Optimization During the Reservoir Life Cycle

Case Study: San Andres Reservoirs
Permian Basin, USA

San Andres Reservoirs in the Permian Basin

- Two examples of life cycle reservoir management from fields in the Permian Basin of west Texas
- Both fields produce from the San Andres formation – a major carbonate reservoir in the basin
- Field “A”
  - “New Oil in Old Places,” by Robert Sneider
- The Means San Andres Unit
  - SPE 3301, 11023, 11987, 17349, 20751, 88770, 145229
Field “A” Development History

1955
- Developed on 40-acre spacing and produced by solution gas drive

1971
- Begin improved recovery by peripheral water injection

1980
- Conduct new reservoir study to understand uneven waterflood response
- Review stratigraphic correlations and net pay assumptions
- Evaluate benefits of infill drilling

This San Andres reservoir in Permian Basin, Texas is typical of many limestone reservoirs where geology is complex and rock properties vary both areally and vertically.
Geological Zonation Study

- A new correlation based on a depositional (tidal bar and channel) model shows that reservoir continuity is totally different from the original description of flow units and flow barriers
  - Original interpretation: Alternating layers of Oolite beds and flow barriers and localized thinning and thickening of both
  - Revised interpretation: Oolite beds are localized deposits separated from each other by continuous flow barriers

New Geologic Correlation
New Net Pay Criteria

- Conduct petrophysical studies to establish productivity criteria.
- The new porosity cut-off value from the revised $\Phi$-$K$ relationship is lower (4% for $K = 0.1$ md) than that based on the original relationship (10% for $K = 1.0$ md).
- The revised cut-off values are confirmed by selective production testing of low permeability intervals in newer wells and by conducting core flood tests in laboratory.
Reservoir Study Conclusions

- Revised zonal correlations
- Improved net pay definitions
  - Increased oil-in-place volume
- Convert to 5-spot waterflood pattern
- Infill drilling appears justified
- Implement pilot program to evaluate infill response
  - Results encouraging
- Expand drilling and pattern conversion to the entire field
  - Ensure that all wells are drilled through and completed in all of the available pay

Waterflood on 20-Acre Well Spacing

- Rapid response – higher oil rate, lower GOR, and higher inter-well pressure
Rate-Time Performance

Flood Pattern is Modified by Well Conversions

Sources of Recovery Enhancements

There is no magic bullet – optimization is not one activity but the combined result of a number of activities conducted in a comprehensive and deliberate manner.
Mean San Andres Unit Location Map

Discovered 1934
North-South Anticline with East-West Dense Structural Saddle.
- Grayburg Formation
  - Will not focus on here
- San Andres Formation
  - Depth 4800 ft, with gross pay 200-300 ft.
  - Fluid expansion and weak water drive.
  - Up to 5,000 BOPD well potential

Means San Andres Unit Pertinent Data

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<th>Means San Andres Unit Reservoir and Fluid Properties</th>
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<td>Saturation pressure, psig</td>
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<td>Estimated OOIP, MMBO</td>
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(Valenti)
**MSAU Rock Properties by Facies Type**

**TYPICAL MEANS SAN ANDRES PARASEQUENCE**

- FACIES
  - LOW ENERGY
  - HIGH ENERGY
- AVG.
- PENCESTRAL LAMINATE
- GIRD OR
- PELLET OR
- LAMINATED MUDR
- SKELETAL PELLET OR
- FEUGULINO M8

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**1935 Reservoir Study**

- Only 10 wells drilled and completed
- Three technical areas addressed:
  - Optimize Drilling – Increase drilling pressure to allow lower mud-weight systems – safer and cheaper (<50% of cost)
  - Reservoir Characterization – Good reservoir correlation between electric logs and subsequent productivity
  - Completion Techniques – Acidizing recommended over nitroglycerin shot holes because safer and cheaper
1959 and 1963 Reservoir Studies

- Forecast secondary recovery response
- Recommend unitization
- Design initial waterflood pattern
  - Peripheral for lower San Andres
  - 40-acre well spacing
  - Expect later implementation of 5-spot to flood tighter intervals in the upper San Andres pay
- Response difficult to quantify because MSAU was at top allowable

1969 Engineering and Geologic Study

- MSAU became capacity-limited in 1967
- Peripheral injectors were unable to provide sufficient pressure support for higher allowables
- Study correlated pressure data to 3 major San Andres reservoir intervals
- Recommend interior injection with 3:1 line drive pattern on 40-acre well spacing
- Oil production increased from 13,000 bpd in 1970 to > 18,000 bpd in 1972
MSAU: Line-Drive Performance

EUR under line drive estimated at 125 MMSTB assume:

- $S_o = 0.71$
- $S_{orw} = 0.34$ (SPE 17349)

Calculate $E_D$

What is the volumetric sweep efficiency based on a 415.5 MMSTB OOIP?

Is There Opportunity?

Recovery Factor (RF) = $\frac{125}{415.5} = 0.301$

$RF = E_D \times E_{VOL}$

$E_D = \frac{S_o - S_{orw}}{S_o}$

$E_{VOL} = \frac{RF}{E_D}$

- $E_D = (0.71 - 0.34)/0.71 = 0.52$
- $E_{VOL} = 0.301/0.52 = 0.58$

Would like $E_{VOL}$ to be higher
1975 Reservoir Study

Based on interpreted poor sweep efficiency

Study objectives

• Improve reservoir description (lateral and vertical distribution)
• Estimate current remaining reserves
• Recommend waterflood improvements to existing operations
• Evaluate alternate injection patterns
• Evaluate infill drilling

Recommended 20-acre well spacing with 80-acre inverted 9-spot pattern in 1976

Infill drilling continued through 1983 and pattern gradually converted to 40-acre 5-spot

MSAU: Pay Continuity With 40-Acre Data

Graph showing continuity progression with data points and percentages.
MSAU: Pay Continuity With 40-Acre Data

20-Acre Vs. 40-Acre Performance
Recovery Under 20-Acre Well Spacing

- EUR through 1983 estimated at 150 MMSTB (36.1% of 415.5 MMSTB OOIP)
- Assume same $E_D$ of 0.52
- What is the new volumetric sweep efficiency?

Is There Additional Opportunity?

- $RF = E_D \times E_{VOL}$
- $E_{VOL} = \frac{RF}{E_D}$
  \[ E_{VOL} = \frac{0.361}{0.52} = 0.694 \]
- Better, but would still like better sweep efficiency
- Also almost 64% of OOIP would be left – EOR target
1981 Reservoir Study – CO₂ Tertiary Project

Analogy to other proposed San Andres CO₂ floods looked encouraging

Major differences:
- Higher oil viscosity – 6 cp versus 1–2 cp
- High minimum miscibility pressure (MMP), 2000 psia
- Low formation parting pressure (2700–2800 psi)
- Potential low injectivity due to small pressure difference
- Possible CO₂ override

Recommend 10-acre well spacing with 40-acre 9-spot
- 1980 10-acre pilot showed promising results

Recommended enhanced surveillance program

MSAU: Original CO₂ Project Design

40% HCPV CO₂ slug size
2:1 water-alternating-gas (WAG) ratio
9.1% SOR to CO₂
- E₀ now 0.87

8,500 acre flood area (172 patterns)
16.6 MMSTBO incremental recovery due to CO₂ injection (7.1% of flooded OOIP)

21.4 MMSTBO incremental recovery due to 10-acre infill
MSAU: Continuity With 10-Acre Well Data

OOIP Revised to Greater than 700 MMstb

$E_{\text{VOL}}$ was MUCH Poorer than Previously Calculated!

MSAU: Variation in Pay Distribution
CO₂ Surveillance Program

Areal flood balancing: adjust injection volumes and WAG ratios to optimize CO₂ breakthrough and producing fluid ratios (GOR, WOR) while maintaining MMP

Vertical conformance monitoring: monitor, evaluate, and adjust wellbore production and injection profiles

- Annual injection profiles
- 4 3-well cross-sections for each pattern to ensure completion in floodable zones
- Remediate casing and packer leaks, out-of-zone injection and compare to kh and Фh profiles

MSAU: CO₂ Surveillance Program (continued)

Production monitoring: Identify and understand anomalies and breakthroughs. Resolve the following:

- Mechanical, scale or paraffin problems
- Reservoir pressure
- Thief zones in offset injectors

Injection monitoring: Optimize injection by balancing minimum parting pressure, MMP, and CO₂ / water quality

Data acquisition and management: Ensure quality, and timely collection and reporting of data
MSAU Performance Under 10-Acre Spacing and CO₂ Flood

Means San Andres Unit Performance

MSAU: Recovery Projection

Means San Andres Unit Performance
MSAU: EUR History

- 40-acre well spacing and line drive waterflood 125 MMStb
- 20-acre well spacing and 5-spot pattern waterflood 150 MMStb
- 10-acre well spacing and CO₂ flood 260 MMStb

Recovery factor in CO₂ flood areas now estimated at 45% OOIP (SPE 88770)

Operator is evaluating expansion of the CO₂ flood to lower oil saturation areas closer to the FWL (SPE 145229)

Means San Andres Unit Summary

- Excellent example of identifying and capturing new opportunities through infill drilling and injection processes
- Demonstrates need for improved reservoir surveillance and data management during improved and enhanced recovery operations