A History of Past Waterflood Operations in the Permian Basin

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Flood Starts

Through 1981 – 2053
Reported start dates – 1286
NW Shelf – Levelland Slaughter Statistics

- NW Shelf – 10% U.S. Reserves
- NW Shelf – Cume 4 BBO
- NW Shelf – Carbonate Reservoirs
- Levelland Slaughter – Cume 1.6 BBO
- Levelland Slaughter – 57 MBO/day
- Levelland Slaughter – 6% State’s Production
Permian Basin Waterfloods

- No of Floods
- Cum Oil 1981

Field names include: ABO, CANYON, REFF, CLEARFORK, DELAWARE SAND, DEVON, ELLENBURGER, GLORIETA, QUEEN, SAN ANDRES, SPRABERRY, YATES, YATES FIELD.
Evaluation

• Understand the Geology
• Understand the Petrophysics
• Understand the Reservoir Fluids
• Evaluate the Reservoir
Geologic Concepts are Important
Carbonate Ramp Schematic
Denver Unit
Peripheral Pattern
Denver Unit 9 Spot
Plus Irregular Patterns
Lucia Rock Classification

PETROPHYSICAL CLASSES

GRAIN-DOMINATED FABRIC
GRAINSTONE
PACKSTONE

MUD-DOMINATED FABRIC
PACKSTONE WACKESTONE MUDSTONE

Note: bar is 100 microns
Lucia Porosity – Permeability Transforms
Denver Unit Patterns Modifications

80 Acre Inverted 9-Spot
20 acre well spacing
Well Density: 3 prod./80 acres
1 inj./80 acres

80 Acre Semi-line Drive
13 acre well spacing
Drill 4 new producers (2 wells/pattern)
CTI 2 new injectors (1 well/pattern)
Well Density: 4 prod./80 acres
2 inj./80 acres
Means San Andres
Shoal – Correlation and Discontinuity

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**Stratigraphic Cross Section A - A'**

- **C** Waterflood Unit, Permian Basin

**Sections:**

(a) A (NW)

(b) “Conventional” Correlation

- Anhydrite Marker

(c) New Correlation Based on Conceptual Model and Cores

(d) Conceptual Model

- Dolomite Bars
- Flow Channels
- Producer
- Injector
- Dolomite Reservoir
- Flow Barriers
Means San Andres
McElroy Grayburg Field
McElroy Field

Waterflood Realignment Started

Waterflood Started

Proj Oil Cum: 221,516.79 Mbbl
Oil Rem: 0.00 Mbbl
Oil EUR: 221,516.79 Mbbl
Depositional Environment - Partitioning Levelland Slaughter
Potential Reservoir-Forming Settings

- Oolitic delta
- Beach-dune complexes
- Reefs
- Tidal channels
- Tidal flats
- Interior dunes
East West Cross Section
Through the Levelland Field
## Reservoir Petrophysical Properties

### Ramp Type

**San Andres Carbonate**

<table>
<thead>
<tr>
<th>Area</th>
<th>Shoal</th>
<th>Lagoon (Levelland)</th>
<th>Near Shore Intertidal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Depth</strong></td>
<td>4900</td>
<td>4900</td>
<td>4900</td>
</tr>
<tr>
<td><strong>Net Pay Primary (feet)</strong></td>
<td>70</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td><strong>Net Pay Secondary (feet)</strong></td>
<td>70</td>
<td>30</td>
<td>17</td>
</tr>
<tr>
<td><strong>Gross Pay (feet)</strong></td>
<td>120</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td><strong>Porosity Range (fraction)</strong></td>
<td>0.08 – 0.18</td>
<td>0.08 – 0.16</td>
<td>0.08 – 0.11</td>
</tr>
<tr>
<td><strong>Average Porosity (fraction)</strong></td>
<td>0.12</td>
<td>0.11</td>
<td>0.09</td>
</tr>
<tr>
<td><strong>Water saturation – Initial (frac)</strong></td>
<td>0.28</td>
<td>0.20</td>
<td>0.30</td>
</tr>
<tr>
<td><strong>Permeability – Range (md)</strong></td>
<td>1.0 – 40</td>
<td>0.1 - 30</td>
<td>0.1 - 30</td>
</tr>
<tr>
<td><strong>Permeability Geo Mean (md)</strong></td>
<td>2.5</td>
<td>1.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$k_{ro}$ @ Swi (frac)</td>
<td>0.57</td>
<td>0.57</td>
<td>0.57</td>
</tr>
<tr>
<td>$S_{ro}$ (frac)</td>
<td>0.28</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>$k_{rw}$ @ Sor (mD)</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>$S_{wi}$ (frac)</td>
<td>0.21</td>
<td>0.25</td>
<td>0.35</td>
</tr>
<tr>
<td><strong>Oil Saturation – At start of flood (frac)</strong></td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td><strong>Gas Saturation – At start of flood (frac)</strong></td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
</tr>
</tbody>
</table>
Infill Drilling - Shoal

Oxy Sundown Unit

- Oil (bbl/mth)
- Gas (mcf/mth)
- Water (bbl/mth)
- Water Inj (bbl/mth)
- No Prod
- No Inj

Infill Drilling
Infill Drilling – Lagoon & Near Shore

Whiteface Unit

Date

May-67
May-69
May-71
May-73
May-75
May-77
May-79
May-81
May-83
May-85
May-87
May-89
May-91
May-93
May-95
May-97
May-99
May-01
May-03

Infill Drilling

Oil (bbl/mth)
Gas (mcf/mth)
Water (bbl/mth)
Water Inj (bbls/mth)
No Prod
No Inj
SOUTHEAST LEVELLAND UNIT
At unitization

- Oil Rate (Cal. Day) ( bbl/d )
- Water Injection (Cal. Day) ( bbl )
Start of WF project -December 1964
FEB 1967

- Oil Rate (Cal. Day) ( bbl/d )
- Water Injection (Cal. Day) ( bbl )
Dec 1971
Oct 1973

Legend:
- Green circle: Oil Rate (Cal. Day) (bbl/d)
- Blue triangle: Water Injection (WI Day) (bbl)
Dec 1982

- Oil Rate (Cal. Day) (bbl/d)
- Water Injection (WI Day) (bbl)
Jan 1997

- Oil Rate (Cal. Day) ( bbl/d )
- Water Injection (WI Day) ( bbl )
Increased Water Injection Rate per Well in 1999
Milnesand Unit

- Injection Rate slowly Decreasing
- Reduced injection rate by 40%

WORₜ₀ = 4.0
m' = 1.16
Vertical Heterogeneity

Dykstra and Parsons’ coefficient of permeability variation” ($V$)

$$V = \frac{\bar{k} - k_\sigma}{\bar{k}}$$

Where $\bar{k} =$ permeability at the 50th percentile of the cumulative sample and $k_\sigma =$ Permeability at 84.1 percent of the cumulative sample.

Assumes a log normal distribution
Shoal Permeability Distribution

LLU 742

cume %

k (mD)
# Summary of Flood Evaluation by Area

<table>
<thead>
<tr>
<th>UNIT/LEASE NAME</th>
<th>AREA</th>
<th>WOR AT START OF FLOOD</th>
<th>PEAK OIL:INJ RATIO</th>
<th>VOIDAGE RATIO</th>
<th>S:P</th>
<th>WOR₀</th>
<th>m'</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxy West RKM</td>
<td>Shoal</td>
<td>0.25</td>
<td>0.26</td>
<td>1.2</td>
<td>2.5</td>
<td>0.5</td>
<td>1.79</td>
<td></td>
</tr>
<tr>
<td>Oxy Sundown</td>
<td>Shoal</td>
<td>0.40</td>
<td>0.23</td>
<td>1.3</td>
<td>4.8</td>
<td>0.9</td>
<td>1.85</td>
<td>0.77</td>
</tr>
<tr>
<td>Oxy Levelland</td>
<td>Shoal</td>
<td>0.35</td>
<td>0.26</td>
<td>1.1</td>
<td>2.3</td>
<td>0.5</td>
<td>1.92</td>
<td>0.73</td>
</tr>
<tr>
<td>Energen Whiteface</td>
<td>Lagoonal</td>
<td>0.60</td>
<td>0.27</td>
<td>1.4</td>
<td>2.8</td>
<td>0.8</td>
<td>1.22</td>
<td>0.88</td>
</tr>
<tr>
<td>Oxy Southeast Levelland</td>
<td>Shoal</td>
<td>0.25</td>
<td>0.30/0.23</td>
<td>1.2</td>
<td>3.6</td>
<td>0.7</td>
<td>1.53</td>
<td></td>
</tr>
<tr>
<td>Walsh Starnes</td>
<td>Intertidal – Near Shore</td>
<td>0.35</td>
<td>0.21</td>
<td>2.5</td>
<td>0.8</td>
<td>1.0</td>
<td>1.11</td>
<td>0.88</td>
</tr>
<tr>
<td>Devon M.G. Gordon</td>
<td>Shoal</td>
<td>0.15</td>
<td>0.47</td>
<td>1.1</td>
<td>1.5</td>
<td>0.2</td>
<td>2.22</td>
<td>0.90</td>
</tr>
<tr>
<td>North Central Levelland</td>
<td>Lagoonal</td>
<td>1.00</td>
<td>0.30</td>
<td>1.9</td>
<td>2.4</td>
<td>0.5</td>
<td>1.72</td>
<td></td>
</tr>
<tr>
<td>Milnesand</td>
<td>Shoal and Intertidal</td>
<td>0.70</td>
<td>0.09</td>
<td>1.6</td>
<td>0.7</td>
<td>4.0</td>
<td>1.16</td>
<td>0.46</td>
</tr>
</tbody>
</table>
RCU Evolution of Waterflood Patterns

1970-1977
- 40-AC. SPACING
- 80-AC 5-SPOT
- ▲ 40-AC. IW
- ● 40-AC. PW

1977-1982
- 20-AC. SPACING
- 80-AC. INVERTED 9-SPOT
- ○ 20-AC. PW

1982 TO PRESENT
- 10-AC. SPACING
- 40-AC. INVERTED 9-SPOT
- ▲ 40-AC. CONVERSION
- □ 10-AC. PW
South Wasson Clearfork Unit
South Wasson Clearfork Sequence Stratigraphy Defines Flow Layers
West Dollarhide
Queen Sand Unit
Lea Co, NM

Figure 17 - Redevelopment Phase Areas
Sirgo-West Dollarhide Queen Sand Unit
Dollarhide Queen Sand Unit Infill Drilling and Re-Development
Salt Creek
Salt Creek Canyon
Figure 1: Salt Creek Field Unit location map.
Salt Creek Canyon
Ford Geraldine (Delaware Sand)
Ford Geraldine – Type Well Flood Response
Dollarhide Devonian Unit
<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>WOODFORD SHALE</td>
<td>UPPER DOLOMITE</td>
</tr>
<tr>
<td></td>
<td>UPPER POROSITY ZONE</td>
</tr>
<tr>
<td>MIDDLE BIOCLASTIC LIMESTONE</td>
<td></td>
</tr>
<tr>
<td>LAMINATED TRIPOLITIC CHERT</td>
<td>LOWER POROSITY ZONE</td>
</tr>
<tr>
<td>BURROWED CHERT-DOLOMITE</td>
<td></td>
</tr>
<tr>
<td>Silurian Wrister</td>
<td>CARBONATE-CHERT MUDSTONE</td>
</tr>
</tbody>
</table>
Dollarhide Devonian Unit

Field:

Major Phase: Oil

Projected Oil Cum: 137,047.41 Mbbbl
Oil Rem: 0.00 Mbbbl
Oil EUR: 137,047.41 Mbbbl

Projected Gas Cum: 92,268.21 MMcf
Gas Rem: 0.00 MMcf
Gas EUR: 92,268.21 MMcf
Generic Version of CO₂ Project (Waterflood Phase) Permitted BHP Injection Pressures

Permitted Operating Pressure Gradient*

<table>
<thead>
<tr>
<th>Project</th>
<th>Op Pressure Gradient (psi/ft) **</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penn, Horseshoe Atoll</td>
<td></td>
</tr>
<tr>
<td>Devonian</td>
<td></td>
</tr>
<tr>
<td>Delaware Sand</td>
<td></td>
</tr>
<tr>
<td>Spraberry Unit</td>
<td></td>
</tr>
<tr>
<td>Clearfork - CBP</td>
<td></td>
</tr>
<tr>
<td>San Andres - CBP</td>
<td></td>
</tr>
<tr>
<td>San Andres - No Shelf</td>
<td></td>
</tr>
</tbody>
</table>

*Ref: TRRC Bulletin 82; All Calculated Pressures use Gradients of 0.4333 psi/ft

** Op Pressure Gradient Calculated by Adding Surf Pressure to a 0.4333 psi/ft Depth Gradient / IBHP
Injection Pressure 1982

797 of 1340 floods (Reporting) Injecting Over Frac Gradient
Step Rate Test

Is there a difference after shut in and while on injection?
Hall Plot

- A - Stable or normal injector after fill-up
- B - Negative skin/injecting above parting pressure
- C - Water channeling/out of zone injection
- D - Positive skin/poor water quality

Cumulative Pressure - PSI x Days/BBL

Cumulative Water Injection - BBL

Gas Fill-Up
Vertical or Horizontal?

\[
\frac{Q_h}{Q_v} = k_{\text{anisot}} \frac{H_h}{H_v} \frac{\ln \left( \frac{2r_e}{r_w} - 0.75 + S \right)}{\ln \left( \frac{2r_e}{r_w} \right) - 0.75 + S_{mh} + S_h + S_{cah} - 1.386}
\]

Where:
- \( k_{\text{anisot}} \) = permeability anisotropy \( (k_{\text{max}}/k_{\text{min}}) \)
- \( H_h \) = thickness of layer containing the horizontal wellbore
- \( H_v \) = sum of all completed layers in a vertical well
- \( r_e \) = drainage radius
- \( r_w \) = wellbore radius
- \( S \) = negative vertical – well skin factor due to stimulation
- \( S_{mh} \) = the mechanical well skin damage to a horizontal well
- \( S_h \) = the negative skin factor due to the horizontal well = \(-\ln(L/4r_w)\)
- \( S_{cah} \) = the shape related skin factor (function of drainage shape, well length, \( H_h \), and \( k_v/k_h \)) given by a correlation derived from charts
- \( L \) = horizontal wellbore length
Vertical or Horizontal?

Effect of $H_h/H_v$ on $Q_h/Q_v$ at various $S_m_h$
Permian Basin Stress Map
Capillary Pressure Curves

FLUID DISTRIBUTION IN A HETEROGENEOUS RESERVOIR
Net Pay - Fractional Flow Curve

Mallet Unit - Slaughter Field

Critical Swi = 0.42
Sw (frac)

fwbt=0.87

Swbt= 0.57
Texas Tech Christmas Wish List

• West Texas Consortium – TTU’s Backyard
  – Study Brownfields of the Permian Basin
  – Catalog and organize data
  – Group waterfloods by geology/reservoir characteristics
  – Collect and catalog stress data
  – Look at failed waterfloods for solutions

• Specific Field Studies
  – Fields studies include all SCA and PVT work
  – MRI tools available
  – Miscibility lab work

• Operational studies
  – Horizontal Drilling, completion, cementing, etc

• A winning football team……..aka BCS Bowl Appearance