LITHOLOGY, MINERALOGY AND MATURITY
10.10 Exploring The Lithological Differences Between The Bakken And Other Resource Plays To Understand The True Source Of Its Productiveness

WhitMar Exploration Company

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BAKKEN TIGHT OIL CONGRESS
LITHOLOGY, MINERALOGY AND MATURITY
10.10 Exploring The Lithological Differences Between The Bakken And Other Resource Plays To Understand The True Source Of Its Productiveness

• Assessing petroleum system considerations: maturity, expulsion, fracturing, and migration and how they relate to Bakken/Three Forks sub-plays

• Examining facies, fracturing, and completions and how they affect productivity

• Understanding Bakken productivity relative to thermal maturity and implications for assessing other resource plays

• Using understanding of the Bakken to discover other resource plays with similar characteristics and production potential

• Comparing the Bakken and the Des Moines of the Lusk Embayment
Assessing petroleum system considerations: MATURITY & EXPULSION

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Nordeng, 2009 Modified from Meissner, 1978

Pore Fluid
Pressurization by Maturation of Kerogen

Kerogen → Oil
Solid → Fluid

1) Generated oil displaces pore water.
2) Oil generated at the expense of load bearing kerogen.
3) Water displacement and reduced porosity caused by shale compaction increase pore fluid pressure when confined in low permeability rocks.

“IMMATURE”
WATER-SATURATED PORES, LOW-RESISTIVITY, NORMAL FLUID PRESSURE.

“EARLY MATURE”
OIL-WET MATRIX, CONTINUOUS-PHASE OIL AND WATER-SATURATION; WATER EXPLOSION.
MODERATELY-HIGH RESISTIVITY
NO COMPACTION
HIGH FLUID-PRESSURE

“MATURE”
HIGH CONTINUOUS-PHASE OIL-SATURATION AND EXPLOSION, LOW DISCONTINUOUS WATER-SATURATION.
VERY HIGH RESISTIVITY
SOME COMPACTION
HIGH FLUID-PRESSURE

LEGEND

MATRIX
KEROGEN
NON-ORGANIC
PORE FLUID
WATER
OIL

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Nordeng, 2009 Modified from Meissner, 1978
Assessing petroleum system considerations: EXPULSION

Chromatographic analysis of whole oil samples provides a “fingerprint” of hydrocarbons from C1 to C44, when present. An oil fingerprint is a histogram of the yield and distribution of resolvable compounds present in an oil. Quantitative results from these analyses were used to characterize and type these oils, infer source rock characteristics, determine thermal maturity, assess mixing or commingling of production, and predict oil expulsion temperatures.

Madison oils are distinct from Bakken oils indicative of different sources. This is based on 6-ring preference in the C7 hydrocarbons shown by Madison oils which is evident in Madison source rocks as well as biomarker data, the latter of which demonstrates that Madison Group oils are derived from carbonate or marly shale source rocks. *Lodgepole mound, Bakken, and most of the Nisku oils studied are Bakken-sourced oils with the Lodgepole oils being lower maturity oils than typical Bakken-produced oils.*

Spatial variation of Bakken or Lodgepole oils in the Canadian Williston Basin Zhuoheng Chen, Kirk G. Osadetz, Chunqing Jiang, and Maowen Li

AAPG Bulletin, v. 93, no. 6 (June 2009), pp. 829–851
Map showing organic matter percentage conversion (transformation ratio or “TR”) to hydrocarbons. While there is good Bakken/Three Forks production in the highly mature core areas (TR>60), there is also good production in areas of low TR.

TR = S1/S1+S2
TR is not a measurement of generated hydrocarbons.
Assessing petroleum system considerations: MATURITY & EXPULSION

HI = \([100 \times S_2]/TOC\)


By U.S. Geological Survey Williston Basin Province Assessment Team

By U.S. Geological Survey Williston Basin Province Assessment Team
Empirical evidence for large magnitude postglacial warming

- Heat flow in southern hemisphere shields averages approximately 61.4 mWm\(^{-2}\), but heat flow in northern hemisphere shields averages 37 mWm\(^{-2}\).
- Brazil 64.8 ± ? mW m\(^{-2}\) (86)
- Africa 52.3 ± ? mW m\(^{-2}\) (145)
- Australia 68.1 ± ? mW m\(^{-2}\) (157)
- N. America 33.1 ± ? mW m\(^{-2}\) (315)
- Fennoscandia and East European Craton 35 - 40 mW m\(^{-2}\) (1,352)

Kinetic Parameters for some Type II Source Rocks

<table>
<thead>
<tr>
<th>Source Rock</th>
<th>E (kJ mol⁻¹)</th>
<th>A (s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bakken Shale¹</td>
<td>226.1</td>
<td>4.750 x10¹³</td>
</tr>
<tr>
<td>Monterey Shale²</td>
<td>143.4</td>
<td>2,224 x10⁷</td>
</tr>
<tr>
<td>Phosphoria Shale²</td>
<td>178.7</td>
<td>1.388 x10¹⁰</td>
</tr>
<tr>
<td>Alum Shale²</td>
<td>201.3</td>
<td>4.899 x10¹¹</td>
</tr>
<tr>
<td>Woodford Shale²</td>
<td>218.3</td>
<td>1.792 x10¹³</td>
</tr>
</tbody>
</table>


Note various curve shapes; a function of mix of kerogens.

Note low Ea associated with higher sulfur OM.

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Assessing petroleum system considerations: MATURITY, EXPULSION, MIGRATION

Figure 11—Patterns of transformation ratio (TR) at the present, calculated using the geographically variable, time-invariant thermal history and distribution of oil saturations if (a) only Bakken and Ordovician sources are considered and (b) Winnipegosis and Lodgepole sources are considered. The elevation of isomaturity contours varies by 1000 m from the region of enhanced heat flow and hydrocarbon generation beneath the Ness Formation anticline. Model oil saturations are calculated once thermal history, source rock kinetic parameters, and permeability structure were determined. These saturations can be compared to the known pattern of hydrocarbon accumulation in the basin (Figure 3). Saturations between 0.02 and 0.05 represent the drainage system; saturations above 0.1 represent oil accumulation or depleted source rocks. Arrows = active oil migration (Darcy velocities). The thickness of Bakken and Winnipegosis strata has been exaggerated to improve clarity.

A Two-Dimensional Regional Basin Model of Williston Basin Hydrocarbon Systems
Jean Burrus,2 Kirk Osadetz,3 Sylvie Wolf,2 Brigitte Doligez,2 Kees Visser,4 and David Dearborn4
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DIVIDE CO WELL

MIDDLE BAKKEN

THREE FORKS

6.0 MMBO/mi²
Sw 50%+

20.5 MMBO/mi²
Sw 50%+

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Assessing petroleum system considerations: MATURITY

Figure 10. Log resistivity (in ohm-m) of upper shale member, Bakken Formation. Modified from Hester and Schmoker (1985). Area of abnormally high formation pressure (bold dashed line) approximated from Meissner (1984). Resistivity >100 ohm-m indicated by dark-shaded area; resistivity transition zone in lighter shaded areas between 25- and 100-ohm-m contours.
McKenzie County (475 wells)

1.41 Mcf/BO
28.5% water
74 MBO/well cumulative

Divide County (139 wells)

1.04 Mcf/BO
52.1% water
50 MBO/well cumulative

Rate vs Time for horizontal wells with 1st production after 1/1/2010
Maturity and Organofacies Assessment of Bakken Shale: Implications for New Areas for Exploration and Production

Daniel M. Jarvie and Michael S. Johnson

Bulk open-system kinetic data measured on several Bakken Shale samples is used to evaluate relative rates of oil generation. While source rocks have been identified that generate hydrocarbons at lower thermal thresholds than classical onset of hydrocarbon generation windows, these are usually high sulfur Type II-S kerogens such as the Monterey Formation, rather than low sulfur, marine shales such as the Bakken. Our experience, however, is that all kinetic models currently in use, tend to under predict early hydrocarbon generation. A revised assessment of these results provides some insights as to why this may occur.

“A key issue that arises from this investigation is the possibility of identifying additional Bakken and shale-oil plays in other basins that have been described as too low thermal maturity for indigenous hydrocarbon generation.”

AAPG Search and Discovery Article #90092©2009 AAPG Rocky Mountain Section, July 9-11, 2008, Denver, Colorado
HMFs were found to be **most abundant in dolostone lithology**, and were rare or absent in calcite-dominated lithology. The association with dolomite suggested subsurface propagation because dolostone is more brittle than limestone only at subsurface temperature and pressure conditions. If HMFs had propagated as a result of coring, calcite and dolomite lithologies would have experienced similar microfracturing, and no disparity would have been observed.

HMFs were **most abundant within a ten-foot proximity of a source-rock**. The working hypothesis that in situ HMF propagation was driven by hydrocarbon generation and expulsion explains the source-rock proximity trend.

HMFs were **most abundant where macroporosity** (pores resolvable with standard transmitted light optics) **was least**.

**Figure 8:** A) A photomicrograph of horizontal microfracture with a blue-green halo. Transmitted white light was not adequate to photograph the zone of discoloration, so epifluorescence was used to assist imaging. The photomicrograph is from sample 10319.00, which is a laminated silty dolostone with a HMF density of 5.1 HMFs/cm and has rare macroporosity. The blue epoxy injected into the pores is spiked with fluorochromes. Under wide-band UV reflected light, the epoxy fluoresces a bright blue. The same view is shown in B) imaged only with epifluorescence, reveals all porosity filled with epoxy in bright blue.
Diagenetic Model for Parshall

Dolomitization shortly after deposition of Upper Middle Bakken

- **Upper Middle Bakken - Time of Dolomitization**
  - Algal laminated facies at Parshall
  - Dolomitic silts with organic rich algal laminae
- **Shoal: “Clean Gamma” Unit**
  - Limey Ooid to Skeletal Grainstone
  - Very low porosity; Self cementing at deposition
  - Intermittent in eastern “Parshall” trend
- **Lower Middle Bakken**
  - Bioturbated facies
  - Dolomitic and limey silt interbeds
  - Poor dolomitization underneath shoals

**Dolomitization**
- Represents Early conversion of
- $\text{CaCO}_3 \rightarrow \text{CaMg(CO}_3)_2$
- Recrystallization with larger Crystals
- Results in New Rock Fabric
- Creates Porosity
- Microfractured Texture at Parshall
- BETTER RESERVOIR ROCK
- Associated with Higher Oil Saturation at Parshall
Examining facies, fracturing, and completions and how they affect productivity

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Understanding Bakken productivity relative to thermal maturity and implications for assessing other resource plays

- Several maturity bands:
  - Mature: overpressured, higher GOR.
  - Parshally mature
  - Early maturity: higher Sw and lower energy. (Look for migrated oil sweet spots!)
  - Immature with only migrated oil traps.
Assessing petroleum system considerations: maturity, expulsion, fracturing, and migration and how they relate to Bakken/Three Forks sub-plays

- Bakken productivity elements:
  - Maturity $\rightarrow$ OOIP, Sw, microfractures.
  - Organic material type $\rightarrow$ OOIP, Sw, microfractures.
  - Lithology $\rightarrow$ OOIP, perm, resource vs. conventional, fracture propensity, migration.
  - Tectonic Fracturing $\rightarrow$ deliverability, water.
  - Relatively quiet structural history $\rightarrow$ preservation, remigration.
Using understanding of the Bakken to discover other resource plays with similar characteristics and production potential

- Bakken Play Type Critical Elements:
  - Highly oil prone organic material.
  - Large volumes of organic material.
  - The “Oreo cookie”: interbedded oil prone source rocks and relatively low perm brittle reservoir facies.
  - Oil window thermal maturity
  - Relatively quiet structural history
Using understanding of the Bakken to discover other resource plays with similar characteristics and production potential

**Bakken Kerogen Quality**

- Bakken shales are an excellent source rock
  - Quantity of “crackable” kerogen
  - Total amount of kerogen
Using understanding of the Bakken to discover other resource plays with similar characteristics and production potential

Bakken Shale Contains Oil Prone Kerogen

- Bakken contains Type I and Type II kerogen.
- Type I and II kerogens tend to generate oil.

Where are other highly oil prone source rocks?

Using understanding of the Bakken to discover other resource plays with similar characteristics and production potential

- **Pennsylvanian Oil Prone Source Rocks:**
  - Paradox/Gothic Shale (DesMoines)
  - Cline Shale (Missourian)
  - 13 Finger (Atokan)
  - Lusk Embayment Penn Shales (DesMoines)
Using understanding of the Bakken to discover other resource plays with similar characteristics and production potential

With permission from Ron Blakey, http://jan.ucc.nau.edu/rcb7/nam.html
Comparing the Bakken and the Des Moines of the Lusk Embayment

**World class source rock interbedded with fractured dolostones**

**Bakken:**
Continuous oil accumulation in fractured low perm lithology adjacent to world class source rocks in the oil maturation window

- Bleeding oil from fractures in core samples
- Lots of historical DST shows
- Numerous shows and spotty production from vertical tests.
- 3000BOPD IP rates from multistage fracked horizontals adjacent to dry hole verticals.

**DesMoines:**
Continuous oil accumulation in fractured low perm lithology adjacent to world class source rocks in the oil maturation window

- Bleeding oil from fractures in core samples
- Lots of historical DST shows
- Numerous shows and spotty production from vertical tests.
- Never multistage fracked in a horizontal wellbore.
Source Rock (Black Shale) Geochemistry

**Bakken (shale):**
- TOC = 6-20% Avg: 9%
- S1 = 3.6 mg/g
- S2 = 7.35 mg/g
- H.I. = 450-550
- Tmax = 426-430
- Vro = 0.6 – 0.8

Values derived from recent industry presentations

**Des Moines (shale):**
- TOC = 1-30% Avg: 8.8%*
- S1 = 3.29 mg/g*
- S2 = 48.74 mg/g *
- H.I. = 403*
- Tmax = 428*
- Vro = 0.55 – 0.8

*average of 21 black shale samples in this interval
SOURCE ROCKS

- High TOC (~25% uncooked & 9% in subsurface) due to excellent preservation in restricted basin setting.
- Largely Type I & II sapropelic kerogen derived from photosynthetic sulfur bacteria and algae.
- Traditional thermal maturity measurements (Vro & Rock Eval) suggest early oil window.
- Similar kerogens have been shown to generate considerable oil at lower maturity levels due to high S concentration (0.3-5.0 weight percent).
Comparing the Bakken and the Des Moines of the Lusk Embayment

Figure 1—Late Paleozoic paleogeographic elements, Colorado, Wyoming, and Nebraska. Also shown is a simplified stratigraphic column, Late Pennsylvanian–Permian. Modified from Garfield et al. (1988).

DEPOSITIONAL FACIES
1. HALITE
2. ANHYDRITE
3. RESTRICTED DOLOMITE
4. BLACK SHALE
5. SILTSTONE / LIMESTONE
6. CARBONATE SHOALS
7. ARKOSE

Montgomery et al., 1998, AAPG Bulletin, V. 82, No. 12, p. 2173-91
Comparing the Bakken and the Des Moines of the Lusk Embayment

Desmoines GR>120*

API Isopach

*GR values estimated from background on old logs.
Comparing the Bakken and the Des Moines of the Lusk Embayment

**Pseudo Van Krevelen Plot (HI vs OI)**

- TYPE I KEROGEN
  - Oil Prone
- TYPE II KEROGEN (usu. Marine)
  - Oil Prone
- Mixed Type II/III KEROGEN
- TYPE III KEROGEN
  - Gas Prone

**Hydrogen Index vs Tmax**

- TYPE I KEROGEN
- TYPE II KEROGEN
- TYPE III KEROGEN
- TYPE IV KEROGEN
• Bakken Type Log and Teal Type Log (same scale). Note similar organic shale thickness and interbed reservoir qualities
Interbed Lithology and Basic Reservoir Properties

Bakken Interbed:

Calcareous siltstone to sandstone, dolostone, silty limestone, and oolitic limestone

- Phi range = ~2 – 9%
- Phi Average = ~7%
- Grain Density range = 2.7-2.8
- Grain Density Average = 2.74

DesMoines Interbeds:

Dolomite with interbeds of particulate limestone, dolostone, vfg sandstone, and secondary anhydrite

- Phi range = ~2 – 18%
- Phi Average = ~7%
- Grain Density range = 2.66-2.92
- Grain Density Average = 2.79
overall source-rock thickness does not seem to affect HMF intensity, and thus unlikely affects HMF density. However, proximity to the source-rock, within ten feet in this study, appears to heavily control the location of HMF-dense zones.

24.6 MMBO/mi$^2$
\( \Phi_i = 10.8' \)
\( Sw = 47.2\% \)
Bakken Prospect Predrill list of Pros and Cons from Michael S. Johnson (geologist responsible for the discovery).

Pennsylvanian Shales?

- **Plus**
  - Oil in the system
  - High Toc
  - Middle member present
  - Overpressuring evident
  - Open acreage
  - Using Archie’s Sw equation everything is productive.

- **Minus**
  - Low Rt
  - Variable lithology in middle member (dolomite).
  - No commercial production
  - Horizontal drilling had failed.
  - Why wasn’t the acreage leased.
  - Low Ro

Bakken Prospect (Parshall) predrill 2006.

Bakken Prospect (Parshall) 2010.

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THANK YOU!

Please contact me directly with any comments or questions.

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