Report on the Potential of Residual Oil Zones in the San Andres

2011 CO$_2$ Conference
David Vance, ARCADIS,
Bob Trentham, CEED/UTPB, and
Steve Melzer, Melzer Consulting
Thanks go the PB ROZ Team

- Our Corporate Partners
  - Chevron
  - Legado
- Martin Cassidy, University of Houston
- Phil Eager, Consultant
- Bob Kiker, PTTC and APTA
- Bill LeMay, Consultant
- Blake Wineinger, Consultant
- The ARCADIS Folks led by Steve Tischer and David Vance
- Trentham and Melzer
# The Size of the Prize

**Calibrating the Oil Recovery Models and Estimating Technically Recoverable ROZ Oil – MPZ and TZ/ROZ Oil in Place**

56 fields in five major Permian Basin oil plays that have potential for significant TZ/ROZ resources were identified by ARI. **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>
**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

**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>
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<td>1.7</td>
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<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>
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
The List of On-going ROZ Projects

<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>
</tr>
</thead>
<tbody>
<tr>
<td>Active CO₂ miscible</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chevron</td>
<td>Vacuum San Andres Grayburg Unit</td>
<td>NM</td>
<td>Lea Co.</td>
<td>4,550</td>
<td>San Andres/Grayburg</td>
</tr>
<tr>
<td>Fasken</td>
<td>Hanford</td>
<td>Tex.</td>
<td>Gaines</td>
<td>5,500</td>
<td>San Andres</td>
</tr>
<tr>
<td>Hess</td>
<td>Seminole Unit-ROZ Phase 1</td>
<td>Tex.</td>
<td>Gaines</td>
<td>5,500</td>
<td>San Andres</td>
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<tr>
<td>Hess</td>
<td>Seminole Unit-ROZ Phase 2</td>
<td>Tex.</td>
<td>Gaines</td>
<td>5,500</td>
<td>San Andres</td>
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<tr>
<td>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>
</tr>
<tr>
<td>Legado</td>
<td>Goldsmith-Landreth Unit</td>
<td>Tex.</td>
<td>Ector</td>
<td>4,200</td>
<td>San Andres</td>
</tr>
<tr>
<td>Occidental</td>
<td>Wasson Bennett Ranch Unit</td>
<td>Tex.</td>
<td>Yoakum</td>
<td>5,250</td>
<td>San Andres</td>
</tr>
<tr>
<td>Occidental</td>
<td>Wasson Denver Unit</td>
<td>Tex.</td>
<td>Yoakum</td>
<td>5,200</td>
<td>San Andres</td>
</tr>
<tr>
<td>Occidental</td>
<td>Wasson ODC</td>
<td>Tex.</td>
<td>&amp; Gaines</td>
<td>5,200</td>
<td>San Andres</td>
</tr>
</tbody>
</table>

Announced Additions: Exxon at Means (2011)
Rumored Additions: Conoco at East Vacuum (2011)
Chevron at Central Vacuum (2012)
XTO at CA Goldsmith (2013?)
Tabula Rasa at E. Seminole and Lindoss (2013)
The Science of Residual Oil Zones
Original Oil Accumulation Under Static Aquifer Conditions (A Hypothetical Example)
Original Accumulation with a Breached then Repaired Seal & Forming a ROZ

TYPE 2 ROZ
TYPE 3. Change in Hydrodynamic Conditions, Sweep of the lower part of the Oil Column and Development of a Residual Oil Zone.
Post-Subsidence Phase of Permian Basin Development

(From Lindsay, R. (2001)

Phase I Initial Uplift, Late Oligocene - Early Miocene
RIO GRANDE RIFT

PERMIAN BASIN

Initial Uplift Created
Massive Recharge Area Into Permian Basin

Area of Displaced Hydrocarbon Columns by Massive Meteoric Recharge
Extensional Phases and Reduction of Hydrodynamic Gradients in the Permian Basin (From Lindsay, R. (2001))
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

Closing of the Midland Basin**

* Brown, 1999

** Ward et al, 1986
Relationship of San Andres outcrops and San Andres Fairways in New Mexico.
FIGURE 2: ROZ FAIRWAY MAP  
DRAFT #5 

Fairway Mapping as of Jul ‘11  
Melzer CQnsulting
Seminole Field - The Gold Standard

<table>
<thead>
<tr>
<th>Net Thickness</th>
<th>Average Permeability</th>
<th>Initial Oil Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Pay Zone (MPZ): 126'</td>
<td>9 md</td>
<td>84%</td>
</tr>
<tr>
<td>Residual Oil Zone (ROZ): 213'</td>
<td>12 md</td>
<td>32%</td>
</tr>
</tbody>
</table>

December 4, 2008
Seminole Field
ROZ Projects
GREENFIELDS
Future Targets or goat pasture?

• A Clearfork test, the **IP #1 Campbell Heirs “158”** set pipe on “WET” San Andres test just south of Seminole.

• All wireline logs, drill time, gas curves and sampleshows 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.
Permian Basin, San Andres Oil from Goldsmith Field

MPZ Reservoir Oil

From ROZ Interval

Acquired with corporate support from

LEGAĐO resources

....as per Martin Cassidy, UH
Although we are gathering data for any ROZ, the first model will concentrate on the Artesia Fairway and the west side of the Central Basin Platform.
Modeling of the system that created “Mother Natures Waterflood”.

• Focus on/Identify/Define the Artesia - West Central Basin Platform Trend
• Gather
  • Well data – location, tops, correlations (Cross Sections)
  • Pressure Data - DST’s, Well Test Data
  • Permeability and Porosity Data (Core)
  • Water Chemistry
• ARCADIS will use ModFlow, a U. S. G. S. developed, finite ground water modeling program with regional capabilities.
Karsted Pgs (U. San Andres) Outcrop

Slaughter Fairway

Bottomless Lakes Recharge Field

Roswell Fairway

Artesia Fairway
Relationship of San Andres outcrops and San Andres Fairways in New Mexico.
Pathway from NW Shelf to CBP
DISCHARGE PATH CONCEPTS (Hose Nozzle)

- We have a source of the water, we also need discharge points in order to have movement of the meteoric water.
- Direction of OWC tilt is evidence of both Movement and Direction.
- Do we have other pathway clues?
The ‘Heel of the Boot’ of the Central Basin Platform is also the location of Sulfur mines which document exit pathways for the system.

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

San Andres Water Salinities and Sulfur Deposits
GATHERING THE “ANECDOTAL” EVIDENCE

Evidence from a growing number of exploration and production 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 explorationists and review and reinterpretation of research articles on Permian Basin fields, a set of common ROZ characteristics is developing:

- **Oil Shows:** DSTs, Cuttings, Cores
- **Water Salinities, Sulfur Water, Sour Oil**
- **Corrosive Zones**
- **Pervasive Zonal Dolomitization**
- **Discharge Paths, Lineaments**
- **Sulfur Deposits**
Examples of Anecdotal Evidence

- The presence of sulfur crystals associated with gypsum/anhydrite in the swept carbonates,
- Evaporites 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.
- Transition from Dolomite in ROZ to Limestone beneath Paleo O/W contact
- Sample shows of oil and/or gas of similar quality to Main Pay Zones
- Sulfur water produced on DST’s or attempted production tests
- Cores with 20-40% oil saturation,
- Log calculations that suggest producible hydrocarbons.
- Pervasive “late” dolomitization which may indicate meteoric sweep.
- Documentation of Sulfur Deposits, Pecos County.
Hydrogeologic Modeling

• Modeling Team - ARCADIS
  – Kuohui Suchecki – Midland, Texas
  – Scott Niekamp – Columbus, Ohio
  – Leone Gaston – Highlands Ranch, Colorado
  – David Vance – Midland, Texas
Hydrogeologic Modeling
The Approach

• Using Groundwater Vistas with Modflow
• Three vertical layers
• Nodes on half mile centers
• Total model has 374 rows and 160 columns
• Approximately 50,000 of the 59,840 nodes are active
Simulation of Geologic Past

• Conceptualize Past Geologic Structure.
• Conceptualize Past Climatic Conditions.
• Conceptualize Flow Regime.

• Focus is on the Early Miocene.
Tectonics and Theorized Geologic Structure (Early Miocene)

- Laramide orogeny begins in late Cretaceous/Early Cenozoic (~65 MYA)
- Second phase of hydrocarbon emplacement in Oligocene and Early Miocene in response to heating from tertiary intrusives and extrusives to the South (20-40 MYA).
- Extensional tectonics - broad structural arching and uplift centered on Rio Grande rift with minimal folding and faulting in Late Oligocene to Early Miocene (25-15 MYA).
- Eastward tilting of the Permian Basin resulted from uplift.
- Guadalupian system theorized to be unbroken to the west of current Guadalupe Mountains.
- Rocks extended upward to the center of the Rio Grande Rift (westward), perhaps as high as 12,000 feet as suggested by current elevation of Sierra Blanca Peak in Sacramento Mountains.
- Tilting of the geologic structure caused hydraulic gradients and hydrodynamic flow to occur.
- Enhanced conditions for meteoric recharge.
- Early Miocene flushing of hydrocarbons.
Geologic Structure
(middle Miocene to present)

- In middle Miocene (~15 MYA), rifting and block faulting disconnected the previously continuous Guadalupian system.
- Likely reduced meteoric recharge, which would reduce hydrodynamic flow in Permian Basin.
- Down-cutting of Pecos River formed a sink, which isolated portions of the fairway from recharge in the Guadalupe Mtns.
- Reduced hydrodynamic flow.
Climate Patterns Over Time

65 Million Years of Climate Change

- Warm, Wet Climate Early-Middle Miocene
- Gradual Cooling and Drying Late Miocene
- Continued Cooling, Arid western U.S. Weakened summer monsoon Pliocene-Pliestocene

Millions of Years Ago

Benthic δ18O (per mil)

Polar Ocean Equivalent ΔT (°C)

Eocene Optimum

PETM

Antarctic Glaciation

Antarctic Thawing

Antarctic Reglaciation

Rapid Glacial Cycles

6.5 million years ago

Pli

Pliocene

Pleistocene
Climate (early-middle Miocene)

- Western U.S. covered with extensive mixed deciduous-conifer forests.
- Distributed to all altitudes (not just high altitude wet zones).
- Estimated that 400 mm (16 in.) of summer precipitation alone would be required to support this plant assemblage.
- 89-100 cm (35-39 in) total precipitation estimated in central Nevada.
- Probably around 30-35 inches total for eastern deciduous flora.
- Local climate less well understood.
- Gradual global cooling and drying of western U.S. begins following middle Miocene climate optimum (15 MYA).
- Arid conditions predominate by 5 MYA with change to arid flora except at high elevations.
- Cause attributed to cooling of the Pacific Ocean and secondarily to rain shadows caused by uplift of mountain ranges to the west.
- Greatly weakened summer monsoon.
Relationship of San Andres outcrops and San Andres Fairways in New Mexico.
Data Gathering – Delimiting the Trends

• Focus on/Identify/Define the Artesia - West Central Basin Platform Trend

• Gathered
  • Well data – location, tops, correlations (Cross Sections)
  • Pressure Data - DST’s, Well Test Data – 738 Wells
  • Permeability and Porosity Data (Core)
  • Water Chemistry – 3,315 wells
Modeling the Chosen Fairway

DST and Water Chemistry Data collected from various sources, by county

Wells by County
346/1563

DST / Water Chem

Regional Hydraulic Conductivities

- Documented enhanced hydraulic conductivity zones in the San Andres Limestone in Lea County and Pecos County

- Lesser quantities of water likely discharge into the Artesia group since enhanced hydraulic conductivity is lacking.

Hydraulic Conductivity map Source: Stratigraphy and Ground-water Hydrology of the Capitan Aquifer, Southeastern New Mexico and Western Texas. (Hiss, 1975).
Conceptual Model
Model Boundaries

• Simulates flow into and out of the Artesian Fairway.

• Boundary heads assigned based on pre-development potentiometric surface map.

• Boundary conductance's assigned based on hydraulic conductivities of the formation.

• Northeast and southeast boundaries represent flow exiting (or entering) the Fairway in Gaines and Pecos Counties.

• Northwest boundary represents inflow from adjacent units that supports the groundwater flow divide.

• Western boundaries represent flow entering (or exiting) the Fairway in Lea and Pecos Counties.
Head Calibration

• Model is able to reproduce heads in the middle of the Fairway very well.

• Over-simulates heads at the edge of the fairway in eastern Lea, Winkler, and Ward Counties. Eastward component to the hydraulic gradient that can’t be simulated.

• Under-simulates heads in northeastern Lea County

• Compromise between reproducing flows and reproducing heads in this area.

• Error = difference between simulated head and measured head

<table>
<thead>
<tr>
<th>Error Type</th>
<th>Error Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Error</td>
<td>-17.8 feet</td>
</tr>
<tr>
<td>Absolute Mean Error</td>
<td>59.8 feet</td>
</tr>
<tr>
<td>RMSE/range in heads</td>
<td>14%</td>
</tr>
</tbody>
</table>
Artesia Fairway – Guadalupe Mountains (early Miocene)

- The Pecos river is very young. Not present in early Miocene. Present groundwater divide absent.
- San Andres limestone likely extended westward, possible connected to the ridge over the Rio-Grande valley.
- Increased recharge and stronger hydraulic gradients
- Decreased karstic porosity?
Flow in the San Andres Modern Time, but Pre-Development

Legend

- Artesia Fairway
- Capitan Reef Complex
- Head Contour
- Flow through Artesia Fairway

Flow Divide
Flow in the San Andres in the Geologic Past

Legend

- Artesia Fairway
- Capitan Reef Complex
- Head Contour
- Flow through Artesia Fairway
Pecos County Discharge Points

- Thickness maps of Sulfur ore bodies suggest the presence of 4 discharge locations in geologic past.
- Sulfur mines were located at three of these locations.
- Sulfur deposits theorized to have formed during episodes of hydrocarbon flushing, especially in late Oligocene–early Miocene.
- \( \text{H}_2\text{S} \) generated from microbial metabolism of flushed hydrocarbons along with reduction of sulfate from evaporites in chimney structures.
- \( \text{H}_2\text{S} \) oxidized to native sulfur
- Accumulated in structures defined by lineament chimney traps.
- Theorized discharge point for flow moving through the Artesia Fairway.
- Estimates of flow volumes required to produce sulfur deposits would be useful to refine water budget.

Isopach of net thickness of sulfur.

“Geologic Occurrence and Regional Assessment of Evaporite-Hosted Native Sulfur, Trans-Pecos Texas”
Hunt et al., 1989
The Role of Sulfur Biogeochemistry

- The sulfur deposits in Pecos County were formed from the biogeochemical interactions of petroleum and calcium sulfate (gypsum/anhydrite)
- Similar reactions have taken place in the fairway flow path
- Sulfate biogeochemical processing effects:
  - Porosity driven by changes in carbonate mineral suites
  - Chemical composition of the petroleum
    - Hydrocarbons are consumed and graded by sulfate reducing microbes
    - That process generates hydrogen sulfide that inhibits microbial activity at concentrations over 100 to 200 mg/L – That prevents total hydrocarbon consumption
  - Mobility of the petroleum hydrocarbons
    - Sulfate reducing microbes generate biosurfactants that enhance the mobility of petroleum in the flow system
Preliminary Simulations

General Observations

- Flow traveling down the Fairway in Eddy and Lea County discharges into Gaines County.
- Source of flow in Ward and Winkler County is the northern limb of the Capitan Reef Complex.
- Most of the recharge entering the Capitan Reef Complex from the Glass Mountains likely discharges in Pecos County.
- **Pore volume flushing ranges from 20 to 50 pore volumes over 15 million years (Late Oligocene through Middle Miocene)**

Legend

- Flow outside model Area
- Flow through Capitan Reef Complex
- Flow through San Andres Artesia Fairway
- Flow inside model Area (San Andres)
- Flow emanating from the Capitan Reef Complex
- Flow emanating from the Artesia Fairway
Questions to be Answered
Future Work

Some we will do and some needed to be done by others

– a. Greenfield Fluid Sampling
– b. Water Salinity Impacts
– c. Permian Basin Wide Study
– d. Extrapolation to Other Basins (note ongoing Wyoming Work)
– e. ROZ vs. MPZ: Permeability Enhancements in the ROZ
– f. Size of the Oil Prize
The PB 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 (Hydrodynamic 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

Visit our website at: Residualoilzones.com