Geological characterization of the Muddy/Newcastle Sandstone reservoir, Fiddler Creek Field, Weston County, Wyoming

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Enhanced Oil Recovery Institute
Presentation Objectives

- Introduction
- Data
- Geological Characterization
- Geological Modeling
- Volumetric OOIP
- Dynamic Modeling
- Comparison to the Grieve study
- Conclusions
Introduction

• On eastern margin of Powder River Basin.
• Divided into East and West units.
• Muddy/Newcastle Sandstone (Lower Cretaceous) incised-valley fill reservoir.
• Underpinned by major basement lineaments (Fiddler Creek and Weston/Hat Creek).

Modified from Martinsen (2003), Marrs & Raines (1984)
• On eastern margin of Powder River Basin.
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Introduction

- Generalized stratigraphic cross section of the Muddy Fm., showing member level stratigraphy.
  - Note the major lowstand surfaces of erosion (Skull Creek, Lazy B, and Rozet unconformities).
  - In more landward areas (e.g. Fiddler Creek), Rozet Unconformity cuts directly into the Skull Creek Shale and is overlain by the Ute(?) and Springen Ranch Members.

Martinsen, 1994
• 212 wells with SP log data.
• 49 wells with other data (other logs, information from well files, etc).
• 68 wells (at minimum) with no data.
• 85 wells with core porosity and/or permeability.
• 0 wells with currently available core in reservoir interval.
• Associated maps and production data.
• **Picking several horizons on SP logs:**
  - Mowry Shale datum;
  - Top Newcastle Fm.;
  - Top Newcastle Sandstone;
  - Top NC Sst with $\geq 15$ mv SP deflection;
  - Mid NC Sst: SP and/or resistivity kicks, core poro-perm changes;
  - Base NC Sst with $\geq 15$ mv SP deflection;
  - (Rozet Unconformity (= Base Newcastle Fm. in this field).)

• **Several wells have SP logs that did not penetrate into or through reservoir interval, even though there is/was production.**
  - Use of cable tool to drill into reservoir.

• **Characterization of SP log facies** carried out based upon linking shape to facies and depositional regime.
*Top Newcastle Formation = transgressive surface of erosion (TSE)
### SP Log Facies

- **SP log facies**
  - Seven separate log facies can be identified based on the character of the available SP logs.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Character</th>
</tr>
</thead>
<tbody>
<tr>
<td>0) Incomplete</td>
<td>Blocky</td>
</tr>
<tr>
<td>1) Rounded/Cylinder</td>
<td>Upward-fining</td>
</tr>
<tr>
<td>2) Bell</td>
<td>Upward-coarsening</td>
</tr>
<tr>
<td>3) Funnel</td>
<td>Spikey</td>
</tr>
<tr>
<td>4) Inverse Serrate</td>
<td>Serrate</td>
</tr>
<tr>
<td>5) Serrate</td>
<td>Upward coarse/fine</td>
</tr>
<tr>
<td>6) Modified</td>
<td>Sand-poor</td>
</tr>
<tr>
<td>7) Flat</td>
<td></td>
</tr>
</tbody>
</table>
Generalized depositional model, vertical sequences and electric log profiles of a meander belt sand body produce by a high sinuosity channel.

(A) and (B) illustrates a complete fining-upward sequence typical of the mid or down-stream point bar.

(C) illustrates the truncated vertical sequence commonly found in the upstream end of the bar.

### SP Log Facies

<table>
<thead>
<tr>
<th>Number</th>
<th>Type</th>
<th>Facies Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Incomplete</td>
<td>Unknown; probably channel</td>
</tr>
<tr>
<td>1</td>
<td>Rounded/Cylinder</td>
<td>Blocky</td>
</tr>
<tr>
<td>2</td>
<td>Bell</td>
<td>Upward-fining</td>
</tr>
<tr>
<td>3</td>
<td>Funnel</td>
<td>Upward-coarsening</td>
</tr>
<tr>
<td>4</td>
<td>Inverse Serrate</td>
<td>Spikey</td>
</tr>
<tr>
<td>5</td>
<td>Serrate</td>
<td>Serrate</td>
</tr>
<tr>
<td>6</td>
<td>Modified</td>
<td>Upward coarse/fine</td>
</tr>
<tr>
<td>7</td>
<td>Flat</td>
<td>Sand-poor</td>
</tr>
</tbody>
</table>

**Channel fill, axis**
- Channel fill, off-axis/point-bar
- Crevasse splay
- Levee
- Floodplain
- Modified channel fill; possible OWC?
- Shales

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*SP log interpretation*

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*After Wilson & Nanz (1959), Galloway (1977) and Hamilton (1995)*
### SP Log Facies

<table>
<thead>
<tr>
<th>CHANNEL TYPE</th>
<th>COMPOSITION OF CHANNEL FILL</th>
<th>CROSS SECTION</th>
<th>CHANNEL GEOMETRY</th>
<th>INTERNAL STRUCTURE</th>
<th>LATERAL RELATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEDLOAD CHANNEL</td>
<td>Dominantly sand</td>
<td>High width/depth ratio</td>
<td>Low to moderate relief on basal scour surface</td>
<td>Broad continuous belt</td>
<td>Irregular, filling-up poorly developed</td>
</tr>
<tr>
<td>MIXED LOAD CHANNEL</td>
<td>Mixed sand, silt, and mud</td>
<td>Moderate width/depth ratio</td>
<td>High relief on basal scour surface</td>
<td>Complex, typically &quot;beaded&quot; belt</td>
<td>Variety of filling-up profiles well developed</td>
</tr>
<tr>
<td>SUSPENDED LOAD CHANNEL</td>
<td>Dominantly silt and mud</td>
<td>Low to very low width/depth ratio</td>
<td>High-relief scours with steep banks, some segments with multiple thalwegs</td>
<td>Shoestring or pod</td>
<td>Multistory channel fills, encased in abundant overbank deposits</td>
</tr>
</tbody>
</table>

- Classification of fluvial styles, following the fluvial-geomorphological classification of Schumm (1963), as given in the left-hand column. From Galloway (1981).
• **Classification of SP log facies indicates *some* patterns.**
  - More overbank deposits (crevasse splay, levee) in east unit.
  - May be possible to “join the dots” in west unit to get through-going sinuous channel.
SP Log Picks

Mowry Shale datum
Red wells: SP logs
Blue wells: Other data
White wells: No data

Top Newcastle Formation
Red wells: SP logs
Blue wells: Other data
White wells: No data
Top Newcastle Sandstone

Red wells: SP logs
Blue wells: Other data
White wells: No data

Base Newcastle Sandstone

Red wells: SP logs
Blue wells: Other data
White wells: No data
Isopach Maps

Mowry Datum to Top Newcastle Formation isopach

Thickness increase to east across a distinct boundary

Mowry Datum to Top Newcastle Sandstone isopach

Thickness increase to east across a distinct boundary
Isopach Maps

Newcastle Sandstone isopach:
- Thins should overly sand-rich channel fill (differential compaction of muddy facies around channel)

Top Newcastle Fm to top Newcastle Sst isopach:
- Thicks should indicate good sand, and may illustrate channel meander patterns

Newcastle Sandstone isopach:
Isopach Maps

Sequence A: Mid NC Sst to Base NCE Sst isopach

Sequence B: Top NC Sst to Mid NC Sst isopach
Fly River Delta, Papua New Guinea

Fluvial meander belt in an upper incised valley
Reservoir Analog: Modern

- Early example of tripartite estuarine sedimentation zonation, Yaquina Bay, Oregon (original from Kulm and Byrne, 1967). From Boyd et al. (2006).
Reservoir Analog: Ancient

Dakota “J” Sandstone (Muddy equiv.), Dinosaur Ridge, Morrison, CO.

(A) Fluvial channel incision into underlying tidal muddy siltstones.

(B) Inclined bedding of channel point-bar, indicating channel migration to right.

(C) Intra-channel storey contact, with ripples along top of underlying point-bar sandstones. Channels ~15’ t, 100’ w.
(A) Isopach of fine-grained sandstone, siltstone and mudstone, constituting the fill of the abandoned channel overlying the Q Sandstone at Little Creek Field, LA, and underlying a regional marker that defines the top of the fluvial interval.

(B) Cross sections through the Q Sandstone and overlying beds in Little Creek Field, LA. From Werren et al. (1990).
• Dip attribute maps for each horizon show similar character:
  • ~300’ displacement to SW in western part of west unit – Weston/Hat Creek basement lineament.
  • Isolated structures in central part of west unit.
  • NW-SE and NE-SW linear features through east unit, parallel and normal to basement trend.
Structural Model

- Structure models for Weston/ Hat Creek lineament.

(A) Monocline above lineament.
(B) Fault zone along lineament.
(C) Discrete fault.
3 main structural zones can be defined:

- Lineament zone – large offset over basement lineament.
- "Quiescent" zone – isolated structure.
- Fracture zone – many probable fractures.

All structures appear to be post-depositional.

- Dip attribute structure is also present in the overlying Mowry Shale.
• **Characterize channels:**
  - Channel widths/thickness ➔ model building (82’*82’*1’ grid).
  - Channel sinuosity?
  - Probability maps?

• **Data analysis:**
  - Facies, porosity, permeability, net-to-gross.
  - Distributions.
  - Variogram analysis.

• **Facies modeling.**
• **Petrophysical modeling.**
• **Volumetric OOIP.**
Channel Sinuosity and Aspect

Classification of alluvial channels by sediment load (Schumm 1963, 1985).

<table>
<thead>
<tr>
<th>Type of channel</th>
<th>Bed load (% of total load)</th>
<th>Single-channel systems</th>
<th>Multiple-channel systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspended load</td>
<td>&lt; 3</td>
<td>Suspended-load channel</td>
<td>Anastomosing system</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W/D ratio &lt; 10,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>sinuosity &gt; 2.0,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>gradient relatively gentle</td>
<td></td>
</tr>
<tr>
<td>Mixed load</td>
<td>3–11</td>
<td>Mixed-load channel</td>
<td>Delta distributaries</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W/D ratio 10–40,</td>
<td>Alluvial plain distributaries</td>
</tr>
<tr>
<td></td>
<td></td>
<td>sinuosity &lt; 2.0,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>gradient moderate, may be braided</td>
<td></td>
</tr>
<tr>
<td>Bed load</td>
<td>&gt; 11</td>
<td>Bed-load channel</td>
<td>Alluvial fan distributaries</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W/D ratio &gt; 40,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>sinuosity &lt; 1.3,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>gradient relatively steep, may be braided</td>
<td></td>
</tr>
</tbody>
</table>

W/D = width/depth ratio.
Channel Characterization

Channel and Channel Belt Widths from Thickness, after Bridge & Mackey (1993)

- Determine channel widths from sand thicknesses.

Laterally-offset fluvial channels, Dakota "J" Sandstone, Dinosaur Ridge, Morrison, CO
• Use Newcastle Sandstone isopach map to determine channel probability map.
  • 0=0% probability, 1=100% probability.
• Sinuosity based on correlation of thicks;
  • Between 1.7 and 2.8.
• Upscale logs into modeling grid:
  • Facies, porosity, permeability, $R_{SW}$, $R_{So}$.

• Data analysis:
  • Define probability curves and spatial variograms for parameters.
  • Correlate porosity with facies; permeability with facies and porosity.
Facies Modeling

Representative facies model

- Object-based stochastic modeling:
  - Rule-based modeling of individual channels, crevasse splay, and levees.
  - Based on channel aspect ratio, sinuosity, channel probability mapping.
• Core-based porosity and permeability.
  • High scatter around an exponential correlation of KH with phi.
  • Good sands show KV is ~0.75 of KH. Overall, probably ~0.01 of KH.
- **Core-based porosity and permeability.**
  - Fair correlation of poro-perm with SP facies.
  - Overall poro-perm trend is consistent in E and W units.
• **Sequential Gaussian simulation:**
  - Rule-based distribution of porosity and permeability, correlated by facies.
  - Uses rules (distribution, variograms) derived in data analysis process.
  - Permeability co-krigged with porosity.
Petrophysical Modeling

Representative porosity model

Representative permeability model
• Use porosity models to determine volumetric OOIP.
  • Use dynamic porosity based on facies model, with average reservoir net-to-gross of 75%.
  • Multiple model realizations should provide an accurate estimate.
  • Calculate residual oil saturation from $R_{S_w}$ measured from core data.
  • Formation volume factor=$\sim1.3$
Volumetric OOIP

Representative OOIP model

Volumetrics, 633 runs:

- Pore volume = 98.5 MMBO
- HC Pore volume = 82.3 MMBO
- OOIP = 63.3 MMBO
**MMP Determination**

**Calculation of MMP for CO\(_2\) using oil sample from West Unit.**

- 1.2 PV CO\(_2\) injected in slim tube experiments.
- MMP = 1318 psi.
- Injection at these lower pressures significantly reduces the risk of opening fractures through overpressuring.

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H. Adidharma, pers. comm., 2008
Dynamic Modeling for EOR

- **Significant challenges:**
  - Large field with many wells.
  - Significant reservoir heterogeneity – channel compartmentalization.
  - Significant structural heterogeneity – fractured vs. non-fractured sectors.

- **Carry out sector modeling for each unit (west, east).**
  - Approximates to reservoir structural zonation.

Miall, 1996
Pseudo-excess matrix production map for Steamboat Field, Bighorn Basin, WY (Marathon). Note the two sectors of porosity control – matrix and fractured.

Kulkarni et al., 2008.
• The Fiddler Creek study is, by necessity, different to the Grieve study.
  • Fiddler Creek has more wells by a factor of 8.
  • Fiddler Creek did not have core available.
  • The field is has too many wells for a history-matched field simulation.
• Zone-based modeling is a way to estimate recoverable hydrocarbons using different EOR techniques for different structural sectors:
  • Used by Marathon in Steamboat Field (Kulkarni et al., 2008).
• The study has been a success, even with limited data.
Conclusions

- Fiddler Creek Field represents a thin (~15-20’) fluvial system that is the landward projection of the Springen Ranch Mbr., Muddy/ Newcastle Sandstone.
- Based upon SP log character, the field is characterized by a meandering channel belt that can be divided into lower and upper sequences.
- Structurally, the field can be divided into three main zones - lineament, quiescent, and fracture.
- Stochastic modeling of the reservoir carried out for calculation of volumes:
  - Volumetric OOIP=63.3 MMBO - in agreement with prior estimates.
  - MMP calculation indicates CO₂ can be injected at low pressure.
    - Reduces risk of opening fractures using higher pressures.
  - Currently finalizing injection modeling for recovery estimates.
    - Initial results promising.


