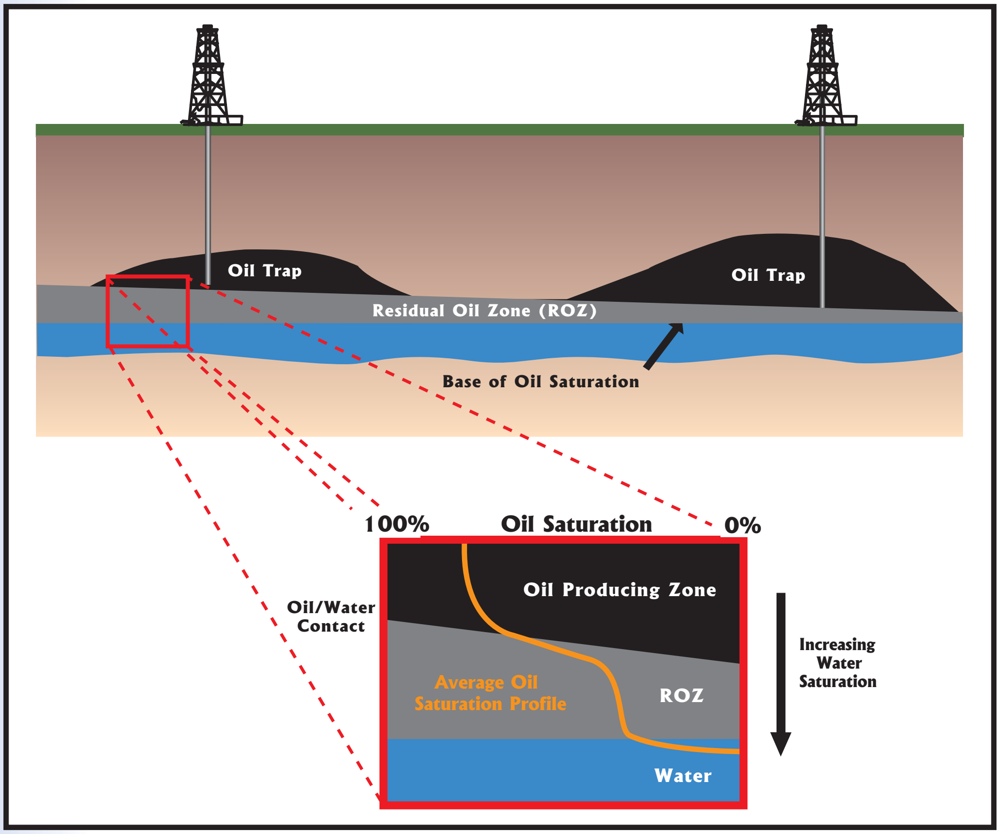
Technical Oil Recovery Potential from Residual Oil Zones: Permian Basin



Prepared for
U.S. Department of Energy
Office of Fossil Energy - Office of Oil and Natural Gas

Prepared by
Advanced Resources International

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I. INTRODUCTION

Residual oil zones (ROZ), the portion of an oil reservoir below its traditional producing oil-water contacts, can hold large volumes of previously undocumented and undeveloped domestic oil resources. The first comprehensive report on this topic, “Stranded Oil in the Residual Oil Zone,” examined the origin, nature and presence of ROZ resources.[1] The second report “Assessing Technical and Economic Recovery of Resources in Residual Oil Zones” provided a reservoir simulation-based study of applying CO_2-EOR to establish the feasibility of recovering oil from residual oil zones in five major oil reservoirs[2]. This third report, “Technical Oil Recovery Potential from Residual Oil Zones: Permian Basin”, provides an in-depth documentation of the in-place and recoverable ROZ potential from this important domestic oil production basin.

A. Overview of ROZ Recovery Potential. Because of their low to moderate oil saturation settings, ROZ resources are not economic when using primary or secondary oil recovery. As such, the traditionally domestic oil wells have traditionally been completed at or above the oil-water contact (the first observance of water) and thus consistently above the residual oil zone. Outside of a small group of forward-looking operators, little is still known about the ability to successfully identify and produce the ROZ resource. However, in the current economic climate, with depleting domestic oil reserves and operators’ desires to extend reservoir life, ROZ resources offer an important new source of domestic oil production. Because of this, there is growing interest in further understanding the resource size and recoverable oil potential in the relatively thick (100 to 300 feet) residual oil zones located beneath the main pay zones of oil reservoirs.

Carbon dioxide (CO_2) enhanced oil recovery (EOR) has emerged as a viable technique for recovering residual oil left behind (“stranded”) after waterflooding, mainly in light oil reservoirs below 3,000 feet in depth. Yet, the oil saturation in the transition

[1] Melzer, S., (2006) “Stranded Oil in the Residual Zone.” U.S. Department of Energy Report.
[2] “Assessing Technical And Economic Recovery Of Oil Resources In Residual Oil Zones”, Advanced Resources International, February 2006, U.S. Department of Energy Report.

(TZ) and residual oil zones (ROZ) of a reservoir is often similar to the oil saturations left after waterflooding. As such, with progress in CO_2 flooding technology and availability of affordable supplies of CO_2, the oil resource in the ROZ could readily become a feasibility target.

Further confirmation of this new oil resource potential is provided by the various residual oil zone CO_2-EOR pilot tests currently underway. Two of these pilot tests are operated by OxyPermian in the Denver and Bennett Ranch Units of the giant Wasson oil field. The Denver Unit pilot was the first to target transition and residual oil zones. A third ROZ pilot test, operated by Amerada Hess, is in the Seminole San Andres Unit. This is a 500 acre pilot TZ/ROZ flood underway since 1996. The response from this field pilot test has been most promising, providing an estimated cumulative recovery of 3 million barrels of oil to date, at an oil rate of1,400 bbls/day.[3] An expanding CO_2-EOR project targeting the ROZ is also underway in the Salt Creek field (by ExxonMobil) involving 36 wells and incremental production of 2,000 bbls/day.[4]

The information on the operation and performance of these ROZ field pilot projects has been most valuable in calibrating the reservoir simulation-based oil recovery assessments of the TZ/ROZ resource examined by this study.

B. Outline for Report. This report assesses the size of the in-place technically recoverable oil resource from the transition and residual oil zones of the Permian Basin. It first provides a very brief introduction to the oil plays and the major fields with tiled oil-water contacts (OWCs) and TZ/ROZ resources in the Permian Basin. Then, it examines, using a reservoir simulation calibrated streamtube model, the technical feasibility of recovering this previously by-passed TZ/ROZ resource using CO_2-EOR.

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[3] "2004 Worldwide EOR Survey," Oil & Gas Journal, April 12, 2004, pp. 53-65.
[4] Wilkinson, J.R., Genetti, D.B., and Henning, G.T., " Lessons Learned fro Mature Carbonates for Application to Middle East Fields", SPE 88770, presented at the SPE 11th Abu Dhabi International Petroleum Exhibition and Conference, October 10-13, 2004.

C. Definition of Terms. The term ***residual oil zone*** **(ROZ),** as used in this study, also includes the more commonly known ***transition zone*** **(TZ).** Although often used interchangeably, the two terms describe different portions of an oil reservoir. All oil reservoirs have a transition zone, an interval tens of feet below the traditionally-defined producing oil-water contact (OWC) where the oil saturation falls rapidly. The thickness of this interval is controlled by capillary forces and the nature of the rock's "wetting phase", with lower permeability oil-wet rocks providing thicker TZs and water-wet rocks providing thinner ones.

While all oil reservoirs have a transition zone, not all have a residual oil zone, as specific hydrological or geological conditions need to have occurred to create a ROZ, as further discussed below. The great bulk of the ROZ will be at a residual oil saturation (similar to that after a conventional waterflood), tapering to near zero oil saturation at the base. A typical reservoir oil saturation profile is shown in **Figure 1**, *Oil Saturation Profile in the TZ/ROZ: Adopted from Wasson Denver Unit Well.*

The transition zone (TZ) is the upper portion of the reservoir interval just below the traditional OWC and produces both water and oil. The residual oil zone (ROZ) is generally the middle and lower portions of the reservoir interval below the traditional OWC and upon initial completion produces primarily water.

The reason that both terms - - residual oil zone (ROZ) and transition zone (TZ) - - are used in this report is to bring special attention to the abnormally thick ROZs that can exist for reasons beyond normal capillary effects. For example, if the original oil trap possessed a thick oil column in its geologic past and the lower portion of this oil column was tilted and/or invaded by water, this lower reservoir interval would have an oil saturation much like that of the residual oil saturation in the swept zone of a water flood. In certain geologic settings, oil reservoirs can have an anomalously thick ROZ and thus could contribute considerable additional CO_2-EOR reserves.

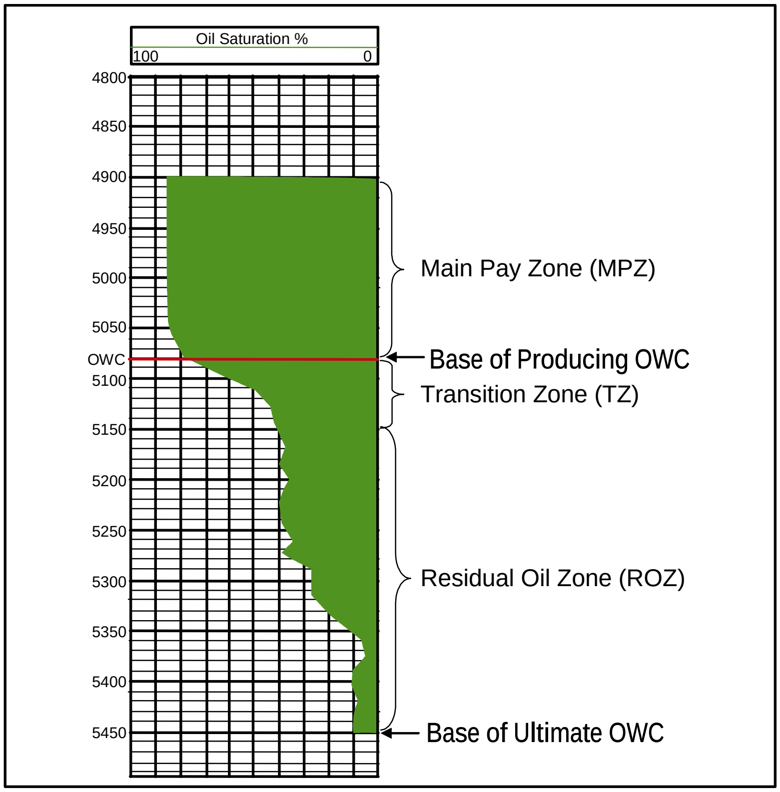

Figure 1. Oil Saturation Profile in the TZ/ROZ: Adapted from a Wasson Denver Unit Well.

D. Origin of Residual Oil Zones. A number of possible actions may create a ROZ after the initial accumulation of oil in a reservoir. Specifically, the original oil accumulation may subsequently be affected by natural forces such as regional basin uplift, seal breach, or a change in the hydrodynamics of the underlying regional aquifer, leading to the development of an ROZ. Additional discussion of the origins and nature of ROZs is provided into previously prepared reports.[5,6]

[5] Melzer, S., (2006) "Stranded Oil in the Residual Zone." U.S. Department of Energy Report.
[6] "Assessing Technical And Economic Recovery Of Oil Resources In Residual Oil Zones", Advanced Resources International, February 2006, U.S. Department of Energy Report.

E. Evidence for ROZs in the Permian Basin. One of the most valuable foundation sources for this study is the exemplary work by Brown, as summarized in **Figure 2**. Oil Fields with *Tilted Oil-Water Contacts in the Northern Shelf and Central Basin Platform, Permian Basin.*[7] The author made a thorough study of tilted OWCs in the carbonate shelf areas of the Permian Basin and concluded that many northern shelf San Andres fields have OWC tilts of hydrodynamic origin. This work, along with other hydrologic information, makes a strong case that the Middle Tertiary uplift in central New Mexico elevated the San Andres outcrops, changing subsurface San Andres reservoir hydrodynamics. The uplift created large hydrodynamic gradients below the oil reservoirs in this portion of the Permian Basin, sweeping substantial oil from the downdip reservoir spill points and creating OWC tilts and ROZs.

In addition, examination of the hydrodynamics history log data and results of two pilot projects, shows that the Canyon formation oil fields in the Horseshoe Atoll play of the Permian Basin also have significant ROZ resources.

The contrasting ROZ oil saturation profiles of two Permian Basin fields demonstrate the variability that hydrodynamic forces may have on creating a ROZ.

- The residual oil zone (ROZ) profile at the Wasson Denver Unit is often referred to as a transition zone (TZ) because of the relatively uniform gradational nature of the water (or oil) saturation profile, (shown previously as **Figure 1**). However, the zone is 300 feet thick on the southwest side which clearly argues for an origin other than normal transition zone capillary forces.

[7] Brown, A., (2001), "Effects of Hydrodynamics on Cenozoic Oil Migration, Wasson Field Area, Northwestern Shelf of the Permian Basin," West Texas Geological Society Fall Symposium, Pub 01-110 (Viveiros, J.J. & Ingram, S.M. eds), Oct 2001, pp 133-142.

Adapted from Brown, A., (2001), "Effects of Hydrodynamics on Cenozoic Oil Migration, Wasson Field Area, Northwestern Shelf of the Permian Basin," West Texas Geological Society Fall Symposium, Pub 01-110 (Viveiros, J.J. & Ingram, S.M. eds), Oct 2001, pp 133-142.

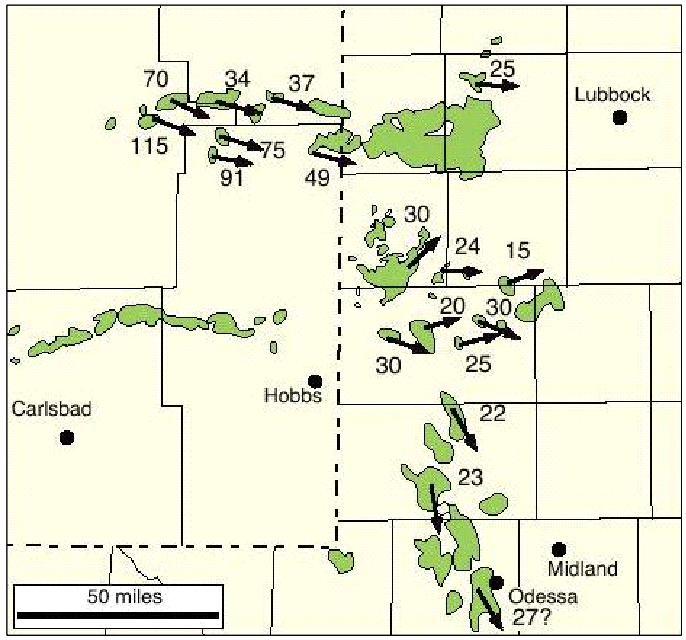

Figure 2. Oil Fields with Tilted Oil-Water Contacts: Northern Shelf and Central Basin Platform, Permian Basin.

- The ROZ profile at the Seminole San Andres Unit is substantially different from the oil saturation profile at Wasson. Here a thick middle zone of nearly constant oil and water saturation is present, **Figure 3**, *Seminole Field Water Saturation Profile***.**

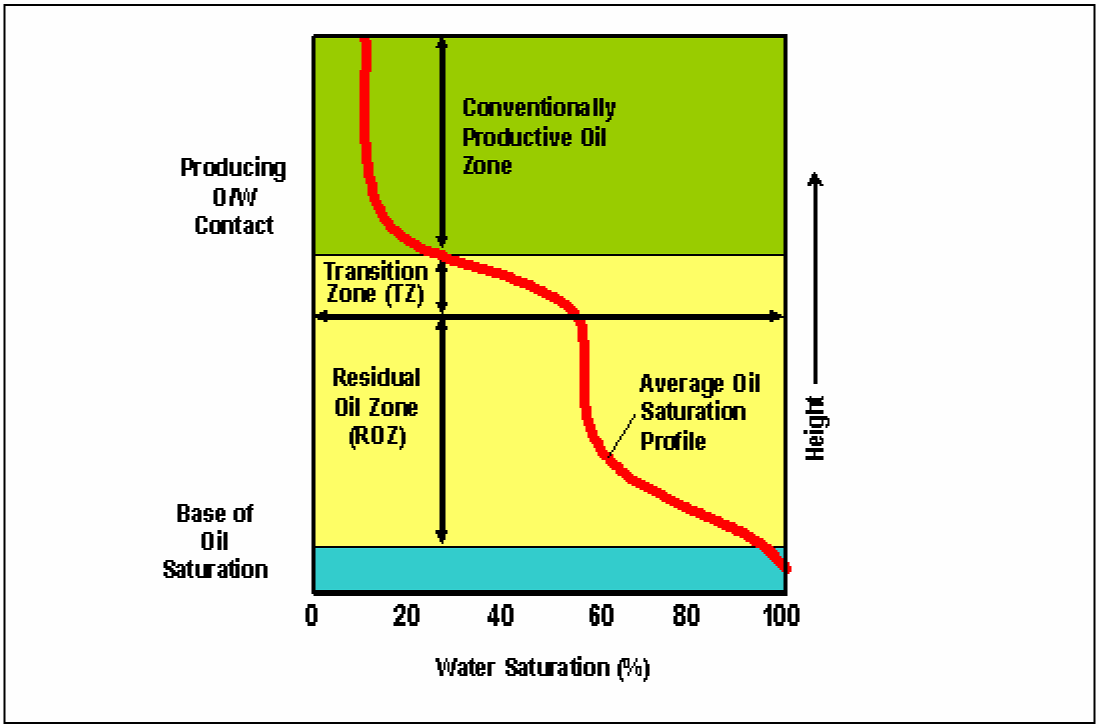

Figure 3. Seminole Field Water Saturation Profile.

- But, both the Wasson and Seminole fields have tilted OWCs, implying past or current hydrodynamic forces at work. Horizontal water influx and flushing of oil would explain both the tilt and the thick ROZ profile in these two oil reservoirs.

Based on the available geologic information, documented OWC tilts and log-based data, a number of major oil reservoirs with ROZs were established in five major Permian Basin oil plays, as follows:

1. Northern Shelf Permian Basin: San Andres Carbonate Formation
2. North Central Basin Platform: San Andres/Grayburg Carbonate Formation
3. South Central Basin Platform: San Andres/Grayburg Carbonate Formation
4. Horseshoe Atoll: Canyon and Cisco Carbonate Formation
5. Eastern New Mexico: San Andres Carbonate Formation

II. IDENTIFYING AND EVALUATING OIL FIELDS WITH ROZ RESOURCES

A. Northern Shelf Carbonate, Permian Basin (San Andres). The Northern Shelf Carbonate oil play in the Permian Basin originated on the northern portion of the Central Basin Platform on a structural feature and then expanded southward by prograded deposition, **Figure 4**. The primary oil reservoirs in this oil play are in the porous portions of the lower San Andres, above the older Abo Reef trend. Detailed mapping of the reservoir at Wasson helped define the irregular oil-water contacts, common to many of the San Andres oil fields in this play.[15] For example, a two mile E-W cross section through the center of the Adair Field shows a 300 to 500 foot change in the oil-water contact (OWC). A ten mile E-W cross section through the southern portion of the Wasson Field shows a 300 to 400 foot change in the OWC and the projected water level.

The Wasson Field contains two CO_2 floods targeting the ROZ, one in the Denver Unit and one in the Bennett Ranch Unit. The ROZ, in both units, has an average net thickness of 150 feet.

Based on the geological and hydrological information for the Permian Basin and identification of ROZs at Adair, Ownby, Reeves, and Wasson oil fields, the following 12 large Northern Shelf Carbonate (San Andres) oil reservoirs are judged to have potential for substantial TZ/ROZ oil resources, **Table 1**.

[15] Ghauri, W.K., Osborne, A.F., and Magnuson, W.L., 1974, “Changing Concepts in Carbonate Waterflooding, West Texas Denver Unit Project – An Illustrative Example”, SPE/American Institute of Mining and Metallurgical Engineers, Permian Basin Oil and Gas Recovery Conference, Dallas, paper no. 4683, p. 33-56.

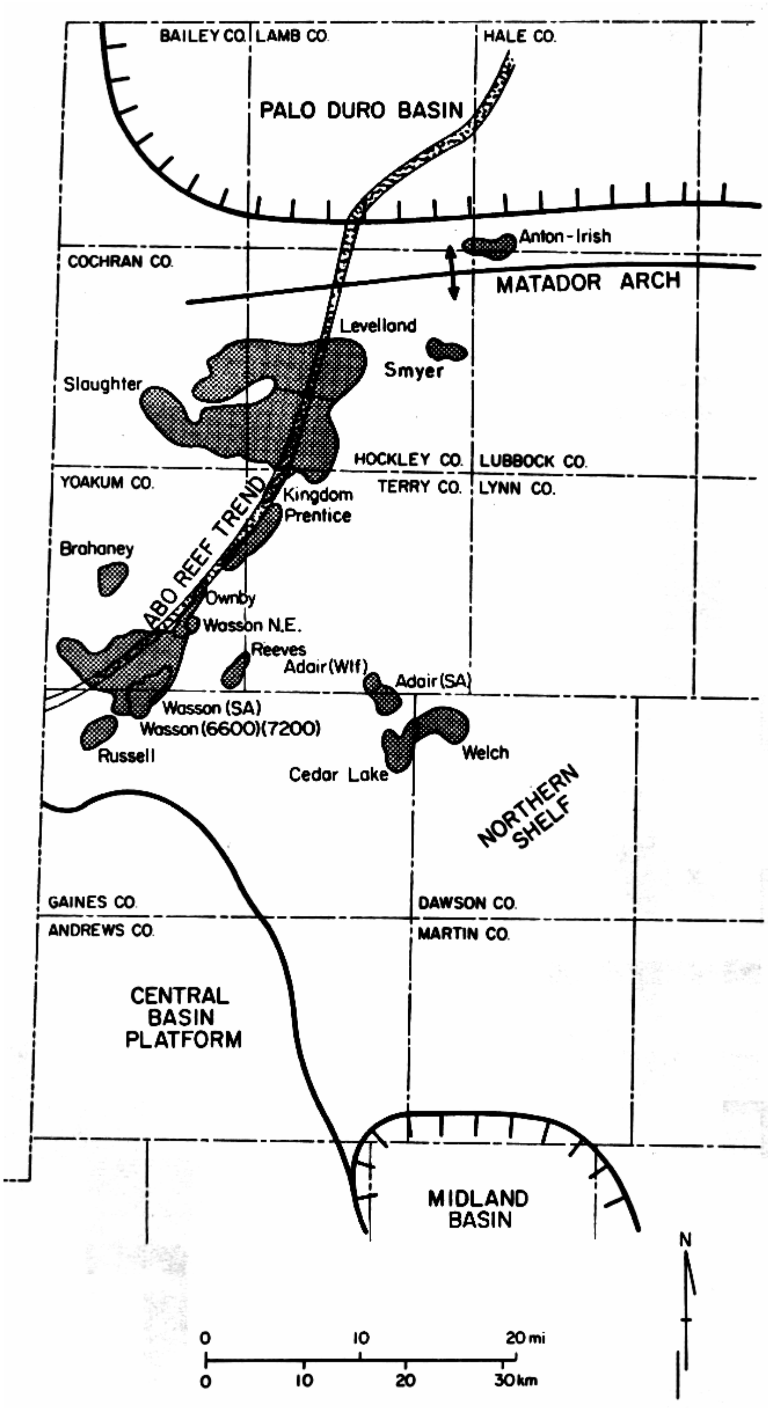

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Figure 4. Location Map of Major San Andres Reservoirs: Northern Shelf, Permian Basin

Table 1. Large Northern Shelf Carbonate (San Andres) Oil Reservoirs with Potential for ROZ Resources

Field	RR District	Cumulative Oil Production (MMB)(1-1-03)
1. Adair	8A	68.1
2. Brahaney	8A	56.0
3. Cedar Lake	8A	110.0
4. Levelland Unit	8A	662.0
5. Ownby	8A	18.9
6. Prentice 6,700	8A	154.2
7. Prentice	8A	48.7
8. Reeves	8A	34.6
9. Slaughter	8A	1,234.7
10. Wasson	8A	1,883.9
11. Wasson 72/66	8A	107.4
12. Welch	8A	173.0

B. North Central Basin Platform (San Andres/Grayburg). This dolomitic Upper Permian-age oil play is located on the northern portion of the Central Basin Platform, **Figure 5**. The large oil reservoirs in this play align along and marginal to the extensive San Andres sponge-algal-grainstone shoal complex.

The traps in this oil play are simple, broad anticlinal closures (such as at Seminole) or partially productive structures (such as at Means). The fields commonly have irregular oil-water contacts.[16] The OWC structure isopach map for the Seminole field provides further evidence of the tilted oil-water contact in this field, **Figure 6**.

[16] Galloway, W.E., et al., "Atlas of Major Texas Oil Reservoirs", 1983, Bureau of Economic Geology, University of Texas at Austin.

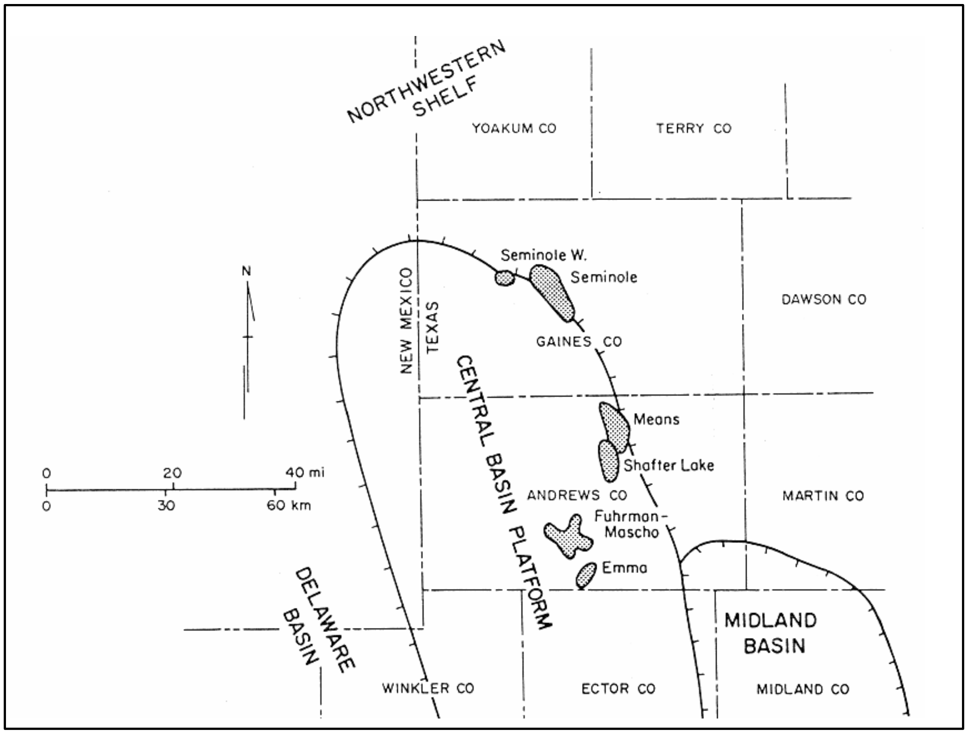

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Figure 5. Location Map of Major San Andres/Grayburg Reservoirs: North Central Basin Platform

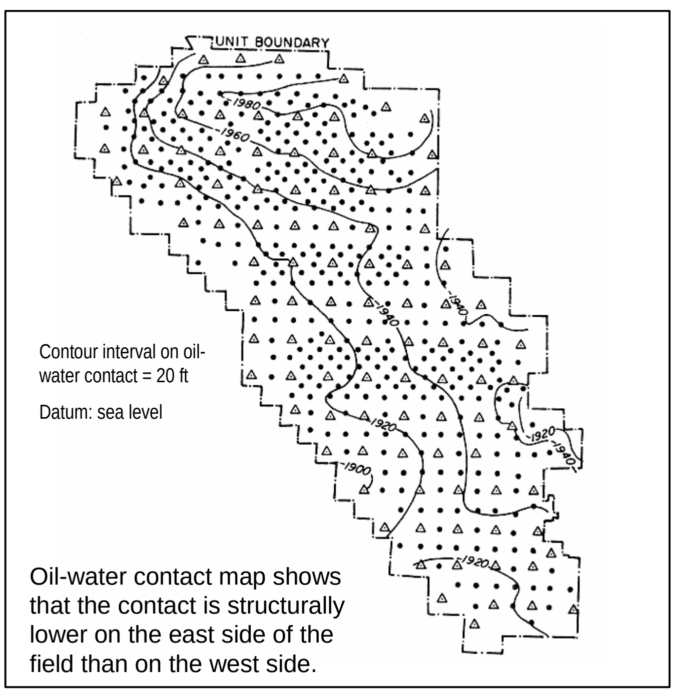

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Figure 6. San Andres Reservoirs, Seminole Field, Gaines County.

In the Seminole Field, which has an on-going 500-acre (ten injection and 15 production wells) CO_2 flood in the ROZ, the gross thickness of the ROZ (in the CO_2 pilot area) is 246 feet, with 197 feet of net pay.[17]

Based on the geologic information, the evidence for ROZs at Fuhrman-Masco and Seminole W. and the direct observation of ROZs at Means and Seminole, the following large North Central Basin Platform (San Andres/Grayburg Formation) oil reservoirs are judged to have potential for substantial TZ/ROZ oil resources, **Table 2**.

Table 2. Large North Central Basin Platform (San Andres/Grayburg) Oil Reservoirs with Potential for ROZ Resources

Field	RR District	Cumulative Oil Production (1-1-03)
1. Emma	8	47.0
2. Fuhrman-Masco	8	119.2
3. Means	8	240.6
4. Seminole	8A	620.5
5. Seminole, W	8A	48.0
6. Shafter Lake	8	50.8

C. South Central Basin Platform (San Andres/Grayburg). The South Central Basin Platform (San Andres/Grayburg) oil play is located along the eastern edge of the Central Basin Platform, **Figure 7**. The carbonate strata were deposited in open to restricted platforms and platform-margin systems.

[17] Melzer, S., (2006) "Stranded Oil in the Residual Zone." U.S. Department of Energy Report.

Structure mapping shows that the oil-water contact in several of the key oil fields is tilted. For example, at the McElroy field, the OWC in the east (basinward) side of the field is at 1,300 feet below sea level; on the westside, it is at 300 to 500 feet below sea level.[18]

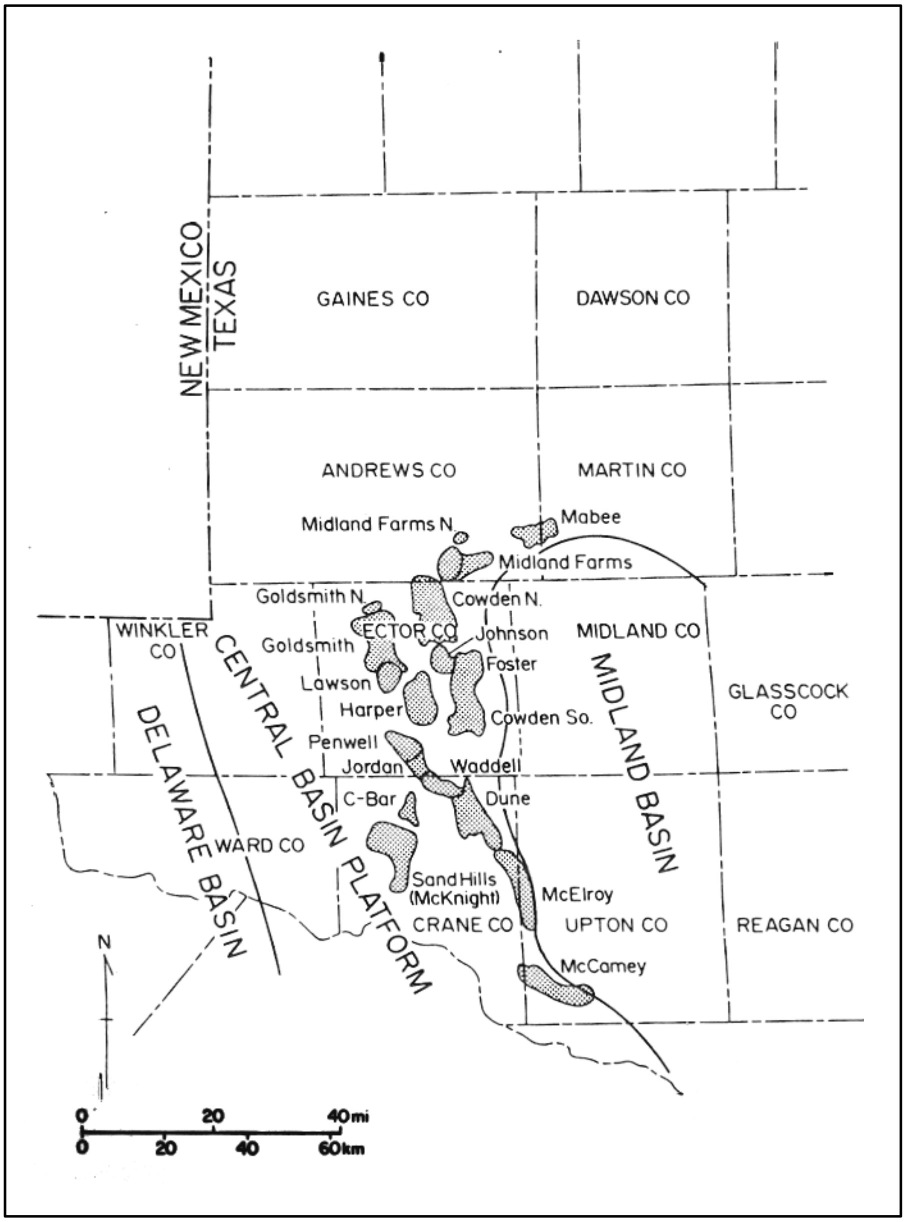

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Figure 7. Location Map of Major San Andres/Grayburg Reservoirs: Southern Part of the Central Basin Platform

[18] Galloway, W.E., et al., "Atlas of Major Texas Oil Reservoirs", 1983, Bureau of Economic Geology, University of Texas at Austin.

Based on the geologic information and identification of tilted oil-water contacts at Cowden N&S and Foster, the following large South Central Basin Platform (San Andres/Grayburg) oil reservoirs are judged to have potential for substantial TZ/ROZ oil resources, Table 3.

Table 3. Large South Central Basin Platform (San Andres/Grayburg) Oil Reservoirs with Potential for ROZ Resources.

Field	RR District	Cumulative Oil Production (1-1-03)
1. Cowden, N.	8	553.8
2. Cowden, S.	8	163.0
3. Dune	8	193.0
4. Foster	8	289.0
5. Goldsmith, N.	8	21.2
6. Goldsmith	8	359.2
7. Harper	8	50.8
8. Johnson	8	36.7
9. Jordan	8	91.5
10. Lawson	8	16.2
11. Mabee	8	118.4
12. McElroy	8	561.6
13. Midland Farms	8	163.3
14. Penwell	8	102.0
15. Sand Hills McKnight	8	129.6
16. Wadell	8	110.0

D. Horseshoe Atoll. The Horseshoe Atoll is a Middle Pennsylvanian-age broad carbonate platform, nearly circular in shape, **Figure 8**. In the Late Pennsylvanian, the Midland Basin began to subside rapidly. Subsequent tilting of the platform with infusion of water into the interior of the atoll created its horseshoe shape.

The Horseshoe Atoll complex consists of massive carbonate units separated by locally correlative shale beds. The greatest thickness and vertical relief of the atoll is along its western margin, where nearly 3,000 feet of carbonate rises above the basin floor. With time and basin subsidence, increasingly isolated carbonate knolls and pinnacles evolved on the laterally continuous atoll foundation. The greatest volume of oil accumulated in the updip, thinner, southeastern rim of the atoll. The thickness of the oil columns and depth of the oil-water contacts (OWC) vary significantly within this play.[19]

1. Kelly-Snyder (SACROC). Kelly-Snyder (SACROC) is the dominant oil field in the Horseshoe Atoll. The northern portion of the oil field is structurally higher, dips steeply to the west and east, and contains the thickest carbonate deposition.

Initially at SACROC, most of the wells were drilled above or to the OWC, at -4,500 feet, the location of the first occurrence of water in a drillstem test or in production data. In the early 1980s, several wells in the southern portion of the lease were deepened below the OWC, providing commercial quantities of oil. In the mid-1990s, a number of wells were drilled to further define the potential of the oil resource below the OWC.

[19] Galloway, W.E., et al., "Atlas of Major Texas Oil Reservoirs", 1983, Bureau of Economic Geology, University of Texas at Austin.

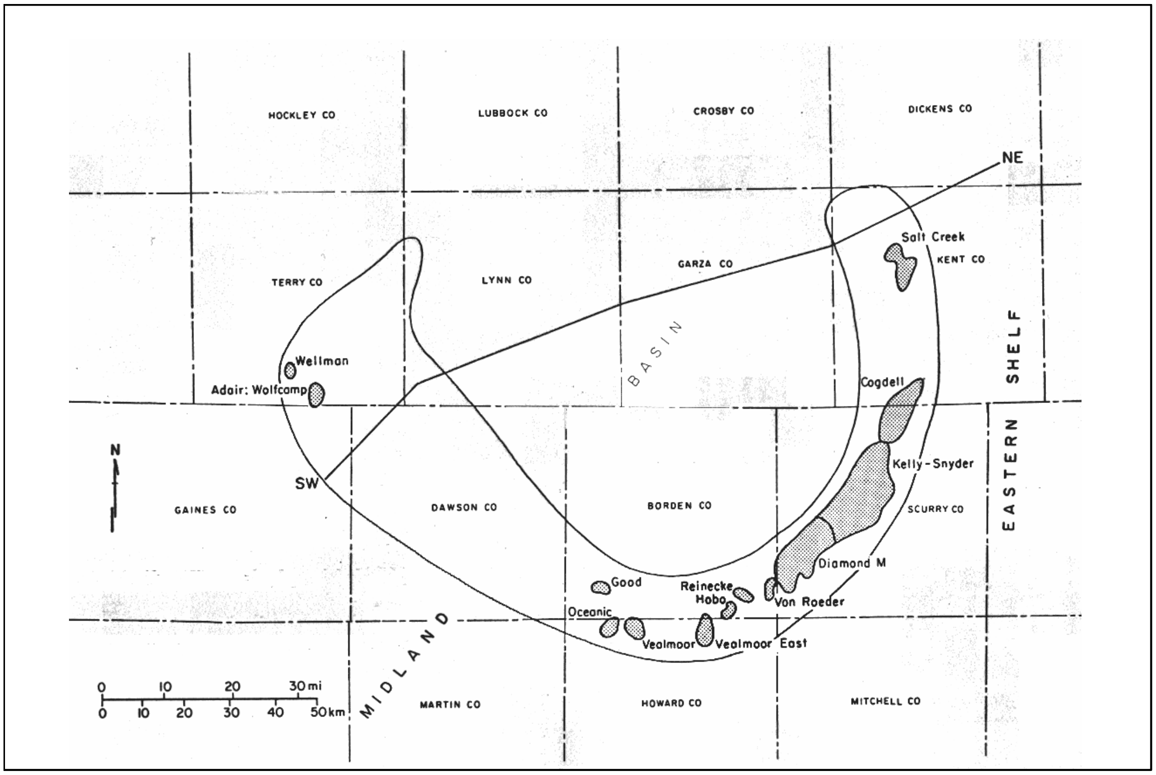

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Figure 8. Location Map of Horseshoe Atoll

Well 206-2, a watered-out, shut in well, was deepened (in mid-1994) by 83 feet. It identified a TZ/ROZ resource extending from the bottom of the Middle Canyon to the base of ROZ #1, **Figure 9**.

- The well identified three new oil producing flow units and produced an additional 20,000 barrels in 18 months **Figure 10**. These lower flow units appear to not communicate with the main Canyon Reef reservoir.[20]

- Based on this, the field producer (Pennzoil, who operated the field from 1990 to 1999) initiated a pattern-based deepening program to CO_2 flood the residual oil in these lower zones.

[20] Bummett, Jr., W.M., Emanuel, A.S., and Ronquille, J.D., "Reservoir Description by Simulation at SACROC – A Case History", SPE 5536, October, 1976

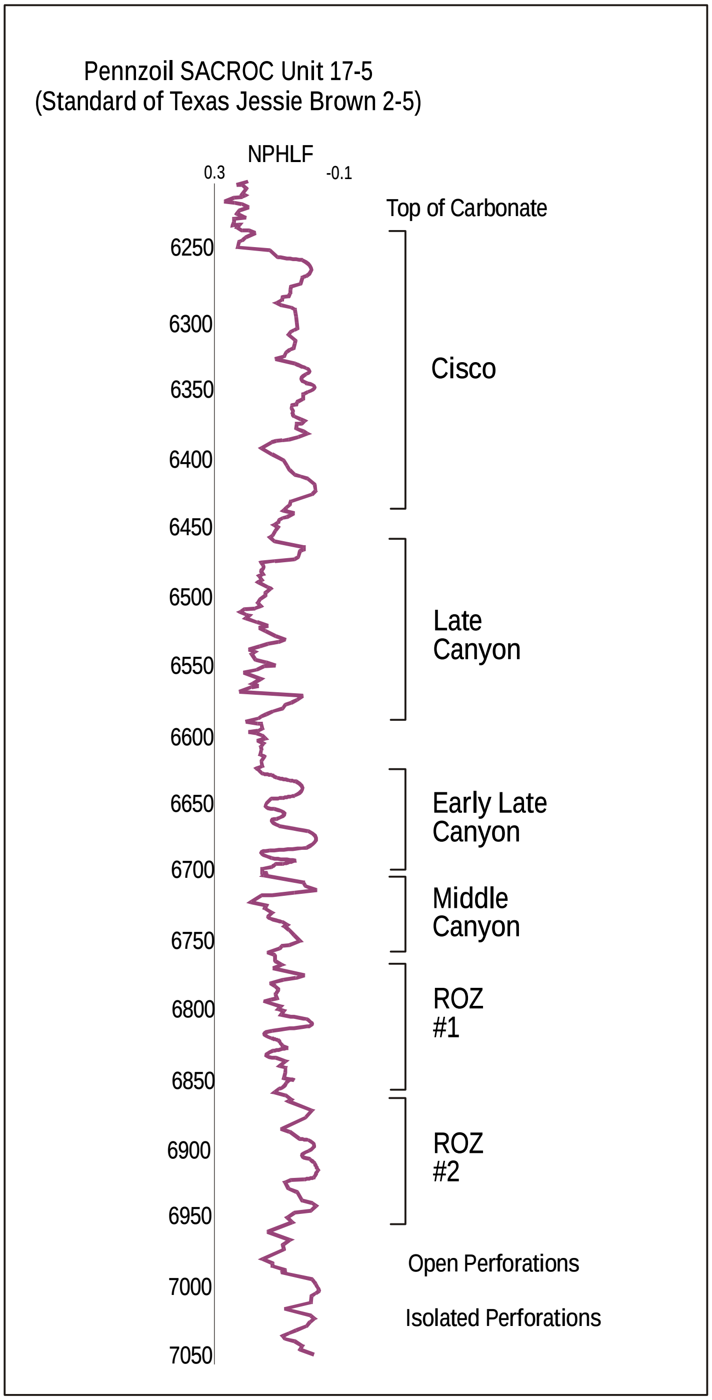

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Figure 9. Log for SACROC Unit Well 17-5, Identifying The Main Pay Zone and Two ROZs.

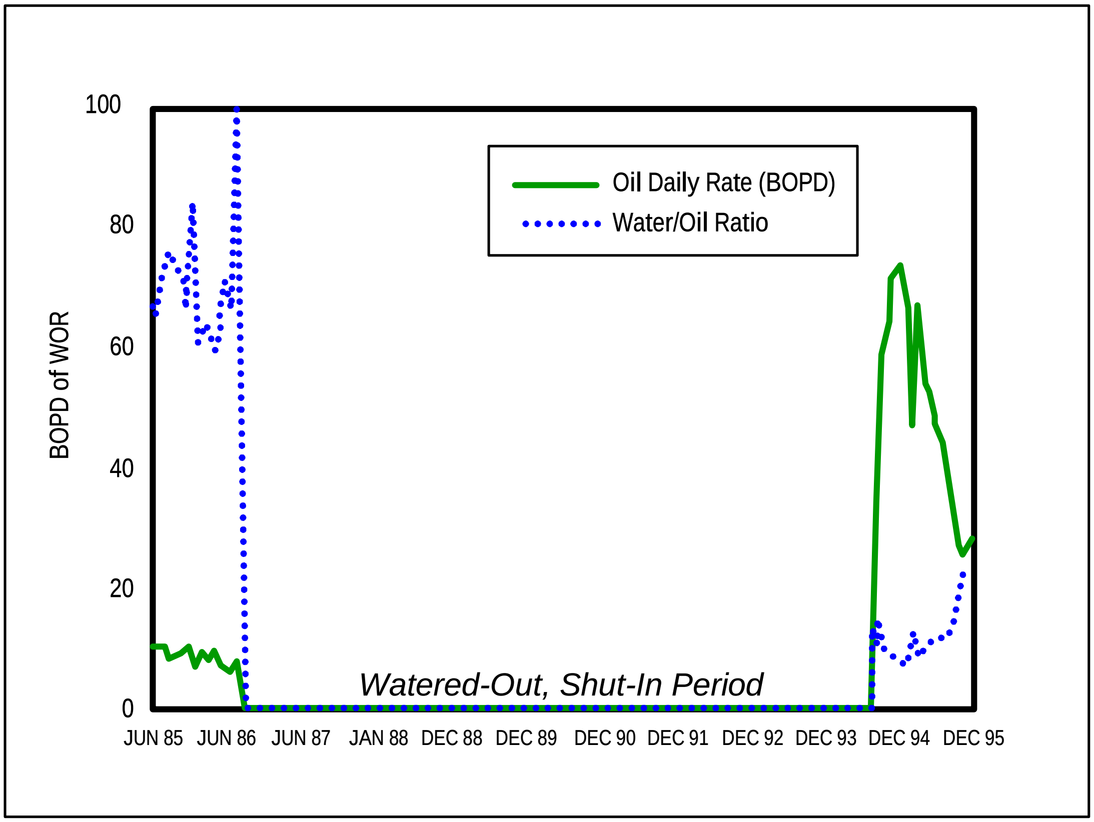

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Figure 10. Well 206-2 Production. Well 206-2 Deepened Below -4,500 ft SS Exposing Three New Flow Units.

Subsequent work by Kinder-Morgan (the operator of the SACROC Unit starting in 2000), has established that a thick transition zone exists below the original OWC. However, this interval appears to have low flow capacity.

2. Salt Creek. The Main Canyon pay zone on the eastern side of the Salt Creek field is underlain by a thick residual oil zone (ROZ) with an average gross thickness of 120 feet, original oil saturation of 50%, and similar reservoir properties as the MPZ.[21]

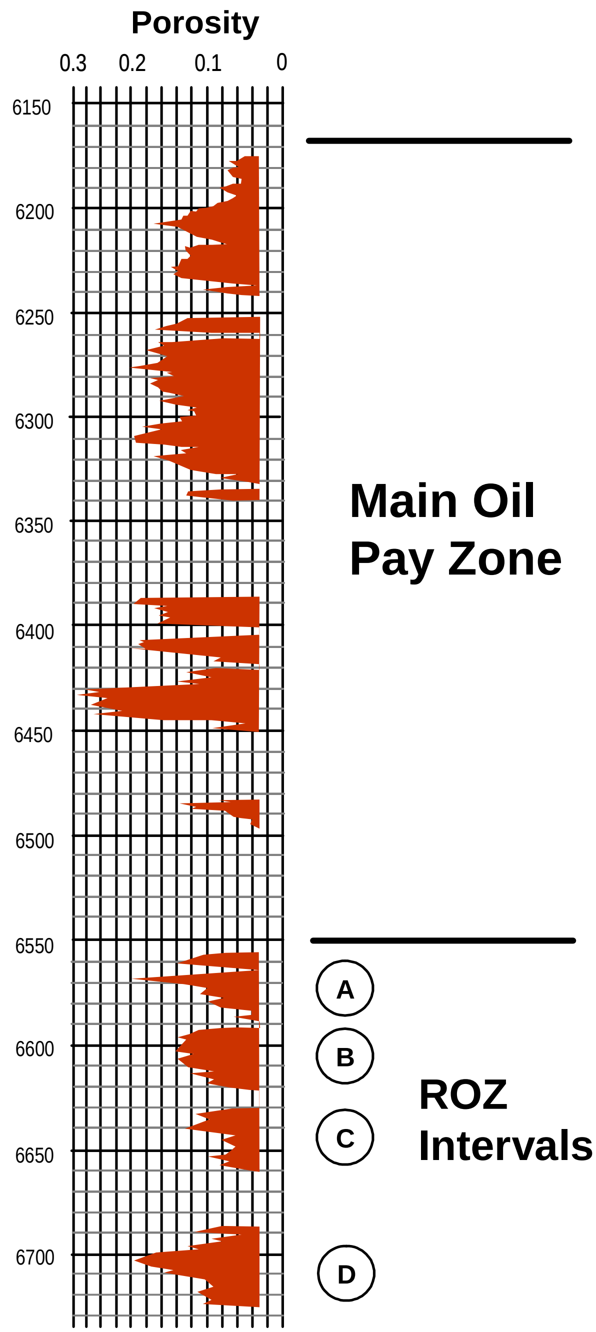
[21] Wilkinson, J.R., Genetti, D.B., and Henning, G.T., " Lessons Learned fro Mature Carbonates for Application to Middle East Fields", SPE 88770, presented at the SPE 11th Abu Dhabi International Petroleum Exhibition and Conference, October 10-13, 2004.

After the start of the Salt Creek CO_2 flood in the MPZ, the operator initiated (in 1996) a 16-well CO_2 injection pilot program (consisting of ten WAG injectors and six producers) in the underlying ROZ, in intervals A, B, and C, **Figure 11**. Larger scale expansion (each involving 18 wells) of the ROZ flood followed, as shown in **Figure 12**, with additional expansions planned for future years. Oil production from the year 2000 and 2001 ROZ development added 2,000 B/D by mid-2002, **Figure 13.**

Based on geologic information and actual definition of the ROZ at Kelly-Snyder (SACROC) and at Salt Creek, the following large Horseshoe Atoll (Canyon) oil reservoirs are judged to have potential for substantial TZ/ROZ oil resources, Table 4.

Table 4. Large Horseshoe Atoll (Canyon) Oil Reservoirs with Potential ROZ Resources

Field	RR District	Cumulative Oil Production (1-1-03)
1. Adair	8A	52.5
2. Cogdell	8A	265.8
3. Diamond M	8A	251.3
4. Kelly-Snyder	8A	1,264.9
5. Reinecke	8A	86.3
6. Salt Creek	8A	367.8
7. Von Roeder (+NVR)	8A	367.8
8. Wellman	8A	74.6
9. Oceanic	8	24.3
10. Vealmoor E.	8	63.0



Source: Bishop, D.L., ExxonMobil Production Company; et. al., SPE paper 88720, “Vertical Conformance in a Mature Carbonate CO2 Flood: Salt Creek Field Unit, Texas”, presented at the SPE 11th Abu Dhabi International Petroleum Exhibition & Conference, Abu Dhabi, 10-13 October 2004.

Figure 11. Salt Creek Type Log (San Andres)

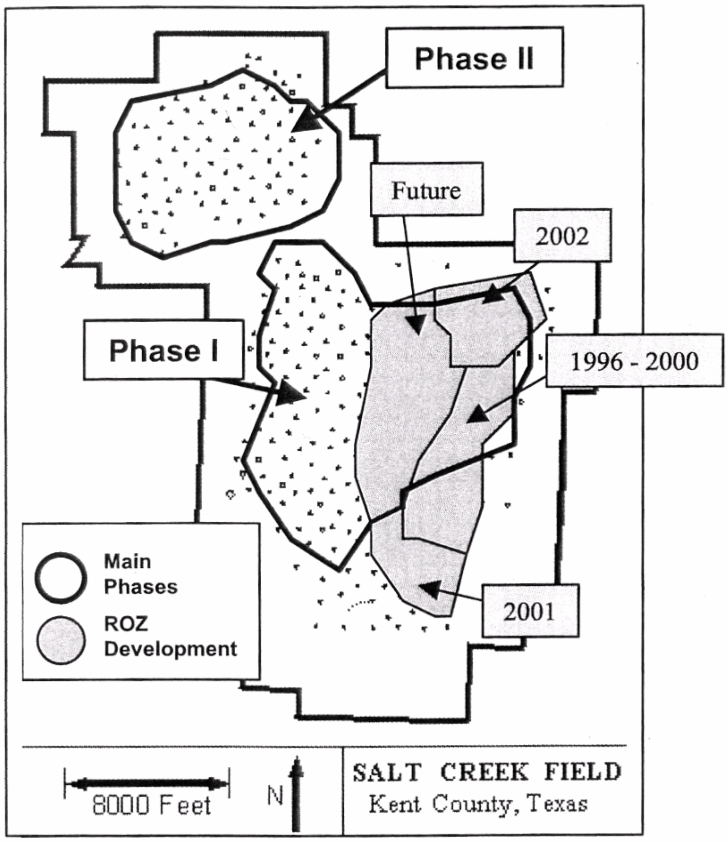


Figure 12. MPZ and ROZ CO2 Flood Implementation (Salt Creek)

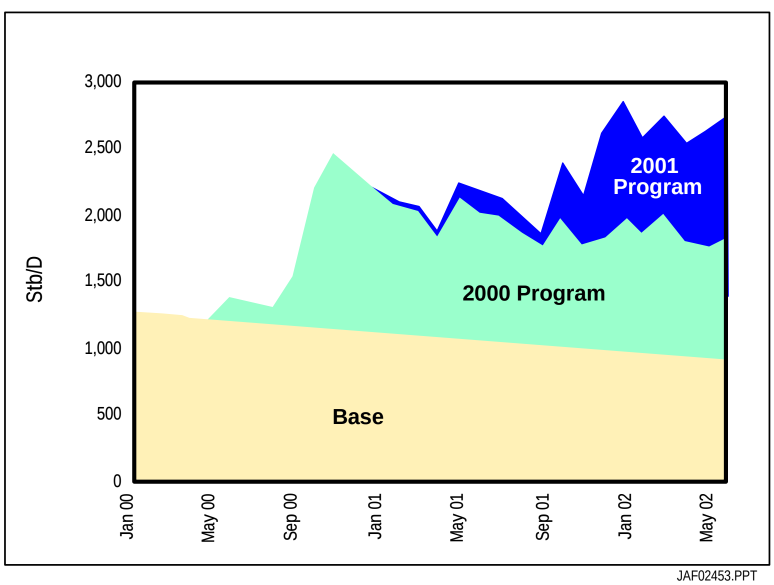


Figure 13. Oil Production from Year 2000 and 2001 ROZ Development (Salt Creek)

E. Eastern New Mexico. The eastern New Mexico portion of the Permian Basin has a geologic setting and reservoir properties similar to Northern Shelf Permian Basin (see above). Prior work has identified a series of oil fields in this area, including Cato, Chaveroo, and Flying M, that have tilted oil-water contacts.[22]

Based on geologic information and identification of tilted oil-water contacts, discussed above, the following large eastern New Mexico oil reservoirs are judged to have potential for substantial TZ/ROZ oil resources, **Table 5.**

Table 5. Large Eastern New Mexico (San Andres) Oil Reservoirs with Projected ROZ Resources.

Field	RR District	Cumulative Oil Production (1-1-03)
1. Cato	East NM	16.3
2. Chaveroo	East NM	24.5
3. Flying M	East NM	11.6
4. Hobbs	East NM	342.7
5. Vacuum	East NM	355.9
6. Bluitt	East NM	2.5
7. Sawyer	East NM	1.8
8. Mescalero	East NM	7.1
9. Todd	East NM	2.9
10. Twin Lakes	East NM	5.6
11. West Sawyer	East NM	9.4

[22] Brown, A., (2001), "Effects of Hydrodynamics on Cenozoic Oil Migration, Wasson Field Area, Northwestern Shelf of the Permian Basin," West Texas Geological Society Fall Symposium, Pub 01-110 (Viveiros, J.J. & Ingram, S.M. eds), Oct 2001, pp 133-142.

III. ESTIMATING TECHNICALLY RECOVERABLE ROZ RESOURCES

This chapter discusses the comparison and calibration of the *CO2-PROPHET* steamtube model with a full-scale, industry standard compositional reservoir simulator. As shown in the following materials, *CO2-PROPHET* provides an excellent match of oil recovery, for both the MPZ and the TZ/ROZ for our four sample major Permian Basin oil fields. As such, there is confidence in using the *CO2-PROPHET* model to estimate oil recovery from the TZ/ROZ for the larger number of Permian Basin oil fields assessed by this study.

A. *Background on CO2-PROPHET.* The *CO2-PROPHET* model was developed by the Texaco Exploration and Production Technology Department (EPTD) as part of the DOE Class I cost-share program.[23]

In its simplest form, this model generates streamlines for fluid flow between injection and production wells, and then uses finite difference methods to determine oil displacement and recovery calculations along the established streamlines. Data input requirements are less demanding and computational times are much shorter for using *CO2-PROPHET* than for using full-scale reservoir simulation. Moreover, input requirements for *CO2-PROPHET* can generally be obtained or calculated using engineering formulations. Key input parameters impacting oil recovery in *CO2-PROPHET* include:

1. Residual oil saturation,
2. Dykstra-Parsons coefficient,
3. Oil and water viscosity,
4. Reservoir pressure and temperature, and
5. Minimum miscibility pressure.

[23] "Post Waterflood CO_2 Flood in a Light Oil, Fluvial Dominated Deltaic Reservoir" (DOE Contract No. DE-FC22-93BC14960).

B. Comparison and Calibration of *CO2-PROPHET* with a Full-Scale Reservoir Simulator. The *CO2-PROPHET* model was compared and calibrated by Advanced Resources with an industry-standard compositional reservoir simulator. The primary reason for the comparison was to determine whether *CO2-PROPHET* could effectively model oil recovery from the TZ/ROZ. A second reason was to better understand how the absence of a gravity override function in *CO2-PROPHET* might influence the calculation of oil recovery in these low oil saturation zones.

As a first step, the Wasson Denver Unit (San Andres) reservoir data set was used as the input file for modeling a simultaneous MPZ and TZ/ROZ CO_2 flood using a full-scale simulator. An analogous data set was placed into *CO2-PROPHET* to replicate the MPZ and TZ/ROZ simultaneous flood. First, for simplicity, all oil saturations in the input database for the *CO2-PROPHET* model were set at residual oil. Under this simplified condition, *CO2-PROPHET* had lower oil recoveries than the full-scale simulator.

A closer review of the two input data sets enabled us to understand the reasons for the divergence. No mobile oil saturations were initially included in the input file for *CO2-PROPHET*; however, the input data file for the full-scale reservoir simulator had higher (and mobile) oil saturation in the TZ interval. Using simple weight-averaging, a small mobile oil saturation (~3%) was added to the reservoir intervals in the *CO2-PROPHET* input file to account for the mobile oil in the TZ. An excellent match for projected Wasson cumulative oil recovery was obtained between *CO2-PROPHET* and the full-scale simulator, after making this adjustment. This two step comparison and match is shown on **Figure 14**.

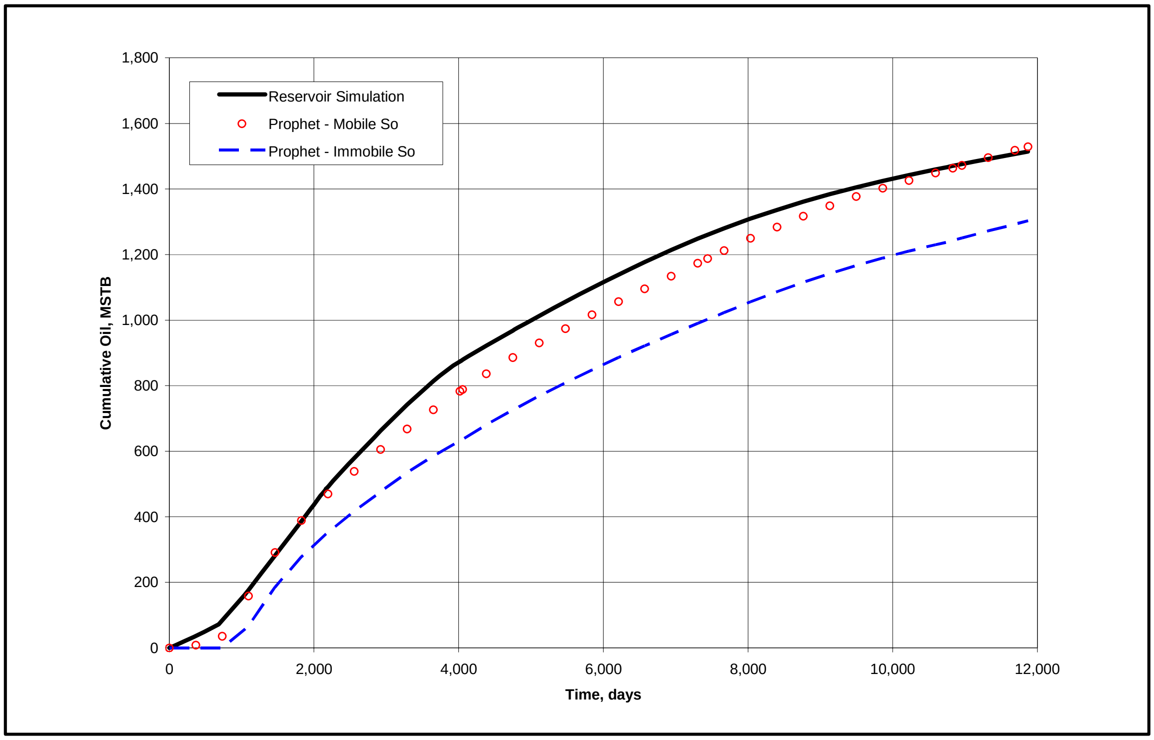


Figure 14. Analysis of Simultaneous MPZ and TZ/ROZ Oil Recovery: Simulation Comparison Results, Wasson Denver Unit.

Similar *CO2-PROPHET* and full-scale simulator comparisons were completed for three additional oil fields - - Seminole (San Andres Unit), Wasson (Bennett Ranch Unit), and Vacuum (San Andres/Grayburg) (**Figures 15 through 17**) - - again showing an excellent match between the two models when the oil saturation modification (discussed above) was included in the *CO2-PROPHET* input data set.

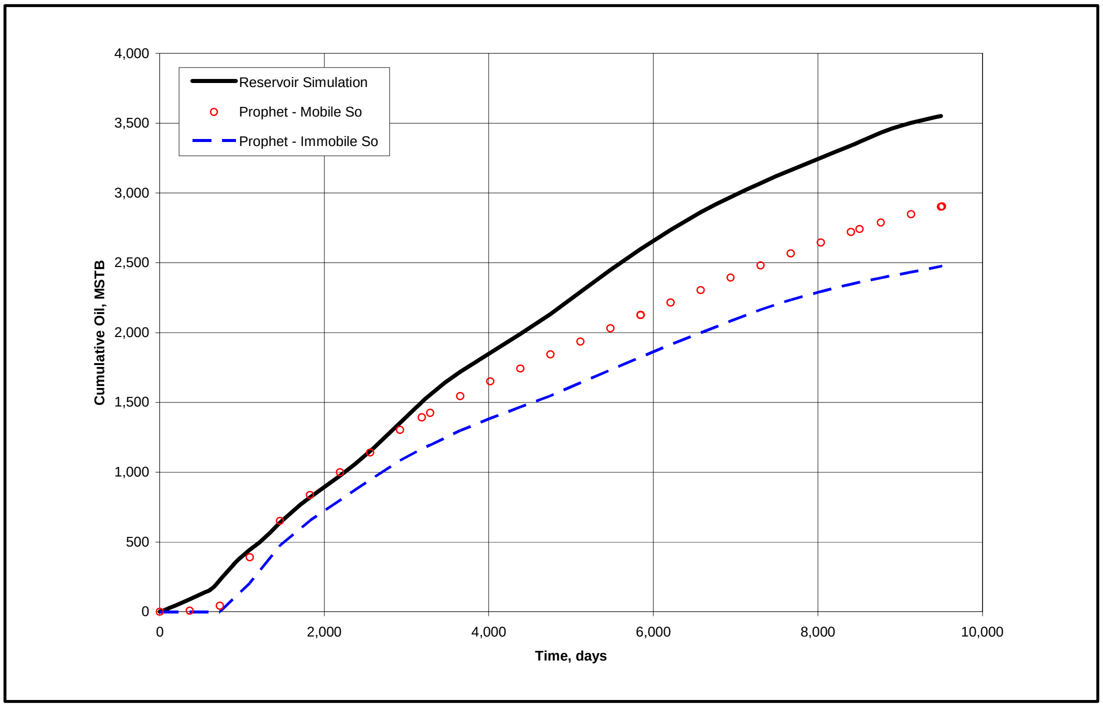


Figure 15. Analysis of Simultaneous MPZ and TZ/ROZ Oil Recovery: Simulation Comparison Results, Seminole San Andres Unit.

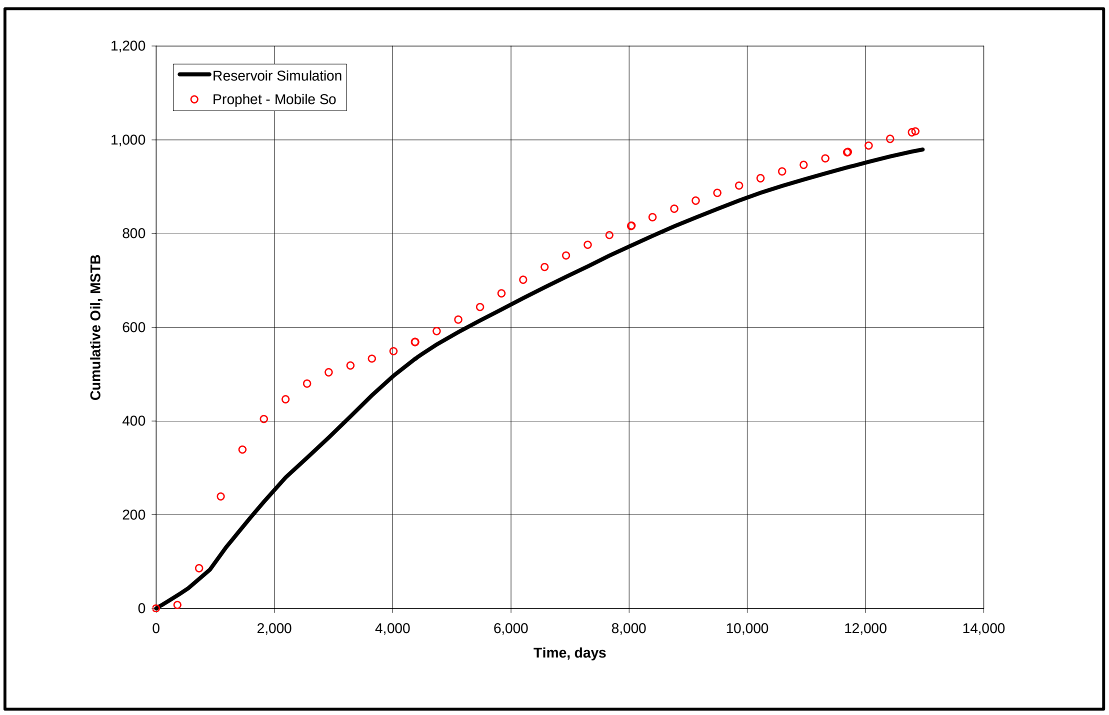


Figure 16. Analysis of Simultaneous MPZ and TZ/ROZ Oil Recovery: Simulation Comparison Results, Wasson Bennett Ranch Unit.

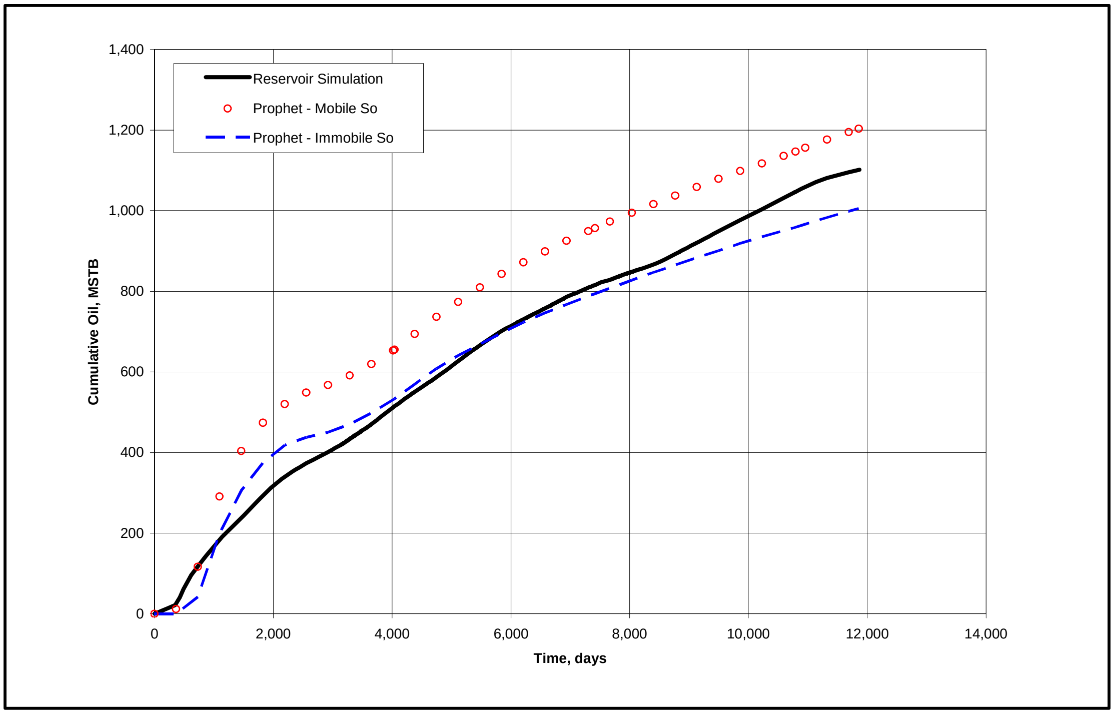


Figure 17. Analysis of Simultaneous MPZ and TZ/ROZ Oil Recovery: Simulation Comparison Results, Vacuum (San Andres/Grayburg)

Table 6 provides the model comparisons, with the ultimate oil recovery from these four oil fields scaled to field level. While oil recovery calculations for individual fields vary somewhat, overall the two models provide an excellent match of the aggregate oil production from the four sample oil fields.

Table 6. Comparison of Compositional Model Simulation and *CO2-PROPHET* Model Simulation

Field/Unit	Compositional Model Simulation: Field Level Oil Recovery (MMB)	*CO2-PROPHET* Model Simulation: Field Level Oil Recovery (MMB)	% Difference Between Models
Seminole (San Andres Unit)	696	569	(18%)
Wasson (Denver Unit)	1,054	1,064	1%
Wasson (Bennett Ranch Unit)	172	179	4%
Vacuum (Grayburg/San Andres)	529	577	9%
Total	**2,451**	**2,389**	**(2%)**

C. Evaluating ROZ Development Strategies. Our analytic work shows that two "best practices" would enable the TZ/ROZ resource to be efficiently developed, namely: 1) selectively completing only the upper portion of the ROZ; and 2) simultaneously CO_2 flooding the MPZ and TZ/ROZ.

***1. Selective Zone Completion in the ROZ**.* Two ROZ completion options were explored: (1) completing only the upper 60% of the ROZ; and (2) completing the full ROZ interval. The two ROZ completion practices were then further examined under variable oil saturation profiles and alternative vertical permeability situations.

- **Methodology**. Reservoir simulation was used to model the injection of one HCPV of CO_2 into the ROZ (only) zone. The Wasson Denver Unit's San Andres reservoir ROZ interval was used as the input data set. Two oil saturation profiles were used: (1) a uniform saturation through the ROZ (uniform); and, (2) a variable, high to low, oil saturation through the ROZ (gradational). Finally, the vertical permeability was varied in the gradational oil saturation case.

- **Results. Table 7** shows the results for the two completion schemes (partial and full) and for each of the three sensitivity cases (uniform ROZ oil saturation, gradational ROZ oil saturation and gradational ROZ oil saturation with large vertical perm). These results are representative of a single forty acre CO_2 EOR pattern.

Table 7. Results from Two ROZ Completion Schemes (Partial And Full)

Project	Cumulative Oil Production (MB)	Cumulative Gross CO_2 Injection (Bcf)	Gross CO_2/Oil Ratio (Mcf/B)	Cumulative Water Production (MB)	Producing Water-Oil Ratio (B/B)
1. Uniform Oil Saturation					
Partial ROZ Completion	273	6	22.0	2,439	8.9
Full ROZ Completion	280	10	35.7	3,965	14.1
2. Gradational Oil Saturation					
Partial ROZ Completion	421	6	14.3	2,239	5.3
Full ROZ Completion	427	10	23.4	3,747	8.8
3. Gradational Oil Saturation/High Vertical Perm					
Partial ROZ Completion	373	6	16.1	2,886	7.7
Full ROZ Completion	441	10	22.7	4,296	9.7

The partial ROZ completion case outperforms the full ROZ completion case (in terms of CO_2-oil and water-oil ratios) and produces nearly as much oil. These results suggest that, in general, a partial ROZ completion should be considered. However, the full interaction of permeability and aquifer strength (not explored here) in combination with the oil saturation profile should be reviewed prior to making a final ROZ completion decision.

2. Simultaneous MPZ and TZ/ROZ CO_2 Flooding. Significant efficiencies may also be gained by simultaneously CO_2 flooding the MPZ and the TZ/ROZ. Even where a MPZ CO_2 flood is already underway, the TZ/ROZ flood can be added. In fact, many of the Seminole San Andres Unit, the Wasson Denver Unit and the Wasson Bennett Ranch Unit patterns are now being developed using joint MPZ and TZ/ROZ CO_2 floods, after initially CO_2 flooding only the MPZ.

- **Methodology**. Reservoir simulation was used to gain further understanding of simultaneously versus separately flooding the MPZ and TZ/ROZ zones. A 40 acre field pattern was modeled using an industry-standard compositional simulator. The input data drew on information from the Wasson Denver Unit's San Andres reservoir. The stacked pay included a 141 foot main pay zone, a 50 foot transition zone and a 150 foot residual oil zone. A weak Carter-Tracy aquifer was applied to the bottom of the reservoir to model water influx from the aquifer. Permeability was allowed to vary based on the Dykstra-Parsons coefficient, with an average permeability of 5 md.

  Development of the reservoir started with a 2 HCPV water flush into the main pay zone (simulating primary and secondary recovery), to reach residual oil saturation. Following the initial MPZ waterflood, 1 HCPV of CO_2 was injected using a coarsely tapered one to one WAG scheme, which consisted of larger CO_2 slugs in the first 0.6 HCPV and smaller CO_2 slugs in the remaining 0.4 HCPV of CO_2. Initially, this CO_2 flooding process was performed separately—first, in the main pay zone, and then followed by the transitional and residual oil zones. Next, both the main pay zone and the TZ/ROZ were CO_2 flooded simultaneously.

- **Results**. **Figure 18** shows the comparison of results for a forty acre pattern. The simultaneous MPZ and TZ/ROZ CO_2 flood has a 25% higher oil recovery than the separate zone CO_2 flooding scheme. Further, oil production is accelerated, which should provide a superior economic return. Water production over the life of the each CO_2 flooding option is similar, **Table 8**.

  A closer look at the reasons for the higher oil recovery efficiency from simultaneous CO_2 flooding of the MPZ and TZ/ROZ shows that the simultaneous CO_2 flood has a more uniform distribution of pressure between the two zones, which limits out of zone CO_2 flow and losses. In the separate CO_2 flooding case, each of the two flooding stages is plagued by out of zone flow (particularly upward flow by the injected CO_2), reducing the overall oil recovery and CO_2 utilization efficiency.

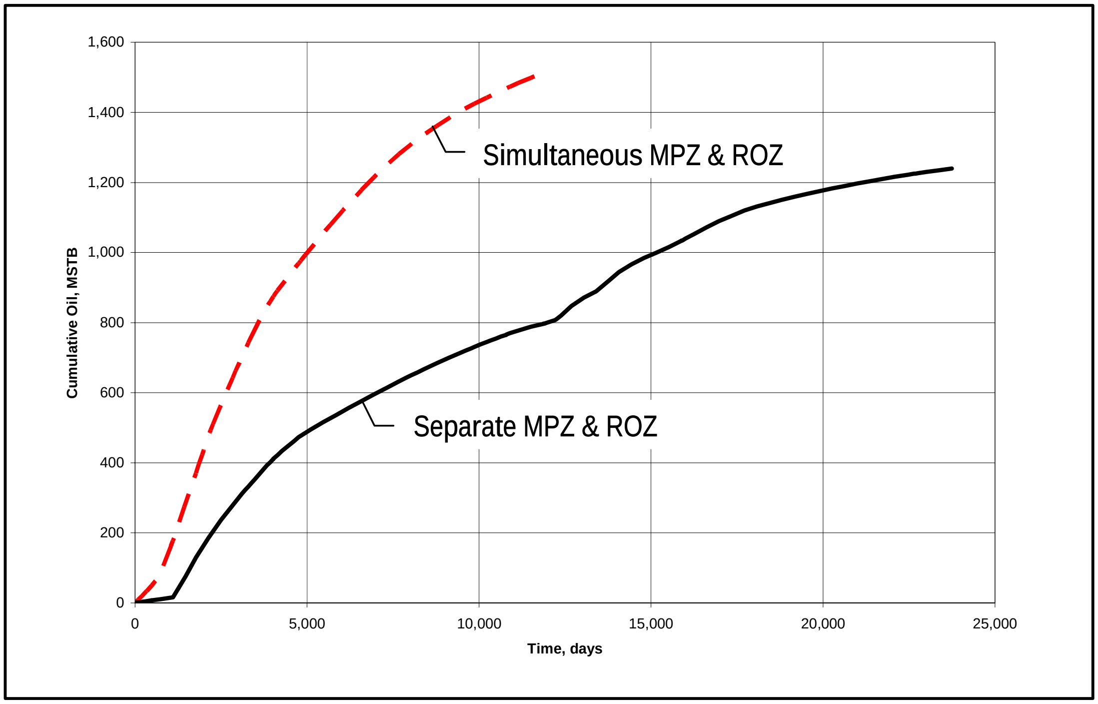


Figure 18. Comparison of Simultaneous and Separate MPZ-ROZ CO2 Flooding, Sample Oil Reservoir.

Table 8. Comparison of Separate vs. Simultaneous MPZ and TZ/ROZ CO_2-EOR Flooding: Sample Oil Reservoir

CO_2-EOR Strategy	Duration (Years)	Cumulative CO_2 Injection (Bcf)	Cumulative Oil (MMB)	Cumulative Water (MMB)
Separate MPZ and TZ/ROZ	65.0	18.8	1.2	7.6
Simultaneous MPZ and TZ/ROZ	32.5	18.8	1.5	7.6

IV. RESULTS

A. TZ/ROZ OIL IN PLACE. In Section II, we identified 56 fields in five major Permian Basin oil plays that have potential for significant TZ/ROZ resources. The TZ/ROZ OOIP in these 56 fields is estimated at 30.7 billion barrels, Table 9.

Table 9. Estimates of TZ/ROZ OOIP in Five Permian Basin Oil Plays

Field/Unit	TZ/ROZ OOIP (BB)	No. of Fields	No. of MPZ Fields with CO2-EOR Projects	No. of Fields with TZ/ROZ CO2-EOR Projects
1. Northern Shelf Permian Basin (San Andres)	13.2	13	5	1
2. North Central Basin Platform (San Andres/Grayburg)	2.6	6	2	1
3. South Central Basin Platform (San Andres/Grayburg)	7.9	16	5	0
4. Horseshoe Atoll (Canyon)	2.9	10	4	2
5. East New Mexico (San Andres)	4.1	11	2	0
Total	30.7	56	18	4

B. Technically Recoverable Resources from the MPZ and ROZ. Based on reservoir modeling of applying CO_2-EOR to the TZ/ROZ resources, we estimate that 11.9 billion barrels is technically recoverable from the 30.7 billion barrels of TZ/ROZ oil in-place in these five Permian Basin oil plays, Table 10.

Table 10. Technical Oil Recovery Totals, Five Permian Basin Oil Plays

Field/Unit	Total CO_2-EOR (BB)	MPZ CO_2-EOR (BB)	TZ/ROZ CO_2-EOR (BB)
1. Northern Shelf Permian Basin (San Andres)	8.3	2.8	5.5
2. North Central Basin Platform (San Andres/Grayburg)	1.5	0.6	0.9
3. South Central Basin Platform (San Andres/Grayburg)	4.6	1.7	2.9
4. Horseshoe Atoll (Canyon)	2.7	1.4	1.3
5. East New Mexico (San Andres)	1.7	0.4	1.3
Total	18.8	6.9	11.9

CO_2-EOR of the TZ/ROZ is underway in four of the study fields, as discussed previously. However, the size of these pilot projects is small, and only limited data on the performances of these pilot projects is publicly available. Therefore, no reductions in the TZ/ROZ oil potential have been made in this study to account for the modest amount of past and ongoing TZ/ROZ development to date.