Petrophysical Analysis of the Bakken Interval, Nance Petroleum, Larson 11-26 Well, Richland County, Montana

Prepared for the Bakken Short Course
Rocky Mountain Section of the AAPG
Jackson, Wyoming

September 24, 2005

Digital Formation, Inc.
Outline

- Goals of the Study
- Data Available
- Basic Petrophysical Interpretation
- Core/Log Comparisons
- Fracture Analysis
- Permeability Modeling
- Pseudo Logs and Mechanical Properties
- Total Organic Carbon
- Conclusions
Goals of the Study

• To determine a petrophysical porosity/saturation model and compare with core measurements. Rocks are low porosity and very low permeability dolomitic limestones
• Examine if the reservoir is fractured
• Examine mechanical properties and define differences (if any) between the Bakken producing interval and intervals both above and below – examine barriers to fracture propagation
• Evaluate the Bakken Shale for total organic carbon and Pyrolysis S2 values – using the technique of Passey et al
Data Available

• Logs
  – GR
  – Array Resistivity
  – Acoustic Compressional and Shear
  – Pe
  – Density
  – Neutron
  – Microlog
• Formation Tops

• Core Data
  – Porosity
  – Dry Bulk Density
  – Grain Density
  – Gas Permeability
  – Water Saturation
  – Oil Saturation
  – Comments – particularly whether or not the permeability measurements are valid

• Recent wells (lateral) in the area have produced 342 BOPD and 480 BOPD
Raw Data Logs
## Core Data

### Nance Petroleum
### Bakken Dolomite
### Routine Core Analysis Test Results
### Project No: 500947
### January 23, 2004

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Sample Depth (ft)</th>
<th>Sample Length (in)</th>
<th>Sample Diameter (in)</th>
<th>Ambient Porosity (%)</th>
<th>Dry Bulk Density (g/cc)</th>
<th>Grain Density (g/cc)</th>
<th>Gas Permeability (md)</th>
<th>Saturation</th>
<th>Water (%)</th>
<th>Oil (%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10371.40</td>
<td>0.729</td>
<td>1.509</td>
<td>1.81</td>
<td>2.645</td>
<td>2.694</td>
<td>&lt;0.01</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>Microfractured - Steady State Perm Invalid</td>
</tr>
<tr>
<td>2</td>
<td>10373.60</td>
<td>0.804</td>
<td>1.509</td>
<td>2.17</td>
<td>2.639</td>
<td>2.687</td>
<td>0.028</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>10375.70</td>
<td>0.818</td>
<td>1.509</td>
<td>0.48</td>
<td>2.687</td>
<td>2.700</td>
<td>&lt;0.01</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>10377.20</td>
<td>0.886</td>
<td>1.509</td>
<td>1.24</td>
<td>2.660</td>
<td>2.694</td>
<td>0.021</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>10379.80</td>
<td>shale</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>10381.20</td>
<td>0.794</td>
<td>1.509</td>
<td>2.01</td>
<td>2.621</td>
<td>2.675</td>
<td>&lt;0.01</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>10383.70</td>
<td>shale</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>10385.60</td>
<td>shale</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>10387.00</td>
<td>0.850</td>
<td>1.509</td>
<td>2.20</td>
<td>2.666</td>
<td>2.747</td>
<td>&lt;0.01</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10389.50</td>
<td>0.819</td>
<td>1.509</td>
<td>1.42</td>
<td>2.594</td>
<td>2.733</td>
<td>&lt;0.01</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>10391.20</td>
<td>0.866</td>
<td>1.509</td>
<td>2.99</td>
<td>2.840</td>
<td>2.721</td>
<td>0.040</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>Microfractured - Steady State Perm Invalid</td>
</tr>
<tr>
<td>12</td>
<td>10393.30</td>
<td>0.903</td>
<td>1.509</td>
<td>2.73</td>
<td>2.666</td>
<td>2.741</td>
<td>&lt;0.01</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>Microfractured - Steady State Perm Invalid</td>
</tr>
<tr>
<td>13</td>
<td>10395.20</td>
<td>0.879</td>
<td>1.509</td>
<td>4.33</td>
<td>2.624</td>
<td>2.743</td>
<td>0.071</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>Microfractured - Steady State Perm Invalid</td>
</tr>
<tr>
<td>14</td>
<td>10397.60</td>
<td>shale</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>10405.40</td>
<td>0.830</td>
<td>1.509</td>
<td>6.95</td>
<td>2.608</td>
<td>2.803</td>
<td>&lt;0.01</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>10406.80</td>
<td>0.803</td>
<td>1.509</td>
<td>6.99</td>
<td>2.565</td>
<td>2.778</td>
<td>&lt;0.01</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>10407.40</td>
<td>0.801</td>
<td>1.509</td>
<td>9.10</td>
<td>2.518</td>
<td>2.770</td>
<td>0.028</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>Microfractured - Steady State Perm Invalid</td>
</tr>
<tr>
<td>18</td>
<td>10408.20</td>
<td>0.768</td>
<td>1.509</td>
<td>6.33</td>
<td>2.608</td>
<td>2.785</td>
<td>&lt;0.01</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>10409.40</td>
<td>0.823</td>
<td>1.509</td>
<td>7.24</td>
<td>2.551</td>
<td>2.750</td>
<td>&lt;0.01</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>10411.80</td>
<td>0.747</td>
<td>1.509</td>
<td>6.66</td>
<td>2.506</td>
<td>2.792</td>
<td>&lt;0.01</td>
<td>2.14</td>
<td>38.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>10412.70</td>
<td>0.742</td>
<td>1.509</td>
<td>8.61</td>
<td>2.517</td>
<td>2.754</td>
<td>0.026</td>
<td>0.98</td>
<td>38.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>10413.20</td>
<td>0.880</td>
<td>1.509</td>
<td>8.81</td>
<td>2.526</td>
<td>2.769</td>
<td>0.029</td>
<td>1.23</td>
<td>34.52</td>
<td>Microfractured - Steady State Perm Invalid</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>10414.50</td>
<td>0.690</td>
<td>1.495</td>
<td>8.20</td>
<td>2.530</td>
<td>2.756</td>
<td>0.033</td>
<td>3.18</td>
<td>41.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>10415.20</td>
<td>0.651</td>
<td>1.509</td>
<td>8.24</td>
<td>2.544</td>
<td>2.773</td>
<td>0.030</td>
<td>2.93</td>
<td>34.65</td>
<td>Microfractured - Steady State Perm Invalid</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>10416.30</td>
<td>0.704</td>
<td>1.509</td>
<td>8.27</td>
<td>2.556</td>
<td>2.768</td>
<td>0.016</td>
<td>6.89</td>
<td>42.36</td>
<td>Microfractured - Steady State Perm Invalid</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>10417.20</td>
<td>0.779</td>
<td>1.510</td>
<td>6.35</td>
<td>2.580</td>
<td>2.755</td>
<td>0.025</td>
<td>4.91</td>
<td>42.40</td>
<td>Microfractured - Steady State Perm Invalid</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>10418.40</td>
<td>0.710</td>
<td>1.509</td>
<td>6.85</td>
<td>2.578</td>
<td>2.767</td>
<td>0.025</td>
<td>4.60</td>
<td>37.12</td>
<td>Microfractured - Steady State Perm Invalid</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>10419.30</td>
<td>0.792</td>
<td>1.509</td>
<td>7.50</td>
<td>2.578</td>
<td>2.787</td>
<td>0.074</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Core Data - continued

## Nance Petroleum

**Bakken Dolomite**

**Routine Core Analysis Test Results**

*Project No: 500947*

*January 23, 2004*

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Sample Depth (ft)</th>
<th>Sample Length (in)</th>
<th>Sample Diameter (in)</th>
<th>Ambient Porosity (%)</th>
<th>Dry Bulk Density (g/cc)</th>
<th>Grain Density (g/cc)</th>
<th>Gas Permeability (md)</th>
<th>Saturation Water (%)</th>
<th>Saturation Oil (%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>10420.30</td>
<td>0.758</td>
<td>1.509</td>
<td>4.62</td>
<td>2.614</td>
<td>2.741</td>
<td>0.299</td>
<td>34.10</td>
<td>19.81</td>
<td>Microfractured - Steady State Perm Invalid</td>
</tr>
<tr>
<td>30</td>
<td>10421.40</td>
<td>0.772</td>
<td>1.509</td>
<td>3.46</td>
<td>2.627</td>
<td>2.722</td>
<td>0.090</td>
<td>31.94</td>
<td>28.43</td>
<td>Microfractured - Steady State Perm Invalid</td>
</tr>
<tr>
<td>31</td>
<td>10422.50</td>
<td>0.768</td>
<td>1.509</td>
<td>3.83</td>
<td>2.618</td>
<td>2.724</td>
<td>0.073</td>
<td>16.75</td>
<td>10.95</td>
<td>Microfractured - Steady State Perm Invalid</td>
</tr>
<tr>
<td>32</td>
<td>10423.20</td>
<td>0.790</td>
<td>1.509</td>
<td>3.12</td>
<td>2.636</td>
<td>2.721</td>
<td>2.551</td>
<td>*</td>
<td>*</td>
<td>Coring Induced MicroFractured - SS K Invalid</td>
</tr>
<tr>
<td>33</td>
<td>10424.60</td>
<td>0.770</td>
<td>1.509</td>
<td>2.93</td>
<td>2.637</td>
<td>2.717</td>
<td>0.435</td>
<td>*</td>
<td>*</td>
<td>Microfractured - Steady State Perm Invalid</td>
</tr>
<tr>
<td>34</td>
<td>10425.30</td>
<td>0.802</td>
<td>1.509</td>
<td>2.42</td>
<td>2.642</td>
<td>2.708</td>
<td>3.026</td>
<td>*</td>
<td>*</td>
<td>Coring Induced MicroFractured - SS K invalid</td>
</tr>
<tr>
<td>35</td>
<td>10425.60</td>
<td>0.750</td>
<td>1.509</td>
<td>2.76</td>
<td>2.634</td>
<td>2.709</td>
<td>9.318</td>
<td>*</td>
<td>*</td>
<td>Coring Induced MicroFractured - SS K invalid</td>
</tr>
<tr>
<td>36</td>
<td>10429.20</td>
<td>0.730</td>
<td>1.509</td>
<td>3.92</td>
<td>2.634</td>
<td>2.742</td>
<td>0.891</td>
<td>*</td>
<td>*</td>
<td>Microfractured - Steady State Perm Invalid</td>
</tr>
<tr>
<td>37</td>
<td>10430.20</td>
<td>0.814</td>
<td>1.509</td>
<td>2.02</td>
<td>2.740</td>
<td>2.797</td>
<td>&lt;0.01</td>
<td>*</td>
<td>*</td>
<td>Microfractured - Steady State Perm Invalid</td>
</tr>
<tr>
<td>38</td>
<td>10432.20</td>
<td>0.816</td>
<td>1.509</td>
<td>6.92</td>
<td>2.614</td>
<td>2.809</td>
<td>0.478</td>
<td>*</td>
<td>*</td>
<td>Microfractured - Steady State Perm Invalid</td>
</tr>
<tr>
<td>39</td>
<td>10433.60</td>
<td>Mixed Shale</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Dean Stark analysis is invalid based on original samples tested with the possible exception of sample number 29 which appeared to have similar results to the retort data and is likely one of the most permeable samples.
Density/Neutron

Density/Sonic
$U_{\text{matrix}}$ vs. $\rho_{\text{matrix}}$

$\rho_{\text{matrix}}$ vs. $\Delta T_{\text{matrix}}$
Pickett Plot

File: Larson 11 26.lns
Plot: Interactive Pickett Plot plt
Gross Interval: 1948 to 12372 by 0.5 ft
Ranges: 10370-10385, 10385-10397.5, 10397.5-10405, 10405-10428, 10428-10450
Time: 08:17 PM Date: Mon, Sep 05, 2005

Well Name: LARSON 11-26
Plot Name: Phi Effective vs Rt

[Graph showing a Pickett plot with various data points and lines representing different ranges and values.]
Basic Petrophysical Interpretation and Core/Log Comparisons

- Good correlation between core and log porosity and grain density
- Good correlation between log “unmoved oil” and core oil saturation
- Core water saturation appears to be anomalously low
Fracture Analysis

- Based on abnormal rates of change of raw porosity log curves, and out of gauge hole
- Bakken shale appears to contain both open and closed fractures
- The only fracture indicator in the Bakken dolomite is out of gauge hole
Permeability Modeling

• Timur transform is:

\[ k = \frac{62500 \times \phi_e^6}{S_{wi}^2} \]

And is a very poor predictor of permeability

Timur Variable Exponent transform is:

\[ k = \frac{62500 \times \phi_e^{VariableExponent}}{S_{wi}^2} \]

<table>
<thead>
<tr>
<th>Variable Exponent</th>
<th>Porosity</th>
<th>Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>0.22</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

Correlation is tighter, but still not very good
Permeability Modeling

Porosity

- Dark Blue: 0 - 2%
- Light Blue: 2% - 4%
- Dark Green: 4% - 6%
- Light Green: 6% - 8%
- Yellow: 8% - 10%
Pseudo Logs and Mechanical Properties

• Pseudo logs are derived from a rock physics model using the geophysical Krief equation
• Good reconstruction of all porosity logs indicates data set has very good integrity
• Mechanical properties, derived from pseudo logs agree well with those calculated from measured logs
• Significant contrast between the Bakken shale and carbonates both above and below
• Contrast between the Bakken carbonates and the Three Forks carbonates is much more subtle
Pseudo Logs and Mechanical Properties
Comparison of Mechanical Properties

• Shows that part of the Bakken Shale and the Three Forks, are ductile, and the remainder of the sequence is brittle
Comparison of Mechanical Properties
Total Organic Carbon

• Technique is based on identifying shale intervals to have very low TOC, and to compare resistivity of the organic thick shales with these low TOC Shales (ΔR techniques) See AAPG December 1990 p. 1777 – 1794

• Bakken shale shows a TOC of about 10%, assuming LOM = 11 i.e. good source rock potential
Total Organic Carbon

Figure 3—(A) $\Delta \log R$ diagram relating $\Delta \log R$ to TOC via maturity. The heavy solid diagonal line near the LOM 6 line should be used for maturity less than LOM 6. (B) TOC to $S_2$ via maturity diagram for type II (oil-prone) kerogen. This diagram should be used for type I kerogen as well as for type II kerogen. (C) TOC to $S_2$ via maturity diagram for type III (gas-prone) kerogen.

$$\text{TOC} = (\Delta \log R) \times 10^{\frac{2.197 - 0.1088 \times \text{LOM9}}{2}}$$
Conclusions

• Petrophysical modeling gives good estimates of porosity, fluid substitution, and grain density when compared with core measured values
• Permeability of these Bakken dolomites are extremely low (less than 0.1 md). Petrophysical models to predict permeability from other measurements (porosity, irreducible water saturation) are not very satisfactory
• Mechanical properties of the producing Bakken interval are quite different from the overlying Bakken shale, and subtly different from the underlying Three Forks
• TOC values of the Bakken shale are high (10%) indicating good source rock potential