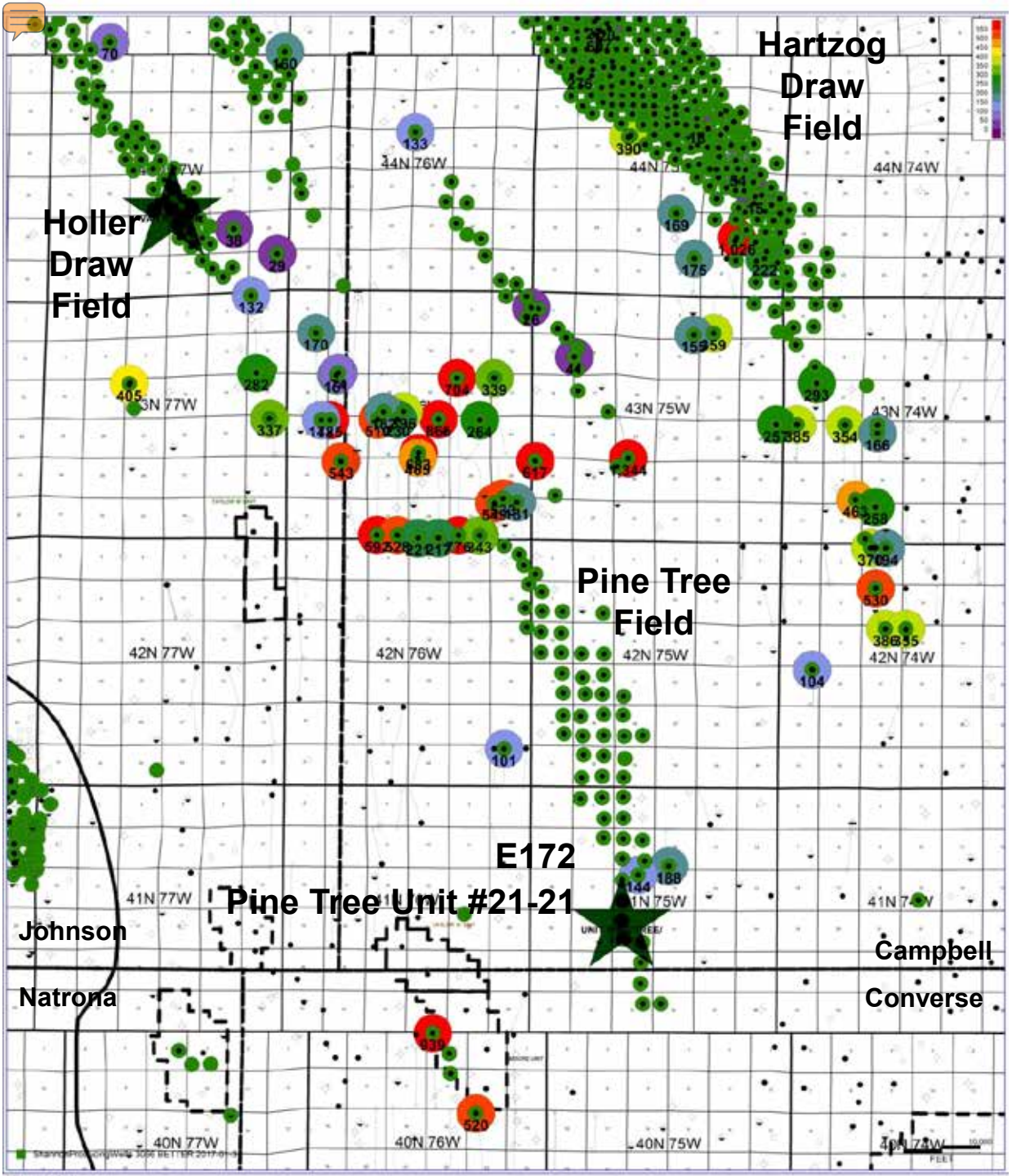
Hornbuckle Field – Post-Frac Gamma Ray Tracer Logs Indicate Unwanted Frac Height Growth



84,000 # Prop	145,000 # Prop	180,000 # Prop	63,000 # Prop
Avg Rate 12 BPM	Avg Rate 15 BPM	Avg Rate 15 BPM	Avg Rate n/a BPM
Frac 97’ Above Top Perf	Frac 133’ Above Top Perf	Frac 162’ Above Top Perf	Frac 39’ Above Top Perf
Frac 38’ Below Bot. Perf	n/a Below Bot. Perf	Frac 25’ Below Bot. Perf	n/a Below Bot. Perf
14’ SS Phi>8%	26’ SS Phi>8%	9’ SS Phi>8%	21’ SS Phi>8%

STIMULATIONS

- Significant Frac Height Growth Above Sussex Pay Zone
- Explains Low Percentage of Load-Water Recovery
- Correlation Between Frac Height & Proppant Pumped
- What is Optimum Frac Design?
  - Maximize IP and Recovery
- Pump More but Smaller Stages?



SHANNON ACTIVITY

Pine Tree Field To Holler Draw Field

Bubbles Max Rate in BOE/day for wells after 1-1-2006

Most Successful Shannon Activity Between and Along Strike With Existing Vertical Fields

BOEPD

- < 0.000
- >= 0.000
- >= 50.000
- >= 100.000
- >= 150.000
- >= 200.000
- >= 250.000
- >= 300.000
- >= 350.000
- >= 400.000
- >= 450.000
- >= 500.000
- >= 550.000

IHS Markit

Well & Production Data From IHS Markit

RMAG Tight Oil Sandstones Core Workshop, March 2, 2017

CORES - ORGANIZATION