Visualization Process Approach to Identify Scenarios to Improve Recovery in a Mature and Stratigraphically Complex Reservoir: El Cordon Field*

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Executive Summary

- Initial production in 1954.
- El Cordon reservoir produces oil and gas from Cañadon Seco, Caleta Olivia and Mina El Carmen formations.
- Very complex sedimentary environment.
- Limited lateral and vertical communication between sands.

Petrophysical Modeling

1. Well log data base for the 138 wells received for the study.
2. The 138 wells represent about 20% of the total number of 626 wells in the reservoir. 41 wells (6%) have Formation Density Logs (FDC), 6 wells (0.9%) had Sonic Logs.
3. Well log information was not areally distributed.
4. Limited tops/zones information.
5. No blue-print headers available.
6. Products were focused in determination of the key parameters for the volumetric estimation of hydrocarbons in-place.
Geocellular Model

- Improve efficiency through reservoir modeling.
- 3D representation of the reservoir features.
- Areal and vertical distribution of sand bodies.
- Control area oil in-place calculation.

OOIP Estimation

- Very complex sedimentary environment.
- Limited lateral and vertical communication between sands.
- Sands average thickness about 2.5 meters.
- Sands extend to a distance between 1-4 well spacing.
- ‘Key Area’ was used to calibrate probabilistic approach.

Scenarios

- Base case
- Well reactivation
- New well drilling
- Infill drilling
- Water flooding
- Polymer injection (screening)
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AAPG GeoSciences Technology Workshop
Houston, November 2010
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Objectives

- Identify Scenarios to improve recovery
- Proved an integrated approach
- Estimate asset value
Reserve Areas
How to indentify and materialize the value

Space of strategic decisions
Value identification

Space of strategic execution
Value materialization

TO VISUALIZE
CONCEPTUALIZE
TO DEFINE
TO EXECUTE
TO OPERATE

Front End Loading

Gate – FEL Checklist y RTP

Scenarios generation,
Technical and economical project feasibility
And business strategies alignment.

Selection and optimization of the best scenario

Project reach, costs,
Timeline, final optimization and budget

Build and operate

Project evaluation and control to assure return over investments.

DSD – Documento de Soporte de Decisión
Executive Summary

- Golfo San Jorge (GSJ) Basin
- Southern Flank
- El Cordon Field
Executive Summary

- Initial Production in 1954
- Implementation of water injection in 1979
- El Cordon reservoir produces Oil and Gas from Cañadon Seco, Caleta Olivia and Mina El Carmen Formations.
- Very complex sedimentary environment
- Limited lateral and vertical communication between sands.
Executive Summary
Efficiency Factors Scoring Technique
Sandstone Reservoir Characteristics

<table>
<thead>
<tr>
<th>SAND MATRIX</th>
<th>FLUID TYPE</th>
<th>RESERVOIR ENERGY</th>
<th>WELL MECHANICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEAN SAND NO SHALE</td>
<td>UNIFORM PERM</td>
<td>HIGH QUALITY OIL</td>
<td>WATER DRIVE</td>
</tr>
<tr>
<td>MEMBERED SANDS VERY SHALY</td>
<td>VARIABLE PERM</td>
<td>LOW GRAVITY OIL</td>
<td>SOLUTION GAS DRIVE</td>
</tr>
</tbody>
</table>

High Recovery 70%

- Vertical Continuity Displacement Efficiency
- Permeability Stratification
- Horizontal Sweep Efficiency
- Oil Mobilization
- Loss of GIP: Residual Oil Cap
- Gas Content Solution Gas Ratio
- Solution Gas Drive
- Well Spacing
- Depth of Artificial Lift Above Perforations
- Efficiency of Artificial Lift
- Quality of Completion

Low Recovery 10%

- Vertical Continuity Displacement Efficiency
- Permeability Stratification
- Horizontal Sweep Efficiency
- Oil Mobilization
- Loss of GIP: Residual Oil Cap
- Gas Content Solution Gas Ratio
- Solution Gas Drive
- Well Spacing
- Depth of Artificial Lift Above Perforations
- Efficiency of Artificial Lift
- Quality of Completion
Six scenarios were considered for maximizing reserves recovery:

1. Base Case
2. Well Reactivation
3. New Well Drilling
4. Infill Drilling
5. Water Flooding
6. Polymer Injection (screening)
Integrated Approach

- 3D G&G
- Economics
- Simulation
- Reservoir Eng.
- Well Opt
- Facilities
- Data
## Data Model

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Petrophysics</th>
<th>Fluids</th>
<th>Historic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seismic</td>
<td>Well Logs</td>
<td>P.V.T. Samples</td>
<td>Well Tests</td>
</tr>
<tr>
<td>Geologic</td>
<td>Cores</td>
<td></td>
<td>Production</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Injection</td>
</tr>
</tbody>
</table>

- No seismic-geologic project.
- 3D volume partial coverage (2/3)
- 138 out of 626 well log were received (22%).
- 41 wells with porosity indicator (6%)
- Scarce Core data (19 sample test)
- 1 recombined sample for PVT, Farigna’s correlation used.
- 2 transient (built up)
- Production history since 1972
- Scattered static pressure data
- Incomplete well events and mechanic diagrams
G & G Review
Petrophysical Modeling

1. Wells log data base for the 138 well received for the study

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G & G Review
Geocellular Model

- Improve efficiency through reservoir modeling
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- Areal and vertical distribution of sand bodies
- Control Area Oil in-Place calculation
Geocellular Model
Cross Section – Porosity Distribution

Porosity Distribution

Well bore

Perforation

Squeeze

EC-446  EC-467  PT-329  PT-461

PHI

• Very complex sedimentary environment
• Limited lateral and vertical communication between sands
• Sands average thickness about 2.5 meters
• Sands extend to a distance between 1 – 4 well spacing
• ‘Key Area’ was used to calibrate probabilistic approach
OOIP Estimation

Probabilistic Approach

\[ \text{POES} = \frac{7758 \times A \times \text{ANP} \times \phi \times (1 - Sw)}{\beta_{oi}} \]
OOIP Estimation

**Forecast: POES (MMBls)**

<table>
<thead>
<tr>
<th>POES P_{10}</th>
<th>POES P_{50}</th>
<th>POES P_{90}</th>
</tr>
</thead>
<tbody>
<tr>
<td>355,506,229.29</td>
<td>484,591,381.34</td>
<td>644,588,726.29</td>
</tr>
</tbody>
</table>

Statistics:
- Trials: 5000
- Mean: 493,597,486.42
- Median: 484,591,381.34
- Mode: ---
- Standard Deviation: 113,270,631.89
- Variance: 1.28E+16
- Skewness: 0.47
- Kurtosis: 3.24
- Coeff. of Variability: 0.23
- Range Minimum: 199,377,471.94
- Range Maximum: 1,028,898,528.82
- Range Width: 822,521,056.88
- Mean Std. Error: 1,602,015.96

Certainty is 80.00% from 355,506,229.29 to 644,588,726.29

**Sensitivity Chart**

Target Forecast: POES (MMBls)

- Porosidad: .75
- Saturación de Agua: -.47
- ANP: .39
- Factor Volume: -1.0
- Area: .99

Measured by Rank Correlation

<table>
<thead>
<tr>
<th>Range Minimum</th>
<th>Range Maximum</th>
<th>Range Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>199,377,471.94</td>
<td>1,028,898,528.82</td>
<td>822,521,056.88</td>
</tr>
</tbody>
</table>

**OOIP: 484,6 MMBls**

**Np May 06: 45,6 MMBls**

**RF May 06: 9.4% 9.4%**
Reservoir Production History

Oil Rate vs Time

1960 – 1979 (19 years)
Primary Recovery
RF = 6.24%

1979 – 2006 (29 years)
Primary + Secondary Recovery
RF = 3.18%
Cum RF = 9.42%

270 m³/d
1698 bpd


19 years
79 WI
29 years
07
Waterflooding

Field water injection history
Waterflooding

Field water injection history
Scenarios

Base Case
Well Reactivation
New well drilling
Infill drilling
Water flooding
Polymer injection (screening)
Scenarios

Considerations

• Review of historical production behavior of all wells in the field.

• Probabilistic distribution modeling for Oil Rate, GOR, Water Cut, Number of wells, emphasizing wells reactivated in the last 2 years.

• Analysis of fracture results.

• Four profiles for each scenario: Low (P10), Most likely (P50), High (P90), and a Maximized case: P90 + 25% increase in the number of wells are considered to illustrate the maximum RF.

• RF_{2017} (P50) = 14.47%, includes all scenarios

• RF_{2017} (Max) = 21.13%, includes all scenarios
Base Case

- Decline of the production curve to estimate ultimate recovery under current conditions
- Diagnostic Plot: Oil cut vs NP, to validate reserves estimation
- Economic limit was assumed as Qo=2 m³/day
- Incremental Recovery: 514 Mm³ @ year 2017
- Incremental Recovery Factor: 0.67% @ year 2017
- Ultimate Recovery Factor: 10.07% @ year 2017
Well Reactivation

- Currently more than 400 wells shut-in
- In the last 3 years, 15 wells/year have been reactivated.
- Probabilistic distribution for these wells shows:
  * P10 case: Qo = 0.71 m³/day/well
  * P50 case: Qo = 1.99 m³/day/well
  * P90 case: Qo = 5.32 m³/day/well
- P10, P50, and P90 Scenarios were considered
- Production improvement for P90 considers:
  * Review fracture techniques
  * High density, high penetration, under-balance.
New Well Drilling (330 m spacing)

- Undeveloped areas near to good producer wells.
- Latest drilling in some of these areas has demonstrated good potential.
- Oil rate probabilistic distribution for these wells based upon the new wells.
New Well Drilling (330 m spacing)

- **P10:**
  - Incremental Reserves: 210 Mm$^3$
  - Incremental RF: 0.27%
  - Ultimate RF (react + base): 10.31%

- **P50:**
  - Incremental Reserves: 305 Mm$^3$
  - Incremental RF: 0.72%
  - Ultimate RF (react + base): 10.76%

- **P90:**
  - Incremental Reserves: 815 Mm$^3$
  - Incremental RF: 1.80%
  - Ultimate RF (react + base): 11.84%

- **Maximized:**
  - Incremental Reserves: 1136 Mm$^3$
  - Incremental RF: 2.69%
  - Ultimate RF (react + base): 12.73%
Infill Drilling (165 m spacing)

- IFD is a technical opportunity for reserves recovery.
- Radius of drainage was modeled.
- Determined that infill drilling could be considered.
- Placed wells at half current well spacing.
- IFD results in acceleration of production in homogeneous reservoir and incremental recovery in heterogeneous reservoir, without reservoir continuity.
Infill Drilling (165 m spacing)

- **P10:**
  - Incremental Reserves: 411 Mm³
  - Incremental RF: 0.53%
  - Ultimate RF (react +base): 10.51%

- **P50:**
  - Incremental Reserves: 1117 Mm³
  - Incremental RF 1.45%
  - Ultimate RF (react +base): 11.49%

- **P90:**
  - Incremental Reserves: 1412 Mm³
  - Incremental RF 1.83%
  - Ultimate RF (react +base): 11.87%

- **Maximized:**
  - Incremental Reserves: 3909 Mm³
  - Incremental RF: 5.07%
  - Ultimate RF (react +base): 15.11%

330 wells are assumed to be drilled to develop the Max Scenario.
Waterflooding

• WI since 1979.
• Small pilot areas with low contribution to the total production of the field. Recovery factor (3.18%).
• Energy support is a high priority.
• WI scenario is based on analogy from current WI pilots and available studies.
• In general well production / pressure behavior reflects the waterflooding influence.
Waterflooding

• **P50:**
  - Incremental Reserves: 1436 Mm$^3$
  - Incremental RF: 1.86%
  - Ultimate RF (react + base): 11.9%
  - No new wells needed—only conversions and workover
  - 108 injector wells
  - 162 producer wells
  - Based on analog
Polymer Injection

Polymer Flooding: better displacement and volumetric sweep efficiencies

- Increasing the viscosity of water
- Decreasing the mobility of water
- Contacting a larger volume of the reservoir

<table>
<thead>
<tr>
<th>Technical Screening Guides</th>
<th>EL CORDON (CS1 / CO / ME)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude Oil:</td>
<td></td>
</tr>
<tr>
<td>Gravity:</td>
<td></td>
</tr>
<tr>
<td>Viscosity</td>
<td>&gt; 25 API</td>
</tr>
<tr>
<td>Composition Not Critical</td>
<td>100 cp critical</td>
</tr>
<tr>
<td></td>
<td>25 / 26 / 31</td>
</tr>
<tr>
<td></td>
<td>27 / 26/ 12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reservoir:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Saturation:</td>
<td>&gt; 10% PV mobile oil</td>
</tr>
<tr>
<td></td>
<td>22</td>
</tr>
<tr>
<td>Type of Formation:</td>
<td>Sandstone, but can be</td>
</tr>
<tr>
<td></td>
<td>used in carbonate</td>
</tr>
<tr>
<td></td>
<td>Sandstone</td>
</tr>
<tr>
<td>Net thickness (m)</td>
<td>Not critical</td>
</tr>
<tr>
<td></td>
<td>3-4 mt</td>
</tr>
<tr>
<td>Average Permeability (mD)</td>
<td>&gt; 10</td>
</tr>
<tr>
<td></td>
<td>250 /200 / 150</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>&lt; about 2743</td>
</tr>
<tr>
<td></td>
<td>1200 / 1300 / 1450</td>
</tr>
<tr>
<td>Temperature (F)</td>
<td>&lt; 200 F to minimize</td>
</tr>
<tr>
<td></td>
<td>degradation</td>
</tr>
<tr>
<td></td>
<td>119 / 126 / 132</td>
</tr>
</tbody>
</table>
Polymer Injection

Surfactant / Polymer Flooding:
- Lowering the interfacial tension between oil and water
- Solubilization of oil
- Emulsification of oil and water
- Mobility enhancement

### Technical Screening Guides

<table>
<thead>
<tr>
<th>Crude:</th>
<th>Technical Screening Guides</th>
<th>EL CORDON (CS1 / CO / ME)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity: &lt; 25 API</td>
<td>&gt; 30 cm</td>
<td>25 / 26 / 31</td>
</tr>
<tr>
<td>Viscosity: &lt; 30 cm</td>
<td>Light intermediates are desirable</td>
<td>27 / 26 / 12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reservoir:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Saturation:</td>
<td>&gt; 30% PV mobile oil</td>
<td>22</td>
</tr>
<tr>
<td>Type of Formation:</td>
<td>Sandstone preferred</td>
<td>Sandstone</td>
</tr>
<tr>
<td>Net thickness (m)</td>
<td>&gt; 3.04</td>
<td>3-4 m</td>
</tr>
<tr>
<td>Average Permeability (mD)</td>
<td>&gt; 20</td>
<td>250 / 200 / 150</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>&lt; about 2435</td>
<td>1200 / 1300 / 1450</td>
</tr>
<tr>
<td>Temperature (F)</td>
<td>&lt; 175 F</td>
<td>119 / 126 / 132</td>
</tr>
</tbody>
</table>
Conclusion

- Incremental Recovery Factor

<table>
<thead>
<tr>
<th></th>
<th>P10 Mm3</th>
<th>%RF</th>
<th>P50 Mm3</th>
<th>%RF</th>
<th>P90 Mm3</th>
<th>%RF</th>
<th>Maximized Mm3</th>
<th>%RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
<td>514</td>
<td>0.67%</td>
<td>514</td>
<td>0.67%</td>
<td>514</td>
<td>0.67%</td>
<td>514</td>
<td>0.67%</td>
</tr>
<tr>
<td>Reactivation</td>
<td>109</td>
<td>0.14%</td>
<td>305</td>
<td>0.40%</td>
<td>815</td>
<td>1.06%</td>
<td>1136</td>
<td>1.47%</td>
</tr>
<tr>
<td>New Wells</td>
<td>210</td>
<td>0.27%</td>
<td>559</td>
<td>0.72%</td>
<td>1386</td>
<td>1.80%</td>
<td>2075</td>
<td>2.69%</td>
</tr>
<tr>
<td>Infill Drilling</td>
<td>411</td>
<td>0.53%</td>
<td>1117</td>
<td>1.45%</td>
<td>1412</td>
<td>1.83%</td>
<td>3909</td>
<td>5.07%</td>
</tr>
<tr>
<td>Water Flooding</td>
<td></td>
<td></td>
<td>1436</td>
<td>1.86%</td>
<td>1436</td>
<td></td>
<td></td>
<td>1.86%</td>
</tr>
<tr>
<td>Incremental RF</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11.75%</td>
<td></td>
</tr>
<tr>
<td>Cum RF</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>21.13%</td>
<td></td>
</tr>
</tbody>
</table>

POES (Mm3) 77164 After Visualization
POES (MMstb) 485 After Visualization
Cum Oil Prod (Mm3) 2005 7733
RF 2005 9.37%
END