ROZ Potential of Tensleep Sandstone in Bighorn Basin, Wyoming

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Acknowledgement

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Residual Oil

- Residual oil, Schowalter (1982):
  - Oil migration through a reservoir or carrier bed.
  - Remigration of oil from a trapped accumulation.
  - By production of a conventional reservoir.
  Isolated droplets of oil

- Schlumberger Oilfield Glossary:

  Oil that does not move when fluids are flowed through the rock in normal conditions, for example primary and secondary recovery, and invasion.
Oil Column after Secondary Migration

Jennings, 1987
Oil Column Resulted from Natural Water Flooding
ROZ Formation in Permian Basin

Trentham, 2013

The Seminole Field (W. Tx) Saturation Profile

Conventionally
Productive Oil Zone

Residual Oil Zone (ROZ)

Average Saturation profile

BASE
OF $S_o$
(BO$S_0$)

Water Saturation ($S_w$) (%)

Oil Saturation ($S_o$) (%)

100

0

Melzer, 2013
Three Types of ROZ in Permian Basin

Type 1 ROZ: Original Accumulation Subject to a Westward Regional Tilt Forming a ROZ

Type 2 ROZ: Original Accumulation with a Breached and Repaired Seal Forming a ROZ

Type 3 ROZ: Change in Hydrodynamic Conditions, Sweep of the Lower Oil Column and Oil/Water Contact Tilt Forming a ROZ

Melzer, 2006
MIDDLE SAN ANDRES PALEOGEOGRAPHY
with Location of Industry Documented ROZ Zones/Fields*

* Adapted from Sagnak (2006), Chevron Presentation at the 12/06 CO₂ Flooding Conference
Bighorn Tensleep vs Permian San Andres

- Multiple oil migration.
- Hydrodynamic effects from outcrop fresh water influx.
Bighorn Tensleep vs Permian San Andres

• Permian San Andres
  – Dolomite in carbonate sequence.
  – Oil generated from source rocks in Permian Basin.
  – Oil migrated into adjacent reservoir rocks.
  – Broad structural or stratigraphic traps.
  – Light oil.

• Bighorn Tensleep
  – Sandstone alternated with dolomite
  – Oil generated in Phosphoria source rock far away to west.
  – Oil migrated to Tensleep through a long way.
  – Sharp anticline traps.
  – Heavy oil
Methodologies

- Lecture review and discussion with Permian Basin Group and operators.
- Data collection: core observation, core measurements, check cuttings, petrographic and mineral investigation, well log analysis, completion test results, and production history.
- Select small region (35 square miles) with good data set for the first study to create a set of methodologies.
- Investigate ROZ potential fairways over the Bighorn Basin.
- ROZ formation mechanisms to predict ROZ fairways.
## Paleozoic Stratigraphy in Bighorn Basin

<table>
<thead>
<tr>
<th>Period</th>
<th>Formation</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permian</td>
<td>Phosphoria</td>
<td>Dolomite, limestone, shale</td>
</tr>
<tr>
<td></td>
<td>Tensleep</td>
<td>Sandstone, dolomite</td>
</tr>
<tr>
<td>Pennsylvanian</td>
<td>Amsden</td>
<td>Sandstone, red shale, limestone, dolomite</td>
</tr>
<tr>
<td></td>
<td>Darwin</td>
<td>Sandstone</td>
</tr>
<tr>
<td>Mississippian</td>
<td>Madison</td>
<td>Dolomite, limestone</td>
</tr>
<tr>
<td>Devonian</td>
<td>Jefferson</td>
<td>Dolomite</td>
</tr>
<tr>
<td>Ordovician</td>
<td>Bighorn Formation</td>
<td>Dolomite</td>
</tr>
<tr>
<td>Cambrian</td>
<td>Gallatin</td>
<td>Sandstone, limestone, shale</td>
</tr>
<tr>
<td></td>
<td>Dunoir</td>
<td>Limestone</td>
</tr>
<tr>
<td></td>
<td>Gros Ventre</td>
<td>Sandy limestone, shale, sandstone</td>
</tr>
<tr>
<td></td>
<td>Flathead</td>
<td>Sandstone</td>
</tr>
</tbody>
</table>
Tensleep Lithology
Tensleep Structural Traps

STONE, 1967

UNIVERSITY OF WYOMING
Distribution of Residual Oil Zone (ROZ)

• Underneath existing Tensleep reservoirs.

• Around or between existing Tensleep reservoirs.

• In non-commercial structures.
Proved and Predicted ROZ Occurrence in Bighorn Basin

Based on:
- EORI study

Base map from Ploeg, 1985

<table>
<thead>
<tr>
<th>13 Tensleep reservoirs</th>
<th>Estimated OOIP (BBbls)</th>
<th>CO2-EOR Potential (BBbls)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPZ</td>
<td>4.5</td>
<td>0.5</td>
</tr>
<tr>
<td>TZ/ROZ</td>
<td>4.4</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Hydrocarbon Shows in Non-productive Tensleep Wells, Bighorn Basin

Base map adopted from Ploeg, 1985
ROZ Between Existing Reservoirs
Frannie-Sage Creek-Homestead area

Legend
- Well
- Field
- State Boundary
- PLSS Town Ring

- Oil show

IP: 56 BO, 123 BW
Cumul Prod: 91616 BO

IP: 60 BOPD, 264 BWPD

Oil stain free oil droplets

Oil stain or saturated

Oil cut water

320786

320172
HC Show & Oil Saturation in a Non-productive Well

320410
C L Zwemer 1
57N-97W-21
Bighorn Basin
Hydrocarbon Show & Oil property in a Non-productive Well

Core Photos

Oil Composition (GC)
Thick ROZ Identified
Frannie-Sage Creek-Homestead area
Hydrocarbon Shows in Non-productive Tensleep Wells, Bighorn Basin
ROZ in Non-productive Structures (1)
ROZ in Non-productive Structures (2)
## Comparison of ROZ Oil with MPZ Oil

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>API Gravity (degree)</th>
<th>Sample Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>Big Polecat</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>Little Buffalo Basin</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>Black Mountain</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>Byron</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>Bonanza</td>
</tr>
</tbody>
</table>

- **Produced oil from reservoir**
- **Oil from adjacent non-productive wells**

**Tensleep Reservoir Oil**
Oil Quality in ROZ

Oil from productive wells

Oil from non-productive wells
Operator’s Comments

- Chris Mullen: Perforation interval in most Tensleep reservoirs depends on the economic cut offs. Perforation too deep will quickly cause water coning.

- Eugene Wadleigh: We knew a lot of oil in the Tensleep Sandstone, Bighorn Basin had not been developed for the primary production.

- Gene George: A lot of oil has not been developed in the Minnelusa sandstones from current production.
Mechanisms for ROZ Generation

- Tensleep oil generated from Phosphoria source rocks.
- Multiple migration and accumulation caused by tectonic movements.
- Hydrodynamic effects.
Evidence of Phosphoria Generated Oil in Tensleep and Minnelusa

- Trace elements exhibit similar patterns in the Phosphoria black beds and in the crude oil farther to the east (Sheldon, 1967).

- Good agreement in both aromatic-type analysis and infrared measurements on molecular distillation fractions between hydrocarbon extracts from a Phosphoria core and oil produced from the Tensleep in a Wind River basin well (Stone, 1967).
Regional Facies of Permian rocks

Sheldon, 1967
Structural Contour map of Permian Rocks at the End of the Early Cretaceous Epoch.

Sheldon, 1967
Occurrence of Phosphoria Sequence Prior to Laramide Orogeny

Claypool et al., 1978
Oil Migrated into Phosphoria and Tensleep by End of Jurassic Time

Modified from Stone, 1967
End of Triassic
Oil migrated into Phosphoria and Tensleep stratigraphic traps.

Stone, 1967
Development of Tensleep Reservoirs, Bighorn Basin

End of Paleocene

Laramide folding, creating fractures and faults.
Previous hydrocarbon accumulations re-migrated into structural traps during the Paleocene and Eocene time.
Reservoirs with horizontal OWC at that time.

Stone, 1967
End of Eocene

Intensified folding, fracturing, faulting, and differential uplift and hydrodynamic flow causing adjustment of oil accumulations and redistribution through faults and regional tilting.

Reservoirs forming level or tilted OWC.

Stone, 1967
Development of Tensleep Reservoirs, Bighorn Basin

Recent

Development of present hydrodynamic environment, and influx of meteoric water into Tensleep Sandstone. Many reservoirs with tilted OWC.

Stone, 1967
Development of Tensleep Reservoirs, Bighorn Basin

End of Triassic

End of Paleocene

End of Eocene

Recent

Stone, 1967
Tensleep ROZ Formed in East Flank of Bighorn Basin

- ROZ Generation
- Bighorn Basin
- Western flank of mountains
- Post Laramide Orogeny (Paleocene)
- Horizontal OWC
- Tar deposits in Tensleep outcrop
- Meteoric water
- Oil flushed Down dip or move up dip
- Big Horn Mountains
- 9,500 ft thick
ROZ Formed after Migration of Oil from Tensleep to Madison

Before oil migrated into Madison

After oil migrated into Madison

Meteoric water flushing
Total Dissolved Solids in Tensleep Formation Waters

- Ocean Water: 70,000 mg/L
- Coastal Sabkhas of Abu Dhabi: 365,000 mg/L
Replacement of Anhydrite by Calcite & Hydrocarbon Residue
(Oxidation of Oil by Sulfate-rich Fresh Water)

\[
\text{Ca}^{2+} + \text{SO}_4^{2-} + \text{HCO}_3^- \rightarrow \text{CaCO}_3 + \text{HS}_2 + \text{HC Residue}
\]
Estimation of ROZ Resources

• Stratigraphic correlation.
• Log analysis for porosity and oil saturation.
• Pick up pay sand (cutoff >8%).
• 3D modeling porosity distribution.
• 3D modeling oil saturation.
• Calculation of oil in place for ROZ.
Location of Sage Creek-North Deaver-Cowley-Homestead Region

Base map adopted from Ploeg, 1985
Data Distribution

- Core
- Porosity log
- Full log suite
- No data
Pay Sands Correlation

(Top of Phosphoria as datum)

A A'

15 Miles

Log Phi/Core Phi

R² = 0.7263
Porosity Modeling

Vertical exaggeration (5x)
Oil saturation Modeling

Vertical exaggeration (10x)

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<tr>
<th>Estimated OOIP In ROZ (BBO)</th>
<th>CO2-EOR Potential (MMBO)</th>
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<tr>
<td>0.8</td>
<td>80 to 120 (recovery factor 10 to 15%)</td>
</tr>
</tbody>
</table>
POTENTIAL AREAS FOR ROZ DEVELOPMENT

- Wedge-shaped intervals between the current tilted OWCs and paleo-level OWCs in existing Tensleep reservoirs.

- Surrounding areas of existing reservoirs, especially the reservoirs with production from Madison and/or older formations.

- Un-developed oil-bearing anticlines.
Development of MPZ with ROZ is Economically Beneficial
Summaries

• Tensleep Sandstone in BHB has extensive and rich residual oil.
• ROZ distribution is the result of tectonic movement, multiple oil migration and accumulation, and hydrodynamic effects.
• Massive ROZ resources are a significant potential target for advanced EOR.
• BLM have changed its Resource Management Plan for the Bighorn Basin based on our research in 2013.
• An operator has started to develop ROZ in an un-productive oil-bearing structure in Bighorn Basin.
• Evaluate Tensleep ROZ in other Wyoming basins.