Synopsis

Oil production in the Powder River Basin has increased from 49,000 BOPD in 2008 to more than 94,000 BOPD in April, 2014, largely due to the applications of horizontal drilling and multi-stage fracture stimulation technologies to low-permeability (“tight”) oil sandstone reservoirs. The primary tight oil sandstone horizontal drilling targets in the Powder River Basin include the Parkman, Sussex, Shannon, Turner, and Frontier Sandstones. Oil production in Laramie County, Wyoming, in the northern D-J Basin, has increased from 800 BOPD in October 2009, to 7100 BOPD in April, 2014, largely due to horizontal drilling in the Codell Sandstone, which is also a tight oil sandstone reservoir. These sandstones are characterized by permeabilities ranging from .001 to .1 millidarcies and have porosities ranging up to 18%.

Tight oil sandstone plays have developed where uneconomic vertical producers were drilled in the past and/or between existing vertical oil fields where locally developed or preserved 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 contain a high percentage of burrowed or bioturbated lithofacies. All of these tight oil sandstone plays are petrophysically challenging due to relatively high clay content, thinly interbedded sandstones and mudstones, and/or complex pore networks.
This workshop focused on Cretaceous sandstones in the Powder River and D-J Basins, including the Turner, Codell, Shannon, Sussex, and Parkman Sandstones. Cores from both the USGS and company collections were presented.

This course was of interest to geologists, engineers, petrophysicists, and geophysicists working on oil resource plays in sandstone reservoirs. This course was also of interest to wellsite geologists and geosteering professionals that desire a better understanding of reservoirs that are actively being exploited with horizontal drilling. Data and cores presented are specific to Rocky Mountain basins, but principles and conclusions are applicable to many other areas and plays.

**Selected References**


Presenter’s notes: Pres Thanks to the Rocky Mountain Section of the SEPM for sponsoring this core workshop and to Mary Carr with the PTTC for her organizational assistance and advice.
ACKNOWLEDGEMENTS

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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

Presenter’s notes: Much appreciation goes to co-authors, co-workers, and others that are and have worked on this core workshop.
AAPG ACE SC-17 Tight Oil Sandstones Core Workshop
June 4, 2015

OUTLINE

8:30 Introductions, Logistics, Safety, Overview
8:45 Tight Oil Sandstones Overview – Conference Room
9:00 Cretaceous Depositional Models Overview – Conference Room
9:15 Sussex & Shannon Sandstones Overview – Conference Room
Cores – Core Viewing Room
Review – Conference Room
10:35 Turner & Frontier Sandstones Overview – Conference Room
Cores – Core Viewing Room
Review – Conference Room
11:55 Lunch
Conference Room
CORES - ORGANIZATION

Conference Room

Main Entrance
TIGHT OIL SANDSTONE RESERVOIRS

• Conventional Exploration – Vertical Drilling
  o Oil Plays Required Good Porosity & Permeability for Economic Results
  o Low Permeability Led to Uneconomic Wells or Dry Holes

• Vertical Tight Gas Plays
  o Low-Permeability Sandstone Reservoirs (e.g., Jonah, Pinedale, Cotton Valley, Piceance, etc.)

• Horizontal Gas Shale Plays
  o Fine-Grained “Reservoirs”, Siliceous & Calcareous Mudstones

• Horizontal Shale Oil Plays
  o Apply Techniques Successful in Shale Gas to Oil Window Thermal Maturities
  o Best Performing Oil Wells Were Hybrid Reservoirs (e.g., Bakken)

• Horizontal Tight Oil Plays (Hybrid)
  o Low-Permeability Sandstones & Carbonates, Proximity to Oil-Prone Source Rocks (Necessary?)
What are they saying? CODELL SANDSTONE

EOG Resources Investor Presentation May 2014

EOG Resources
DJ Basin Horizontal Oil Plays

- 72,000 Net Acres in Sweet Spot
- Estimated Reserve Potential* 125 MMbce, Net to EOG
- Target Well Economics for 9,000' Lateral
  - 695 Mboe EUR/Well, Gross: 566 Mboe, NAR
  - 87.3 MM CWC and >100% Direct ATROR**
- Oil API = 3.6*
- 225 Net Drilling Locations
  - Plan to Drill 26 Net Wells in 2014, 4 Completed YTD
  - Current 1-Rig Program, Increasing to 2 in May
  - 1,300' Spacing
- Initial Well Results (IPs) – 9,000' Lateral

<table>
<thead>
<tr>
<th>Well</th>
<th>Bopd</th>
<th>90-Day Cum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jubilee 103-0433H</td>
<td>1,400</td>
<td>73 Mbo</td>
</tr>
<tr>
<td>Windy 504-1806H</td>
<td>1,400</td>
<td>-</td>
</tr>
<tr>
<td>Jubilee 513-0820H</td>
<td>1,325</td>
<td>-</td>
</tr>
<tr>
<td>Jubilee 584-1765H</td>
<td>1,180</td>
<td>-</td>
</tr>
<tr>
<td>Pole Creek 525-2413H</td>
<td>1,165</td>
<td>-</td>
</tr>
</tbody>
</table>

* Forecasted potential reserves, net proved reserves.
** For more information, seeslide.

EOG Resources Presentation

PDC Energy Presentation June 2014

Waste Management 16-Well Section – Online Fall 2013

PDC Energy Presentation June 2014

Bonanza Creek Investor Presentation January 2015

Contiguous Position Aids Full Development

- ~70,000 net acres in “Extension Area”
- Zero exposure to urban population
- Near established infrastructure
- Blocky acreage attractive for long laterals

Horizonal Codell: Establishing Consistency

- EUR Variability
- Type Well EUR (MMcfe)
- Type Well PV0.9 Value (MM)$
- Range of Type Well PV0.9 Value (MM)$ (Varying Performance from PV0 to PV1.5)$
What are they saying?  

**POWDER RIVER BASIN**

**EOG Resources Investor Presentation May 2014**

**EOG Resources**

**What’s New in 2014?**

1Q 2014
- Increased FY Oil Growth to 28%* and Total Company Growth to 12%*
- Delivered 42% YOY Total Company Oil Growth and 18.5% Overall Growth
- Grew Non-GAAP EPS 56%** and EBITDAX 30%** and Discretionary Cash Flow 28%**
- Net Debt-to-Total Cap Ratio 21% at March 31, 2014**

**Operations**
- Added 10 Years of High-Return Drilling Inventory in DJ and Powder River Basins

<table>
<thead>
<tr>
<th>Basin</th>
<th>Play</th>
<th>Net Acres</th>
<th>Net Locations</th>
<th>Net to EOG***</th>
<th>Crude Oil</th>
<th>API</th>
<th>Direct ATROR*</th>
</tr>
</thead>
<tbody>
<tr>
<td>DJ</td>
<td>Codell</td>
<td>73M</td>
<td>225</td>
<td>125</td>
<td>78%</td>
<td>36%</td>
<td>&gt;100%</td>
</tr>
<tr>
<td></td>
<td>Niobrara</td>
<td>50M</td>
<td>235</td>
<td>85</td>
<td>71%</td>
<td>35%</td>
<td>&gt;40%</td>
</tr>
<tr>
<td>Powder River</td>
<td>Parkman</td>
<td>30M</td>
<td>115</td>
<td>75</td>
<td>69%</td>
<td>41%</td>
<td>&gt;100%</td>
</tr>
<tr>
<td></td>
<td>Turner</td>
<td>63M</td>
<td>160</td>
<td>115</td>
<td>34%</td>
<td>44%=56%</td>
<td>&gt;100%</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>735</td>
<td>400</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Increased Eagle Ford Reserves*** by 45%
  - 2.2 BlnBoe to 3.2 BlnBoe, Net to EOG
- Increased Per Well EUR to 450 MBoe, NAR
- Added 2,300 High ROR Net Drilling Locations in Eagle Ford and Rockies in 2014.

*Based on midpoint of full year 2014 production estimates as of May 9, 2014.
**See reconciliation schedule. Certain metrics reflected are Adjusted.
***Adjusted production reserves, not proved reserves.

**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 4277-36-1F: 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.

**Chesapeake Analyst Day Presentation May 2014**

**POWDER RIVER BASIN**

**RECENT RESULTS**

- 1,740 boe/d
  - Avg. recent Niobrara peak rate (50% Oil)
- 2,025 boe/d
  - Avg. recent Sussex peak rate (50% Oil)
- 1,105 boe/d
  - Recent Parkman peak rate (65% Oil)

**Chesapeake Investor Presentation May 2015**

**POWDER RIVER**

**2015 STRATEGIC FOCUS**

- **1Q’15 operational updates**
  - One rig current through YE’15
  - One frac crew currently; limited crews remainder of year
  - Federal Units limit amount of activity need to hold acreage

- **Strategic priorities**
  - Primarily focused on Sussex
  - Niobrara resource expansion
  - Continuing to drive efficiencies
  - Huge resource potential via stacked plays

- **3,000+** Potential gross locations
- **> 2.0 billion boe** Gross recoverable resources

*Includes Tharp, Parkman, Sussex and Sussex
**Chesapeake included unpeeled lateral net and horizon core expansion. Frontier and Mirror"
What are they saying? SAN JUAN BASIN

Encana Investor Presentation June 2012

San Juan Basin Asset Overview

- 174,000 net acres in oil window
- PIP: 7.5 billion BOE
- Primarily light oil with associated NGLs
- 80% RI
- 905 net locations

Strategy

- Appraise oil window of the Gallup formation
- Establish RPH efficiencies
- Ramp up to commercial development pace

Current Activity/Future Plans

- ECA has 4 gross wells producing, 1 well drilling
- Industry has drilled 3 horizontal wells in gas window

RPH Target Well Parameters

- Well cost: $4.3 million
- EUR per well: 500 MBOE
- Lateral length: 5,000 feet
- TVD: 5,500 feet

WPX Energy Barclays Conference September 2013

Exploration Activities Result in San Juan Oil Discovery

Commencing commercial operations

2013 one rig program

- Plan to drill a total of 12-14 wells in 2013
- 4 exploratory wells drilled
  - Included science and testing in pilot holes
  - All four wells currently producing
- Next phase, 8-10 development wells
- 2013 expected exit rate of 3,400 Boepd
- Approximately 66 MMBoe of resource potential

$1,040 net acres in oil window

- 83.7% NRI
- Targeting additional acreage

Target metrics

- D&B < $5.0MM
- EUR's > 500 MBOE
- Lateral length: 5,000 feet

Encana Investor Presentation November 2013

San Juan Basin

First Mover in New Oil Play

Why We Like It

- Light, sweet of play discovered by Encana
- Capable of producing >50,000 bopd
- Dominant operator in the play
- Strong economics, ability to apply scale
- Consistent well performance at or above type curve
  - 30 day IP 400 - 500 bbls of oil per foot
  - Significant well cost reductions achieved from both execution and supply chain
  - High efficiency: 25 wells/year
  - Drill costs: $4 - $5 million
  - Recent drilling times 2x as fast as original wells
- 45% - 70% rate of return* in Resource Play Hub model

2014 Action

- Acceleration of commercial development program
- Capital: $300 - $400 million
- Rigs: 2 - 4

Rapidly growing oil production

WPX Energy Enercom Presentation August 2014

#1 Returns in the WPX Portfolio

Diversified product mix

Over 30 years’ experience
TIGHT OIL SANDSTONE RESERVOIRS
Cores & Plays on Display Today

• Powder River Basin
  o Sussex Sandstone – Compare Tight Oil Play vs Conventional Play
  o Shannon Sandstone
  o Turner Sandstone
  o Frontier (Wall Creek) Sandstone
  o Parkman Sandstone

• DJ Basin
  o Codell Sandstone

• San Juan Basin
  o Gallup Sandstone (Mancos vs. Tocito vs. Gallup vs. Niobrara)
TOTAL PRODUCTION
Powder River Basin, Wyoming, 1974 - 2014

Conventional Production & Waterfloods

Coal Bed Methane Drilling 1999-2001

First Hornbuckle Horizontal Sussex
Well (Blaylock) December 2006

189,857 BOPD May 1974
51,907 BOPD July 2004
52,232 BOPD January 2009
114,818 BOPD November 2014

Well & Production data from I.H.S. Energy
POWDER RIVER BASIN STRATIGRAPHIC CHART

Tight Oil Plays

- Sussex Sandstone
- Shannon Sandstone
- Niobrara “Shale”
- Turner Sandstone
- Mowry “Shale”
- Muddy Sandstone

After Heasler et al. (1994)
WORKSHOP CORES
Powder River Basin, Wyoming
Tight Oil Sandstone Wells Drilled After Jan. 1, 2006

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
TOTAL PRODUCTION
San Juan Basin, New Mexico and Colorado
1974 - 2015

Coal Bed Methane Drilling

Gas Production Curtailment – “Take or Pay”

“Peak Oil”
25,512 BOPD June 1986

Gavilan Mancos & Fractured Niobrara Play Development

18,438 BOPD Jan 1974

5,523 BOPD Jan 2010

21,827 BOPD Dec 2014

Well & Production data from I.H.S. Energy
SAN JUAN BASIN
GALLUP SANDSTONE
(a.k.a. Mancos)

2 CORES

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
Tight Oil vs Shale Oil vs Conventional Oil

Pore Throat Sizes & Permeability

Independent of Porosity

Figure 2. Sizes of molecules and pore throats in siliclastic rocks on a logarithmic scale covering seven orders of magnitude. Measurement methods are shown at the top of the graph, and scales used for solid particles are shown at the lower right. The symbols show pore-throat sizes for four sandstones, four tight sandstones, and five shales. Ranges of clay mineral spacings, diamonoids, and three oils, and molecular diameters of water, mercury, and three gases are also shown. The sources of data and measurement methods for each sample set are discussed in the text.
TIGHT OIL SANDSTONE RESERVOIRS
What Should I Look For?

- What do these plays have in common?
- Are they all really “tight”?
- Are there any differences between the plays and/or reservoirs?
- 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
TOTAL PRODUCTION
Powder River Basin, Wyoming, 1974 - 2014

Conventional Production & Waterfloods
Coal Bed Methane Drilling 1999-2001
First Hornbuckle Horizontal Sussex

Well (Blaylock) December 2006
114,518 BOPD
November 2014

52,232 BOPD January 2009
51,907 BOPD July 2004
189,857 BOPD May 1974

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

• Vertical Extensions
  - Considered Isolated Fields

• Modern Horizontal Drilling & Completions
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 basin axis. Total Sussex oil production is greater than 80 MMBO as of fall 2013.
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) are stratigraphically complex in this basin.
POWDER RIVER BASIN STRATIGRAPHIC CHART
Tight Oil Plays

- Parkman SS
- Sussex Sandstone
- Shannon Sandstone
- Niobrara “Shale”
- Turner Sandstone
- Mowry “Shale”
- Muddy Sandstone

After Heasler et al. (1994)
Powder River Basin Cretaceous Cross Section
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.
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
5 Cores @ Hornbuckle
2 Cores @ House Creek

SHANNON
2 Cores
Sussex Horizontal Wells Drilled Since January 1, 2006

Converse County Detail

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
Hornbuckle Field Area
Sussex Cores

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources

BOPD

Producing Formation Contains "SSSX"
Producing Formation Cores "SUSSEX"
SussexProducingWells 6/17 2015-03-17
Central House Creek Field
Core Wells Studied

Empire Federal C #1
Mandell Federal #1

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
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 Drilled Since January 1, 2006

Johnson-Campbell County Detail

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
SHANNON SANDSTONE

PINE TREE UNIT AREA, Campbell Co.

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

- Resistivity 10-50 ohms
- Porosity 4-12%
- Vertical Well Cum
  83 MBO + 103 MMCF + 3 MBW

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

- Vertical Well Cum
  100 MBO + 128 MMCF + 3 MBW
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?
- Depositional Environments – Origin of Sandstones?
- Burrow 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?
SUSSEX CORES

Break to Look at Cores

- Start at D915 Highland Flats Federal #13-11
SUSSEX SANDSTONE
Conclusions – Where is the Oil?

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

Empire Federal C #1

Mandell Federal #1
- Depth 8000-8300, normally pressured
- High Porosity 12-18%
- 2.68 gm/cc matrix underestimates core porosity
Woods Petroleum
Empire Federal C #1
SW-NW-29-T45N-R73W
Comp. 3-8-72
CUM = 447 MBO

House Creek Field
High-Energy Cross-Bedded to Horizontally-Bedded Sandstone
8,013-8,014

Sussex Mrkr
RCA @ 8,013
Phi 16.7%,
k 16.7md,
So 16.7%

Depth Shift Log = Core

GR - SP
RES
FDC-CNL

50 Feet
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

50 Feet

High-Energy Cross-Bedded Sandstone
8,167 (8,175 Log)

GR - SP  RES  FDC-CNL

Sussex Mrkr

SUSSEX

STEELE

Sussex Mrkr

RCA @ 8,167
Phi 18.1%,
k 16.0md,
So 6.1%

Depth Shift Log = Core + 8

50 Feet

Dry
**House Creek Field**

**Core Porosity vs Permeability**

- **House Creek Waterflood Feasibility Study - 1986**
  - Depth 8200 ft.
  - Avg. Phi 12%
  - Avg. Perm. 13.6 md
  - Normal Pressure ~ 0.4 psi/ft.

**Facies**
- Cross-Bedded Sandstone = Main Pay
- Interbedded Sandstone & Shale = Marginal Pay
- Bioturbated Sandstone = Not Pay (Conventional)
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
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.
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.
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, 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 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 .07md 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 0.93 md, 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 0.01 md permeability. This facies is the main pay at House Creek where it commonly has porosity greater than 15%. At Hornbuckle this facies ranges from 0 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: 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.
House Creek
- Unfilled Symbols
- Cross-Bedded Sandstone
  Permeability 3-100 md.
- Waterflood

Hornbuckle
- Color-filled Symbols
- “Tight Oil”

Cross Bedded Sandstone
- 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

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

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.
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.
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.
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 7277 BOPD in August 2012. Water production is largely load water.
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?
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

Stright, et al., 2014 (SPE # 169095)
Hornbuckle Field
Southwestern Prod. Corp.
Blaylock Fee #42-34V
NE-34-38N-73W
Spud 9-11-2007

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

Sonic Scanner
Fast Shear Azimuth
Maximum Stress 60°
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

543 Feet Apart at Closest Point

HR-Fed #11-28H
First Oil May 2011
307 BOPD

Hornbuckle #28-1
First Oil Feb 1984
66 BOPD

Well & Production data from I.H.S. Energy
HR-Fed #11-28H Horizontal Competes for Oil with Existing Hornbuckle #28-1 Vertical Well

Hornbuckle #28-1 (vertical)
First Oil Feb 1984
66 BOPD

HR-Fed #11-28H
First Oil May 2011
307 BOPD

Cum 79,174 BO
May 2011

Well & Production data from I.H.S. Energy
Hornbuckle Field 2011 Horizontal Sussex Well
HR-Federal #11-28H

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

Cross-Bedded Facies (Cleaner GR) with 12% Porosity at Top & 0% Porosity at Base

Sleeves (Perfs)

Majority of Lateral in HB-2 Burrowed Facies
Cross-Bedded Facies with 12% Porosity at Top & 0% Porosity at Base
HR-Fed #11-28H
First Oil May 2011
307 BOPD

Hornbuckle #28-1
First Oil Feb 1984
66 BOPD

HR-Fed #44-29H
First Oil Dec 2008
565 BOPD

1980 Dry Hole
w/ Core

1977 Dry Hole

1977 Dry Hole

Productive Limits Based on Vertical Drilling

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

Variable Porosity Along Lateral
Especially in Cross-Bedded Facies

Clean GR Cross Bedded Facies
Low Phi 0% to High Phi 12%
Hornbuckle Field 2011 Horizontal Sussex Well
HR-Federal #11-28H

Reservoir Compartments within Cross-Bedded Facies
Some have High Porosity 8-12% & Permeability .2-5md, Some < 2% <.0001md

Majority of Lateral in HB-2 Burrowed Facies
Architectural Elements – Frontier Sandstone, Raptor Ridge, Natrona County, Wyoming

Northwest

Southeast

Gani and Bhattacharya (2007), JSR v77, P284-302
HORNBUCKLE FIELD
LL & E
Highland Flats Federal #13-11
NW-SW-11-T37N-R73W

GR - SP
RES – Core So
FDC-CNL-Core Phi

Sussex Marker

HB-1

HB-2

Permeability Barriers

Burrowed Sandstone
Burrowed Sandstone
Cross-Bedded Sandstone

Burrowed Sandstone
Burrowed Sandy Mudstone

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

Highland Flats-Fed #11-11
NW-11-T37N-R73W
Cum 158 MBO

Highland Flats-Fed #31-3
NE-3-T37N-R73W
Cum 140 MBO

State #31-14
NE-14-T37N-R73W
Cum 134 MBO

State #41-23
NE-23-T37N-R73W
Cum 75 MBO

84,000 # Prop
Avg Rate 12 BPM
Frac 97’ Above Top Perf
Frac 38’ Below Bot. Perf
14’ SS Phi>8%

145,000 # Prop
Avg Rate 15 BPM
Frac 133’ Above Top Perf
Frac n/a Below Bot. Perf
26’ SS Phi>8%

180,000 # Prop
Avg Rate 15 BPM
Frac 162’ Above Top Perf
Frac 25’ Below Bot. Perf
9’ SS Phi>8%

63,000 # Prop
Avg Rate n/a BPM
Frac 39’ Above Top Perf
Frac n/a Below Bot. Perf
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?
CONCLUSIONS

Shallow Marine Environment of Deposition

Ongoing vigorous debate on origin

- “Offshore Bars” or Shelf Sandstones
- Lowstand Incised Shorefaces
- Erosional remnants of Incised Valleys filled with estuarine/tidal sand bodies

Sussex Sandstones in one place are not necessarily the same as Sussex Sandstones in another place (i.e. Hornbuckle ≠ House Creek ≠ Outcrop)

Tidal Currents?

Progradational, Downward Stepping to Northeast
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 Stimulation.

• 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 & Completions
TURNER & FRONTIER SANDSTONES,
POWDER RIVER BASIN
TURNER & FRONTIER SANDSTONES, POWDER RIVER BASIN

Frontier
3 Frontier (Wall Creek) Sandstone Cores

Turner
5 Turner Sandstone Cores

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
TURNER SANDSTONE

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

5 Turner Sandstone Cores

Higher GOR Area

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
FRONTIER SANDSTONE

E126
USA-Federal #9-1
Finley Draw Field Vertical Dry Hole
Same Section has 906 BOPD IP
Horizontal Producer

D281
Henry-Federal #31-9
Phillips Creek Field
Vertical Producer
206 MBO + 686 MMCF

E123
Federal USA #27-1
Finley Draw Field
Vertical Producer
265 MBO + 2433 MMCF

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
TURNER & FRONTIER SANDSTONES, POWDER RIVER BASIN

Gus Gustason
LUNCH BREAK

Jason’s Deli
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
GALLUP SANDSTONE
(Mancos, Niobrara, ?)
SAN JUAN BASIN
GALLUP SANDSTONE, SAN JUAN BASIN

Gallup vs. Tocito Sandstone vs. Niobrara vs. Mancos

- Asymmetric Laramide Basin
- Predominantly Gas, “Basin-Centered”, Cum 230 MMBO + 48.2 TCFG
- Liquids Production From Late Turonian to Coniacian Strata (Niobrara)
- New “Mancos” Play
- 2 Cores From Active Drilling Area

BOEPD

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
CONIACIAN PALEOGEOGRAPHY, WESTERN USA

NMOCDEFINITION
“GALLUP PRODUCING INTERVAL”: All Producing Reservoirs Below the Point Lookout Sandstone and Above The Greenhorn Limestone

After Nummedal and Molenaar (1995)
GALLUP SANDSTONE, SAN JUAN BASIN
Gallup vs. Tocito Sandstone vs. Niobrara vs. Mancos

"Mulatto Tongue" = Niobrara Transgression

NMOCD DEFINITION
"GALLUP PRODUCING INTERVAL"


Fig. 3--Stratigraphic cross section of the Upper Cretaceous strata from the western margin of the San Juan basin (modified from Molenaar, 1973, 1983a, b)
GALLUP CORE LOCATIONS & NEARBY PRODUCERS

BOE in Avg. Daily Rate BOEPD; Completions Since Jan. 1, 2006

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
**B996 (#25-5)**

**Depth Shift**

- Core 1 +4
- Core 2 + 8
- Core 3 +12

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**B740 (#25-1)**

**Depth Shift**

- Core 1 -20 to -16
- Cores 2-3-4 -24 to -20

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**Upper Mancos**

- Gallup Producing Interval (NMOCD)
- "El Vado" Sandstone
- Niobrara
- Tocito Sandstone
- Gallup Sandstone
GALLUP CORES
What Should I Look For?

- Sedimentary Structures & Facies – What Lithologies Have Porosity?
- Is the best pay in the Gallup, Tocito, Niobrara, Mancos, or what?
- WHAT WOULD BE THE MAIN HORIZONTAL TARGET RESERVOIR?
- Burrow Types & Diversity? (ichnofacies)
- Key Surfaces – Erosion? TSE? LSE? Where is the Basal Niobrara Unconformity?
GALLUP CORES
Break to Look at Cores
GALLUP SANDSTONE
Conclusions

• Where is the Oil?
• What is the best Horizontal Drilling Target?
• What Controls the Location of the Better Wells?
GALLUP CORE LOCATIONS & NEARBY PRODUCERS
Max Month BOE in Avg. Daily Rate, BOEPD; Completions Since Jan. 1, 2006

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
Core 1

Cores 2-3-4

Tocito Sandstone

Gallup Sandstone

"El Vado" Sandstone

Niobrara

Upper Mancos

Gallup Producing Interval (NMOCD)

Core 1 Core 3 Core 2

B740 (#25-1)

Depth Shift
Core 1 -20 to -16
Cores 2-3-4 -24 to -20

B996 (#25-5)

Depth Shift
Core 1 +4
Core 2 + 8
Core 3 +12

Depth Shift
Core 1 -20 to -16 Cores 2-3-4 -24 to -20
El Vado Sandstone (a.k.a. Niobrara B)

B740 (#25-1)

“El Vado” Sandstone

Tocito Sandstone

Gallup Sandstone
Tocito Sandstone (a.k.a. Basal Niobrara)

B740 (#25-1)
Gallup Sandstone

B740 (#25-1)

“El Vado” Sandstone

Tocito Sandstone

Gallup Sandstone
Gallup Sandstone – Alternating Sandier Oil-Stained and Muddier, Bioturbated Sandstones
BIOTURBATED GALLUP = MAIN PAY

Tocito Sandstone

Gallup Sandstone

“El Vado” Sandstone

Upper Mancos

Niobrara

Gallup Producing Interval (NMOCD)

B996 (#25-5)

PERFS

GR-SP Res-Cond GR Res-FDC-CNL Post-Frac Temperature Log

Little or No Flow

Minor Flow

Primary Fluid Flow
CORED WELLS IN REGIONAL SW-NE CROSS SECTION

Regional Erosion
Below Basal Niobrara Unconformity

Maximum Rate of Truncation ~ 5 Miles Wide
Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
CORED WELLS IN REGIONAL SW-NE CROSS SECTION

B996    B740
(#25-5) (#25-1)

Regional Erosion Below Basal Niobrara Unconformity

Gallup Sandstone

Niobrara

Juana Lopez

Tocito 1-2-3

Maximum Rate of Truncation ~ 5 Miles Wide

Modified from Bottjer and Stein (1994)
Gallup – Tocito Sandstones Relationships
Based on Outcrops, Northwestern San Juan Basin

Gallup – Tocito-Niobrara Stratigraphic Relationships
Well Log Correlations & Micropaleontology

Modified from Bottjer and Stein (1994)
Northernmost Outcrop at San Juan River

GALLUP SANDSTONE EXTENTS
From New Mexico State Surface Geological Map

Northeastern Extent of Gallup Sandstone Shoreface

New Mexico State Surface Geological Map
https://geoinfo.nmt.edu/publications/maps/geologic/state/home.cfm
Gallup Sandstone Progradational Limits
Based on Surface Geology
State Geological Map
Gallup Completions Since 1-1-2006 Max Oil Month Avg. Daily Rates in BOEPD

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
Gallup Sandstone Progradational Limits & Niobrara Thermal Maturity (%Ro) Based on Surface Geology State Geological Map

Gallup Completions Since 1-1-2006 Max Oil Month Avg. Daily Rates in BOEPD

After Rice (1983)

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
GALLUP SANDSTONE CONCLUSIONS

- Niobrara-Gallup Unconformity was Cored in B740 (#25-1) at 5517.2 ft (core depth)
- Most Oil Saturated Sandstones are in Tocito SS or Gallup SS zones
- Tocito SS is Thin, Laterally Discontinuous – Good Reservoir for Vertical Completions When Developed, not so great for Horizontal Drilling
- Gallup SS Dominated by Burrowed to Bioturbated Facies (this area!), Commonly Oil Stained
- Best Wells are Being Drilled where Niobrara Source Rocks are in Oil Window %Ro > 0.65, but South of Angular Truncation of Gallup Sandstone
- High-Quality Reservoirs in Upper Gallup Shorface – Permeability too Good, Oil Leaked Updip to South
PARKMAN SANDSTONE
POWDER RIVER BASIN
PARKMAN SANDSTONE, POWDER RIVER BASIN

Two Plays (more?), One Formation Name

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

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
Cretaceous Interior Seaway
75 MA

Ron Blakey

After Wheeler (2010)
Parkman Paleogeography

RMAG, “the Big Red Book”

After Wheeler (2010)
Upper Cretaceous Regional Stratigraphy

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

After Wheeler (2010)
PARKMAN SANDSTONE PLAY

- Northern Cores

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
E959 (Gilbertz Fed. #12-30)  C936 (Durham-Federal #32-1)

Note Core Perm Scale Change to .01-100 md

Main Parkman

Pierre/Lewis

Lower Parkman "A"

Lower Parkman "B"

Steele

Pierre/Lewis

Parkman

Steele

Note Core 2 Cut 60' Rec. 16'

Depths on Core DO NOT Match PxP Depths

Bottom of Log Run 1 / Top Run 2

Note: Core Perm Scale Change to .01-100 md
PARKMAN SANDSTONE PLAY

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

BOPD

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
F014 (Highland Flats Fed. #43-3)
R694 (Coneflower #1)
Vertical Parkman Producer

Core Perm. 100 - .01 md
Cum 105 MBO + 73 MMCF + 63 MBW

Resistivity Barely Reaching 20 ohms
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?
PARKMAN CORES
Break to Look at Cores

- Start at F014 Highland Flats Federal #43-3
- Gus – E959 Gilbertz Federal #12-30
- Compare with Eastern Cores R694 & C936
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, Savageeton Field Discovery
“SMOKING GUN” Well

Davis Oil Zicari State #1

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
Savageton Field Discovery

“SMOKING GUN” Well

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

NO FREE WATER!

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

E959
LL&E
Gilbertz-Federal #12-30
SW-NW-30-T45N-R74W
Comp. 2-13-81

Davis Oil
Zicari State #1
NW-NE-16-T45N-R74W
Comp. 10-19-78

Pierre/Lewis
Main Parkman
Lower Parkman “A”
Lower Parkman “B”
Steele

Core Perm. 100 - .01 md
Core So 0 – 100%

H₂O
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

After Wheeler (2010)
Core Photos

After Wheeler (2010)

Bright UV Fluorescence & Oil Stain in Laminated Facies

Calcite Cement
Parkman Stacking Pattern
Migration and Trapping

East Flank PRB Schematic Structure; SW Dip

Oil Generation and Migration

Van Wagoner, 1990, Siliciclastic sequence stratigraphy

After Wheeler (2010)
Savageton Field

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

Net (>10%) SS Isopach & Structure

Shoreface Thick

After Wheeler (2010)
PARKMAN SANDSTONE

Savagetton Field (Gilbertz #12-30 E959)

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

WHAT ABOUT THE “NEW” EASTERN PARKMAN PLAY?
PARKMAN SANDSTONE PLAY

- 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

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
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)

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

WHAT ABOUT THE “NEW” EASTERN PARKMAN PLAY?

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!

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
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 Crossover 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
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
F014 (Highland Flats Fed. #43-3)  
R694 (Coneflower #1)  
E959 (Gilbertz Fed. #12-30)  
C936 (Durham-Federal #32-1)
Parkman Sandstone Stratigraphic Cross-Section
Southern Cores

F014 (Highland Flats Fed. #43-3)
R694 (Coneflower #1)

Updip / Eastward Pinchout of Parkman Shoreface Facies
Parkman Sandstone Stratigraphic Cross-Section
Northern Cores

E959 (Gilbertz-Fed. #12-30)

C936 (Durham-Fed #32-1)

Updip / Eastward Pinchout of Parkman Shoreface Facies
PARKMAN SANDSTONE PLAY

- Regional Updip Pinchout of Parkman Sandstone
- Multiple Sandstone Pinchouts – Complex System of Traps
- Short Distance Facies Change from Clean Upper Shoreface to “Lam-Scram” Lower Shoreface
- Oil Saturation in High-Porosity, Higher Permeability Laminated Beds
- Burrowed Facies has No to Low So%  
- Migrated Oil?

IS THE PARKMAN A “TIGHT” OIL RESERVOIR?
Codell Sandstone

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

Modified from Noble Energy

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
POWDER RIVER BASIN
TIGHT OIL

Wells Drilled After 1-1-06

Max Oil Month
Avg. Daily Rate
- Parkman
- Sussex
- Shannon
- Turner
- Frontier

BOPD

Well & Production data from IHS Energy, USGS CRC, and Proprietary Sources
GALLUP SANDSTONE, SAN JUAN BASIN

Gallup Sandstone Pinchout

- 2 Cores From Active Drilling Area
- Bioturbated Sandstones Below Basal Niobrara Unconformity are Main Pay
- Stratigraphic Component to Trap
- Updip Water in Cleaner Shoreface Sandstone Facies

Well & Production data from I.H.S. Energy, USGS CRC, and Proprietary Sources
Sussex Core Porosity vs Permeability

House Creek
- Unfilled Symbols
- Cross-Bedded Sandstone
- Permeability 3-100 md.
- Waterflood

Hornbuckle
- Color-filled Symbols
- “Tight Oil”

Cross Bedded Sandstone
- Phi 3-14%, Avg 8.8%
- k 0.01-4.0 md, Avg 0.63md

Bioturbated Sandstone
- Phi 1-14%, Avg 7.1%
- k 0.01-.60 md, Avg 0.12md

Conclusion
- Sussex Sandstone @ Hornbuckle is Different than Sussex Sandstone @ House Creek
Parkman Core Porosity vs Permeability

Permeability (md)

Porosity (Percent)
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
Pore Throat Sizes from Mercury Injection-Capillary Pressure Data – Multiple Reservoirs

- Conventional SS
- Tight SS
- Parkman
- Sussex Cross-Bedded
- Sussex Bioturbated
- Codell Laminated
- Codell Bioturbated
Pore Throat Sizes from Mercury Injection-Capillary Pressure Data – Multiple Reservoirs
TIGHT OIL SANDSTONE PLAYS
COMMON ATTRIBUTES

• Marginal or Uneconomic Vertical Producers
• Muddy Sandstones & Siltstones – Low Resistivity Pay
• Some are Thinly Bedded, Others have Few Mudstone Interbeds
• Significant Oil Pay in Exists in Bioturbated Facies – Moderate Porosity & Low Permeability
• Some are “Hybrid” Tight Oil Reservoirs, with Contribution From Locally Developed High Permeability Reservoirs
• Larger Areal Extent than Typical “Stratigraphic” Traps (e.g. Tocito “Bars” vs Gallup; Sussex “Bars” vs Horizontal Play)
• All of these 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

• Exploitation Has Led to > 60,000 BOPD of New Production in the Powder River Basin
  • DJ Basin Codell (others?)
  • 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
Thank You

Presenter’s notes: View to the north of the Blaylock #13-35A during drilling operations in 2006. Thank you for your attention.