“Residual Oil Zone’s (ROZ’s) as an Unconventional Target
Enhanced Oil Recovery and Carbon Capture Utilization and Storage (CCUS):

CO2 for EOR as CCUS
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\textsuperscript{i}CEED/UTPB-MC, \textsuperscript{ii}Melzer Consulting, \textsuperscript{iii}Arcadis U. S.
• Regional Understanding
• Model of “Mother Nature’s Waterflood”
• The Gold Standard – Seminole Field
• Goldsmith – Independent’s view of CO2 in ROZ’s
• Greenfields
• What Does an ROZ look like?
• Size of the Prize
Our Final Report on the Modeling Project has been submitted and accepted by the Research Partnership to Secure Energy for America (RPSEA).
Key Findings

• The meteoric derived sweep of oil from the ROZ portion of San Andres reservoirs was probable.

• Modeled pore volume flushing in the Artesia Fairway ranges from 20 to 50 pore volumes over 15 million years (Late Oligocene through Middle Miocene), with flow rates of 10 to 25 cm/year.

• This hydrodynamic origin can also explain the Oil/Water contact tilts seen in many of the San Andres reservoirs at the time of discovery.
There are a number of probable pathways that will eventually documented
The Modeling Effort

• Used Groundwater Modeling package.
• Input Core, DST, Produced Water, Ground Water, Log Tops.
• Included pre-existing data sets
• Developed a three layer model with variable permeability.

From Hiss (1975)
Low Permeability
Upper San Andres Top Seal
0.1 mD

Intermed Perm
Outer Shelf Dolomite
0.4-1.0 mD

Hgh Perm Fairway Dolomite
10-40 mD
100 mD

Intermed Perm Inner Shelf Dolomite
0.4-1.0 mD

Updip Low Perm Sabkha
0.1 mD

Low Permeability
Lower San Andres Limestone
0.1 mD
### Horizontal Fluid Movement per 1000 years

<table>
<thead>
<tr>
<th>Conductivity Zone</th>
<th>Velocity (ft/1,000 years)</th>
<th>Velocity (ft/1,000 years)</th>
<th>Velocity (ft/1,000 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer One</td>
<td>1.9</td>
<td>1.1</td>
<td>0.7</td>
</tr>
<tr>
<td>Layer Two – Center Zone</td>
<td>738</td>
<td>446</td>
<td>278</td>
</tr>
<tr>
<td>Layer Two – Intermediate Zone</td>
<td>72</td>
<td>44</td>
<td>27</td>
</tr>
<tr>
<td>Layer Two – Edge Zone</td>
<td>7.2</td>
<td>4.3</td>
<td>2.7</td>
</tr>
<tr>
<td>Layer Three</td>
<td>1.9</td>
<td>1.1</td>
<td>0.7</td>
</tr>
</tbody>
</table>
# Time Period and Pore Volumes

<table>
<thead>
<tr>
<th></th>
<th>$n = 6%$</th>
<th>$n = 10%$</th>
<th>$n = 16%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Pore Volume (ft³)</td>
<td>$1.22 \times 10^{11}$</td>
<td>$2.04 \times 10^{11}$</td>
<td>$3.26 \times 10^{11}$</td>
</tr>
<tr>
<td>Flow Rate (ft³/day)</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Time Period (Million Years)</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Total Flow (cubic feet)</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Number of Pore Flushes</td>
<td>46.0</td>
<td>27.7</td>
<td>17.3</td>
</tr>
</tbody>
</table>
Modeling of the system that created “Mother Natures Waterflood” will be completed as part of this study.

- The large sulfur deposits in northern Pecos County are believed to represent one exit point on the Central Basin Platform for the flushed oil and meteoric waters.
- These deposits are the result of the mutual occurrence of Water, Oil and a Source of Sulfur
  - Water – from the meteoric system
  - Flushed Oil (Replenishing the Food for the Anaerobes)
  - Sulfur – from dissolution of evaporites
    - As the Source of H₂S (and Sour Oil)
- The Sulfur Deposits (product-of-reaction, residue)
  - Are Proof of Oil ‘Passing By’
  - Fairways of Oil Movement
  - As Proof of Oil ‘Consumption’
Seminole Field – The Gold Standard for Brownfield ROZ’s

Pilot Area for the SSAU ROZ Phase I Pilot

Reference 2a
<table>
<thead>
<tr>
<th></th>
<th>Gross Thickness</th>
<th>Net Thickness</th>
<th>Porosity</th>
<th>Permeability Range</th>
<th>OOIP</th>
<th>Oil Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main Pay Zone (MPZ):</strong></td>
<td>160’</td>
<td>126’</td>
<td>12%</td>
<td>0.8-120 md</td>
<td>1 billion stbo</td>
<td>0.84</td>
</tr>
<tr>
<td><strong>Residual Oil Zone (ROZ):</strong></td>
<td>246’</td>
<td>197’</td>
<td>12.6%</td>
<td>0.5-270 md</td>
<td>0.4-1.1 billion stbo</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Reference 2a
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
  - 1938 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**: 19.5 MBOPD, 200 MMCFD CO2+HC 25,500 MBOEPD (Oil+NGL+Gas)

**Diagram Notes**:
- **Producing O/W Contact**
- **Base of Oil Saturation**
- **Residual Oil Zone (ROZ)**
- **Transition Zone (TZ)**
- **Conventionally Productive Oil Zone**
- **Average Oil Saturation Profile**

**Graph Axes**:
- **Water Saturation (%)**
- **Height**
- **ROZ Stage 1 (2007)**
- **ROZ Phase II (2004)**
- **ROZ Phase I (1996)**
Seminole San Andres Unit
Stage 1 Project Area

- Objective: Begin full field development of the Residual Oil Zone
- Twenty-nine 80 acre patterns with inverted five-spots
- Injection commenced October 31, 2007
- Plant Expansion of 70 MMSCFD (Complete Q2 2009)
- Gross capital cost of $132 MM field, $148 MM plant

Figure 12
SECTION - OIL CONTACT
CONTOUR INTERVAL: 10 FT.

SEMINOLE - SAN ANDRES UNIT

47 - MPZ/ROZ Producers
29 - ROZ Only Injectors

December 4, 2008
Summer 2013 Update

• The Two Pilots Plus Stages 1 & 2 now Making >8,000 BOPD

• Now in Stage 3 and Work Underway for implementing Stage 4

• All ROZ Projects in the Permian Basin are Making in Excess of 12,000 BOPD

• With a utilization factor of 10 MCF CO2/barrel of oil, 120 MMCF CO2 are “utilized” a day in the ROZ’s portions of floods alone.
GLSAU 203R – A CO2 Flood Front Caught in the Act

Core Saturations

Apr-2013
Legado Coring Program

Goldsmith-Landreth San Andres Unit

203W  989 fnl, 2360 fwI
203RW  979 fnl, 2495 fwI
So_corrected to reservoir conditions (%)

Core Analysis Shows Similar Saturation Values Between the Main Pay and the ROZ
Detailed Core Description of the GLSAU #190 Well, Goldsmith Landreth Unit, Ector County, Texas. NOTE WELL DEVELOPED MAXIMUM FLOODING SURFACES MARKED WITH BLACK ARROWS
GLSAU #203R – Background

1. Observed major CO\textsubscript{2} injection into LROZ zone in 203w initial profile (MP+ROZ) from 2009.
2. Observed oil and gas response from #190 in 2009 prior to having compression in place.
3. **Plugged back LROZ** and MP in #203 injector (10/2009) - completed as Upper ROZ only injector.
4. Subsequent 203 profiles showed major injection into Upper ROZ.
5. Drilled 203 replacement in 2013 for improved wellbore and to re-establish injection into Lower ROZ.
6. RFT data from 203 replacement well showed elevated pressures in all zones (confirming general injection support in MP and ROZ for the area), with maximum local pressures occurring in the completed Upper ROZ zone (suggests CO\textsubscript{2} injection remained concentrated in Upper ROZ).
7. Obtained core from the 203 replacement well in 2013 and ran routine analysis using Core Labs.
   - Confirmed significant reduction to oil saturations in the equivalent 203W completed UROZ interval (4285-4370) with nearly 40% of the samples being reduced below 15% Sor (versus <2% of pre-CO\textsubscript{2} flood samples measuring below 15%)
   - Saturations in the UROZ completed interval were much lower than both the pre-CO\textsubscript{2} flood oil saturations and the post-CO\textsubscript{2} flood oil saturations in the non-completed LROZ & MP intervals.
   - Results suggest the 203W workover to plug back the LROZ in 2009 was successful at isolating CO\textsubscript{2} injection from that zone.
8. **Completed the Lower ROZ in 203 RW and tested on 4/22/2013.** Flowed ~25 BPH at 5% oil cut with very little gas (FTP 100 psi), confirming isolation from #203W and banked ROZ oil from **miscible CO\textsubscript{2} flood process** (typical oil cut prior to CO\textsubscript{2} is <1%).

Core oil saturations in the 203R demonstrate varying degrees of miscible displacement maturity throughout the Main Pay & ROZ, corresponding to the offset completed CO\textsubscript{2} injection intervals.
GLSAU #203R – Post CO₂ Flood S₀ vs Offset Pre-CO₂ Flood S₀

**203R Post CO₂ Flood Oil Saturations**
(data is taken from intervals not completed in offset #203w: 975-1080, 1162-1190 subsea)
- Data exhibits some evidence of the miscible CO₂ process with a combination of elevated saturations (banked oil) and also some samples reduced oil saturations

**203R Post CO₂ Flood Oil Saturations**
(data is taken from intervals completed in offset #203w: 1080-1162 subsea)
- Data exhibits significant reduction in oil saturation with ~ 40% of samples below 15% S₀

**Pre-CO₂ Flood Oil Saturations**
(data is taken from 190 & 204R cored MP and ROZ intervals in 2008 & 2009)
Velocity shows CO2 injection across completed UROZ interval. SI vs Injecting Temp survey suggests major storage from MTS 2 down to just above LROZ. Temperature reflects packer effect.

Core shows major reduction to oil saturation in Upper ROZ.

Max RFT pressures measured in Upper ROZ.

Plugged Back completion interval (ran liner in 4Q-2009).

GLSAU #203R & 203w – Completion Intervals & Inj Profile Results
GLSAU 204R and 203RW Saturation Comparisons

Pre-\(\text{CO}_2\) Flood 2009

Post-\(\text{CO}_2\) Flood 2013

Green > 15% Reservoir –corrected Sor
What happens when the entire oil column is swept by Mother Nature?
Your left with a tertiary recovery target.

GREENFIELDS
Anecdotal Evidence

The anecdotal evidence from a growing number of exploration wells documents examples of what can be interpreted as ROZ’s where the tests were unsuccessful as there was no associated primary production. From discussions with a number of explorationists and review and reinterpretation of research articles on Permian Basin fields, a set of common ROZ characteristics is developing:

- The presence of sulfur crystals associated with gypsum in the swept carbonates,
- Evaporites may be dissolved or altered in the lower part of the main pay.
- Enhanced porosity and permeability developed as the result of meteoric dissolution of sulfates in the ROZ.
- Sample shows of oil and/or gas,
- Sulfur water produced on DST’s or attempted production tests not salt water,
- Core with 10-40% oil saturation,
- Log calculations that suggest producible hydrocarbons.
- Porosities and Permeabilities can be higher in the ROZ than in the main pay zone as a result of the meteoric dissolution.
- Pervasive “late” dolomitization may indicate meteoric sweep.
Gaines, Future Targets or goat pasture?

- 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.
Westland
#1 Carpenter “281”
Drilled on the west edge of Seminole N. E.
Core with oil,
DST with Oil, Gas, and Sulfur Water.
Produced 264 BO from upper perfs.

Over 400’ of possible ROZ based on shows and gas on sample logs.
George Allen Field. Peripheral ROZ Flood.

The George Allen Field, discovered in 1956, has recently been the site of the development of 2 “rings” of wells (Blue Box) of CO2 producers and injectors OUTSIDE the original boundaries of the field.
When does a “One Of a Kind” become a Trend?

• There appears to be a number of attributes of the BOSO at or near the base of the ROZ:
  – Large vugs (removed Anhydrite Nodules) filled or partially filled with SULFUR
  – “Spotty” oil stain/SHR/Dead Oil in the tight portions of more porous intervals
  – Transition from dolomite above to limestone below
  – The presence of a baffle or barrier to vertical flow (Sequence or Cycle Set Boundary)
  – Solution enhanced fractures
Gypsum with Sulfur
Calcite with Sulfur
Late solution enhanced features with no SHR on faces
“Spotty” high oil saturation near BOSO
These late features can be found at or near the base of an ROZ regardless of the formation.
A characteristic “bow” shape on logs is generally present in the ROZs with decreasing resistivity and increasing porosity below the oil/water contacts.
# 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>
<tr>
<td>4. Horseshoe Atoll (Canyon)</td>
<td>2.7</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>5. East New Mexico (San Andres)</td>
<td>1.7</td>
<td>0.4</td>
<td>1.3</td>
</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
Summary

• Our ROZ Team has only just begun their Studies
• ROZ’s are real and a major tertiary recovery target for today and long into the future.
• Modeling using regional scale groundwater modeling package has demonstrated slow hydrodynamic flushing and results consistent with the observed tilted OWCs.
• Documentation of areas/fields with large potential is underway.
• Phase 2 study will give the estimates of ROZ oil in place.