Residual Oil Zones: The Long term Future of Enhanced Oil Recovery in the Permian Basin and Elsewhere*

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Abstract

Residual Oil Zones (ROZ's) have for 60 years intrigued both explorationists and production engineers and geologists. ROZ's have very similar core, cuttings, fluid and log properties as producing wells in modern waterfloods, and typically produce large volumes of water but little if any oil on tests. They are the result of "Mother Nature's Waterflood" during the Cenozoic, as tectonically driven lateral flushing has swept oil and connate fluids out of the lower portions of Permian Basin oil reservoirs.

Over the past two decades, a number of operators have demonstrated that ROZ's beneath existing fields are economically viable targets for EOR. These ROZ's are only producible with tertiary recovery methods (CO₂ and, presumably, Chemical) and it is estimated that there are >10 Billion barrels of recoverable reserves in the ROZ's in the upper Guadalupian carbonate reservoirs in the Permian Basin alone. "Greenfields" are areas with no associated Main Pay zones, where significant thicknesses of ROZ's exist. Large areas on the northern Central Basin Platform and the Northwest Shelf are believed to be underlain by San Andres Greenfields. These areas also have multi-billion barrel potential and can serve as sites for combined CO₂ EOR and Carbon Sequestration.

There are additional ROZ's in other producing intervals in the Basin which await documentation. Substantial ROZ's are believed to also exist in other basins in the U.S.. Regional and reservoir modeling of this natural waterflood process is ongoing.
References


“Residual Oil Zones: The Long Term Future of Enhanced Oil Recovery in the Permian Basin and Elsewhere”.

Dr. Bob Trentham, University of Texas of the Permian Basin.
The 100 Billion Barrel Question

• For decades, when asked, geologists would say there were +/-100 BB OOIP in the Permian Basin and that we have produced roughly ~1/3 of that total.
• 75 MYA the answer to that question may have been 300 BB OOIP.
• Today, with our new understanding of the potential extent of, and oil saturation within, Residual Oil Zones (ROZ’s) the answer lies somewhere between those numbers.
• How did we get here from there?
• Throughout Mother Nature’s Waterflood.
### Size of the Prize

56 fields in five major Permian Basin oil plays that have potential for significant TZ/ROZ resources were identified by Advanced Resources Intl. TZ/ROZ OOIP in these 56 fields is estimated to be 30.7 Billion Barrels.

<table>
<thead>
<tr>
<th>Field/Unit</th>
<th>MPZ OOIP (BB)</th>
<th>TZ/ROZ OOIP (BB)</th>
<th>No. of Fields</th>
<th>No. of MPZ Fields with CO2-EOR Projects</th>
<th>No. of Fields with TZ/ROZ CO2-EOR Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Northern Shelf Permian Basin (San Andres)</td>
<td>13.0</td>
<td>13.2</td>
<td>13</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>2. North Central Basin Platform (San Andres/Grayburg)</td>
<td>2.9</td>
<td>2.6</td>
<td>6</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3. South Central Basin Platform (San Andres/Grayburg)</td>
<td>9.9</td>
<td>7.9</td>
<td>16</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>4. Horseshoe Atoll (Canyon)</td>
<td>5.4</td>
<td>2.9</td>
<td>10</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>5. East New Mexico (San Andres)</td>
<td>2.3</td>
<td>4.1</td>
<td>11</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>33.5</strong></td>
<td><strong>30.7</strong></td>
<td><strong>56</strong></td>
<td><strong>18</strong></td>
<td><strong>4</strong></td>
</tr>
</tbody>
</table>

Koperna, et, al., 2006
### Technically Recoverable Resources from the MPZ and ROZ

Based on reservoir modeling of applying CO$_2$-EOR to the TZ/ROZ resources, ARI estimates that there are **11.9 Billion BO is technically recoverable from the 30.7 Billion BO of TZ/ROZ oil in-place** in these five Permian Basin oil plays.

<table>
<thead>
<tr>
<th>Field/Unit</th>
<th>Total CO$_2$-EOR (BB)</th>
<th>MPZ CO$_2$-EOR (BB)</th>
<th>TZ/ROZ CO$_2$-EOR (BB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Northern Shelf Permian Basin (San Andres)</td>
<td>8.3</td>
<td>2.8</td>
<td>5.5</td>
</tr>
<tr>
<td>2. North Central Basin Platform (San Andres/Grayburg)</td>
<td>1.5</td>
<td>0.6</td>
<td>0.9</td>
</tr>
<tr>
<td>3. South Central Basin Platform (San Andres/Grayburg)</td>
<td>4.6</td>
<td>1.7</td>
<td>2.9</td>
</tr>
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<td>2.7</td>
<td>1.4</td>
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<td>1.7</td>
<td>0.4</td>
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</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>18.8</strong></td>
<td><strong>6.9</strong></td>
<td><strong>11.9</strong></td>
</tr>
</tbody>
</table>

Koperna, et al., 2006
Mother Nature’s Waterflood
Changes in Hydrodynamic Conditions, Sweep of the lower part of the Oil Column, and Development of a Residual Oil Zone.

Uplift to the west of Permian Basin

Meteoric drive

Dynamic System

Areas with ROZ without associated field
### Timing of Post Permian Tectonic Overprint and Meteoric Flushing

<table>
<thead>
<tr>
<th>Era</th>
<th>Time Span</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
<td>Pliocene - Pleistocene - Holocene -5 Ma to Present</td>
<td>Base level downcutting of ancestral Pecos River. At ~600 Ka Capitan Aquifer hydrologically connects with Pecos River at Carlsbad. Possible draining of lower Carlsbad and Lechuguilla Caverns.</td>
</tr>
<tr>
<td></td>
<td>Late Miocene -12 to -5 Ma</td>
<td>H2S ascends into Guadalupe Mtns from basin. Sulfuric acid caves develop from SE to NE, enlarge and cut across older thermal caves.</td>
</tr>
<tr>
<td></td>
<td>Paleocene -65 to -58 Ma</td>
<td>Laramide uplift continues into Early Tertiary. Older caves get enlarged and connected.</td>
</tr>
<tr>
<td>Meso</td>
<td>Cretaceous-Gulfian -95 to -65 Ma</td>
<td>Late Cretaceous Laramide Orogeny begins. Guadalupe and Apache Mtns. Lifted 1000’s of feet above sea level.</td>
</tr>
<tr>
<td>Paleo</td>
<td>Guadalupian -255 to -251 Ma</td>
<td>Seven Rives Yates and Tansill Backreef, Capitan Reef, Delaware Mountain Group Deposition. Early dolomitization in Apache and Glass Mountains.</td>
</tr>
</tbody>
</table>

The top of the San Andres was uplifted over 7000’ by the tectonism. A gradient of ~80’ mile exists today between the Guadalupe Mountains (+6000’) and the Central Basin Platform (-1000’).

Modified from Hill, 1996
Bob Lindsay, correlated outcrops to Guadalupian fields, identifying the flushing pathway of “Mother Nature’s Waterflood” and framed it’s history.
Alton Brown documented the distribution of Tilted Oil-Water Contacts in the Northern Shelf and Central Basin Platform Areas of the Permian Basin*

The direction of OWC tilt may be influenced by the age of the producing interval and it’s relationship to the shelf margin.

* Brown, 1999,
** Ward et al, 1986
Proximity to the recharge. Relationship of San Andres outcrops and San Andres Fairways in New Mexico.
THEORIZED (U. PERMIAN) HYDRODYNAMIC FAIRWAYS

There are a number of probable pathways that will eventually documented
The Gold Standard
Seminole Water Saturation Profile.

- **Reservoir Description**: Limestone and dolomite deposited in a shallow carbonate ramp environment.

- **Fluid Type**: Saturated black oil.

- **Drive Mechanism**: Gas in solution and gas cap during primary. External energy from water and CO2 injection during secondary and tertiary recovery.

- **Develop. History**:
  - 1936 Discovery
  - 1936 First Production
  - 1969 Unitized/Waterflood
  - 1983 MPZ CO2 Flood Begins
  - 1996 ROZ Phase 1 Pilot
  - 2004 ROZ Phase 2 Pilot
  - 2007 ROZ Stage 1

- **Cumulative Production**: 675 MMBO, 40 MMBOE NGL, 702 BCF HC Gas.

- **Current Rate**: 19.6 MBOPD, 200 MMCFD CO2+HC, 25,500 MBOEPD (Oil+NGL+Gas).

The diagram illustrates the water saturation profile with the following zones:

- **Producing Oil Contact**
- **Transition Zone (TZ)**
- **Residual Oil Zone (ROZ)**

The graph indicates the relationship between water saturation and height, with the base of oil saturation at the bottom and water saturation ranging from 0% to 100%.
Anecdotal Evidence

- Info from a growing number of exploration wells documents what can be interpreted as ROZ’s where the tests were unsuccessful as there was no associated primary production. Data from a number of explorationists and review and reinterpretation of research articles on Permian Basin fields, suggest a set of common ROZ characteristics:
  - Sample shows of oil and/or gas throughout the ROZ interval,
  - Sulfur water or salty sulfur produced on DST’s or attempted production tests, not salt water,
  - Cores with 20-40% oil saturation,
  - Log calculations that suggest producible hydrocarbons,
  - IP’s similar to mature waterflood.

- Evaporites may be dissolved or altered in the lower part of the main pay.
- The presence of sulfur crystals associated with gypsum/anhydrite/calcite in the ROZ,
- Solution enhanced fractures in lower portion of the ROZ
- Enhanced porosity and permeability in the ROZ relative to in the main pay zone as the result of meteoric dissolution of sulfates.
- Pervasive “late” dolomitization indicating meteoric sweep.
- “Tight” high So intervals near the BOSO transition.
- Sequence stratigraphic boundaries to top and bottom of ROZ.
- Possible oil and water chemistry differences between main pay and ROZ.
The new Residual Oil Zone Paradigms

• Large intervals and areas have been swept by the tectonically driven “Mother Natures Waterflood” which occurred post basin subsidence and oil emplacement.
• Thick intervals within the ROZ’s intervals have the same saturation characteristics as mature waterfloods (30-40% Sorw).
• Tests of ROZ’s produce high percentage of water on DST’s or completions, but not a “deal killer”.
• ROZ’s often are interpreted/calculated as producible in Exploration Wells, and Primary and Secondary Production Environments:
  – Good Odor, Cut, Fluorescence, and Gas in samples
  – 20 -40 % oil saturations in core
  – Calculate as oil productive on logs
• The “faux-productive” appearance of ROZ’s with significant thicknesses (50 to 300’) of CO2 EOR producible hydrocarbons and 20-50% So exist beneath both producing fields (Brown Fields) and in areas where there is no, or a minimum, producible oil column (Green Fields).
Pre Laramide
Original Oil Water contact at base of present ROZ
Post Basin and Range -
Flow units, deeper in the reservoir and with higher permeability are swept

Field Wide - Tidal Flat/Sabkha provide updip permeability trap.
MP - Flow units within Main Pay unaffected by Meteoric derived sweep.
ROZ - Updip shallow subtidal and intertidal will produce low volumes/low water cut
Downdip higher energy shelf produces “Mature Waterflood” oil cuts and volumes
Post Basin and Range
Most higher permeability Flow Units are Swept

Field Wide - Tidal Flat/Sabkha provide updip permeability trap.
Main Pay- Either thin producing interval or no associated producing interval
ROZ - Updip shallow subtidal and intertidal will produce low volumes/ low water cut
Downdip higher energy shelf with “Mature Waterflood” oil cuts & large volumes
Post Basin and Range
Updip shallow subtidal and Intertidal are productive, downdip swept with mature waterflood IP’s

Well 5. Wet
Attempted completion in ROZ deeper than Well 3

Well 4. Wet
Attempted completion in Well 2 zone

Well 3. Wet
Attempted completion in ROZ only

Well 2. Producer
Lower Volumes from tite facies

Well 1. DH
All intervals tite

Wells drilled in different portions of the interval will have different recoveries.
W. A. Estes “Holt” Field (actually Glorieta)
Discovered in 1991, produced over 1MMBO from a small closure with “tight” tidal flat and shallow subtidal carbonates. Why did it take so long to discover it?

It’s a cap for a thick porous dolomite considered to be the “pay” in the area. The interval had shows & calculated as productive, DST’s a skim of oil and lots of sulfur water, tested a few times and left alone.

What is going on? It’s postulated that the lower, porous portion was swept and only the tight, up-dip facies were left with >70% $S_o$.

Thick, porous ROZ with CO2 potential?

The pay is the upper Glorieta/San Angelo. The more porous lower section calculates as productive on logs and is oil stained BUT 100% sulfur water productive.
Outer Shelf to Tidal Flat
The updip section thinned by pre San Andres tilt and Erosion

- Fluor, Cut, Minor Gas
- No Shows
- Sulfur Water
- Tight
What is the impact of the prograding Capitan Reef?
Eunice Monument/South Monument

- Grayburg productive with NaCl rich connate water
- San Andres mostly wet with sulfate rich connate water
- Two different sources for the connate waters
- Thickness of San Andres swept reservoir?

**Eunice Monument South Unit** Productive from the Grayburg with minor production from the underlying San Andres Formation—

- Discovery Oil/Water contact - 350’
- Unitization Oil/Water contact - 540’
- Deepest Grayburg Oil in core - 664’
- Deepest San Andres Oil in core - 719’

- >300’ thick SADR w/oil saturation below O/W in Eunice Monument
North Monument Grayburg, Eunice Monument, Eunice Monument South "B", Eunice Monument South, and Arrowhead Grayburg Unit.

- Area combined total of 57 square miles.
- Lindsay suggests the sulfate poor edge water is recharged from the Guadalupe Mountains thru the Goat Seep Reef. The Sulfate-rich bottom water drive in the San Andres is recharged from the Sacramento Mountain thru the evaporite rich San Andres. **Eunice Monument South Unit.** The edge water was pulled into the oil leg since production was established in 1929 (from Lindsey, Chevron in-house pubs).
- Structural closures formed by re-activation of existing deep seated faults which folded and fractured the Permian. The structural event increased closure on the reservoir and trapped a larger oil column.

- **Eunice Monument**
  - -150 G/O, -400’ O/W (150’ below top SADR).
  - Na 2000ppm, Cl 2950ppm, TDS 7800PPM (similar to Capitan Reef in Winkler Co.)

Lindsay (2000)
The two meteoric sourced waters take different pathways.

What happens when the entire oil column is swept by Mother Nature?
"Green Field" an ROZ without an associated field.

Your left with a tertiary recovery target.
Gaines, Future Targets or goat pasture?

- A Clearfork test, the **IP #1 Campbell Heirs “158”** pipe on “WET” San Andres test just south of Seminole.
- All wireline logs, drill time, gas curves and sample shows said “slam dunk” oil production. Atlas log analyst said it should be a producer.
- 100% water test with barely a sniff of live oil. ROZ?
- **Anschutz #1 Patrick Keating “447”**, drilled for San Andres west of Seminole, had good shows but made only water for a few months before P & A (3600 BW, 3 BO). Water analyses show progressive drop in TDS over the two months of production.
- The 2 CORED intervals, from 5464 – 5602, had oil saturations ranging from 15 to 35%, 3 - 12% porosity, & 50-100% fluorescence.
- These are what we term “GREENFIELDS”
- TZ/ROZ’s are “BROWNFIELDSD”. 
ROZ Regional Context

• Establish regional flow paths through and between reservoirs along the “reservoir trend”.
• Modeling to establish inflow and outflow pathways.
• Determine timing of oil emplacement(s) relative to potential regional sweep events.
• Develop a regional understanding and time line for the relationships among major post depositional/oil emplacement tectonic events and the meteoric associated flushing that create the ROZ’s.
• Understand the impact of tectonic events on the fluid/rock properties along the reservoir trend.
• Characterize the difference and similarities between “classic” reservoir and Residual Oil Zone (ROZ) Reservoir.
Regional San Andres

- Placing the San Andres in a regional context is important in understanding the development of the ROZ’s.
- The San Andres can be divided into three intervals:
  - A lower San Andres composed of L7 & L8 (Holt) and G1 & G2 (McKnight),
  - a middle San Andres composed of G3-G4 (Intermediate), and
  - an upper San Andres composed of G8-G9 (Pre- and Post-Lovingston Sand).
- In addition, the southern end of the Central Basin Platform has had a different tectonic history then the northern end of the platform, the Northwest Shelf and the Guadalupe Mountains.
The major San Andres Sequence Stratigraphic boundaries may act as the boundaries for the original O/W (base of ROZ) and between the present day Main Pay and TZ/ROZ.
The “top” of the San Andres can be anywhere. As a result of PERMIAN tectonism, the San Andres can range from 650 to 1650’ thick.
“Early” Reservoir Parameters

Main Pay
- >80% So
- Salt Water – higher TDS
- Will respond to Waterflood
- CO2 EOR Potential
- Dolomite Reservoir
- Infill potential
- More Karst
- No Sulfur in cuttings and core
- Lower Porosity and Permeability
- Mixed wet
- No Greenfield Potential
- Oil Gravity
- Man made flowpaths /fractures

Residual Oil Zone
- 20 to 40% So
- Sulfur Water – lower TDS
- NO waterflood potential
- CO2 EOR Potential
- Dolomite Reservoir
- Deepening potential
- Less Karst
- Sulfur in cuttings and core
- Higher Porosity and Permeability
- Wettability issues
- Greenfield Potential
- Oil Gravity
- “Virgin” Reservoir Conditions
### “Late” Reservoir Parameters

<table>
<thead>
<tr>
<th>Waterflooded Main Pay</th>
<th>Residual Oil Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 to 40% So</td>
<td>20 to 40% So</td>
</tr>
<tr>
<td>Salt Water – ???? TDS</td>
<td>Sulfur Water – lower TDS</td>
</tr>
<tr>
<td>No remaining Waterflood Potential</td>
<td>NO waterflood potential</td>
</tr>
<tr>
<td>CO2 EOR Potential</td>
<td>CO2 EOR Potential</td>
</tr>
<tr>
<td>Well known reservoir parameters</td>
<td>Estimated reservoir parameters</td>
</tr>
<tr>
<td>Enhanced high perm streaks</td>
<td>Potentially more homogeneous</td>
</tr>
<tr>
<td>Mixed wetability</td>
<td>Wettability questions</td>
</tr>
<tr>
<td>Man made flowpaths /fractures</td>
<td>Untouched</td>
</tr>
</tbody>
</table>
The first modeled Fairway is the “Artesia” Fairway and the west side of the Central Basin Platform.
Some other questions to consider:

- The total thickness of the San Andres at major producing field ranges from 650-750’ [Yates and Goldsmith] to 1400 to 1600’ [Seminole to Vacuum], yet,
  - The ratio of ROZ to main pay thickness in many of those large field may remain close to 1:1.
  - In other fields the thickness of the ROZ can equal or exceed the thickness of the main pay AND the ROZ elsewhere, and
  - Where there is no main pay, “Greenfields”, the ROZ can be 50 – 300’ thick or more. WHY?
- Why is there no major San Andres, Grayburg or Clearfork production south of the Texas/New Mexico border on the west side of the Central Basin Platform?
- How many pore volumes of water passed through the ROZR during Mother Nature’s Waterflood (MNW)?
- How does that relate to the volumes of water that passed through our Main Pays during modern Waterfloods.
- Consider the time frame in which these two “sweeps” occur, would you expect to see the same results?
- Significant ROZ’s appear to be present in the Leonard (Glorieta and upper and lower Clearfork) which are below the San Andres (Guadalupian) path across the San Simon channel.
Camels passing through the eye of a needle

- Dolomitizing pathways.
- Basin dewatering is often invoked for late dolomitization of reservoirs.
- How many pore volumes can you pass through a reservoir when the updip traps are sabkha’s?
- What is the pathway down dip to up dip then parallel to the margin?
Working backward from what we see.
Characteristics of the ROZ vs. the Main Pay.

- Sulfur crystals associated with anhydrite and calcite in vuggy porosity at the Base of ROZR.
- Patchy high oil saturation above/at/below the Base of Saturation of Oil (BOSO) in low permeability intervals.
- Late stage solution enhanced fractures
- Solid Hydrocarbon Residue
- Oil Chemistry differences
- Oil Gravity differences
- Transition from limestone below the ROZ reservoir, to dolomite within the ROZ reservoir.
- Relationship of Limestone to dolomite transition to Sequence Stratigraphic Boundaries
- Enhanced Porosity due to the limestone-to-dolomite conversion
- Enhanced Porosity due to the dissolution of evaporites
- Enhanced Permeability due to limestone to dolomite conversion and secondary dolomitization
- Changes in wettability
- Vertical ROZ salinity variations
- Lateral/Trend salinity variations
- Chloride to sulfate water transition
- Bow Shaped, Pervasively Dolomitized Intervals (PDI)
- Relationship between ROZ and MP thickness.
- 90 degree turn for fluids
- Relationship of MP/ROZ/100% water transitions to Sequence Stratigraphic boundaries.
Summary

- We’ve only just begun.
- ROZ’s are real and a major tertiary recovery target for today and long into the future.
- Modeling using regional scale groundwater modeling package is underway.
- Documentation of areas/fields with potential is underway.
- Phase 2 – testing models in the field has begun.
- A number of presentations have been/or will be made and can be found on our RPSEA supported website: Residualoilzones.com.

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