Permian CCS Center
Carbon Capture & Storage Technology

CCS (and CO₂ EOR) in the Permian Basin — Reservoir Characterization

September 1, 2010
R.E. Trentham
Steve Melzer
Three World Class Organizations

Petroleum Technology Transfer Council
Tech Transfer, Workshops, Newsletter, Tech Alerts
www.pttc.org

American Association of Petroleum Geologists
37,000 Members, Publications and Conferences
Distance Learning www.aapg.org

Applied Petroleum Technology Academy
CO₂ Course, CO₂ Conference www.aptapb.org
A Brief Introduction of the Presenters

• Dr. R.E. Trentham – Univ. Tx PB & APTA

• L. Stephen Melzer – APTA & Melzer Consulting

• Other Instructors* (Mr. Robert D. Kiker, APTA & Dwight Rychel, PTTC)

* Other Instructors will be present for Operations and Capture Courses
Carbon Capture And Storage
Today’s Webinar Topics

1. Reservoir Characterization – BT & SM

2. New Frontiers (ROZs and PDIs) – SM & BT
Key Elements of Reservoir Geology for CO$_2$ Sequestration, based on 40 years of CO$_2$ EOR

Robert Trentham
The Geoscientist’s Role
In the CO₂ Flood or Sequestration Project

• Plays a critical roll in preparing for implementation of a CO₂ Flood or Sequestration project
• Many Permian Basin reservoirs are very “forgiving” during the waterflood, but CO₂ floods have highlighted flaws in initial and subsequent interpretations
• Continue the integrated team approach throughout the life of the CO₂ flood or sequestration project to promote optimum oil recovery or CO₂ retention
Life Cycle Management:
Oil Field vs. Sequestration Target

- Discovery
- Development
  - Primary Recovery
  - Secondary Recovery
  - Tertiary Recovery
  - Quaternary Recovery
  - $CO_2$ Sequestration
- Abandonment

- Identify Sequestration target
- Develop Aquifer/Reservoir
  - Development of Target
  - $CO_2$ Injection
- Closing
- Monitoring
CO$_2$ EOR Has Been Used On Permian Basin Fields For 40 Years

Permian, Pennsylvanian, Lower Paleozoic

Continuous Reservoir Management is key to recovering additional mobile oil or successful CO$_2$ sequestration.

Integration of Data Bases
Engineering Data
Geological Data
Field Production Data

There is a tendency to reduce geoscience input after initiation of the flood / injection UNLESS something goes wrong!
Question -- When you start the CO\textsubscript{2} Flood or Sequestration Project, where are you in the geologic reservoir characterization of the field?

- Typically, if the waterflood has been successful, and it probably has been if you’re going to CO\textsubscript{2} flood, you’re basing a lot on the assumption that since we were successful …  
  \textbf{THE MODEL WAS RIGHT}

- We know what the reservoir looks like…  
  \textbf{WE DON’T NEED TO REVISIT OUR ASSUMPTIONS}

- All the Fields on trend have water-flooded well and look like they’ll be CO\textsubscript{2} flood successes so…  
  \textbf{THIS FIELD SHOULD RESPOND THE SAME WAY}
Any Field Reservoir Characterization Project

Goal: Build an integrated reservoir management tool

• Data sets:
  – 0-12,000’ of core
  – 10’s to 1000’s wells
  – Old 2D
  – 3D Seismic volume
  – 4D Seismic (repeated)
  – 80 year production
  – 40 year waterflood

• Do you have/need this much data at your site?

• Phases:
  – Regional Geology
  – Outcrop Work
  – Key facies from core
  – Log cleanup
  – Log/Core facies predictions
  – Stratigraphic framework delineation
  – Iterative rock property distribution
**Project Specific Workflows**

These areas must be addressed to be successful

<table>
<thead>
<tr>
<th>Regional Depositional Context</th>
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</thead>
<tbody>
<tr>
<td>Regional Diagenetic/Tectonic Context</td>
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<tr>
<td>Geologic Facies and Depositional Model</td>
<td></td>
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<tr>
<td>Sequence Stratigraphic Framework</td>
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<tr>
<td>Facies Predictions</td>
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<td>Petrophysics for 3-D Models</td>
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<tr>
<td>Seismic Inversion and Time-2-Depth</td>
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<td>Mini-Model „Flow Calibration“</td>
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<tr>
<td>3-D Geologic Model Construction</td>
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<tr>
<td>Secondary Perm and Fracture Integration</td>
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</tbody>
</table>

**Reservoir Project Management**
Regional Geologic Context

• Start with an understanding of the Basin’s Depositional History
• Without a firm understanding of the depositional history, errors will be imbedded in any study
• Most basins will have post depositional and post oil emplacement events which impact both reservoir and fluid distribution
• Start with the Rocks
• What if you don’t have much rock left?
• What if your budget doesn’t include multiple new cores?
• Tie FMI’s to Limited Core?
Sequence Stratigraphic Framework

- Tie the rocks to the logs
- Use 2-D correlations to pick major sequence boundaries that will constrain the 3-D model’s property distributions.
Facies Prediction

- Why predict facies?
- Impact of Diagenesis/Karst on Facies Distribution
Log data that is sufficient for 2-D Cross-Sections may not be sufficient for property distribution in 3-D Models
3-D Geologic Model Construction

• How does the different 1D, 2D and 3D data fit together in a single 3-D geo-model?

(or...)

Some Assembly Required!!
Seismic Inversion, Time-2-Depth, Value of 3D and 4D Seismic

- Possible use of Acoustic Impedance
- Value of 2D
- 3D Seismic Surveys
- 4D Seismic
Engineering Use Of The Geologic / Geophysical /Petrophysical Data

• Operations Engineering:
  – Reservoir Surveillance
  – Fluid Breakthrough Management
  – Workover Candidate Selection
  – Injection Pattern re-alignment

• Reservoir Engineering:
  – Effect of post-depositional changes on Fluids Distribution
  – Historical Recovery Efficiency
  – IOR-EOR Design and Risk Management
Carbonate And Clastic Reservoirs Are Inherently Heterogeneous And Challenging To CO$_2$ EOR And Sequestration

• Due to:
  – Depositional Environment
  – Diagenesis
  – Tectonic History
  – Nature of Trap
  – Fluids/Gases in Reservoir
Diagenesis:

Creates Porosity - Preserves Porosity - Destroys Porosity

- Penecontemporaneous
- Shallow Burial
- Deep Burial
- Regional Uplift
- Recent “Diagenesis”
  - Secondary and Tertiary Recovery or CO$_2$ Injection
Trapping Mechanisms

- Stratigraphic Trap
- Structural Trap
- Combination Trap
  - Stratigraphic
  - Structural
- Local Seal
- Regional Seal
Reservoir Characterization

Requires knowledge of:

- Reservoir heterogeneity caused by Facies changes and post-depositional diagenesis
  - Cementation, dissolution, and diagenetic history
- Sequence Stratigraphy
- Petrophysical properties
  - Porosity, permeability, relative permeability, saturation, and capillary pressure
- Characterization of Rock Properties
  - Mineral, chemical, and pore network
Why Emphasize Cycles And Cyclo-stratigraphy?

• Small-scale depositional cycles (parasequences) in both clastics and carbonates are extremely important!
  – Cycles are the flow units of your reservoirs!
  – Cycles provide information as to the regional depositional model (e.g., ramp, rimmed shelf margin) to apply to your reservoir
  – Cycles provide information as to the depositional setting you’re producing from (e.g., lagoon, shoals, barrier bars)
  – Ultimately, cycles provide clues to the (lateral) location and continuity of reservoir-quality rocks

• Cycle stacking patterns allow you to predict:
  – The location of reservoir-quality rocks (facies) through time
  – This is critical information for step-outs or horizontal wells!!!

*CYCLES = FLOW UNITS*
A cycle records a single sea level rise and fall.

It is the building block of all other orders of cyclicity!

Example of Asymmetric mud-based – grain topped cycles, Lawyer Canyon Window, Guadalupe Mountains
Cycle with Grain-rich Top = Excellent Reservoir to Good Reservoir
Grains + Mud Rich = Fair Reservoir
Mud Rich = Poor Reservoir
Muddy Base = Barrier to vertical flow

Double Whammy: CO₂ tends to ride over the water in an aquifer & the best reservoir is often at the top of the flow unit.
Identifying Cycle Boundaries (Barriers to Vertical Flow)

• What are some things to look for to help identify cycle boundaries?
  – Exposure surfaces
    • Oxidized horizons, bored surfaces, soil zones
  – Karst development
    • Brecciated (collapse) zones, cave fill, sediment filled fractures
  – Erosional surfaces
    • Truncated grains, intra-/lithoclasts in overlying bed
  – Radical shift in facies (non-Waltherian)
  – Often difficult to visualize surfaces as barriers to vertical flow.
At SACROC, There Are Large Scale, Vertical Porosity Variations

Can you believe there are at least 9 different sets of correlations for this area?
Although flow units are easily identified, because of changes in facies, the Porosity and Permeabilities change within the flow unit.

Facies changes will impact the flow unit's ability to store CO₂ or sweep oil.

In reservoirs with karst overprint, flow unit boundaries can be beached and CO₂ would not be confined to correlatable flow units.
Outcrop studies help clarify problems hinted at in the subsurface in Permian Basin Carbonate Reservoirs.
Core is more often used to identify cycles/flow units in reservoir studies.

Although this interpretation works well for FCU, at Sand Hills Field, deeply developed karst(s) has destroyed the horizontal flow layering.

Which do you have in your project?
Step VI: Integrate Regional Geophysics & Geology, Basin Overview & Data Collection

Evaluate input from existing seismic

Three different 3D seismic surveys were merged to create this more regional picture
<table>
<thead>
<tr>
<th>Event</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Karstification</td>
<td>XXXX</td>
</tr>
<tr>
<td>Compaction</td>
<td>XXXX</td>
</tr>
<tr>
<td>Dissolution of Soluble Grains</td>
<td>XXXX</td>
</tr>
<tr>
<td>Anhydrite Cementation</td>
<td>XXXX</td>
</tr>
<tr>
<td>Geopedal infilling</td>
<td>XXXX</td>
</tr>
<tr>
<td>Inclusion-rich Dolomite Cement</td>
<td>XXXX</td>
</tr>
<tr>
<td>Inclusion Free dolomite</td>
<td>XXXX</td>
</tr>
<tr>
<td>Dissolution Event</td>
<td>XXXX</td>
</tr>
<tr>
<td>Kaolinite crystallization</td>
<td>XXXX</td>
</tr>
<tr>
<td>Evaporite Alteration</td>
<td>XXXX</td>
</tr>
<tr>
<td>Partial Dolomite Dissolution</td>
<td>XXXX</td>
</tr>
<tr>
<td>Stylolitization</td>
<td>XXXX</td>
</tr>
<tr>
<td>Evaporite Cementation</td>
<td>XXXX</td>
</tr>
<tr>
<td>Hydrocarbon Migration</td>
<td>&gt;&gt;&gt;&gt;&gt;</td>
</tr>
</tbody>
</table>

Sequence of Diagenetic Events, McElroy Field, Crane Co., TX

On average, the “typical” Permian Basin Carbonate will endure 36 modifications during its history.
<table>
<thead>
<tr>
<th>Time Period</th>
<th>Duration</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
<td>Holocene</td>
<td>-10 ka to present</td>
</tr>
<tr>
<td>Plio-Pleistocene</td>
<td>-5 Ma to -10 Ka</td>
<td>Basin and Range Tectonism - Flushing continues at reduced rate.</td>
</tr>
<tr>
<td></td>
<td>Early Miocene</td>
<td>-25 to -12 Ma</td>
</tr>
<tr>
<td></td>
<td>Oligocene</td>
<td>-40 to -25 Ma</td>
</tr>
<tr>
<td></td>
<td>Eocene</td>
<td>-58 to -40 Ma</td>
</tr>
<tr>
<td></td>
<td>Paleocene</td>
<td>-65 to -58 Ma</td>
</tr>
<tr>
<td>Cenozoic</td>
<td>Cretaceous-Gulfian</td>
<td>-95 to -65 Ma</td>
</tr>
<tr>
<td></td>
<td>Cretaceous - Comanchian</td>
<td>-135 to -95 Ma</td>
</tr>
<tr>
<td></td>
<td>Triassic-Jurassic</td>
<td>-250 to -135</td>
</tr>
<tr>
<td>Paleozoic</td>
<td>Ochoan</td>
<td>-251 to -250 Ma</td>
</tr>
<tr>
<td></td>
<td>Guadalupian</td>
<td>-255 to -251 Ma</td>
</tr>
</tbody>
</table>
Geologic/Geophysical Integration into Reservoir Characterization is a Multi Step Process

- Step I: Basin Overview and Data Collection
- Step II: Database Development, Well File Review, Data Loading, Establish Baseline
- Step III: Detailed Structural Mapping
- Step IV: Stratigraphic Context/Sequence Stratigraphy
- Step V: Facies/Rock Property Modeling
- Step VI: Integrate Geology and Geophysics
- Step VII: Reservoir Mapping and Porosity Prediction
- Step VIII: Input Geologic Data into History Match and Reservoir Simulation. Iterate as often as necessary
- Step X: Be ready for New, Unswept or Poorly Swept Pay or New Pool or New Field Discovery!
New Frontiers

Residual Oil Zones (ROZs) and

Pervasively Dolomitized Intervals (PDIs)

Steve Melzer
The Reservoir Characteristics that are important to EOR are also important for storage:

<table>
<thead>
<tr>
<th></th>
<th>STORAGE</th>
<th>EOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permeability</td>
<td>Injectivity</td>
<td>Injectivity, ROR</td>
</tr>
<tr>
<td>Porosity</td>
<td>Storage capacity</td>
<td>Oil in place</td>
</tr>
<tr>
<td>Thickness</td>
<td>Storage capacity</td>
<td>Oil in place</td>
</tr>
<tr>
<td>Compartmentalization</td>
<td>Storage capacity</td>
<td>Sweep efficiency, recovery</td>
</tr>
</tbody>
</table>

A Good Tool for a Deeper Understanding of Flooding (The KinderMorgan Spreadsheet Model)
Reservoir Characterization (2)

The Kinder Morgan Spreadsheet Scoping Model

KINDERMORGAN (nee SHELL) CO2 FLOOD SCOPING MODEL
San Andres
http://www.kme.com/business/co2/tech.cfm

<table>
<thead>
<tr>
<th>RESERVOIR DATA INPUT</th>
<th>OUTPUT</th>
<th>SUMMARY OF CO2 FLOOD PREDICTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Oil Rate (1260 bbl/d)</td>
<td>Total CO2 Injected (238 bcf)</td>
<td>PERFORMANCE PLOTS</td>
</tr>
<tr>
<td>Current Oil Cut (0.04)</td>
<td>CO2 Purchased (0.72 bcf)</td>
<td>Oil Rates</td>
</tr>
<tr>
<td>Decline Rate (0.11 fraction/year)</td>
<td>EOR Recovery (10.6 mcf/bbl)</td>
<td>Production Rates</td>
</tr>
<tr>
<td>Existing Injectors (32)</td>
<td>Net CO2 Utilization (5.8 mcf/bbl)</td>
<td>Injection Rates</td>
</tr>
<tr>
<td>New Injectors (0)</td>
<td>Nominal Injection (0.668 bcf/yr)</td>
<td>Undisc Cum NCF Above WF</td>
</tr>
<tr>
<td>Existing Producers (32)</td>
<td>Effective Injection (0.668 bcf/yr)</td>
<td></td>
</tr>
<tr>
<td>New Producers (0)</td>
<td>HCPY (4029071)</td>
<td></td>
</tr>
<tr>
<td>TAI Producers (0)</td>
<td>OOP (3552858)</td>
<td></td>
</tr>
<tr>
<td>Average Depth (6000 ft)</td>
<td>Initial Investment (4.6 mm$)</td>
<td></td>
</tr>
<tr>
<td>Pattern Size (40 acres/pattern)</td>
<td>Recycle Investment (14.9 mm$)</td>
<td></td>
</tr>
<tr>
<td>Average Net Pay (3.55)</td>
<td>Total Investment (15.6 mm$)</td>
<td></td>
</tr>
<tr>
<td>Average Porosity (0.15 fraction)</td>
<td>PVPAT (at 10% nominal discount) (18.9 mm$)</td>
<td></td>
</tr>
<tr>
<td>Initial So (0.85 fraction)</td>
<td>B0 (Initial) (1.51 rh/ft)</td>
<td></td>
</tr>
<tr>
<td>B0 (Current) (1.23 rh/ft)</td>
<td>BCO2 (0.45)</td>
<td></td>
</tr>
<tr>
<td>Water Inj Rate (360 bb/d)</td>
<td>Injection Pressure (0.052 fraction)</td>
<td></td>
</tr>
<tr>
<td>Injection Losses (0.052)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

INPUT FOR CASH FLOW CALCULATION

- Royalty (0.125 fraction)
- Oil Price (15.00 $/bbl)
- Increase (0.02 fraction/year)
- CO2 Price (0.65 $/mcf (flat nominal))
- Inflation (0.02 fraction/year)
- Recycle Cost (0.20 $/mcf)
- Lift Cost (0.10 $/bbl)
- Fixed Cost (0.05 $/month)
- Discount Rate (0.10 fraction/year)
- Fed Tax Rate (0.35 fraction)
- EOR Tax Credit (0.15 fraction)
- See Tax Relief (0.025 fraction)

INPUT FOR CAPITAL INVESTMENT CALCULATION

- CO2 Source (1.0 miles (Distance from major CO2 pipeline))

The Kinder Morgan Spreadsheet Scoping Model
Freeware at http://www.kne.com/business/co2/tech.cfm
Reservoir Characterization (3)
Oil Response To CO\textsubscript{2} Injection

**SELECTED CO\textsubscript{2} FLOOD RESPONSE CURVES**

- **GMK So.**
- **Salt Creek (Tx)**
- **Mahoney**
- **Mallet**
- **Seminole**
- **Denver**

Basis for the KM Scoping Model (San Andres)
Northern Central Basin Platform Area

First Currings Sample Shows = 5330’

Base of Cuttings “Strong” Flour = 5620’

ROZ

PDI

DST 486” H₂O
A New Concept Being Pioneered in the Permian

Ref: Hess’ CO$_2$ Conf Presentation – 12/2001
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
Time for Some Questions
Permian CCS Center

Carbon Capture & Storage Technology

CCS (and CO$_2$ EOR) in the Permian Basin – Reservoir Characterization

R.E. Trentham
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Additional Reference Materials
### The ‘Significant’ CO₂ Companies

#### CURRENT (1/10) CO₂ SUPPLIERS AND OPERATORS

**SIGNIFICANT CO₂ SUPPLIERS +**

<table>
<thead>
<tr>
<th>Company</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denbury Resources (Jackson***</td>
<td></td>
</tr>
<tr>
<td>Kinder Morgan (McElmo*, Bravo*)</td>
<td></td>
</tr>
<tr>
<td>ExxonMobil (McElmo*, Sheep Mtn*, LaBarge**)</td>
<td></td>
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<tr>
<td>Occidental (Bravo*, Sheep Mtn*)</td>
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<tr>
<td>Dakota Gasification (N. Dak)</td>
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<tr>
<td>SandRidge (Val Verde‘)</td>
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<tr>
<td>Chevron (McElmo*)</td>
<td></td>
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<tr>
<td>Chaparral Energy (Ok)</td>
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<tr>
<td>Chevron (McElmo*)</td>
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<tr>
<td>Core Energy (MI)</td>
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</tbody>
</table>

**CO₂ FLOOD OPERATORS**

<table>
<thead>
<tr>
<th>Company</th>
<th>Locations</th>
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<tbody>
<tr>
<td>Occidental* (31)</td>
<td></td>
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<tr>
<td>Denbury*** (13)</td>
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<tr>
<td>Core Energy (8)</td>
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<td>Chaparral Energy (7)</td>
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<td>Chevron (7)</td>
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<td>Merit Energy** (7)</td>
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<td>Anadarko** (5)</td>
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<td>Fasken* (5)</td>
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<td>Apache Corp* (4)</td>
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<td>Hess Corporation* (4)</td>
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<td>Whiting Petroleum (4)</td>
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<td>XTO Energy* (4)</td>
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<td>ConocoPhillips* (2)</td>
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<td>Kinder Morgan* (2)</td>
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<td>Resolute Natural Resources (2)</td>
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<td>Devon*** (1)</td>
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<td>Energen* (1)</td>
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<td>George R. Brown Partnership* (1)</td>
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<td>Great Western* (1)</td>
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<tr>
<td>Murphin Drilling (1)</td>
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<tr>
<td>Orla Petco* (1)</td>
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<tr>
<td>Stanberry Oil (1)</td>
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</tbody>
</table>

* Perman Basin, ** Wyoming, *** Mississippi

+ Includes non-operating owners
“Quaternary” Oil

Note: This Quaternary Peak Assumes full field deployment and a 200” net thickness ROZ at 32% residual oil saturation
Reservoir Characterization

$\textit{CO}_2 \textit{EOR}$* Rules Of Thumb

- **PERCENT OF OOIP (ORIG OIL IN PLACE)**
  - 8 TO 18 (12)

- **RATIO – TERTIARY REC / (PRIM + SEC REC)**
  - 20 TO 35 (25)

- **VOLUMETRIC SWEEP EFFICIENCY (E)**
  - 25 TO 50 (35)

- **RATIO – Et / E(P+S)**
  - 50 TO 60 (50)

* Miscible Flooding

\[ \text{CO}_2 \text{ Swept Vol} \approx \frac{1}{2} - \frac{3}{5} \text{ths} \text{ Waterflooded Vol} \]

\[ \text{CO}_2 \text{ Contacts} \approx \frac{1}{4}^{th} - \frac{1}{2} \text{ of Reservoir Vol} \]