Tensleep TZ/ROZ Study, Bighorn Basin
A Revolutionary Concept on Oil Recovery

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Main Pay Zone (MPZ), Transition Zone (TZ) & Residual Oil Zone (ROZ)

Jennings, 1987

ARI, 2006
Tensleep Sandstone
Structural Contour Map of Tensleep Sandstone

Zapp, 1953
Tensleep Sandstone Potentiometric Map

Bredehoeft et al., 1992
Topics

• Tensleep TZ/ROZ in Bighorn Basin.

• Mechanisms for Thick TZ/ROZ.

• Active ROZ CO$_2$-EOR Production in Permian Basin.

• Comments and Future Study.
Tensleep TZ/ROZ in Bighorn Basin

- Below main pay zone within existing reservoirs.

- Around existing reservoirs.

- Non-productive structures (green fields).

- Oil Properties are similar in TZ/ROZ and MPZ.
Below Main Pay Zone within Existing Reservoirs.

Thick permeable intervals with high $S_o$ not produced during primary and secondary production.
Perforation Interval in a Tensleep Reservoir

Total Tensleep thickness: 180 ft
Average perforation thickness: 47 ft
Non-commercial Wells around Existing Reservoirs

Wells with high $S_o$, but not economically viable by primary and secondary recovery techniques
Core Photos, Non-productive Well

320410
C L Zwemer 1
57N-97W-21
Bighorn Basin
Oil Saturation Obtained from Core Analysis

Legend:
- Well
- Field
- State Boundary
- PLSS Township

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Traps with Oil Saturation not High Enough for Primary and Secondary Recovery (Green Fields)
Well Located in Non-commercial Structure (Green Field)

Tectonic information from Ploeg, 1985)
Total thickness of Tensleep Sandstone: 142 ft.

3706-3750 ft, sandstone, even light brown heavy oil stain, free oil droplets in samples and within pore spaces, even dark yellow fluorescence, strong petroleum odor.

10-12% log porosity.

Perf: 3718-3728 ft (10 ft thick).

No production, plug & abandon.

Tectonic information from Ploeg, 1985)
Produce 75 bbls/day with 70% water cut constant over one year

Data from Aufricht, 1965
Tensleep Reservoirs
Aufricht, 1965

• Oil-water transition zone of several hundred feet in thickness.

• Transition zone with $S_o$ of 80% still produce with extremely high water cuts.

• OOIP approaching 1000 barrels per acre foot may produce at water cuts greater than 95%.

• Intervals with $S_w$ of 15 to 30% are commercially interest for primary and secondary recovery techniques.
ROZ CO$_2$-EOR Potential

- ARI estimated TZ/ROZ OIP in 13 Bighorn Basin Tensleep Productive reservoirs: **4.4 BBbls**
  
  These 13 Tensleep reservoirs with cumulative production: from 345.4 to 6.2 MMBbls

<table>
<thead>
<tr>
<th></th>
<th>MPZ OOIP (BBbls)</th>
<th>MPZ Remaining OIP (BBbls)</th>
<th>TZ/ROZ OIP (BBbls)</th>
<th>Total Reserve for CO$_2$-EOR (BBbls)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. CO$_2$-miscible fields: 8</td>
<td>4.5</td>
<td>3.1</td>
<td>4.4</td>
<td>7.5</td>
</tr>
<tr>
<td>2. CO$_2$-immiscible fields: 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>CO$_2$-EOR recovery: 11%</td>
<td>0.34</td>
<td>0.48</td>
<td></td>
<td>0.82</td>
</tr>
<tr>
<td>CO$_2$-EOR recovery: 30%</td>
<td>0.93</td>
<td>1.32</td>
<td></td>
<td>2.25</td>
</tr>
</tbody>
</table>
Oil Properties are similar in TZ/ROZ and MPZ

Reservoir Oil

From Non-productive Wells

GC Analysis
A Revolutionary Development for Production and Exploration

Green Field

TZ/ROZ
CO₂-EOR

Green Field

TZ/ROZ
CO₂-EOR

Brown Field

MPZ
Primary & secondary

TZ/ROZ
CO₂-EOR
CO₂-EOR Potential

Original

Current

MPZ

TZ

Perforation

ROZ (100% water Production)
Mechanisms for Thick TZ/ROZ

• Tertiary oil migration from stratigraphic to structural traps creates rich TZ/ROZ.

• Heavy oil reservoirs favor to generate thick TZ/ROZ.

• Reservoir heterogeneity retards gravity separation of oil from water, resulting a thick TZ with uneven oil saturation.

• Strong hydrodynamic flow aids to generate rich TZ/ROZ.
Late Permian Paleogeographic Map
(Phosphoria Period)

Miller et al., 1991
Oil Migrated into Tensleep Through Unconformity

Bighorn Basin

Modified from Stone, 1967

Oil Accumulated in Stratigraphic Traps before Laramide Orogeny
Folds and Thrust Faults Generated during Laramide Orogeny

Zapp, 1953
Re-Migration of Oil Creating Rich TZ/ROZ

Bighorn Basin

Tensleep

Bighorn Mountain

Post-Tensleep Strata
9500’ thick

After Laramide
(Paleocene-Eocene)

Oil migrated and accumulated in structure top

Meteoric water
Flushing

Tensleep outcropped

Oil flushed downdip or escaped updip
East Flank of Bighorn Basin
An Example of Present Hydrocarbon Distribution

Map form Ver Ploeg, 1985
Reservoir with Tilted OWC

Madison

Big Horn

Gallatin

Tensleep

Amsden

Phosphoria

Tensleep

Amsden

Oil

TZ/ROZ

Three Forks & Jefferson

Fault
Perforation Bottom Deepening from NE to SW
Reservoir with Horizontal OWC

After Lawson and Smith (1966)
Stratigraphic Trap

Tensleep

Madison

Big Horn

Gallatin

Amsden

Phosphoria

TZ/ROZ

Oil
Mechanism of Secondary Hydrocarbon Migration and Entrapment

- Driving force: buoyancy caused by difference of density between hydrocarbon and water.
- Resistant force: capillary pressure.
  - Radius of pore throats.
  - Hydrocarbon-water interfacial tension.
  - Wettability of reservoir rocks.

\[ R: \text{Radius of pore throat.} \]
\[ \theta: \text{contact angle of oil and water against the solid.} \]

From Schowalter, 1979
Heavy Oil Reservoirs with Thick TZ/ROZ

Thickness Difference Due to Oil Density

\[ P_c = h(\rho_w g - \rho_o g) \]

From Aufricht, 1965
Water Cut as Functions of Relative Permeability and Oil Viscosity

\[
\text{Water cut, } \% = 100 \times f_w = \frac{100}{1 + \frac{\mu_w}{\mu_o} \left( \frac{k_o}{k_w} \right)}
\]

From Aufricht, 1965
Hydrodynamic Traps Contributed by Bed Thinning, Faulting, or Bending

Levorson, 1966

Pedry, 1975
ACTIVE ROZ CO$_2$-EOR PROJECTS IN PERMIAN BASIN

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

* Adapted from Sagnak (2006), Chevron Presentation at the 12/06 CO$_2$ Flooding Conference
ROZ Oil Saturation

API: 30-50°
Oil Production Increase by Including ROZ CO₂-EOR

Goldsmith San Andres Unit

Seminole San Andres Unit

Thurmond, 2010

2010 CO₂ Flooding Conference
ROZ & MPZ Have Consistent Properties in Permian Basin

Concluded by Thurmond for Goldsmith San Andres Unit, 2010

- Core oil saturation is consistent.
- Reservoir quality is consistent.
- Bulk oil composition is consistent.
- Chemical process behavior is consistent.
Ideas and Future Study

• Recognition of thick Tensleep TZ/ROZ in Bighorn Basin.
  – TZ/ROZ below main pay zone.
  – TZ/ROZ around current reservoirs.
  – TZ/ROZ in non-commercial structures.

• New discovery of CO$_2$-EOR resources in Bighorn basin.
  • EOR resources not counted by traditional main pay zones.

• There will be high potential for CO$_2$-EOR, and even a new wave of exploration for EOR targets.

• Further integrate the TZ/ROZ concept in Tensleep reservoirs.
• Evaluation of all non-productive structures (green fields).
• Search for rich TZ/ROZ fairways.
• Estimation of CO$_2$-EOR potential in TZ/ROZ.
• Communication and cooperative with oil companies.
Thanks

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