Two Geological Case Histories of Residual Oil Zones (ROZ’s) in the Permian Basin by Independent Operators: with Core Observations.

Dr. Bob Trentham,
Geology,
Univ. of Texas of the Permian Basin
Acknowledgements

- Legado Resources Staff
- Steve Melzer
- Arcadis Staff
- Advanced Resources International Staff
- Emily Stoudt
- Toyly Abdullayev
- Phil Eager
- Chevron, Tabula Rasa, ER Operating, BC Operating
- And....
- DOE and RPSEA
You’ve heard this all before........

• Theory of “Meteoric-Derived Flushing”
• Tilted Oil/Water Contacts
• Modeling of fluid movement
• Fluid Properties of ROZ’s
• Rock Properties of ROZ’s
• The Gold Standard (Seminole) and other projects
• But you may not have seen this related to actual core.
Tectonic Mechanism for Permian ROZ’s

- Uplift in Rio Grande Rift area increased recharge area and hydrodynamic head
- Subsequent extension reduced hydrodynamic head; re-equilibration of reservoirs

*Ref: Lindsay, R.F. (2001), W. Tx Geological Society Fall Symposium, Oct 01, Midland Tx USA*
<table>
<thead>
<tr>
<th>Time Period</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pliocene - Pleistocene - Holocene</td>
<td>~5 Ma to Present</td>
</tr>
<tr>
<td>Late Miocene</td>
<td>-12 to -5 Ma</td>
</tr>
<tr>
<td>Paleocene</td>
<td>-65 to -58 Ma</td>
</tr>
<tr>
<td>Cretaceous-Gulfian</td>
<td>-95 to -65 Ma</td>
</tr>
<tr>
<td>Guadalupian</td>
<td>-255 to -251 Ma</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 & Sacramento Mountains (+6000’) and the Central Basin Platform (-1000’). Modified from Hill, 1996
Permian Basin ROZ Fairways

- GLSAU is located in the middle of an established Hydrodynamic Fairway

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 its relationship to the shelf margin.

* Brown, 1999, ** Ward et al, 1986
A minimum of 300 and possibly between 400 & 500' of middle and upper San Andres is missing at Goldsmith compared to Vacuum.

Understanding the regional correlations is important on targeting the best reservoirs.
## Hydraulic Conductivity

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
<th>Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Perm Slope</td>
<td>0.1 mD</td>
<td></td>
</tr>
<tr>
<td>Low Permeability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper San Andres Top</td>
<td>Seal</td>
<td>0.1 mD</td>
</tr>
<tr>
<td>Low Permeability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower San Andres</td>
<td>Limestone</td>
<td>0.1 mD</td>
</tr>
<tr>
<td>Intermed Perm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer Shelf Fairway</td>
<td>Dolomite</td>
<td>0.4-1.0 mD</td>
</tr>
<tr>
<td>High Perm Fairway</td>
<td>Dolomite</td>
<td>10-40 mD</td>
</tr>
<tr>
<td>Low Perm Sabkha</td>
<td>0.1 mD</td>
<td></td>
</tr>
<tr>
<td>Updip</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Perm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>0.1 mD</td>
<td></td>
</tr>
<tr>
<td>Low Permeability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner Shelf</td>
<td>Dolomite</td>
<td>0.4-1.0 mD</td>
</tr>
<tr>
<td>High Perm Fairway Inner</td>
<td>Dolomite</td>
<td>100 mD</td>
</tr>
<tr>
<td>Low Perm Sabkha</td>
<td>0.1 mD</td>
<td></td>
</tr>
</tbody>
</table>

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**Legend**

- **State Boundary**
- **County Boundary**
- **Major Roads**
- **City/Town Center**
- **Artesia Fairway**
- **Active Model Cell**
## Horizontal Fluid Movement per 1000 years

<table>
<thead>
<tr>
<th>Conductivity Zone</th>
<th>Velocity (n = 6%) (ft/1,000 years)</th>
<th>Velocity (n = 10%) (ft/1,000 years)</th>
<th>Velocity (n = 16%) (ft/1,000 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Layer One</strong></td>
<td>1.9</td>
<td>1.1</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Layer Two – Center Zone</strong></td>
<td>738</td>
<td>446</td>
<td>278</td>
</tr>
<tr>
<td><strong>Layer Two – Intermediate Zone</strong></td>
<td>72</td>
<td>44</td>
<td>27</td>
</tr>
<tr>
<td><strong>Layer Two – Edge Zone</strong></td>
<td>7.2</td>
<td>4.3</td>
<td>2.7</td>
</tr>
<tr>
<td><strong>Layer Three</strong></td>
<td>1.9</td>
<td>1.1</td>
<td>0.7</td>
</tr>
</tbody>
</table>

CCS: Fluids move at less than 1’ year over 1000 years.
## 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><strong>Total Pore Volume (ft(^3))</strong></td>
<td>1.22 x 10(^{11})</td>
<td>2.04 x 10(^{11})</td>
<td>3.26 x 10(^{11})</td>
</tr>
<tr>
<td><strong>Flow Rate (ft(^3)/day)</strong></td>
<td></td>
<td>1,030</td>
<td></td>
</tr>
<tr>
<td><strong>Time Period (Million Years)</strong></td>
<td></td>
<td>15</td>
<td></td>
</tr>
<tr>
<td><strong>Total Flow (cubic feet)</strong></td>
<td></td>
<td></td>
<td>5.64 x 10(^{12})</td>
</tr>
<tr>
<td><strong>Number of Pore Flushes</strong></td>
<td>46.0</td>
<td>27.7</td>
<td>17.3</td>
</tr>
</tbody>
</table>
Initial Reservoir Parameters

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

**Residual Oil Zone**
- 20 to 40% So (not economic)
- Little gas
- 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 changes
- Greenfield Potential
- Oil Gravity lower
- “Virgin” Reservoir Conditions
“Late” Reservoir Parameters

Waterflooded Main Pay
- 20 to 40% So
- Salt Water – ???? TDS
- No remaining Waterflood Potential
- CO2 EOR Potential
- Well known reservoir parameters
- Enhanced high perm streaks
- Mixed wetability
- Man made flow paths /fractures
- Heterogeneous oil saturation

Residual Oil Zone
- 20 to 40% So
- Sulfur Water – lower TDS???
- NO waterflood potential
- CO2 EOR Potential
- Estimated reservoir parameters
- Potentially more homogeneous
- Wettability Changes
- Unaltered flow paths
- More homogeneous oil saturation
ROZ Reservoir Characteristics

**Main Pay**
- Open Marine -> Restricted Marine -> Shoal -> Tidal Flat Capped shoal -> Tidal flats
- Cycles/Flow Units thinning upward
- More “Baffles to Flow”
- Dolomitized Reservoir
- Increasing mud upward

**ROZ**
- Predominantly Open Marine
- Thicker Cycles/Flow Units in ROZ
- Fewer “Baffles to Flow”
- “Double Dose” Dolomitization
- Limestone (unaltered) below ROZ
- Missing Anhydrite
Geologic Setting

- Located on the Central Basin Platform
- Analogous depositional setting to Wasson, Seminole

<table>
<thead>
<tr>
<th></th>
<th>Goldsmith</th>
<th>Wasson</th>
<th>Seminole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formation</td>
<td>San Andres</td>
<td>San Andres</td>
<td>San Andres</td>
</tr>
<tr>
<td>Discovery (Yr)</td>
<td>1935</td>
<td>1936</td>
<td>1936</td>
</tr>
<tr>
<td>Depth (Ft)</td>
<td>4,200</td>
<td>4,900</td>
<td>5,200</td>
</tr>
<tr>
<td>Pinit (psi)</td>
<td>1,712</td>
<td>1,850</td>
<td>2,020</td>
</tr>
<tr>
<td>Temperature (Deg)</td>
<td>95</td>
<td>107</td>
<td>108</td>
</tr>
<tr>
<td>API Gravity (Deg)</td>
<td>34</td>
<td>33</td>
<td>35</td>
</tr>
<tr>
<td>MMP (psi)</td>
<td>1,150</td>
<td>1,280</td>
<td>1,300</td>
</tr>
<tr>
<td>Porosity (Frac)</td>
<td>0.11</td>
<td>0.11</td>
<td>0.12</td>
</tr>
</tbody>
</table>
Not all ROZ’s are the same......

<table>
<thead>
<tr>
<th>Grayburg</th>
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<tr>
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<td>Holt</td>
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<tr>
<td>Vacuum</td>
<td>Lemex</td>
<td>Flying M</td>
<td>George Allen</td>
<td>ER</td>
<td>Sand Hills</td>
<td>Goldsmith</td>
<td>H.S.A.</td>
</tr>
</tbody>
</table>

**Eroded or Sabkha**

**Production**

**ROZ**

**Water**
Goldsmith

- Legado’s portion of the Goldsmith field has produced 74 million barrels since 1934,
- The company has 70 CO2 injectors and 93 producers.
- Legado sends the oil water and CO2 to a processing station, recycles CO2 back to the reservoir, and has a Third Party NGL Facility at the facility.
- EOR (CO2) has potential to recover more reserves from the MP and ROZ than was recovered from primary and secondary of MP only
FIGURE 5.1: LEGADO RESOURCES GOLDSMITH SAN ANDRES CO2 EOR (+ROZ) PRODUCTION

- 25 years primary recovery
- ~12 years secondary response
- 1986 crash
- Becoming uneconomic

Legado Acquires GLSAU in 2008 when production less than 200 BOPD & 10,000 BWPD

1934 Field Discovery
- Field Initial Gas Cap Pressure
- Field Gas Oil Ratio
- Field Water Oil Ratio
- Well Operation
- Well Completion
- Well Repair
- Well Decommissioning
- Field Decommissioning

Initiated CO2 Injection (8/09)
Legado Assumes Operations
- 2%
- 1%

LEGADO RESOURCES GOLDSMITH SAN ANDRES CO2 EOR (+ROZ) PRODUCTION
- Top San Andres
  - Actually top of lower San Andres

- Top San Andres Porosity
  - First significant porosity zone
  - 975
  - -975; Base of Gas Cap

- OOWC,GLSAU
  - -1080+/-; Oil water contact
  - 1939 study shows irregular/tilted OWC from drilling data

- Base ROZ LGMKR
  - -1230; base of economic ROZ
  - Base of economic ROZ or where ROZ is truncated by lithology change

- Top Holt
Goldsmith Structure

- Top of San Andres porosity conforms to top San Andres structure
- Structural high on GLSAU southern boundary
GLSAU Core Data

- Good core data coverage across the field...

- 7 Legado Cores
- 4 BEG Cores
- 9 Pan Am/Amoco
GLSAU Cored Intervals

• ...and good coverage vertically through the reservoir.
<table>
<thead>
<tr>
<th>Top San Andres</th>
<th>GOC</th>
<th>OWC</th>
<th>Base ROZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>4130' - 924'</td>
<td>4154' - 948'</td>
<td>4181' - 975'</td>
<td>4411' - 1205'</td>
</tr>
</tbody>
</table>

Main Pay

ROZ

Gas Cap

Low Porosity Cap

Reservoir (limestone)

Formation

San Andres

Pilot

*San Cap top is tilted; partially re-saturated with oil during waterflood

*Discovered in 1984, water flood began in 1963

*Residual Oil Zone CO2 pilot initiated in 2001; Phase 2 main pay/ROZ co-development to begin in 2010

*Liny San Andres not considered "floatable" in ROZ due to lower permeability

204R
Tilted ROZ Contact (sub -1230’ SS)

- Calculated $S_w$ curves have a strong correlation with core data
- Used $S_w$ to map a tilted Base of ROZ contact
- Seminole also exhibits a tilted Base of ROZ contact (*Honarpour, SPE 133089*)
Prior to 60mya oil saturated the entire column above free water... some tilting event “waterflooded” a portion of this zone and reduced the oil saturation to Sorw... the same residual saturation we can take a feild down to by active, forced, manmade or traditional Waterflood.
• Similar oil saturation in lower Gas Cap, Main Pay, and ROZ
**Core Fluorescence – GLSAU 204R**

- Consistent fluorescence throughout CO$_2$ flood interval.

<table>
<thead>
<tr>
<th>Gas Cap</th>
<th>Main Pay Oil Zone</th>
<th>Residual Oil Zone</th>
<th>Below ROZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Resaturated)</td>
<td>(MPZ)</td>
<td>(ROZ)</td>
<td></td>
</tr>
</tbody>
</table>

**TOP**

**BASE**
Base ROZ (Base of Commercial Sor)

- Base ROZ identified using core saturations, fluorescence, and log response
- Commercial CO₂ flood interval is based upon a flat base of ROZ (-1230’)

- Base ROZ (-1230 ss)
- Gradual oil saturation decrease
- Lithology remains constant
- Transition zone present
Base ROZ (Lithologic Change)

- Lithology change can be mapped using log and core data
- Small portion of ROZ is truncated by non-reservoir rock

- Abrupt decrease in oil saturation
- Resistivity decreases
- Grain density decreases
- PE curve increases
Porosity Calculation and Data Control

- Consistent methodology used to calculate porosity across the field
- Good log data coverage across the field

Calibrated log porosity using measured core porosity
  - Sonic porosity:
    - Matrix 41.1 µs/ft
    - Fluid 185 µs/ft
  - Neutron Porosity:
    - Generated a porosity transform based on Neutron True Porosity correction chart to fit GLSAU core porosity
    - Only open hole neutron logs were used

Log Coverage Used For Volumetric Calculations
Volumetric Maps - OOIP

Gas Cap phi-h
(Top SA Phi to -975)

Main Pay phi-h
(-975 to -1080)

ROZ phi-h
(-1080 to -1230)

<table>
<thead>
<tr>
<th>TOTAL UNIT</th>
<th>PV (MMRB)</th>
<th>HCPV (MMRB)</th>
<th>OOIP (MMBO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper GC (Top φ - 960)</td>
<td>104</td>
<td>83</td>
<td>0</td>
</tr>
<tr>
<td>Lower GC (960-975)</td>
<td>58</td>
<td>46</td>
<td>34</td>
</tr>
<tr>
<td>Main Pay (975-1080)</td>
<td>431</td>
<td>345</td>
<td>254</td>
</tr>
<tr>
<td>ROZ (1080-1230)</td>
<td>482</td>
<td>385</td>
<td>283</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1,074</td>
<td>860</td>
<td>571</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO2 FLOOD PHASE AREAS</th>
<th>PV (MMRB)</th>
<th>HCPV (MMRB)</th>
<th>OOIP (MMBO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper GC (Top φ - 960)</td>
<td>96</td>
<td>77</td>
<td>0</td>
</tr>
<tr>
<td>Lower GC (960-975)</td>
<td>54</td>
<td>43</td>
<td>32</td>
</tr>
<tr>
<td>Main Pay (975-1080)</td>
<td>400</td>
<td>320</td>
<td>235</td>
</tr>
<tr>
<td>ROZ (1080-1230)</td>
<td>441</td>
<td>353</td>
<td>259</td>
</tr>
<tr>
<td>TOTAL</td>
<td>991</td>
<td>792</td>
<td>526</td>
</tr>
</tbody>
</table>
Gas Cap - Tidal Flat Cap Shoal

Legado Resources

#126 R Goldsmith Landreth San Andres Unit

<table>
<thead>
<tr>
<th>Well or Measured Section Name</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLSAU # 126 R</td>
<td>ECTOR COUNTY, TEXAS</td>
</tr>
</tbody>
</table>

Logged by: EMILY STOUTD AND TOYLV ABDULLAYEV  
Date Logged: JULY-SEPTEMBER, 2012

Formation(s): SAN ANDRES  
Depth or Outcrop Interval: 4073-4192

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**Gas**

**Oil**

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**GAS CAP TOP**

**MAIN PAY TOP**
Main Pay - Restricted to Open Marine

Legado Resources

#204 R Goldsmith Landreth San Andres Unit

Gas Cap
Main Pay
Main Pay
ROZ
ROZ
Water
ROZ and Below – Open Marine

Legado Resources
#190 Goldsmith Landreth San Andres Unit
Decreasing Fusulinids upward
Increasing mud upward
Cycles thinning upward
Tidal Flat Cap Shoal
Dolo-Limestone below ROZ

T/SADR
Tidal Flat
Shoal
Restricted Shelf
Shallow Open Shelf
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.
Stacked Pays and ROZ’s

- An un-named area in the Permian Basin where there has been production established in multiple zones above the residual oil zones (ROZs) for over 75 years and production below the zones for almost 50 years.

- The area encompasses ~140 sq miles (20 miles long by 7 miles wide) in which there were ~250 wells that penetrated the ROZs, most being drilled to develop deeper production.

- The major productive horizons above (100’s of millions of BO) and below (10’s of millions of BOE) the ROZs do not themselves have documented ROZs.
• The five ROZs are in a series of stacked carbonate ramps to shallow shelves with Up-dip stratigraphic traps where porosity and permeability are lost up-dip in evaporite rich sabkha deposits (see schematic cross section depiction in Fig. 1).
• There has been less than 3 MMBO produced from the five intervals with associated ROZs between the shallower and deeper major producing horizons.
• These ROZs are Pervasively Dolomitized Intervals (PDIs) of the type where the porous sections have been swept by Mother Nature’s Waterflood (MNW) in the “Y” direction in the schematic cross section.
• There is only minor primary production in isolated, unswept portions of the stratigraphic traps. This ROZ-heavy vertical interval, without major main pays, has a gross thickness of 3000 to 3500’ and reservoir quality rock approaching 2000’ feet in some areas.
• The individual zones are separated by sections dominated by mud rich facies. Most of the section must have had oil entrapped prior to the MNW.
In one of the intervals, the primary production is restricted to a relatively small structure and has 125’ of pay. There is, however, over 200’ of ROZ beneath the field (Brownfield), and the ROZ extends down dip 550’ below, and as much as 3 miles away from the field (Greenfield).
ROZ’s identified by Core Description

• A recently drilled well was cored thru the Upper Leonardian section in a field with 1MMBO production from 14 wells in that formation.

• A net of 170’ of interval with good - excellent stain and oil saturation in the 200’ thick ROZ was identified, below the established production.
12-17% (RED BOX) oil saturation in this conventional core would equate to 24-34% oil saturation in the reservoir.
The producing interval in this field has thin intervals of subtidal dolopackstone and thick intervals of tidal flat dolowackstone to dolopackstone.

The ROZ is composed of thick dolopackstones with cross beds and burrowed intervals.
There are shoal cap facies with Mangrove-Type islands. Suggesting more normal marine waters than above.

Beach facies are also present.
As seen elsewhere, SULFUR is common at the base of the ROZ. Here, the SULFUR is present in fractures. There is also SULFUR present at the base of the Middle ROZ Zone. This suggests that the “tite” zone between the Middle and Lower ROZ Zones acted as a barrier and the zones were swept separately.
ROZ’s in Core

• Historically, ROZ’s have not been cored.
• The oil saturations in analyzed ROZ core support the concept of uniform So throughout the ROZ.
• The same diagenetic products, associated with meteoric derived sweep, are seen in many fields and formations.
• The ROZ’s, in many cases, are better CO2 sweep targets than the main pays.