Residual Oil Zones (ROZs):
A Review of ROZ Science and Engineering
(with a Few New Thoughts Thrown in)

Presented at Enhanced Oil Recovery’s Tensleep III Workshop
“ROZ & CO₂ EOR in the Bighorn Basin” - July 8-9, 2013

Steve Melzer
PRESENTATION OVERVIEW

• Transition Zones vs. Residual Oil Zones
• ROZ Science
  – Origins and Predominant Type
  – Log Character and ‘Pervasive’ Dolomitization
  – Greenfields and Brownfields
  – Permian Basin ROZ Distribution
• The Engineering
  – On-going ROZ Projects
  – Waterflood Management
• New ROZ Findings and Wrap-up
Transition Zone Thinking

Bighorn Basin Tensleep Oil Column

Permian Basin Wasson Field Oil Column

Perforation

MPZ

(Tidal Flat Anhydrite, Silts)

TZ

Restricted Lagoon Carbonates, Anhydrites

Oil Column

Already developed by Water Flooding & CO2 Flooding

Transition Zone Potential (Upper 150 ft)

Base of Oil (BOSO)
I think we can say that the Permian Basin industry has broken out of the transition zone mentality.

The Seminole Field (W. Tx) Saturation Profile*

Now, these are the transition zones, so what causes that in the middle?

* Re: Alton Brown, WTGS Fall Symposium (2001)
Thus, the Shapes of These So Curves Have to Be Controlled by More Than Capillarity and Surface Tension

• Why Would You Find Vertical Intervals with Nearly Constant Oil Saturation for 100’ or more?
• We Have Seen Many Fields Go From 70-80% Oil Saturation to 0% in just a Few Vertical Feet? Then Others Transition So Values for a hundred feet.
• How Many Basins Do you Know of that Had Just One Stage of Tectonics? (i.e., the Subsidence and Entrapment Stage)
• A Second (third, fourth...) Stage is Very Common
  – Basinal Tilt (Type I)
  – Faulting, Salt Diapirs, etc. leading to Seal Breaches (II)
  – Uplift and Lateral Sweep (III)
• All Lead to Readjustments of Oil/Water Contacts: Mother Nature’s Waterflood

Engineering

Science
The Science of Residual Oil Zones

(we apologize if this is repetitive)
The Science

- Many Basins in the U.S. have had more than one stage of tectonics affect them
- Any Post Subsidence/Oil Entrapment Stage can move oil around
- The oil industry is expert at looking at where the oil went
- We are just now realizing where it came from is also valuable (let’s call those zones ‘naturally waterflooded’ intervals)
- And, Just Like in Man’s Waterfloods, Nature Leaves Oil Behind the Sweep too
Original Oil Accumulation Under Static Aquifer Conditions (A Hypothetical Example)
Original Accumulation Subject to a (Down-to-the-West) Regional Tilt, a Re-equilibrating Oil/Water Contact, & Forming a ROZ

TYPE 1 ROZ
Original Accumulation with a Breached then Repaired Seal & Forming a ROZ

TYPE 2 ROZ
Change in Hydrodynamic Conditions, Sweep of the Lower Oil Column, Oil/Water Contact Tilt, and Development of the Residual Oil Zone

Areas with ROZ without associated field

Note: Tilted Oil / Water Contact

TYPE 3 ROZ

aka “Laterally Flushed”
SO LET’S INTRODUCE SOME HANDY TERMINOLOGY

IT’S TIME TO TALK ABOUT THE SWEEP IN TERMS OF

BROWNFIELDS* AND GREENFIELDS

Greenfield = Effectively no Main Pay Zone

TYPE 3 ROZ

* Residual Oil Zone Beneath a Main Pay Zone
And...the Concept of Sweep “Fairways”

Karsted Pgs (U. San Andres) Outcrop
Slaughter Fairway
Bottomless Lakes Recharge Field
Roswell Fairway
Artesia Fairway
Animation of the Type 3 (Laterally Flushed) ROZ in the Permian Basin

http://www.melzerconsulting.com/index.php/ongoing-research

*(scroll down to near the bottom)*
So...Do We Think the Lateral Sweep (ROZ Type 3) Predominates?

*What is New, Why is That Important?*

The On-going Research – The (PB) ROZ Study Group and Their Industry Sponsors
MAP OF KEY PERMIAN BASIN FEATURES + SOME KEY FIELDS FOR THIS DISCUSSION

NEW MEXICO
TEXAS
Delaware Mtns.
Guadalupe Mtns.
CARLSBAD
New Mexico
Texas
Delaware Basin
Apache Platform
Hovey Channel
Glass Mtns.
Marathon Fold & Thrust Belt

WASSON FIELD
SEMINOLE FIELD
GOLDSMITH FIELD
YATES FIELD

NEW MEXICO
TEXAS

Diablo Platform
Apache Platform
Glass Mtns.
Hovey Channel
DIABLO CHANNEL

80KM
50 MI

Enhanced Oil Recovery Institute
Melzer Consulting
Distribution of Tilted Oil-Water Contacts in the Northern Shelf & Central Basin Platform Areas of the Permian Basin*

* Adapted from Alton Brown, WTGS Fall Symposium (2001)
The Fields Line up in Fairways But Note the Areas with Missing Fields

(We Will Come Back to this Idea)
But, First....Let’s Talk About a Particularly Significant Observation in the Permian Basin

*We Often Wonder Where Else This Occurs*
IS THERE A “PERVASIVE” DOLOMITIZATION PROCESS?

- Magnesium Rich Flush Waters
- Porosity/Perm Enhancements
- Pervasive Zonations
- Geological Timing (Late Stage, Biogenic Alterations)
- Anhydrite Conversion
Did You Ever Feel You Were Just Out Paddling Along Enjoying Life’s Scenery and....
And you were suddenly caught up in something really big!!!
Permian Basin ROZ Petrophysics

Porosity and PhotoElectric Crosssection Log

Northern PB San Andres Formation Example

PhotoElectric Crosssectional Value of 3:  = Dolomite
(Anhydrite and Calcite = 5+)
Midland Basin Shelf (PB) Log Illustrating ‘Pervasive Dolomitized Interval’ (PDI)
Anaerobic Bacteria

1) Requirements of Life
   1) Have to Live in Water
   2) Eat Components out of the Oil
   3) Have a Source of Sulfur to Get their Oxygen

2) All Requirements Met in the ROZ (not met in the MPZs)

Free Lunch!
Anaerobic Bacteria

1) Requirements of Life
   1) Have to Live in Water
   2) Eat Components out of the Oil
   3) Have a Source of Sulfur to Get their Oxygen

2) All Requirements Met in the ROZ (not met in the MPZs)

3) Evidence of their “Work”
   1) Soured Oil and Gas
   2) Occasional Free Sulfur (especially at the Base of the Flow Unit
   3) Altered Rock Properties

This is Where it gets Interesting
Key Anecdotal Evidence

• Mutual Occurrence of Water, Oil and a Source of Sulfur
  – Water (‘Home’ for the Microbes)
  – Flushed Oil (Replenishing the Food for the Anaerobes)
  – Sulfur (product-of-reaction, residue)
    • As the Source of H₂S (and Sour Oil)
    • As Proof of Oil ‘Passing By’ & Fairways of Oil Movement
    • As Proof of Oil ‘Consumption’
Reservoir ‘Alchemy’

Biogenic Reaction

\[ \text{CaSO}_4 + \text{HC} \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} + \text{H}_2\text{S} \]

Abiotic Chemical Reactions

\[ \text{CaCO}_3 + \text{Mg} \rightarrow \text{MgCa(CO}_3)_2 \]

Picked up as Flush
Water Moves through Mg Salts

Reservoir Rock
Bow-Shaped Log Character
Northern Central Basin Platform Area

Gamma Ray Log

Neutron Log

DST 486' Sulfur
H₂O

First Currings Sample Shows = 6330'

ROZ

Base of Cuttings ‘Strong Flour = 5620'

PDI

6000'

T/Griante
So....Maybe you are **Still** a Transition Zone Loyalist?
Lateral Sweep &
Late Stage* Diagenesis
A “Smoking Gun?”

* Tertiary in Age
Porosity and Sulfur Composition (CES) Log

NE Shelf San Andres Formation (PB) Example

Sulfur Track on CES Log
Increasing Sulfur in the Inverted Transition Zone
Our Latest View of the PB ROZ Fairways

This is our Current “Fairway” Map for Defining the PB Fairways More Completely in our Second RPSEA Grant Awarded (July ‘11)
Shading Represents Latest Mapping of San Andres ROZ “Fairways”

Research Sponsored by the Research Partnership to Secure Energy for America (RPSEA)
ROZ Science Conclusions to Date

- Intervals Below the OWC with Shows Are More Appropriately Viewed as Residual Oil Zones and Owe Their Origins to a Variety of Causes Beyond Transition Zones
- PB ROZ Prevalent Type is Type 3: Laterally Flushed
- ROZs Can be Very Thick and Contain Huge Amounts of Oil
- ROZs Can Lie Below Main Payzones (Brownfields) and Exist Where no Main Payzones are Present (Greenfields)
- There are ‘Fairways’ of Sweep and, if the Swept Interval was an Oil Entrapment in the Past, a ROZ will be present
- On-going Regional Work Illustrates that PB ROZs have Log Characteristics and Rock Properties Differing from the Main Payzones Requiring Biogenic Diagenesis and a Late Stage Dolomitic Overprint
“Science is really special…. but it is WONDERFUL if it matters economically” ¹

¹ Not Sure Who First Said That (wish it were me)
ROZ Engineering
CO$_2$ Enhanced Oil Recovery

- 143 on-going projects Worldwide
- Making about 392,000 bopd of which almost 80% of that (306,000) is directly attributable to CO$_2$ EOR
- Permian Basin has 68 active projects and all of these but three started with a tertiary stage (post waterflood) of a main pay zone
- Twelve of these projects have now extended injection to below the Oil/Water Contact (OWC); One is a Greenfield
- The Permian Basin (San Andres) is the only place in the world exploiting oil below the OWCs (so far......at least)
# The List of ROZ CO₂ EOR Projects

## ON-GOING AND PLANNED ROZ CO₂ EOR PROJECTS

**IN THE PERMIAN BASIN REGION OF THE U.S.**

<table>
<thead>
<tr>
<th>Type and operator</th>
<th>Field</th>
<th>State</th>
<th>County</th>
<th>Top MPZ Depth, (ft)</th>
<th>Pay zone</th>
<th>Lithology</th>
<th>MPZ Start Date</th>
<th>ROZ Start Date</th>
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</thead>
<tbody>
<tr>
<td><strong>Active CO₂ miscible</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Chevron</td>
<td>Vacuum San Andres Grayburg Unit</td>
<td>NM</td>
<td>Lea Co.</td>
<td>4,550</td>
<td>San Andres</td>
<td>Dolo.</td>
<td>2007</td>
<td>2007</td>
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<tr>
<td>2. Fasken</td>
<td>Hanford</td>
<td>Tex.</td>
<td>Gaines</td>
<td>5,500</td>
<td>San Andres</td>
<td>Dolo.</td>
<td>7/86</td>
<td>8/09</td>
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<td>3. Hess</td>
<td>Seminole Unit-ROZ Phase 1</td>
<td>Tex.</td>
<td>Gaines</td>
<td>5,500</td>
<td>San Andres</td>
<td>Dolo.</td>
<td>7/83</td>
<td>7/96</td>
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<tr>
<td>4. Hess</td>
<td>Seminole Unit-ROZ Phase 2</td>
<td>Tex.</td>
<td>Gaines</td>
<td>5,500</td>
<td>San Andres</td>
<td>Dolo.</td>
<td>7/83</td>
<td>4/04</td>
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<td>5. Hess</td>
<td>Seminole Unit-ROZ Stage 1 Full Field Dev</td>
<td>Tex.</td>
<td>Gaines</td>
<td>5,500</td>
<td>San Andres</td>
<td>Dolo.</td>
<td>7/83</td>
<td>10/07</td>
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<td>6. Hess</td>
<td>Seminole Unit-ROZ Stage 2 Full Field Dev</td>
<td>Tex.</td>
<td>Gaines</td>
<td>5,500</td>
<td>San Andres</td>
<td>Dolo.</td>
<td>7/83</td>
<td>5/11</td>
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<td>7. Legado</td>
<td>Goldsmith-Landreth Unit</td>
<td>Tex.</td>
<td>Ector</td>
<td>4,200</td>
<td>San Andres</td>
<td>Dolo.</td>
<td>8/09</td>
<td>8/09</td>
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<td>8. Occidental</td>
<td>Wasson Bennett Ranch Unit</td>
<td>Tex.</td>
<td>Yoakum</td>
<td>5,250</td>
<td>San Andres</td>
<td>Dolo.</td>
<td>6/95</td>
<td>2000</td>
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<td>10. Occidental</td>
<td>Wasson ODC</td>
<td>Tex.</td>
<td>&amp; Gaines</td>
<td>5,200</td>
<td>San Andres</td>
<td>Dolo.</td>
<td>Nov-84</td>
<td>2005?</td>
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<td><strong>Planned CO₂ miscible</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>16. XTO</td>
<td>CA Goldsmith</td>
<td>Tex.</td>
<td>Ector</td>
<td>4,200</td>
<td>San Andres</td>
<td>Dolo.</td>
<td>2013</td>
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<td>17. Tabula Rasa</td>
<td>East Seminole</td>
<td>Tex.</td>
<td>Gaines</td>
<td>5,400</td>
<td>San Andres</td>
<td>Dolo.</td>
<td>2013</td>
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<td>18. Undisclosed</td>
<td>Greenfield (GF) ROZ</td>
<td>Tex.</td>
<td>Undisclosed</td>
<td></td>
<td>San Andres</td>
<td>Dolo.</td>
<td>n/a</td>
<td>2013</td>
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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
Seminole Field: Water Saturation Profile*

* from Brown, A. (1991)
EXTENDING THE EOR BELOW THE OIL/WATER CONTACT

<table>
<thead>
<tr>
<th>Main Pay Zone (MPZ):</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></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>Residual Oil Zone (ROZ):</td>
<td>246’</td>
<td>197’</td>
<td>12.6%</td>
<td>0.5-270 md</td>
<td>960 million stbo</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Reference Slides are from the 2001 and 2008 CO₂ Flooding Conferences

Gross
Net
Porosity
Permeability Range
OOIP
Initial Oil Saturation
Primary, Secondary and Tertiary at the Seminole Field

SEMINOLE FIELD PRODUCTION HISTORY

PRIMARY PHASE  SECONDARY  TERTIARY

OIL PRODUCTION - BOPD

WATERFLOOD START (10/69)

CO2 START (4/83)

DATE

Melzer CQnsulting
‘Quaternary’ Oil at the Seminole Field
(Forecasts Shown are Based upon Plentiful CO₂)

Total, Primary, Waterflood, Main Pay and ROZ CO₂ Performance
(the Concept of "Brownfield" Quaternary Oil)

* SHAPE OF THE CURVE WILL BE DICTATED BY THE AVAILABILITY OF AMPLE, AFFORDABLE CO₂
ROZ Engineering

• Twelve On-going Projects (six different operators)
• Wasson, Seminole, Vacuum, Goldsmith, George Allen and Hanford Fields (all San Andres)
• Currently Making >13,000 bopd from below the OWC
• As Stated, Several New Projects to be Implemented Soon
• A Partial Greenfield Project Started in 2013
THUS, THE TARGETS FOR CO$_2$ EOR HAVE BROKEN FREE FROM JUST THE MAIN PAY ZONES
New ROZ Findings and Wrap-up
Emergent Findings for Exploitation of ROZs

• PDIs Appear to be Very Widespread in San Andres North Shelf, Central Basin Platform
• Upper Several Hundred Feet of PDIs (San Andres) are ROZs Almost Where ever We’ve Looked So Far
• The Body of Evidence (Thus Far) Supports Better Sweep Efficiency in the ROZs
  – Did Mother Nature Manage Her Floods Better than Man? and....or....
  – Is the Rock a Bit Better?
• ROZs are Going ‘Mainstream’
WE HAVE ONLY BEGUN THIS ROZ JOURNEY

• What about ROZ Type 3 Distributions in the PB?
• We are Excited about Discovering More About ROZ Origins and Distributions in the Big Horn and other Basins?
• What about the Size of the Greenfields?
• What about the Relative EOR Performance of ROZs to Waterflooded MPZs?
• What about Lower Water Salinities in the ROZ?
• What About Commercial Thresholds of Residual Oil Saturation Levels?

It is Very Clear to Us Now that ROZ Targets are Immense – But Just How Large are They?
Other Reservoirs/Basins

- The Characteristics of Tensleep ROZs Will Undoubtedly be Different from San Andres
- The Characteristics of the Studied Glorieta ROZ in the PB is a Bit Different
- And What Will the Williston Basin ROZ Reservoirs Be Like?
- Other?
To Be Continued....

For More Permian Basin Information Visit:

www.residualoilzones.com
www.CO2Conference.net
www.aptapb.org
www.melzerconsulting.com
Understanding ROZ Response

ROZ Science

Permian Basin Regional

And Looking Outside the PB as Well

RPSEA I
May '09 - Apr '12

DOE NEXT GEN
Mar '11 - Mar '13

RPSEA II
May '11 - May '14

PRIVATE CLIENT ROZ STUDIES

INDUSTRY PARTNERS

INDUSTRY PARTNERS

INDUSTRY PARTNERS
The End

Questions?

Thanks goes to EORI, our ROZ Study Group in the Permian Basin, Participating Industry Partners, the Research Partnership to Secure Energy for America, the U.S. DOE & NETL, and the Annual CO₂ Flooding Conference (early Dec of each year)

www.CO2Conference.net
Questions?
Backup Slides
### Permian Basin Stratigraphic Chart with Cum Production and Estimated Original Oil in Place by Formation

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>SERIES</th>
<th>STRATIGRAPHIC UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permian</td>
<td>Guadalupian</td>
<td>San Andres</td>
</tr>
<tr>
<td></td>
<td>Ochoan</td>
<td>Dewey Lake, Rustler, Salado, Castile</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Capitan, Tansill, Yates, Seven Rivers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Goat Seep, Queen, Grayburg</td>
</tr>
<tr>
<td>Pennsylvanian</td>
<td>Leonardian</td>
<td>Clear Fork, Sprayberry, Dean</td>
</tr>
<tr>
<td>Mississippian</td>
<td>Wolfcampian</td>
<td>Wolfcamp, Cisco, Canyon, Strawn, Bend</td>
</tr>
<tr>
<td>Devonian</td>
<td>Silurian</td>
<td>Mississippian</td>
</tr>
<tr>
<td>Ordovician</td>
<td>Cambrian</td>
<td>upper, middle, lower, Eilenburger</td>
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</table>

#### Cumulative Production

<table>
<thead>
<tr>
<th></th>
<th>Permian Basin</th>
<th>San Andres</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30 BBO</td>
<td>12 BBO</td>
</tr>
<tr>
<td></td>
<td>95 TCF</td>
<td>2 TCF</td>
</tr>
</tbody>
</table>

#### Estimated OOIP

<table>
<thead>
<tr>
<th></th>
<th>Permian Basin</th>
<th>San Andres</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 BBO**</td>
<td>40 BBO**</td>
</tr>
</tbody>
</table>

** Does not includes OOIP in ROZs
Photo Electric Cross Section Log and Cross Plot Porosity for the Glorieta Interval, Ector County Well

Cross Plot Porosity and PhotoElectric Cross Section Log

- PEF8
- PEFZ
- PXND_HILT (Rt Scale)

Depth in Feet

Pervasively Dolomitized Interval

Base of Holt

MPZ/TZ/ROZ Pkg 1

ROZ Pkg 2

ROZ Pkg 3

ROZ Pkg 4

Clearfork L. Glorieta

PhotoElectric Xsection (Barnes/electron)
DOLOMITIZATION & PERVERSIVE ZONATION
Dolomites are Good!

\[ V_t = \text{Total Volume} = V_s \text{ (Vol solids)} + V_f \text{ (Vol water)} \]

and \[ V = \frac{m}{\rho} \] where \( m \) = mass and \( \rho \) = density

Assume porosity saturated with fresh water (\( \rho_f = \rho_w = 1 \text{ gm/cc} \))

For a unit mass of 1, \[ V_t = \frac{(1-\varnothing_i)}{\rho_s} + \varnothing_i/\rho_w \]

Assume initially that is all limestone (\( \rho_s = 2.71 \text{ gm/cc} \)) and then becomes completely replaced by dolomite (\( \rho_s = 2.87 \text{ gm/cc} \)). Say that the \( \varnothing_i \) for limestone rock was 8%)

\[ V_t = (1-.08)/2.71 + .08/1 \]

\[ V_t = 0.34 + 0.08 = 0.42 = \text{Total Volume of the unit mass} \]
DOLOMITIZATION & PERVERSIVE ZONATION
Creates More Porosity and Better Permeability

Now, Conserving Volume with complete dolomite replacement of limestone solids – what is new $\phi$ ($\phi_n$)?

\[
0.42 = \frac{(1-\phi_n)}{\rho_s} + \frac{\phi_n}{\rho_w}
\]

\[
\rho_s \times (0.42) = 1-\phi_n + \rho_s \times \frac{\phi_n}{\rho_w}
\]

\[
\rho_s \times (0.42) - 1 = (\rho_s / \rho_w - 1) \times \phi_n \text{ or } \phi_n = \frac{\rho_s \times (0.42) - 1}{\rho_s / \rho_w - 1}
\]

\[
\phi_n = \frac{(0.42 \times 2.87 - 1)}{(2.87/1 - 1)}
\]

\[
\phi_n = 0.21/1.87 = 0.109 - 10.9%
\]

**Final**

POROSITY ENHANCEMENT OF 10.9-8.0 = 2.9%
ROZ

The Engineering
Engineering Oil from the ROZ

- The oil industry goes after the residual oil targets left behind in our own waterfloods
- Why can’t the industry go after those zones that have been naturally waterflooded?
- Let’s call those residual oil zones (ROZs)

But, of Course, Our Industry is (quietly) doing just this today in the Permian Basin
The ROZ Research Work

RPSEA I: Commercial Exploitation and The Origin of Residual Oil Zones: Developing a Case History in the Permian Basin of New Mexico and West Texas (Hydodynamic Modeling: North and West Side of the Delaware Basin)

DOE Next Generation EOR: Commercial Exploitation and The Origin of Residual Oil Zones: Developing A Case History In The Permian Basin Of New Mexico And West Texas (Goldsmith-Landreth San Andres Unit)

RPSEA II: Identifying and Developing Technology for Enabling Small Producers to Pursue the Residual Oil Zone (ROZ) Fairways of the Permian Basin, San Andres: Regional PB Studies and Extrapolation to the Bighorn and Southern Williston Basins
When we Joined Legado’s GLSAU CO₂ EOR Project
The Latest Status at the GLSAU CO₂ EOR Project

LEGADO RESOURCES GOLDSMITH SAN ANDRES CO₂ EOR (+ROZ)
PRODUCTION

Initiated CO₂ Injection (8/09)
Legado Assumes Operations

BOPM
Well Count

Month-Yr

Jan-94 Jan-96 Jan-98 Jan-00 Jan-02 Jan-04 Jan-06 Jan-08 Jan-10 Jan-12 Jan-14