

Sussex Sandstone, Hornbuckle Trend, Powder River Basin, Wyoming: Lithofacies and Reservoir Properties in a Tight Oil Play*

Richard J. Bottjer¹, Michael L. Hendricks², Daniel H. Stright³, and John A. Bettridge⁴

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¹Cirque Resources, Denver, CO, USA (rbottjer@cirqueresources.com)

²Hendricks & Associates, Centennial, CO, USA (oilmlh@aol.com)

³Reservoir Management Services, Montrose, CO, USA (dstright@yahoo.com)

⁴Southwestern Production Corp., Denver, CO, USA (john@southwestproduction.com)

Abstract

Oil production was first established from the Campanian Sussex Sandstone in the Powder River Basin with the discovery of House Creek Field in 1968. Oil production from a second Sussex Sandstone trend was discovered when production was established at Spearhead Ranch (1983) and Hornbuckle (1984). The first Sussex horizontal well in the Hornbuckle-Spearhead trend was drilled in 2006 by Southwestern Production Corp. The Blaylock-Federal #13-35A had excellent shows, but high formation pressures necessitated completion of the well through cemented drill pipe, resulting in a peak rate of 79 BOPD. Overpressure up to 0.65 psi/foot was underestimated due to low reservoir permeability. This geological success set the stage for additional horizontal drilling, which has now increased Sussex production in this trend from less than 500 BOPD to more than 6500 BOPD and basin wide Sussex production to more than 8000 BOPD.

The Sussex Sandstone at Hornbuckle consists of interbedded very fine to medium-grained glauconitic and calcareous sandstone, chert pebble and siderite-clast conglomerate, and silty shale. These heterolithic strata are burrow-mottled at the base and coarsen upwards. Burrow structures show a change from Cruziana to Glossifungites ichnofauna, corresponding to the overall bathymetric shallowing and coarsening of detritus. Porosity ranges from 4 to 14 percent and is developed within the entire sandstone interval, with the best porosity developed in the higher-energy facies. Engineering analysis of production data identifies heterogeneities not observed with widely-spaced geological data, establishes the importance of the bioturbated facies to net pay, and facilitates mapping of reservoir compartments. Integration of geological models with production data analysis provides a consistent reservoir description that can be used to help maximize production from horizontal and vertical well development.

References Cited

Blakey, R.C., 2005, North American paleogeography, 85 mya: Northern Arizona University, Ron Blakey webpage. Web Accessed November 6, 2014. <http://jan.ucc.nau.edu/~rcb7/namK85.jpg>.

Heasler, H.P., R.C. Surdham, and J.H. George, 1994, Pressure compartments in the Powder River Basin, Wyoming and Montana, as determined from drill-stem test data: in Peter J. Ortoleva, Basin compartments and seals: American Association of Petroleum Geologists Memoir 61, p. 235-262.

AAPG Rocky Mountain Section

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**Sussex Sandstone Tight Oil Play, Powder
River Basin, Wyoming: Extension of the
Hornbuckle-Spearhead Trend with
Horizontal Drilling**

Richard J. Bottjer

Cirque Resources

Michael L. Hendricks

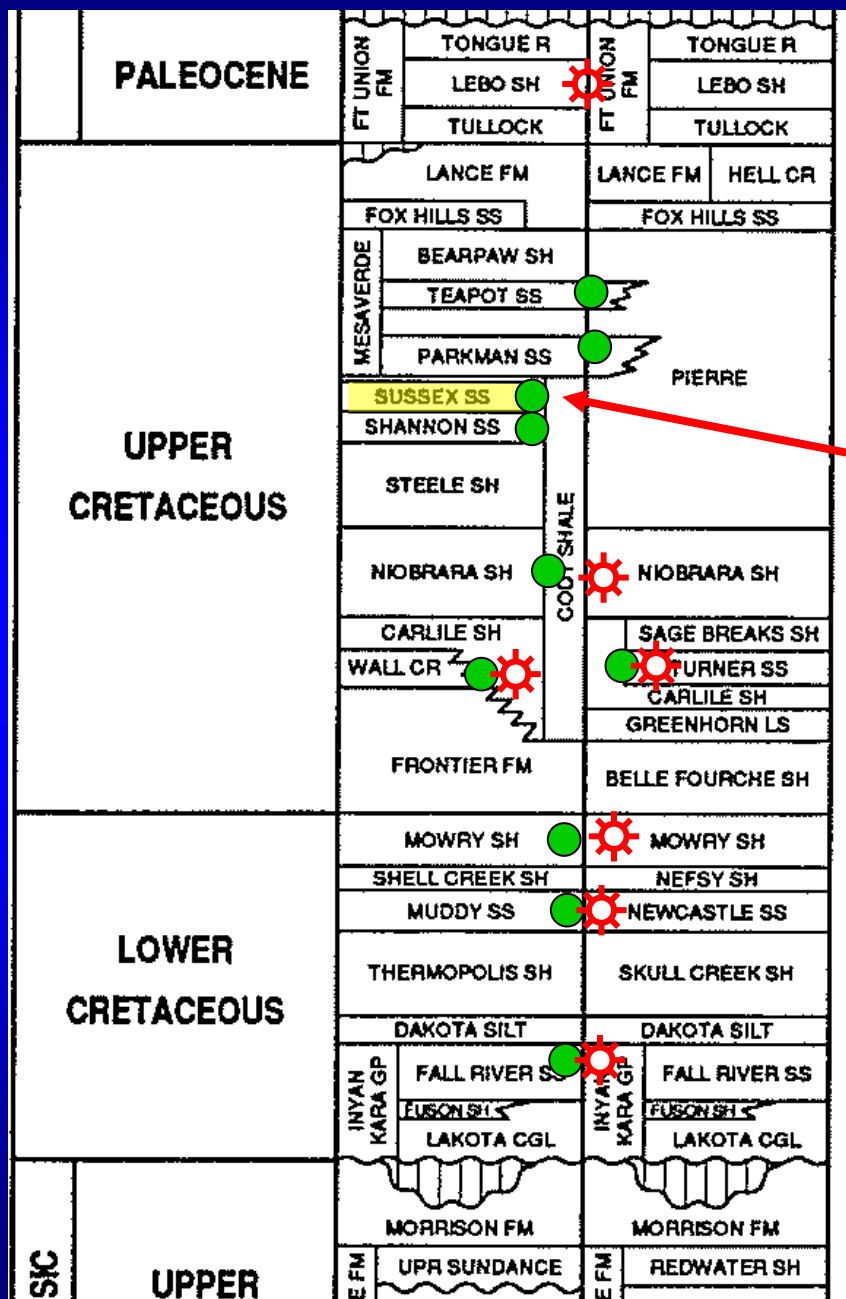
Hendricks & Associates

Daniel H. Stright, Jr.

Reservoir Management Services

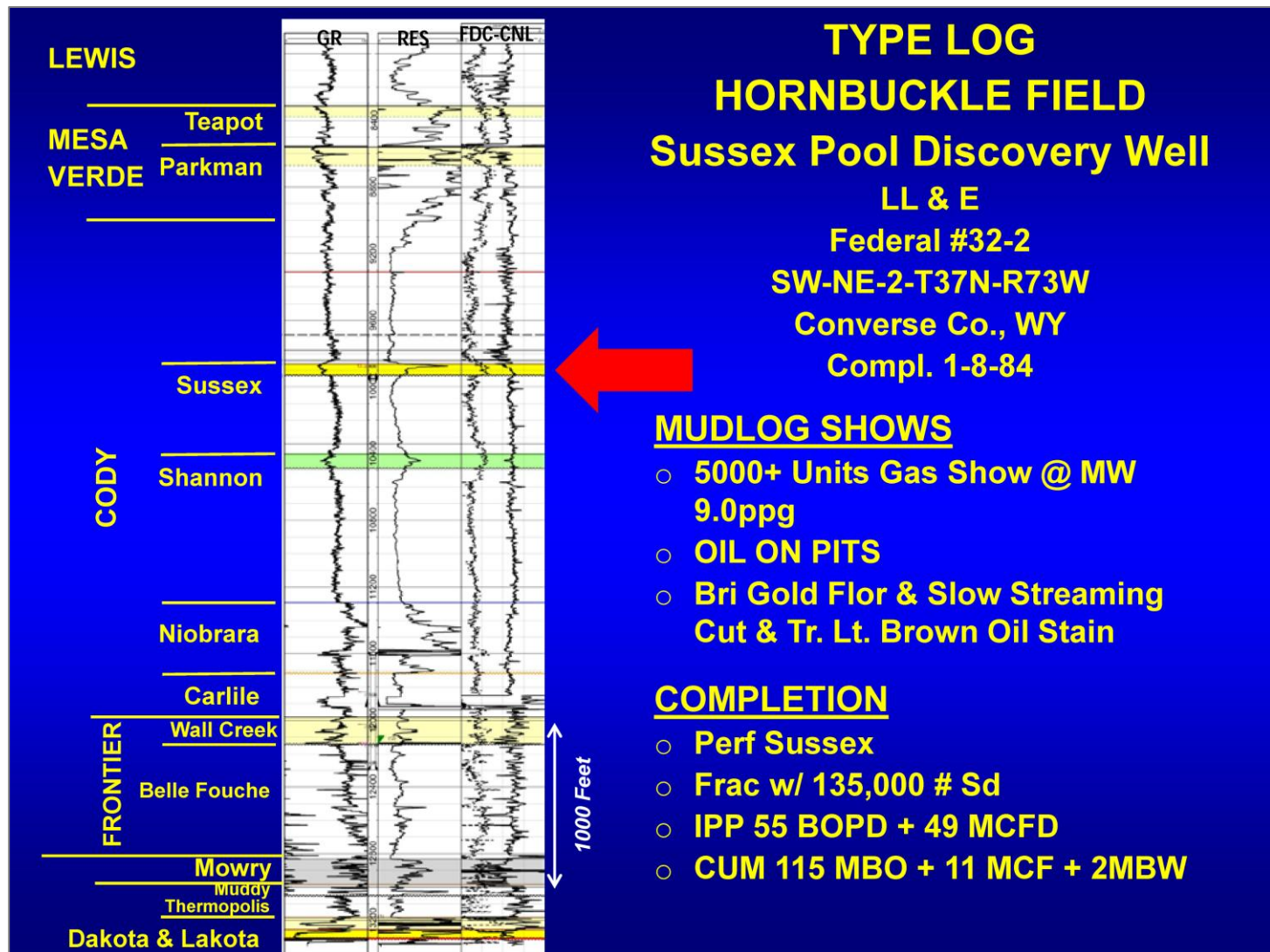
John A. Bettridge

Southwestern Production Corp.



POWDER RIVER BASIN STRATIGRAPHIC CHART

*Sussex Sandstone
Campanian*

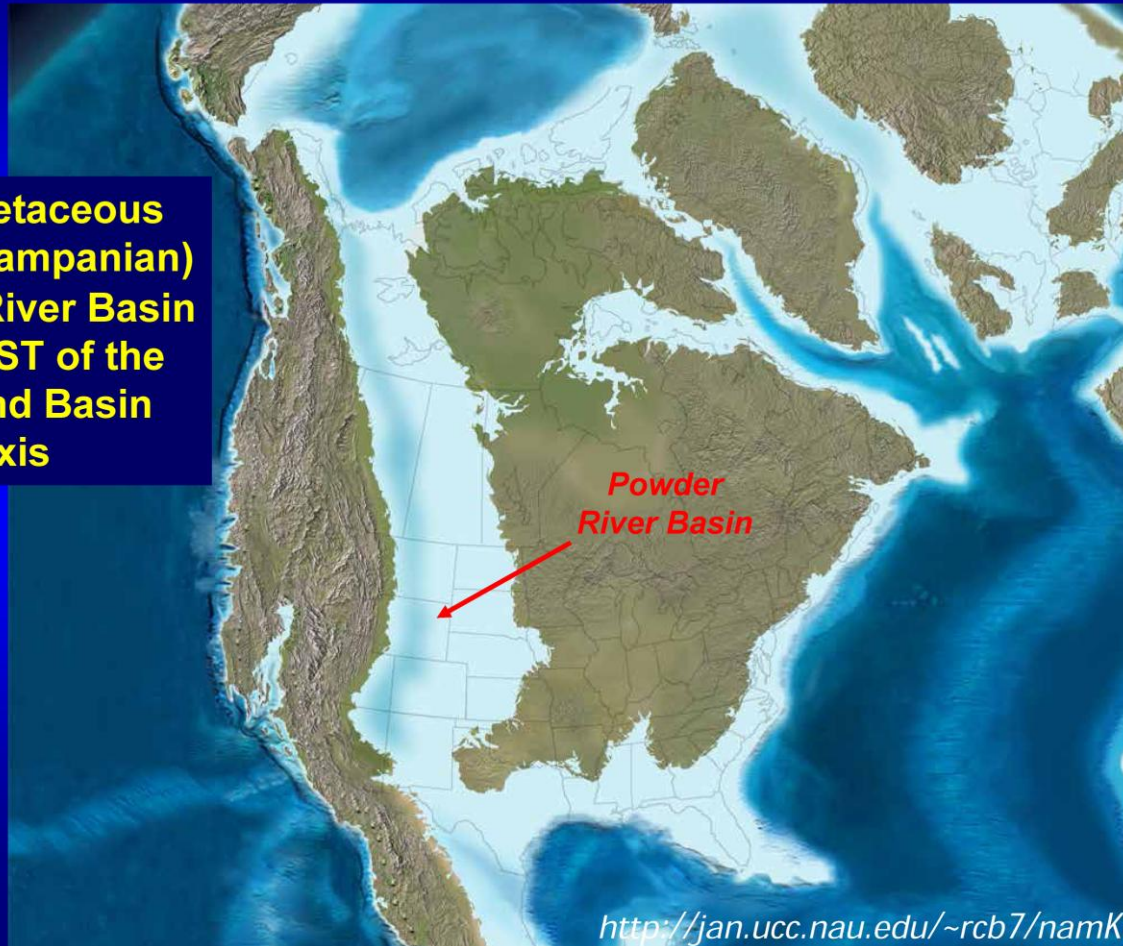


Presenter's notes: Type Log for Hornbuckle Field, showing discovery well drilled by LL&E in 1984. Note excellent show in Sussex while drilling to Muddy-Dakota targets. Hornbuckle was discovered by accident; the prospect was drilled for a deeper objective. Spearhead Ranch/Powell Sussex production was also discovered while drilling for deeper targets.

Late Cretaceous Paleogeography

North America ~ 85 MYA (Blakey 2005)

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



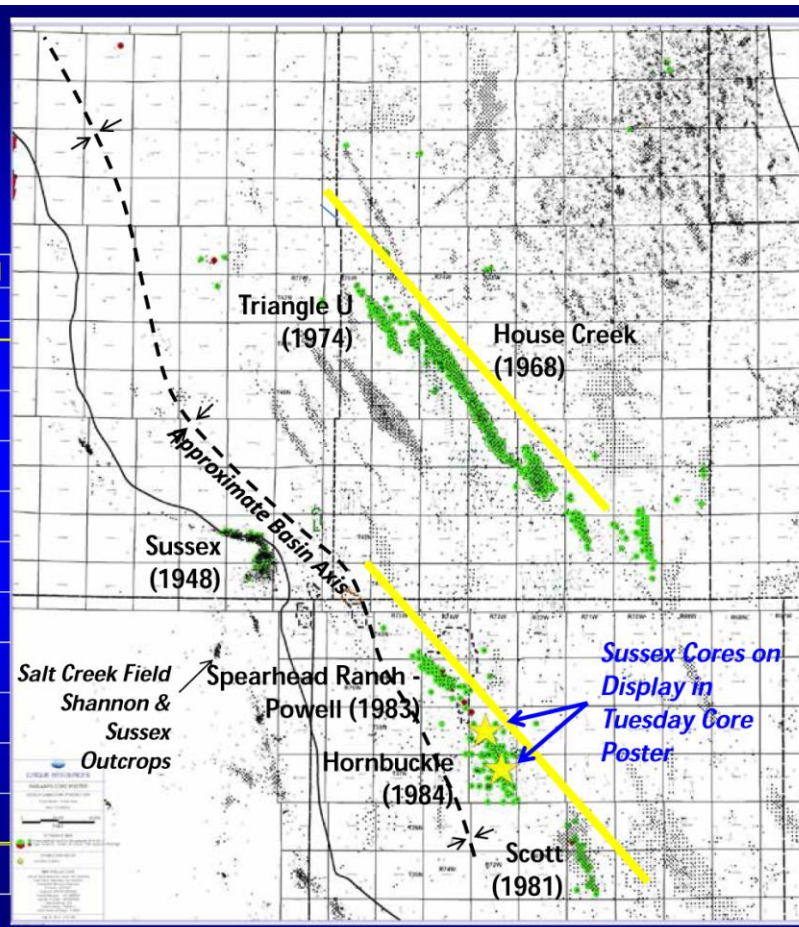
<http://jan.ucc.nau.edu/~rcb7/namK85.jpg>

Presenter's notes: Ron Blakey's paleogeographic reconstruction of North America at approximately 85 mya (Campanian). Note that the Powder River Basin was east of the foreland basin axis and was therefore an area of limited accommodation space. This explains in part why the Sussex (and other Late Cretaceous sandstones) is stratigraphically complex in this basin.

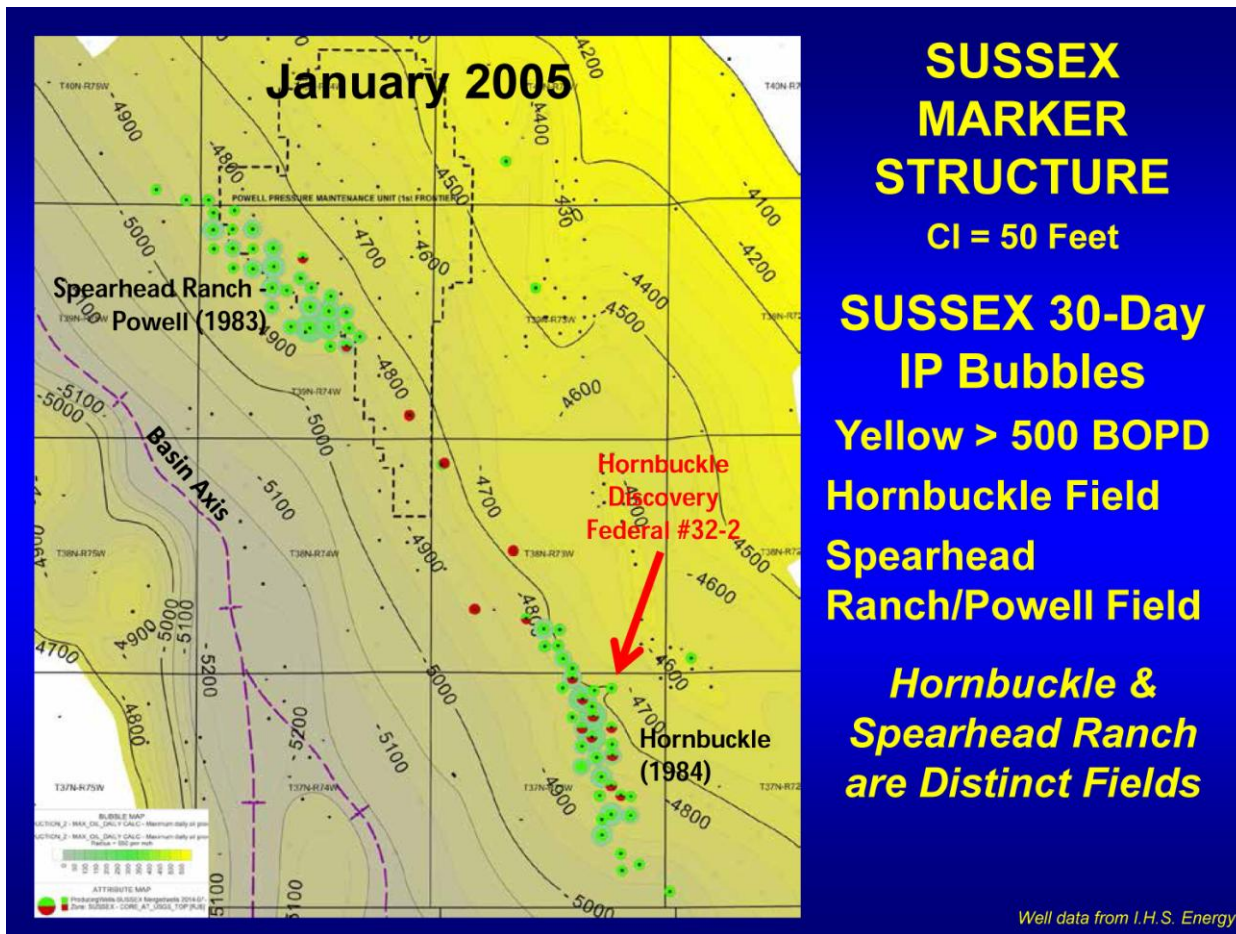
SUSSEX OIL PRODUCTION Powder River Basin

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

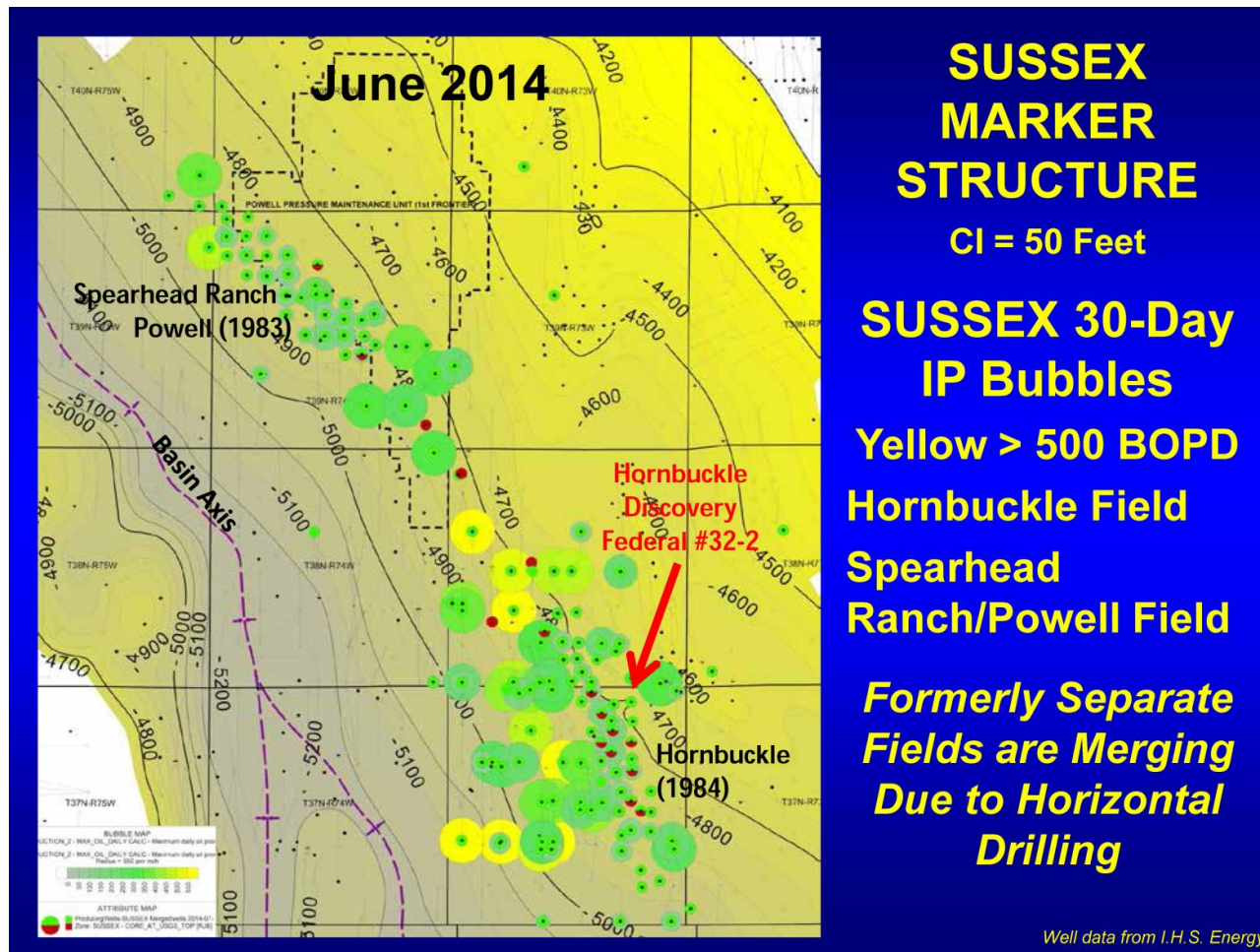
Well & Production data from I.H.S. Energy



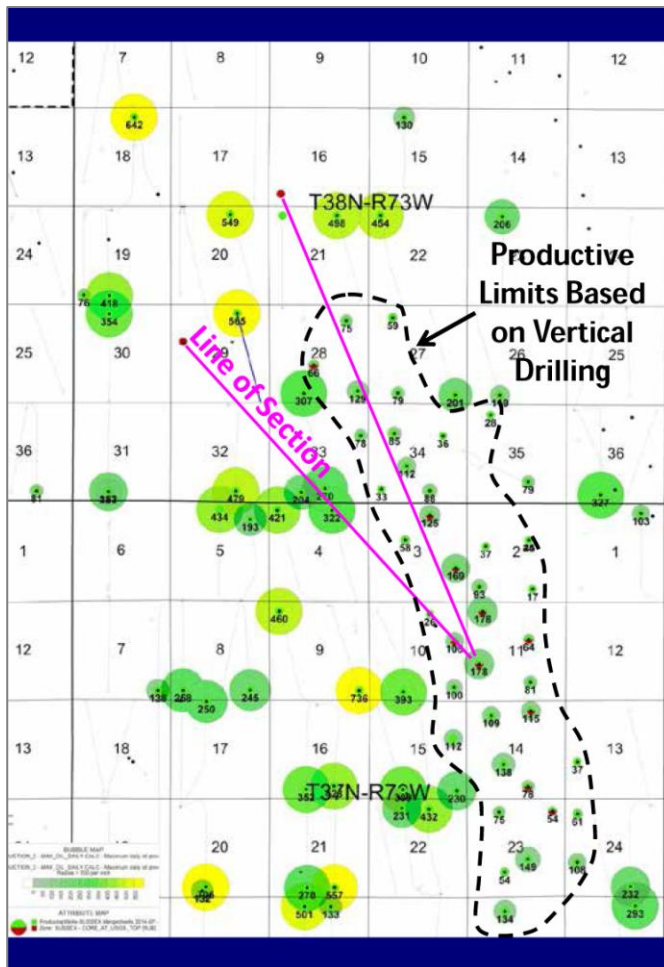
Presenter's notes: Oil production from the Sussex Sandstone was discovered in 1948 at Sussex Field, on the northeast flank of Teapot Dome. Prospecting for stratigraphic traps in the 1960s and 1970s led to the discovery of House Creek, Triangle U, and other conventional fields. Exploration for deeper targets led to the discovery of Scott (1981), Spearhead Ranch/Powell (1983), and Hornbuckle (1984) and opened the Sussex oil play in Converse County. Yellow lines represent approximate locations of northeast (updip) pinchouts of major sandstone units in the Sussex interval, so both the House Creek "trend" and the Hornbuckle "trend" are large stratigraphic traps east of the present-day Powder River Basin axis. Total Sussex oil production is greater than 80 MMBO as of fall 2013.



Presenter's notes: Top Sussex Marker Structure, Contour Interval = 50 Feet, Basin Axis of Powder River Basin in southwestern corner of the slide. Sussex penetrations and Sussex oil producing wells (green circles) shown as of January 2005, just prior to drilling the first horizontal well. Initially Sussex oil fields in this trend were thought to be isolated stratigraphic traps much like those in the House Creek-Triangle U trend, except that these are in a deeper part of the basin. Red dots are preserved Sussex cores, most are at the USGS (thanks to the USGS CRC for collecting and preserving this valuable dataset), and one key core is owned by Wexpro / QEP Resources (thanks to them for access and permission to discuss it). Vertical well IPs are up to about 180 BOPD, so the diameter of the green bubbles is quite small.



Presenter's notes: Top Sussex Marker Structure, Contour Interval = 50 Feet, Basin Axis of Powder River Basin in southwestern corner of the slide. Sussex penetrations and Sussex oil producing wells (green circles) shown as of June 2014, after horizontal drilling was established and successfully implemented. Note that horizontal drilling has effectively filled in the area between Hornbuckle and Spearhead Ranch/Powell so that the entire area is now oil productive. These fields are no longer isolated stratigraphic traps, but are part of a larger more regional trap. Horizontal well 30-day average IPs are up to about 800 BOPD, so the diameter of the bubbles is larger – yellow bubbles are wells with first 30-day average IPs > 500 BOPD.



HORNBUCKLE FIELD

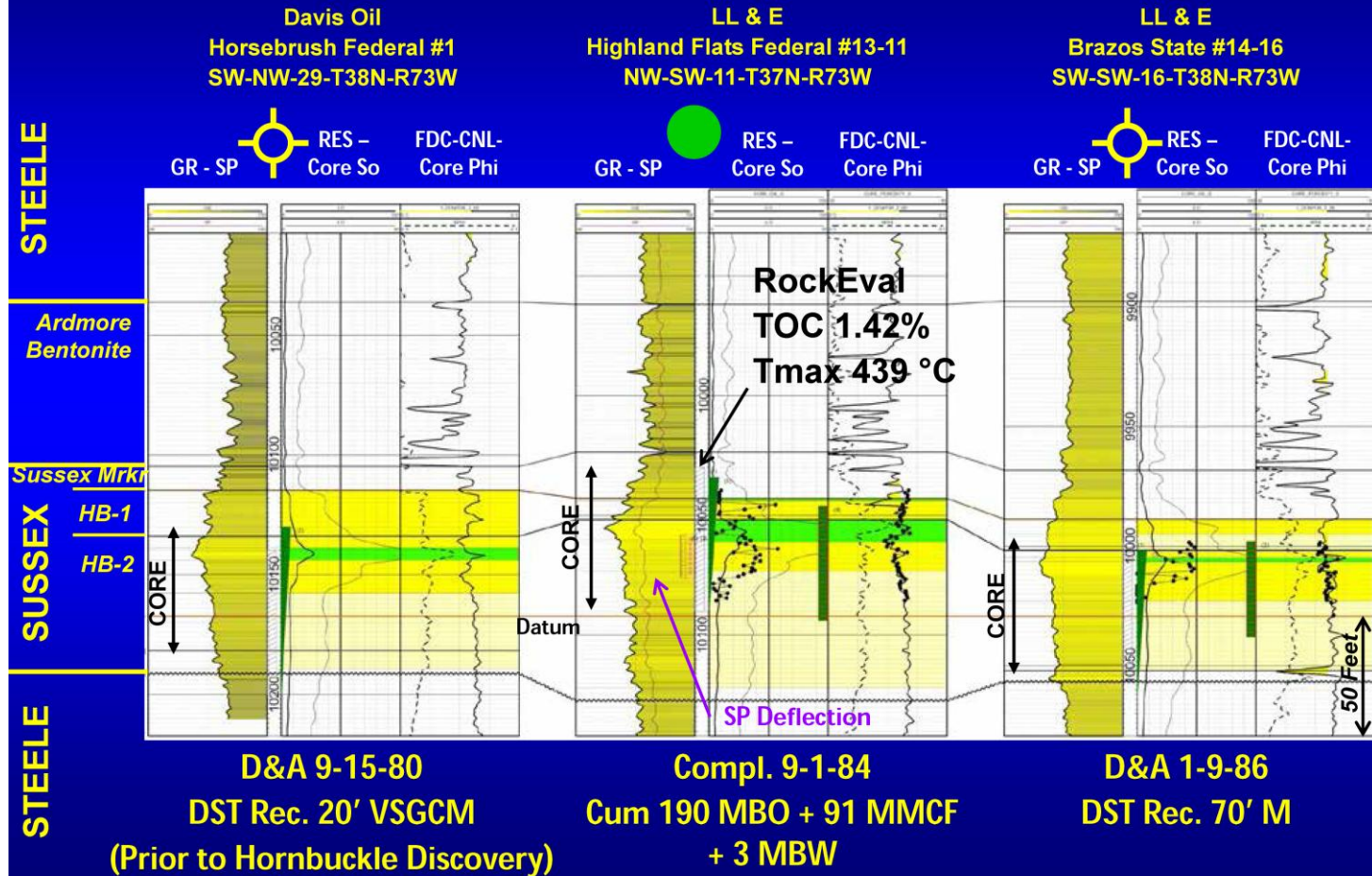
Vertical Production Discovered 1984

- 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)
- Low Water Cut (<5%)
- 160 Acre Spacing, Wells Not Effectively Draining Spacing Units
- Few Dry Holes At Field Edges

Presenter's notes: Production Bubble Map showing maximum 30-day average oil producing rates in BOPD for Sussex wells in the Hornbuckle Field area. Diameter and color of circles are related to average daily oil rates, so larger circles are higher rates. Limits of the Hornbuckle Field in 2004 based on vertical drilling and completions shown with black dashed line – note how horizontal drilling in 2006-2014 has expanded Sussex production in all directions. The Sussex reservoir at Hornbuckle is at a depth of approximately 10,000 feet. Vertical wells exhibit low decline rates (<6%, some as low as 3%) with 20+ years of production history. The line of section shown in the next Slide is in pink.

Hornbuckle Field Area – 3 Sussex Cores

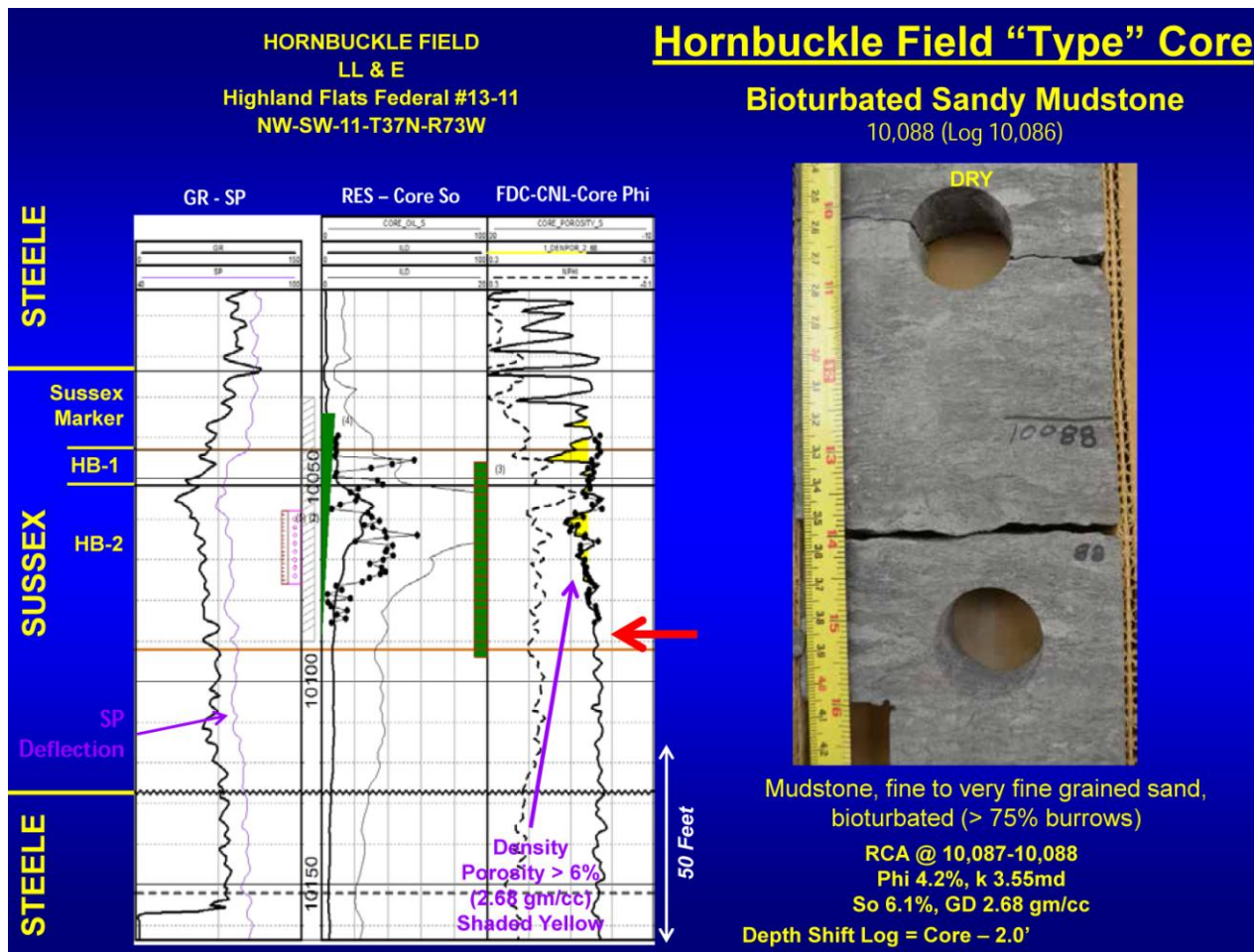
HORNBUCKLE FIELD



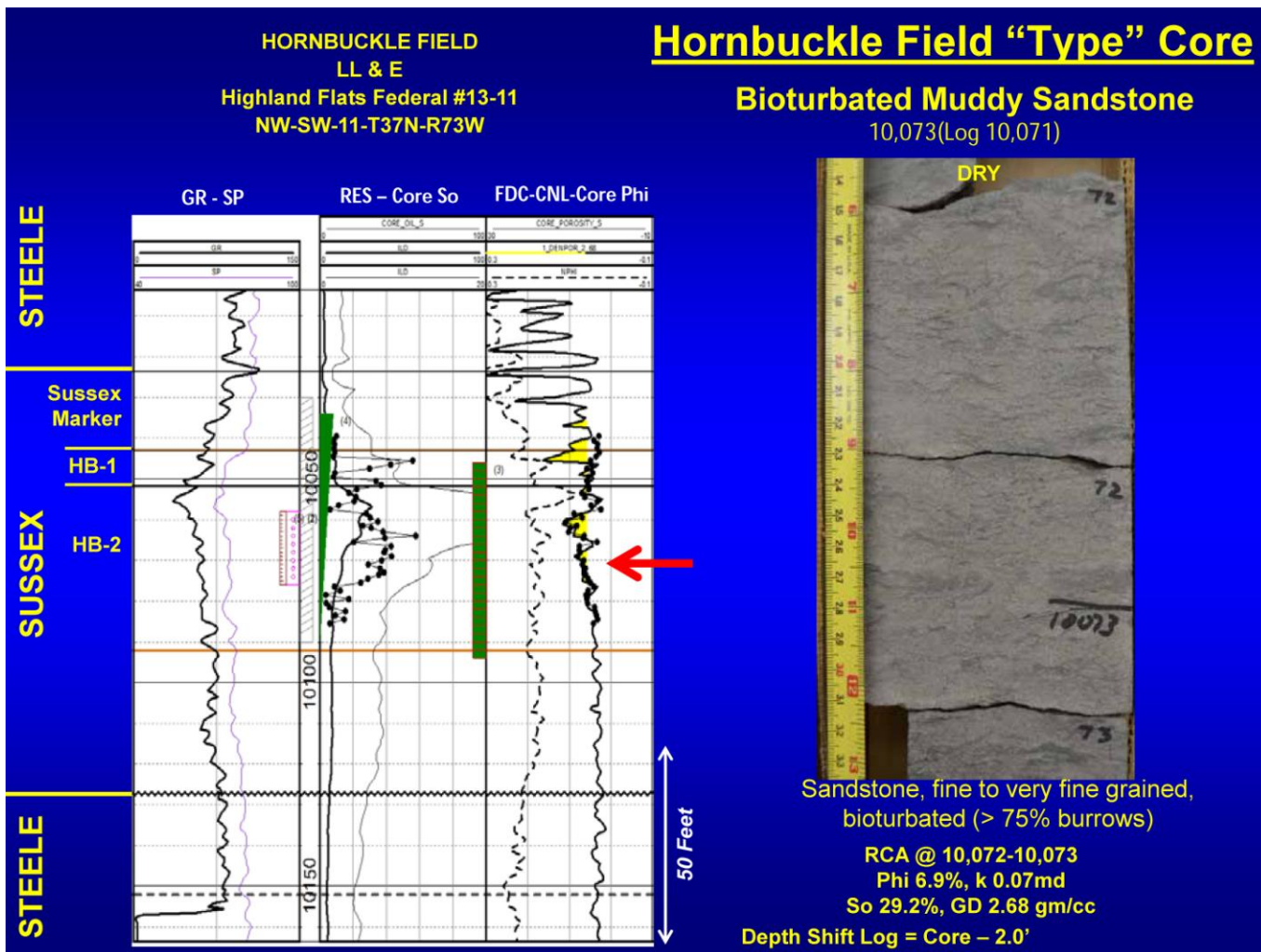
Presenter's notes: Three-well cross section showing three cored wells: a Hornbuckle Field vertical oil producer and two vertical dry holes, both of which are now offset by high-volume horizontal oil producing wells. Logs shown are gamma ray (black) and SP (purple) in track 1, resistivity & core oil saturations in track 2, (Presenter's notes continued on next slide)

(Presenter's notes continued from previous slide)

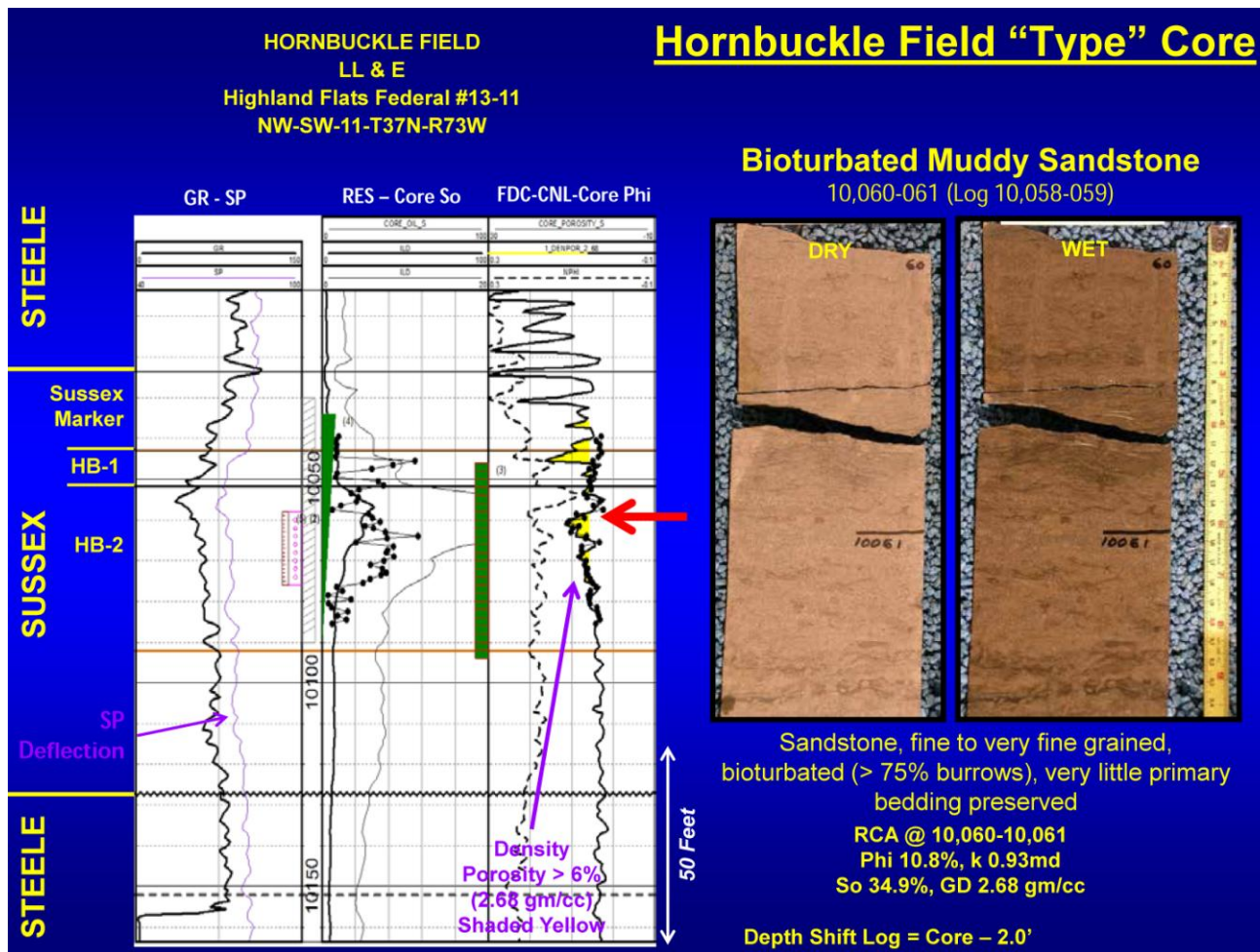
and in track 3 neutron porosity (dashed), density porosity (solid) on a 2.68 gm/cc matrix, and core plug porosity. In tracks 2-3, color shading shows Green = cross-bedded sandstone, bright yellow = bioturbated muddy sandstone, and pale yellow = bioturbated sandy mudstone. Datum is the tan marker within the lower Sussex Sandstone. Note: a) vertical producer has thicker cross-bedded sandstone facies than “dry holes”; b) higher-energy cross bedded sandstone facies tends to be low porosity due to secondary cementation; c) all three wells had core shows but only the #13-11 well had sufficient permeability to complete as a vertical producer. Total Sussex Sandstone thickness is 70-80 feet; this is corroborated by the limits of SP deflection (see #13-11 well). In the #13-11 core, four RockEval samples were collected and analyzed from the transgressive systems tract mudstones overlying the Sussex Sandstone and showed average TOC of 1.42% and Tmax of 439 deg. C, indicating good quality source rocks in the peak oil window. The slides following will illustrate the facies recovered in the core from the #13-11 (center) well.



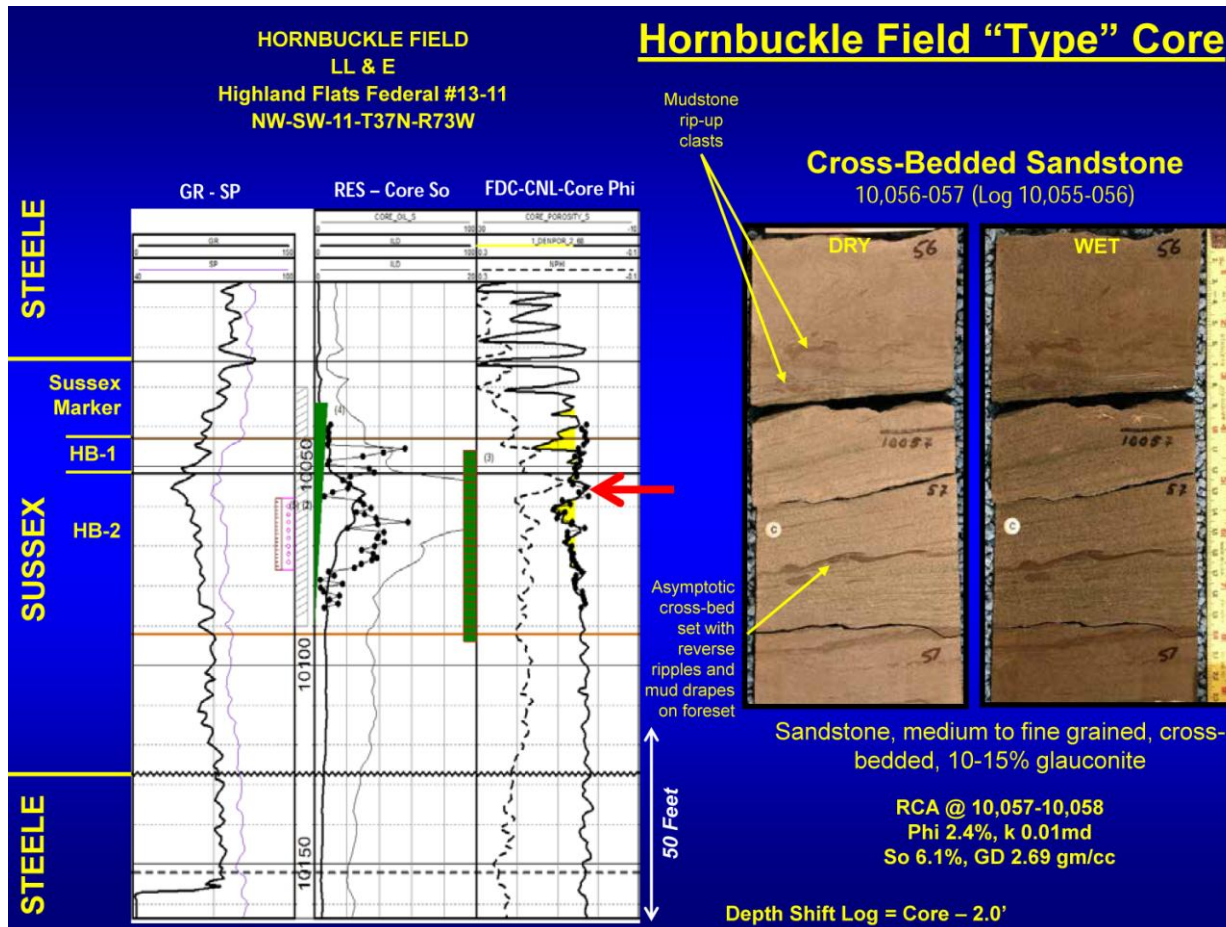
Presenter's notes: The Sussex in the Hornbuckle Field area can be subdivided into two upward-cleaning successions (parasequences), here named HB-1 and HB-2 (upper and lower respectively). HB is short for Hornbuckle. At Hornbuckle Field, the dominant pay zone is the lower HB-2 unit. Starting at the bottom of the Sussex, near the bottom of the core in the #13-11 well, the lower part of the Sussex is a bioturbated sandy mudstone. Core photo location shown with red arrow. This facies is highly bioturbated with few or no primary sedimentary structures remaining after the burrowers completely reworked the sediment. Porosity is low (~4%) in this facies.



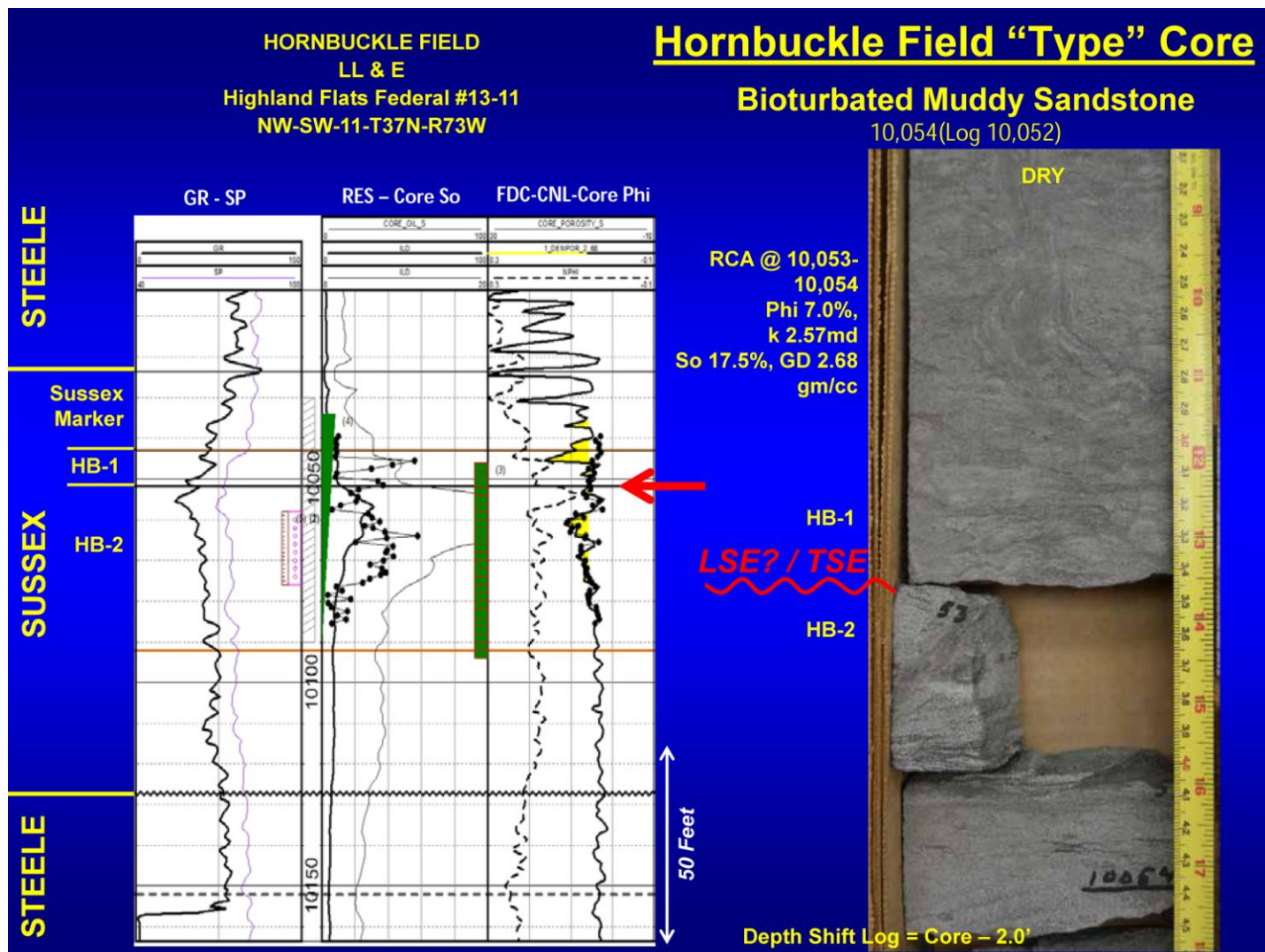
Presenter's notes: The sand content gradually increases upsection in the Sussex; this as a bioturbated muddy sandstone. This facies is completely bioturbated and a core plug in the photographed interval had 6.9% porosity and .07 md permeability. Oil saturation in this core plug was 29% so there is oil saturation in this part of the sandstone. Note the dirty gamma ray response related to the clay content. Also note the Oil Saturations in track 2 on the log – this interval has some of the best oil saturations in this core.



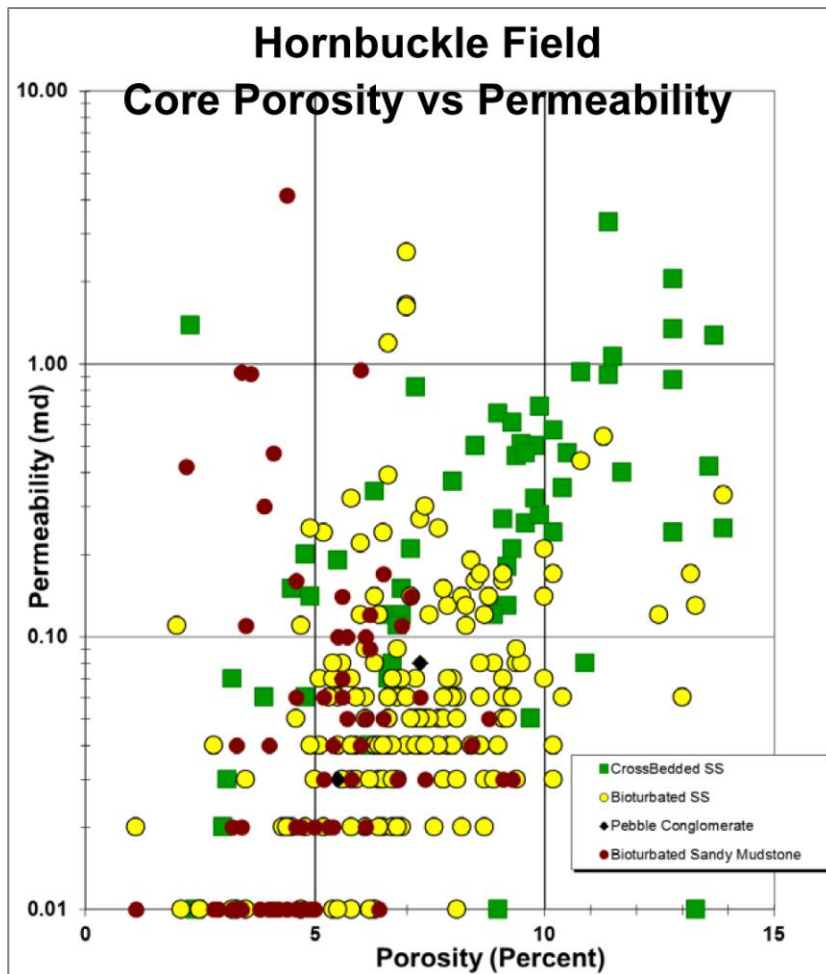
Presenter's notes: This core sample is from the upper part of the HB-2 parasequence, in the interval with the highest density log porosity. This is a bioturbated muddy sandstone; core plug analysis in this sample has porosity of 10.8% and permeability of 0.93md, oil saturation of 34.9%. Based on previous work done at House Creek and older Sussex Sandstone fields from the House Creek Trend, this high porosity interval was expected to be higher energy, cross-bedded sandstone facies. The abundance of bioturbation and relative absence of primary bedding structures in the main pay zone in this well was unexpected and caused us to re-think our reservoir model for the Sussex at Hornbuckle.



Presenter's notes: Near the top of the HB-2 parasequence, we see the high-energy, glauconitic, cross-bedded sandstone facies we expected would be the primary reservoir in the field. Note that the core analysis from this sandstone, and the corresponding log response, had only 2.4% porosity and 0.01md permeability. This facies is the main pay at House Creek where it commonly has porosity greater than 15%. At Hornbuckle, this facies ranges from zero to 20 feet in thickness and has locally good porosity. The best vertical wells are located where this facies is porous. In this example, there are reverse ripples and mud drapes on some of the cross-bed sets, indicating the influence of tidal currents in the Sussex depositional environment.



Presenter's notes: The contact between the HB-2 and HB-1 parasequences is sharp and erosional, with cross-bedded sandstone below and bioturbated muddy sandstone above. The HB-1 upward-cleaning parasequence is similar lithologically to the HB-2 parasequence we just reviewed but at Hornbuckle, the HB-1 parasequence is much thinner.



Cross Bedded Sandstone Facies

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

Bioturbated Sandstone

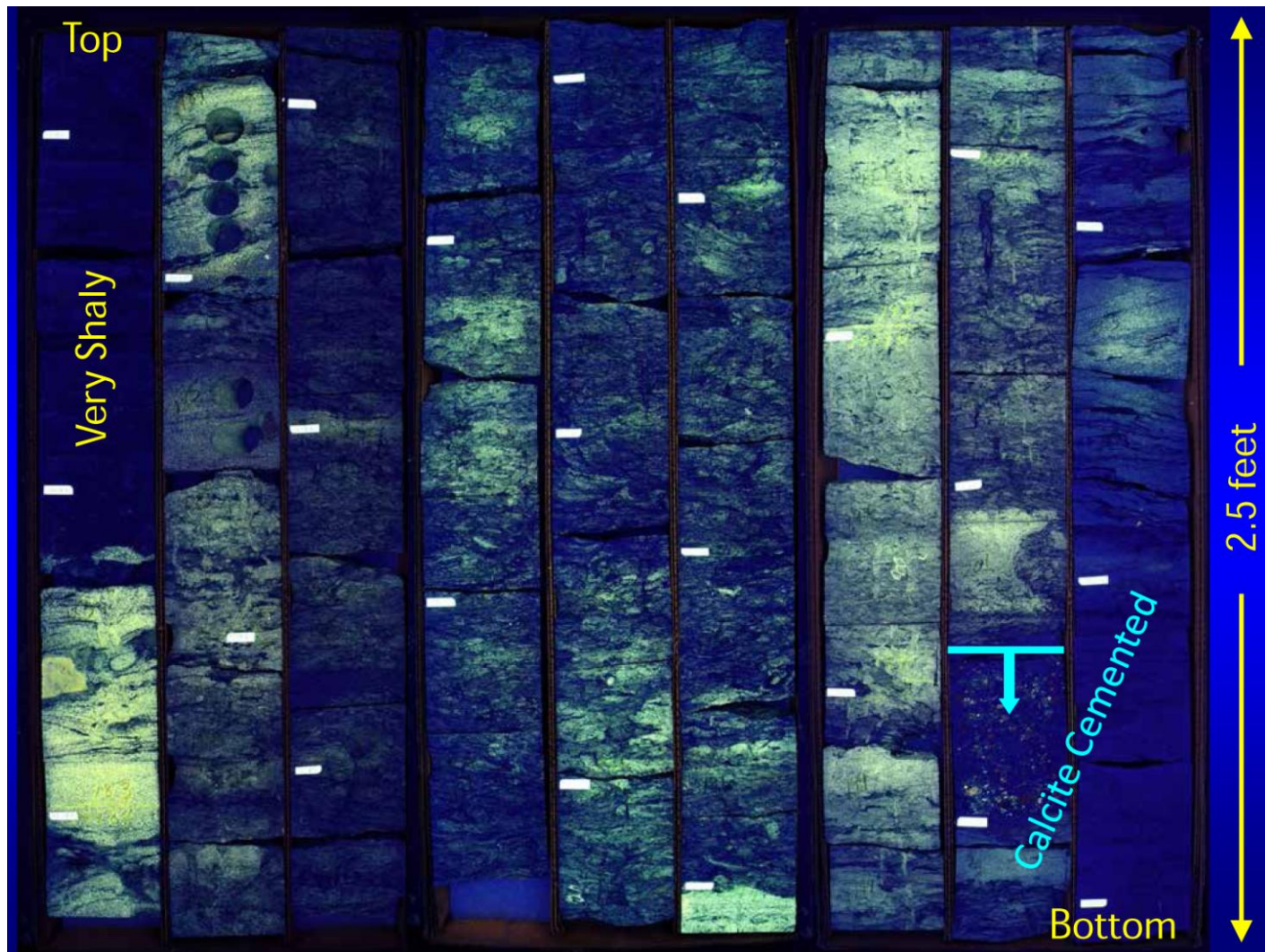
- Phi 1-14%, Avg 7.1%
- k .01-.60 md, Avg 0.12md

Bioturbated Sandy Mudstone

- Phi 1-9%, Avg 5.2%
- k .01-.20 md, Avg 0.16md

- Burrowed Sandstone Facies has Significant Porosity with Lower Permeability – Added Hydrocarbon Storage

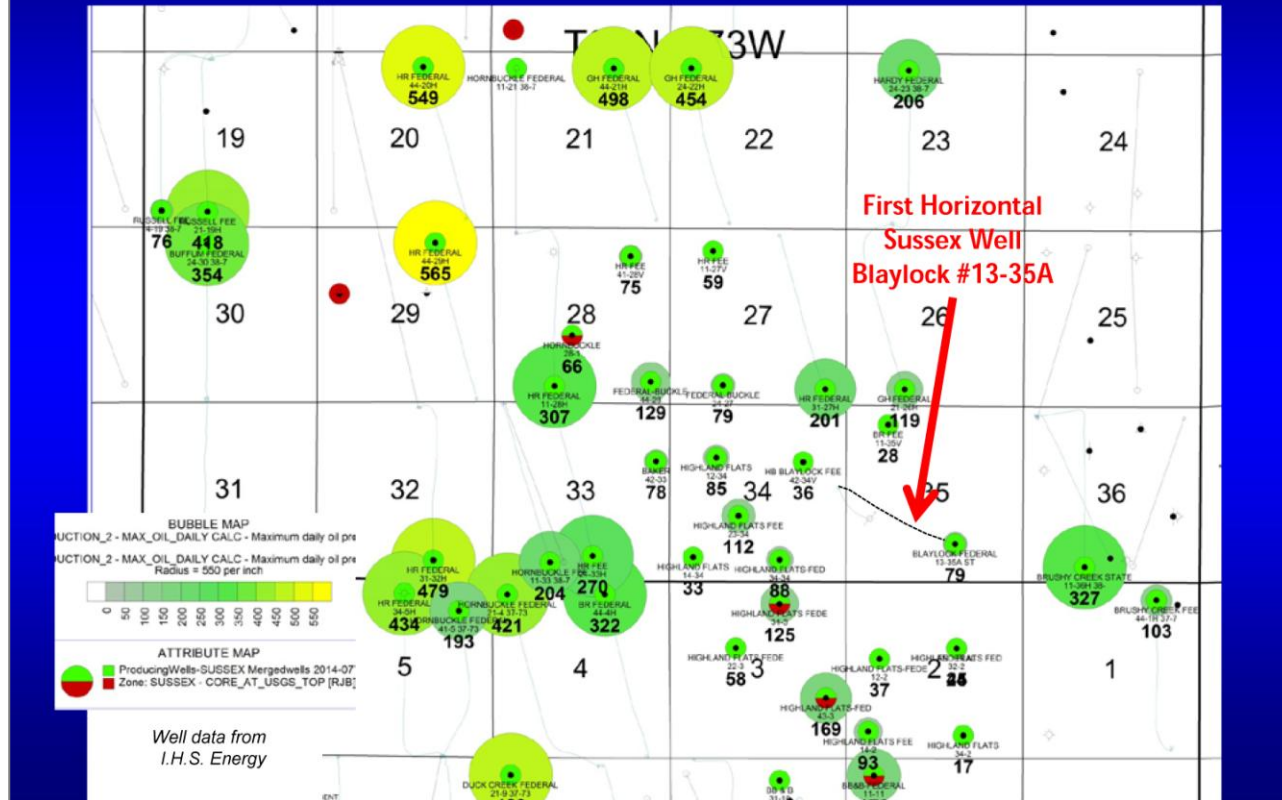
Presenter's notes: Core analysis Porosity vs. Permeability cross plot, with data points subdivided by facies. Cross-bedded sandstones are green squares, bioturbated sandstones are yellow circles, and bioturbated sandy mudstones are red circles. There are a few thin granule to pebble conglomerates located at the tops of HB-1 and HB-2 and they are shown with black diamonds. Porosity in the Sussex ranges from zero to 15% and permeability from .01 to 10 md, with a significant amount of reservoir storage in the laterally continuous bioturbated facies. Where present and porous, the best reservoir properties are in the cross-bedded sandstone facies, but we know that this facies is laterally discontinuous and is locally tightly cemented.



Presenter's notes: Spearhead Ranch Field Sussex Sandstone core photographed with ultraviolet light. Oil saturated intervals have a bright yellow fluorescence. Note that the lower cross-bedded sandstone (top of HB-2) at the right side of the photo is largely non-fluorescing due to calcite cement, but that the bioturbated sandstone facies has bright ultraviolet fluorescence indicating that it is the primary reservoir. Thanks to QEP Energy and Wexpro for permission to present these core photos.

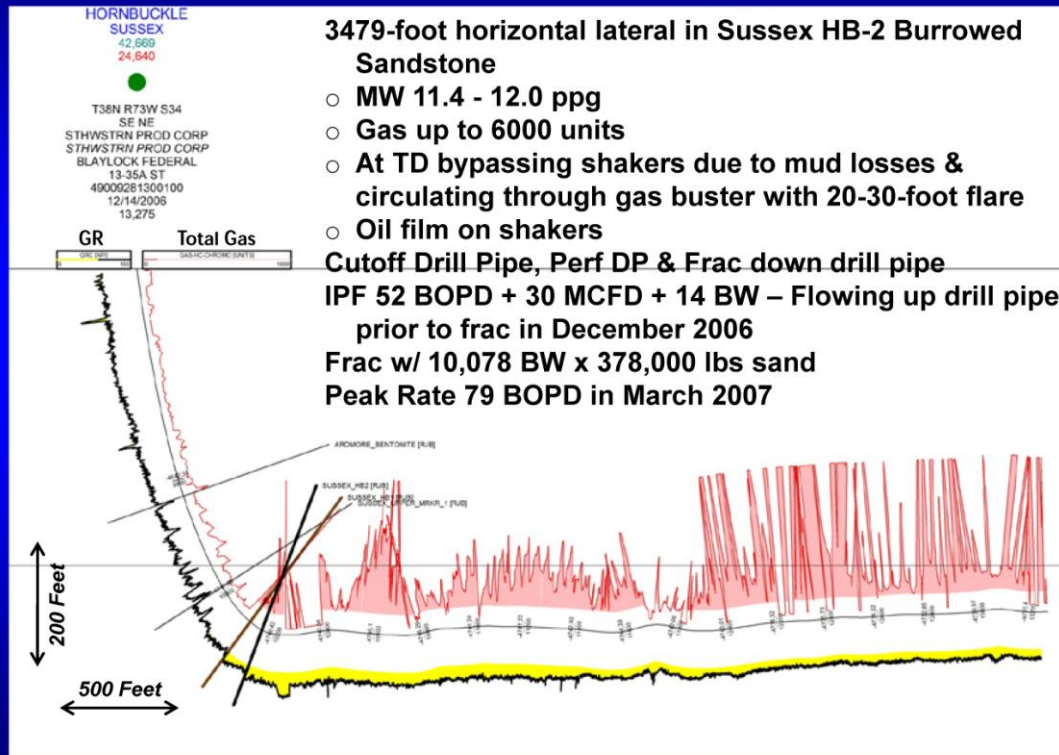
Hornbuckle Field First Horizontal Well 2006

Sussex Maximum Month Average Oil in BOPD



Presenter's notes: The recognition that much of the pay in the Sussex is in bioturbated facies, based on integration of core descriptions with engineering analyses, and that this facies is areally widespread led to the drilling of the first horizontal Sussex well in Converse County in 2006. This was the Blaylock #13-35A in section 35-T37N-R73W (surface location in section 34 due to difficulties obtaining a permit to build a location on US Forest Service surface land) as shown with the red arrow. The map shows Sussex oil producers with green circles and wells with cores with dark red circles. Bubble diameters are proportional to the peak 30-day average daily oil-producing rate; values posted are in BOPD.

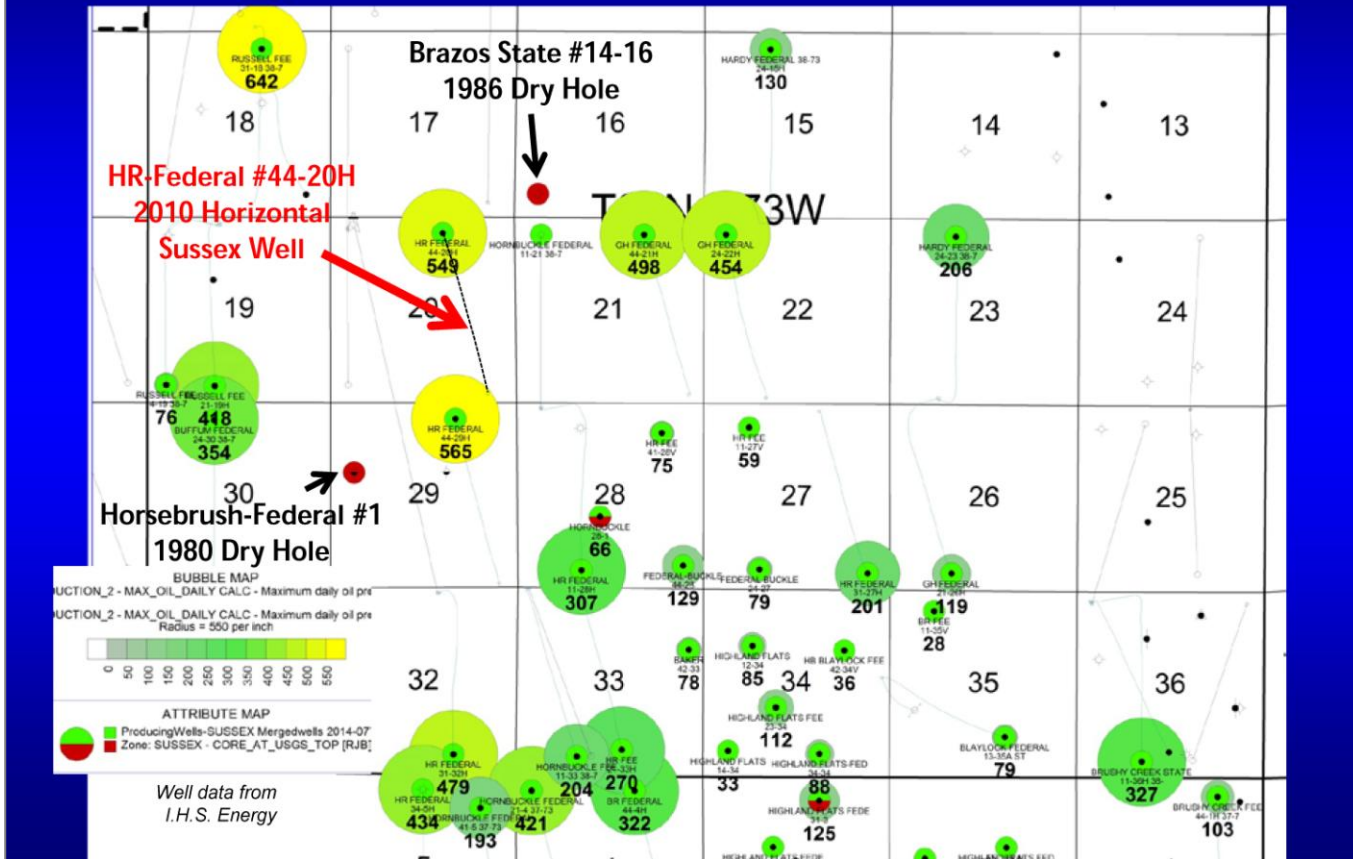
Hornbuckle Field First Horizontal Sussex Well - 2006



Presenter's notes: Cross-section showing the Blaylock #13-35A build and lateral, with gamma ray in track 1 and total gas in track 2. This well had excellent shows with up to 6,000 units of gas against a 12.0ppg mud weight and up to a 30-foot flare, but problems with overpressure required that the drill pipe be cemented in place. The well was fracture stimulated down perforated drill pipe, and the peak rate was only 79 BOPD. This well is best classified as a geological success. Most of the lateral was drilled in the HB-2 bioturbated sandstone facies. At one point near the middle of the lateral, we steered the well up into the cross-bedded sandstone facies and shows decreased significantly, indicating that the cross-bedded facies was tight, so the well was steered back down into the HB-2 bioturbated sandstone facies and drilled to TD.

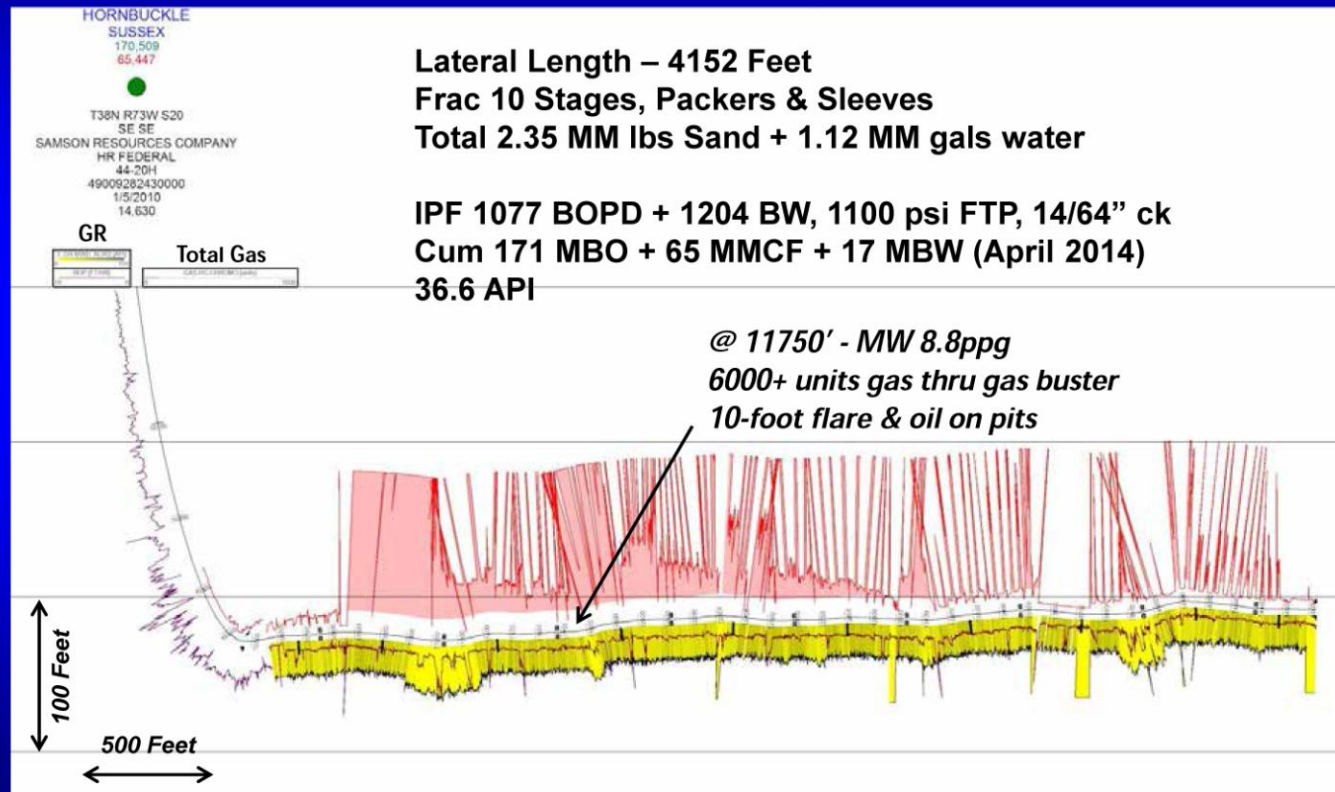
Recent Horizontal Drilling

Sussex Maximum Month Average Oil in BOPD



Presenter's notes: Recent horizontal wells have fared much better than the Blaylock, with peak 30-day rates in the 300 to 650 BOPD range. Note that the two dry holes shown on the earlier cross section are now offset by high-volume horizontal producers. An example of a 2010 horizontal Sussex well, the HR-Federal #44-20H, is highlighted with a red arrow and will be shown on the next slide.

Hornbuckle Field 2010 Horizontal Sussex Well HR-Federal #44-20H

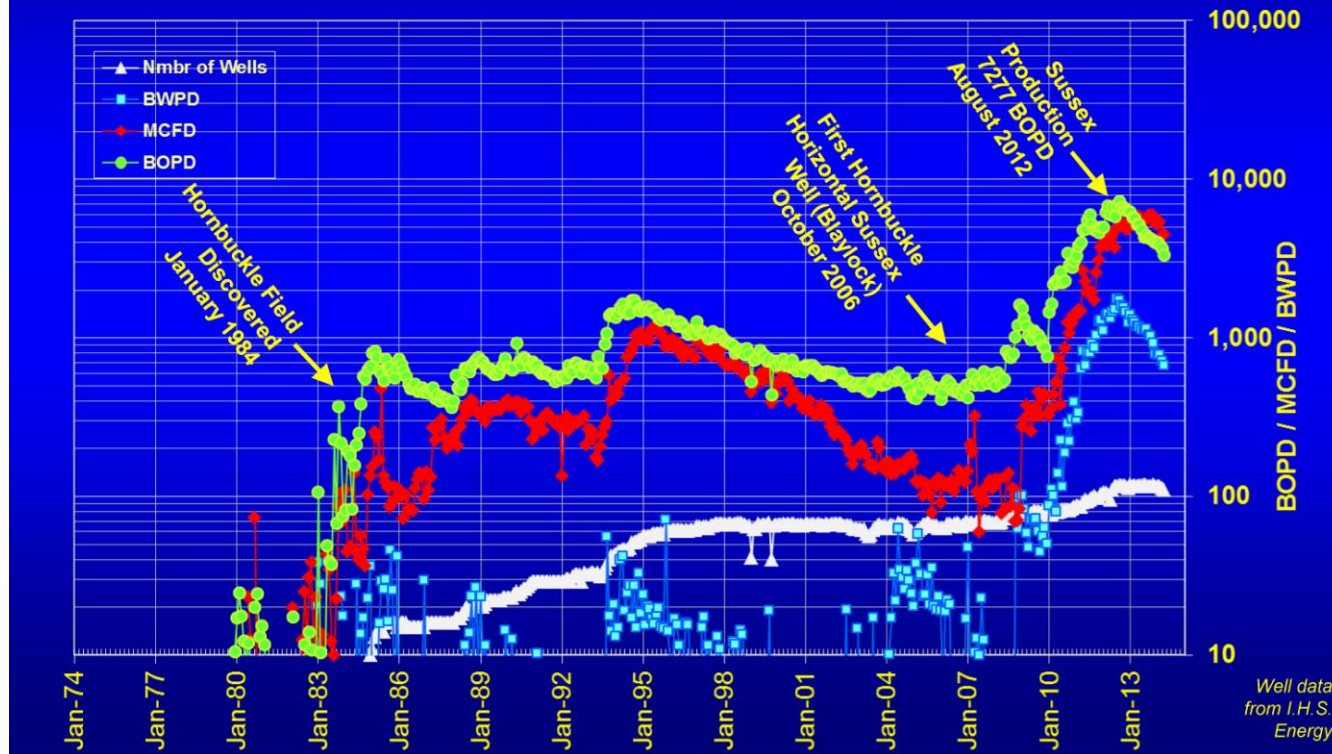


Presenter's notes: A 2010 horizontal Sussex well, the HR-Federal #44-20H. Based on gamma character, most of this lateral was drilled in the bioturbated sandstone facies with only small sections drilled in the cleaner-gamma cross-bedded sandstone facies. This well was completed with a 10-stage fracture stimulation and had a 24-hour IP of 1077 BOPD.

SUSSEX SANDSTONE PRODUCTION

HORNBUCKLE - SPEARHEAD RANCH TREND

Powder River Basin, Wyoming, 1974 - 2014



Presenter's notes: Total Sussex Sandstone oil production rate vs. time for the Hornbuckle-Spearhead trend in BOPD (green), MCFD (red), and BWPD (blue). Vertical development and step-out drilling ended in the mid-1990s and the field production declined to approximately 400 BOPD in 2006, when the first horizontal well (Blaylock #13-35A) was drilled. Subsequent horizontal drilling and completions have resulted in a rapid rise in oil and gas production to a peak of 7,277 BOPD in August 2012. Water production is largely load water.

CONCLUSIONS

- **Initial Hornbuckle-Spearhead Sussex Field Development with Vertical Wells Was Based on Distribution of High-Permeability Cross-Bedded Facies**
- **Significant Oil Pay in 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**

Presenter's notes: In conclusion, the Sussex Sandstone is an ideal candidate for horizontal drilling and multi-stage fracture stimulations. The burrowed and bioturbated nature of most of the oil-saturated sandstone reservoir results in relatively high porosity and oil-in-place volumes, but the low permeability of these lithofacies require horizontal drilling and multi-stage fracture stimulations for efficient recovery of the resource. The integration of geological and engineering analyses was key to recognizing this. Horizontal drilling and completion technology is allowing industry to develop a large oil resource along a regional oil-saturated sandstone trend by connecting previously isolated oil fields. In addition to development of oil and gas resources in the Sussex Sandstone with horizontal drilling and multi-stage fracture completions, the recognition of recoverable oil in bioturbated sandstone facies has led to exploitation of resources in other lithologically similar sandstones including the Turner, Shannon, Frontier, Gallup, and Codell.

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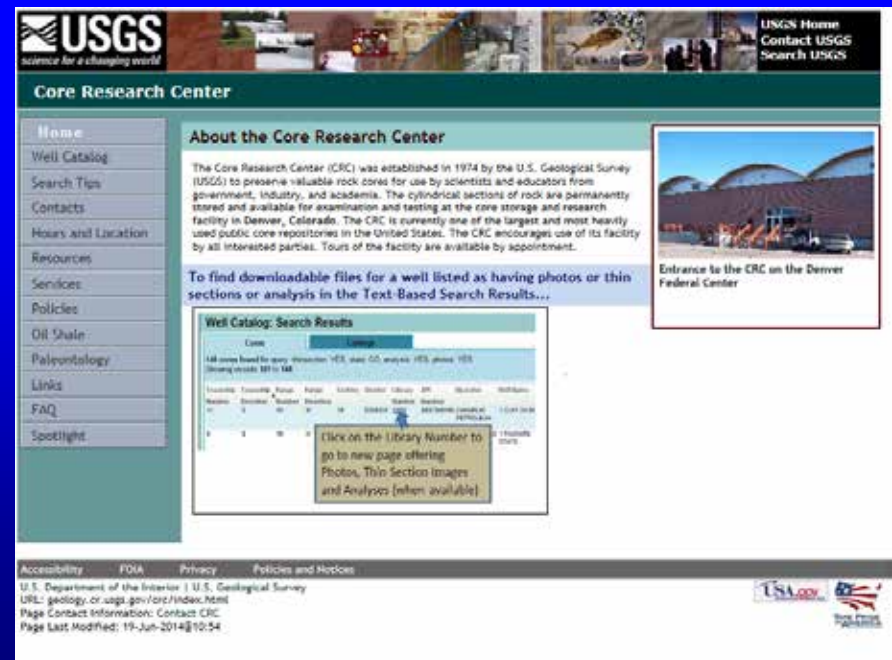
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Randi Martinsen

Jim Williams

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



Thank You



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

References

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Heasler, H.P., Ronald C. Surdham, and J. H. George, 1994, Pressure compartments in the Powder River Basin, Wyoming and Montana, as determined from drill-stem test data, in Ortoleva, Peter J., Basin compartments and seals: American Association of Petroleum Geologists Memoir #61, p. 235-262