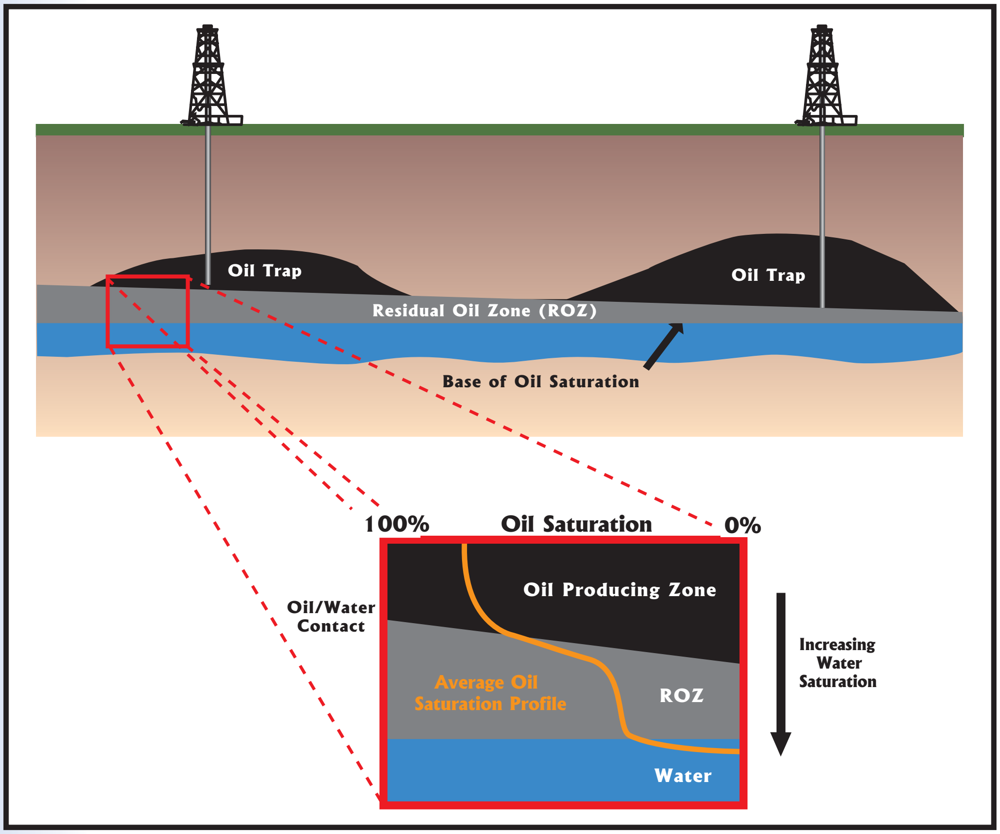
Technical Oil Recovery Potential from Residual Oil Zones: Williston Basin



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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TECHNICAL OIL RECOVERY POTENTIAL FROM RESIDUAL OIL ZONES: WILLISTON BASIN

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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]. The third report and the first in a series of three, "Technical Oil Recovery Potential from Residual Oil Zones: Permian Basin", provided an in-depth documentation of the in-place and recoverable ROZ potential in the Permian Basin. This report, "Technical Oil Recovery Potential from Residual Oil Zones: Williston Basin", is the second in a three part series and explores the in-place and recoverable ROZ potential for the Williston 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.

[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.

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 (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 Williston 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 Williston Basin. Then, it examines, using a reservoir simulation calibrated streamtube model, the

[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.

technical feasibility of recovering this previously by-passed TZ/ROZ resource using CO_2-EOR.

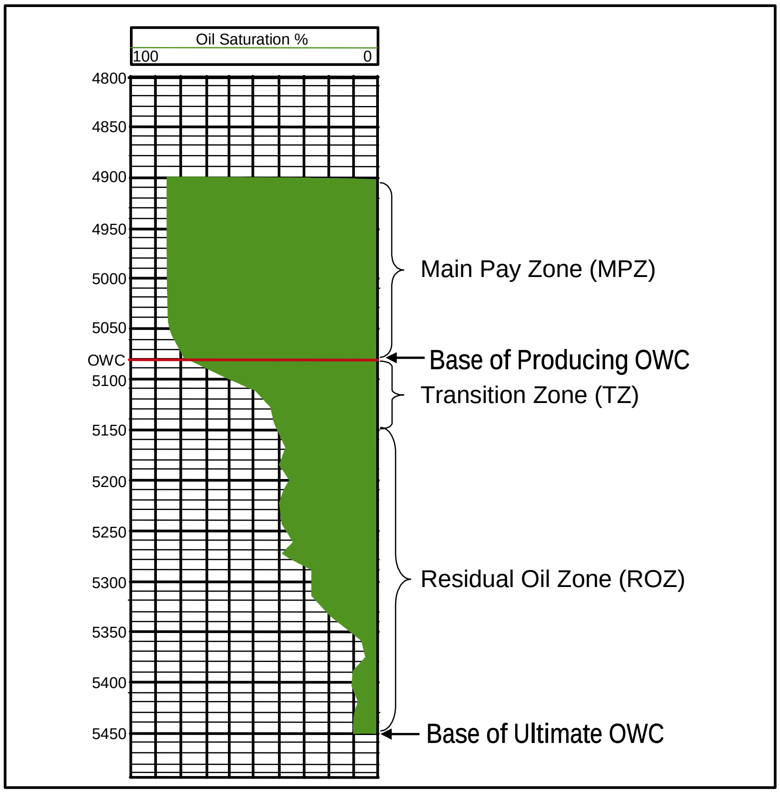
C. Definition of Terms. The term ***residual oil zone* (ROZ),** as used in this study, also includes the more commonly known ***transition zone* (TZ).** Although often used interchangeably, the two terms describe different portions of an oil reservoir. All oil reservoirs have a transition zone, an interval 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 Williston Basin. Much like the work done by Brown to detail the effects of hydrodynamic flow upon the oil-water contact in the northern and central shelf carbonates of the Permian Basin[7], Berg, et. al., developed an excellent treatise of the *Hydrodynamic Effects on Mission Canyon (Mississippian) Oil Accumulations, Billings Nose Area, North Dakota*[8]. The authors studied the hydrogeology of oil fields in the Billings Nose Area of the Williston Basin and concluded that many of the Mission Canyon fields have OWC tilts of hydrodynamic origin. In the Billings Nose area oil accumulations in the Mission Canyon Formation, originally in stratigraphic traps, are tilted to the northeast at gradients of about 25 ft/mi (approximately the same as regional structural dip) by hydrodynamic flow. Additionaly, some oil accumulations in the area owe their location entirely to hydrodynamic flow.

Prevalence of the Mission Canyon Formation (**Figure 2**) throughout the Williston Basin and the presence of similar stratigraphic and hydrodynamic conditions suggest a potential for tilted OWC in other fields in other areas of the basin. Based on the available geologic information and documented OWC tilts, a number of major oil reservoirs with ROZs were established in the Williston Basin oil plays.

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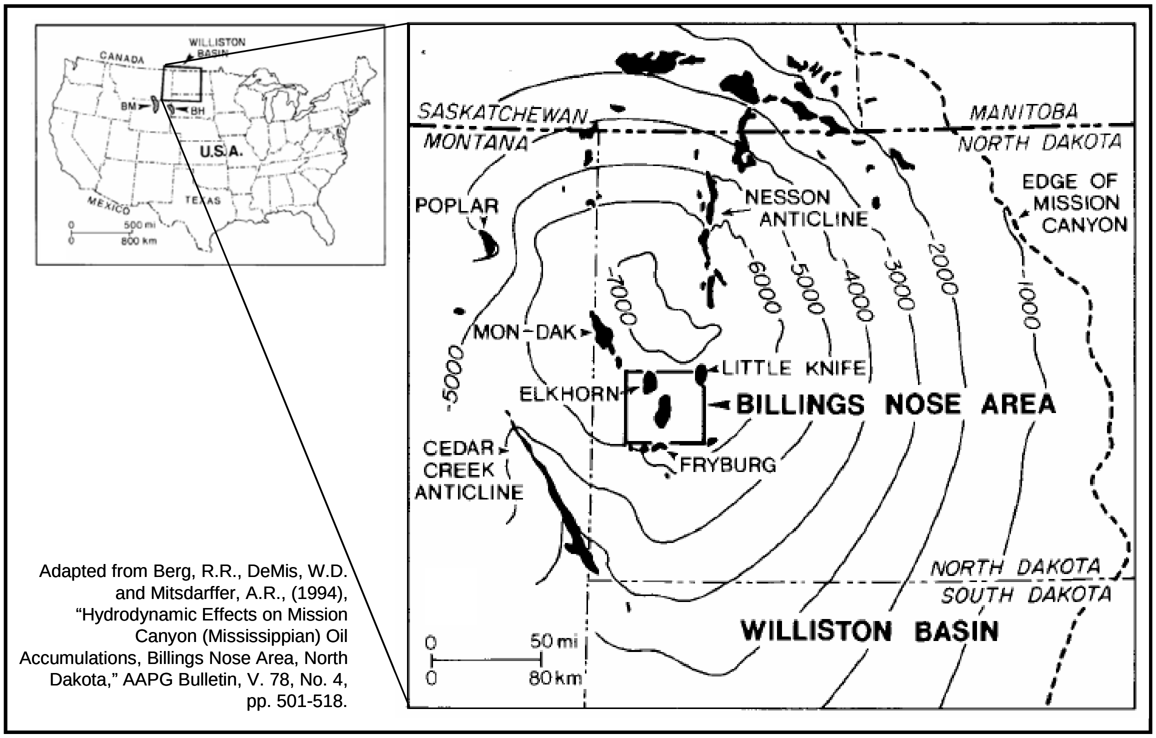
[7] Brown, A., (2001), "Effects of Hydrodynamics on Cenozoic Oil Migration, Wasson Field Area, Northwestern Shelf of the Permian Basin," West Texas Geological Society Fall Symposium, Pub 01-110 (Viveiros, J.J. & Ingram, S.M. eds), Oct 2001, pp 133-142.

[8] Berg, R., DeMis, W., and Mitsdarffer, A., (1994), "Hydrodynamic Effects on Mission Canyon (Mississippisan) Oil Accumulations, Billings Nose Area, North Dakota," AAPG Bulletin, V. 78, No. 4, pp 501-518

Figure 2. Structure on Top of the Mission Canyon Formation (contour interval 1,000ft) and Important Oil Fields in the greater Billings Nose Area, Williston Basin



Adapted from Berg, R.R., DeMis, W.D. and Mitsdarffer, A.R., (1994), “Hydrodynamic Effects on Mission Canyon (Mississippian) Oil Accumulations, Billings Nose Area, North Dakota,” AAPG Bulletin, V. 78, No. 4, pp. 501-518.

II. IDENTIFYING AND EVALUATING OIL FIELDS WITH ROZ RESOURCES

A. Williston Basin (Madison Group). The Williston Basin is vast and roughly circular, covering approximately 300 thousand square miles across parts of North and South Dakota, Montana, and the Canadian provinces of Manitoba and Saskatchewan. The Mississipian-age oil plays in the Williston Basin are contained in thick carbonate sequences made up of primarily three formations, the Lodgepole, Mission Canyon, and Charles, in ascending order, which together is referred to as the Madison Group (North Dakota Geological Survey). The group contains a series of limestones and dolomites that represent a shallowing-upward sequence, with evaporate deposits in the Mission Canyon and Charles Formations creating stratigraphic oil traps. Additional traps are created by layer pinchouts and structural traps. The source rock for these reservoirs is generally the lower Mississippian Bakken Shale located below the Lodgepole. North Dakota contains the majority of the Williston Basin production in the U.S. and 60% of the oil produced in the state has come from the Madison Group, representing nearly 1.0 billion barrels.

The Williston Basin is fairly simple structurally, comprised of a series of long north-south oriented synclines and anticlines that formed as a result of basin subsidence. The major anticlines are all major oil producing structures and named, from west to east, the Cedar Creek Anticline (MT), the Billings Anticline (ND), and the Nesson Anticline (ND). The northern terminus of the Billings Anticline plunges shallowly northward, creating a 60 mile long wedge-shaped structure known as the Billings Nose Area. The large Madison Group reservoirs in the Billings Nose oil fields have produced over 150 MMbbls of oil. Oil-water contacts (OWC) tilted to the northeast due to hydrodynamic flow in the Madison aquifer, have been identified in the area.

Billings Nose Area. Oil was first discovered in the Billings Nose in 1953 and the discovery of the Little Knife field in 1977, with 290 MMbbls of OOIP, attracted increasing attention to the region. Tilted OWC's were identified in many of the fields in the area, and anomalously low salinity regions in the western portion of the region suggested that the tilt was formed as a result of hydrodynamic flow. For example, in the Knutson field on the southeastern flank of the Nose, salinities were observed to decrease from 4,000 ppm in the southwestern part of the field to over 200,000 ppm in the northeast portion of the field (typical Madison salinities). Berg et al. (1994) summarized the evidence for the tilted OWC in the area and identified meteoric recharge from the Bighorn Mountains, where the Williston Basin terminates 200 miles to the southwest, as the source of the hydrodynamic flow and the salinity decrease on the western portions of the Nose area, possibly when the mountains and the basin reached their present elevations two million years ago. The Big Stick and Elkhorn Ranch fields have well defined OWC dips of 25 ft/mile to the east (**Figure 3** and **4**), while the Knutson field has an OWC tilt of 15 ft/mile, with the potential for residual oil zones (ROZ) regions below their main pay zones. In some instances, oil deposits have been found to be displaced downdip to the northeast, in a parallel manner to the porosity pinchouts (**Figure 5**) In this study, six additional large fields with Madison reservoirs were identified in the Greater Billings Nose Area that may contain ROZ's that screen favorably for miscible CO_2-EOR.

Evidence of tilted OWC's in the Billings Nose area suggests that the phenomenon may be basin-wide and may extend to other Madison/Mission Canyon oil accumulations such as a major anticlinal structure to the northeast, the Nesson Anticline. The Nesson contains six large fields with Madison reservoirs that were identified as candidates for miscible CO_2-EOR in their ROZ's. In addition, four large fields with Madison reservoirs were identified in northern North Dakota and Montana, referred to here as the Northern Tier play that are miscible CO_2-EOR candidates. These 20 Madison Group oil fields which were judged to have potential for substantial TZ/ROZ oil resources are shown in **Table 1** and **Figure 6**.

Figure 3. Elevation of the Oil/Water Contact in the Big Stick Oil Field.

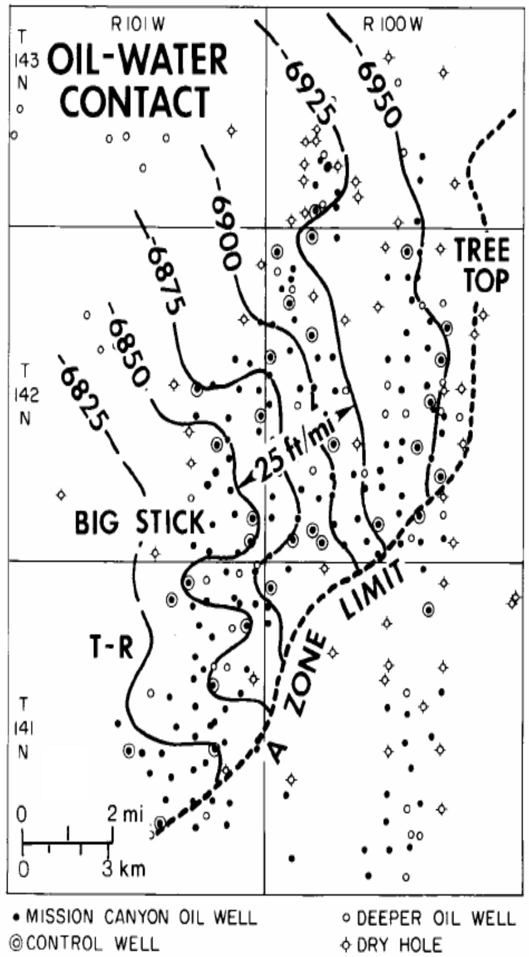
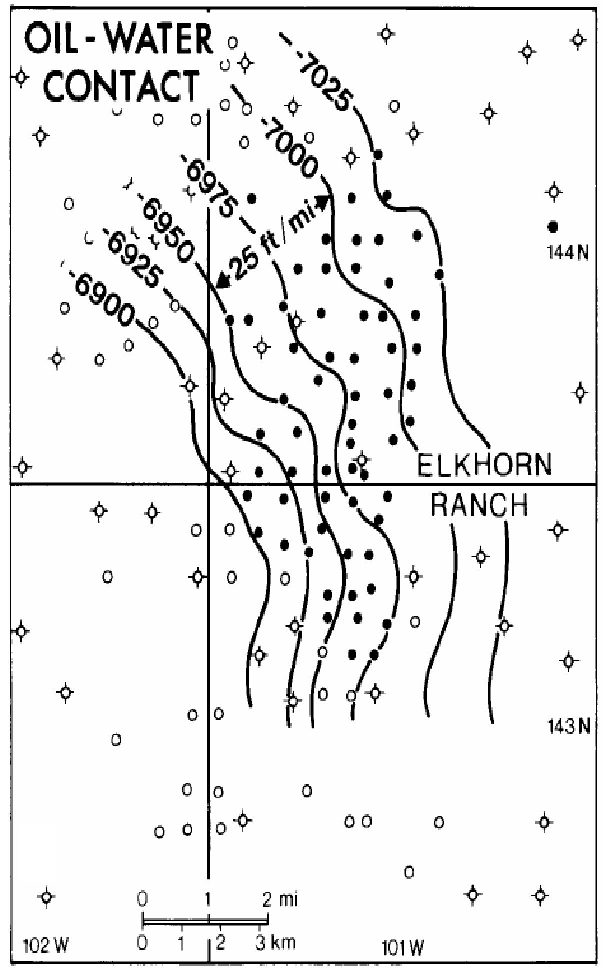


Figure 4. Elevation of the Oil/Water Contact in the Elkhorn Ranch Oil Field.



Adapted from Berg, R.R., DeMis, W.D. and Mitsdarffer, A.R., (1994), "Hydrodynamic Effects on Mission Canyon (Mississippian) Oil Accumulations, Billings Nose Area, North Dakota," AAPG Bulletin, V. 78, No. 4, pp. 501-518.

Figure 5. Sequence of Oil Migration and Accumulation in the Billings Nose Fields, Williston Basin

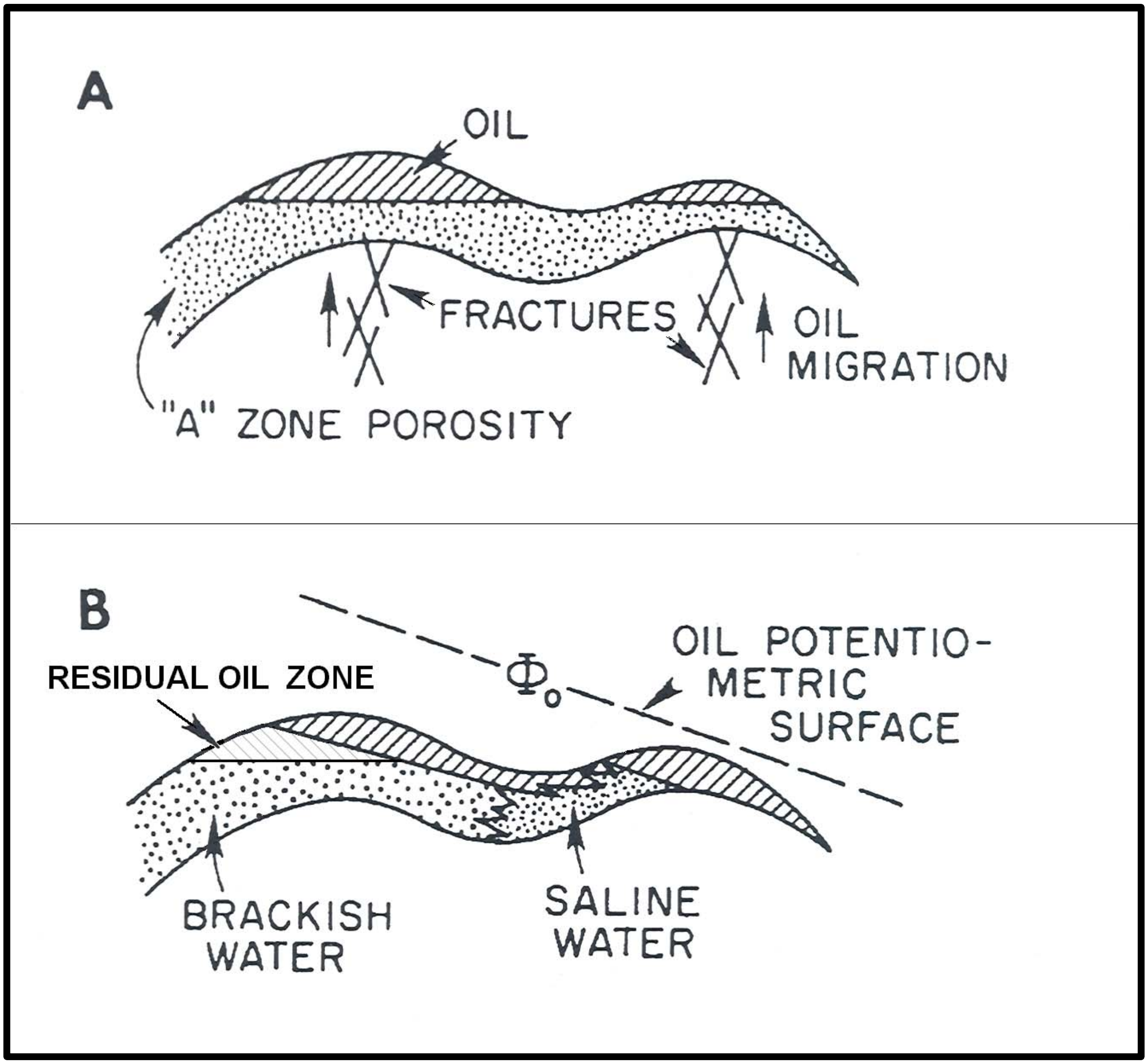


Figure 6. Location Map of Major Madison Group: Williston Basin

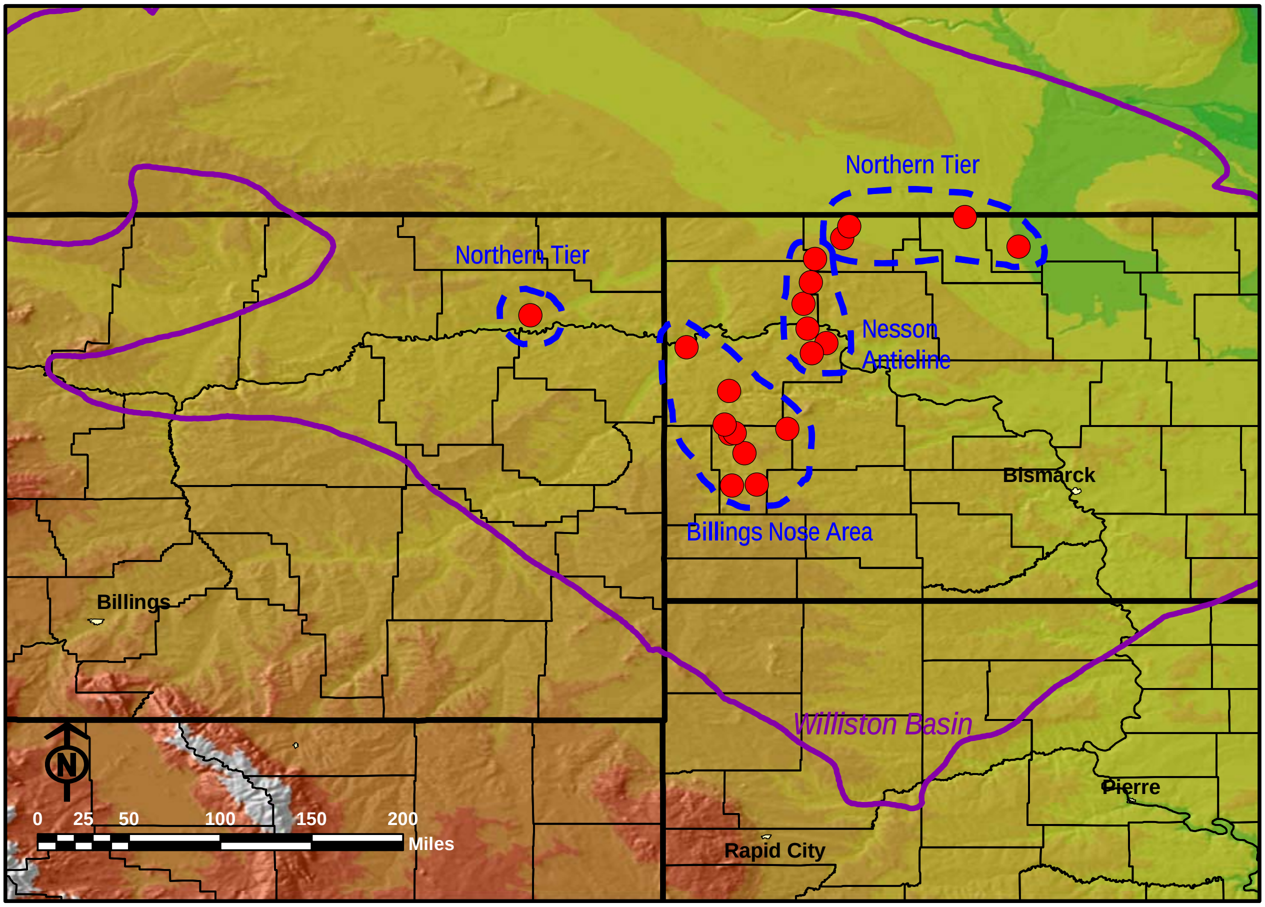


Table 1. Large Williston Basin (Madison Group) Oil Reservoirs with Potential for ROZ Resources

Billings Nose Area			
Field (Reservoir)	State	County	Cum. Oil Production (MMBbls) (1-1-05)
1. Big Stick (Mission Canyon)	ND	Billings	52.0
2. Elkhorn Ranch (Mission Canyon)	ND	Billings	11.8
3. Elkhorn Ranch North (Mission Canyon)	ND	Billings	15.2
4. Fryburg (Madison)	ND	Billings	15.7
5. Glass Bluff (Madison)	ND	McKenzie	6.7
6. Little Knife (Mission Canyon)	ND	Billings	73.3
7. Medora (Madison)	ND	Billings	8.4
8. Red Wing Creek (Madison)	ND	McKenzie	16.3
9. Rough Rider (Madison/Mission Canyon)	ND	McKenzie	17.0
Nesson Anticline			
Field (Reservoir)	State	County	Cum. Oil Production (MMBbls) (1-1-05)
10. Antelope (Madison)	ND	McKenzie	17.1
11. Beaver Lodge (Madison)	ND	Williams	54
12. Blue Buttes (Madison)	ND	Williams	34.1
13. Charlson (Madison)	ND	McKenzie	27.4
14. Tioga (Madison/Rival)	ND	Williams	78.3
15. Tioga North (Midale/Rival)	ND	Burke	18.1
Northern Teir			
Field (Reservoir)	State	County	Cum. Oil Production (MMBbls) (1-1-05)
16. Poplar East (Madison)	MT	Roosevelt	47.1
17. Black Slough (Midale/Rival)	ND	Burke	7.1
18. Rival (Madison)	ND	Burke	15.7
19. Sherwood (Madison/Mission Canyon)	ND	Renville	19.5
20. Wiley (Mission Canyon)	ND	Bottineau	17.4

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 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 Williston 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.[16]

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.

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

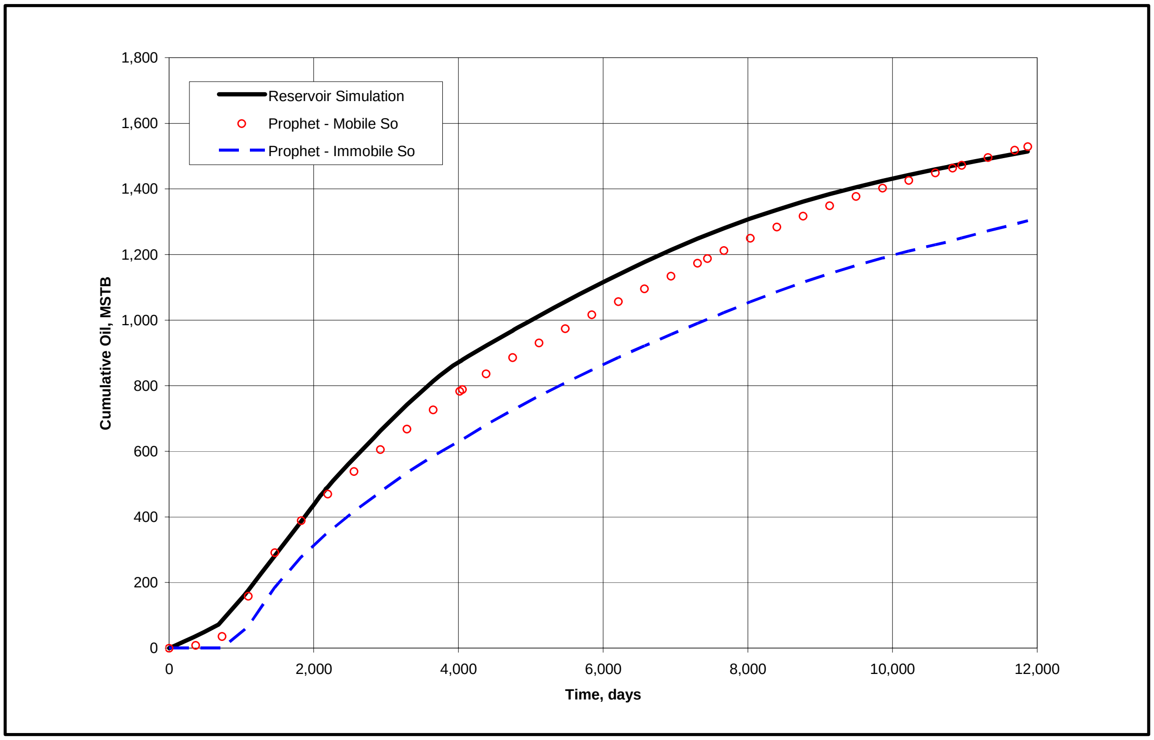
[16] "Post Waterflood CO_2 Flood in a Light Oil, Fluvial Dominated Deltaic Reservoir" (DOE Contract No. DE-FC22-93BC14960).

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 7**.

Figure 7. 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 8, 9** and **10**) - - 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 8. Analysis of Simultaneous MPZ and TZ/ROZ Oil Recovery: Simulation Comparison Results, Seminole San Andres Unit

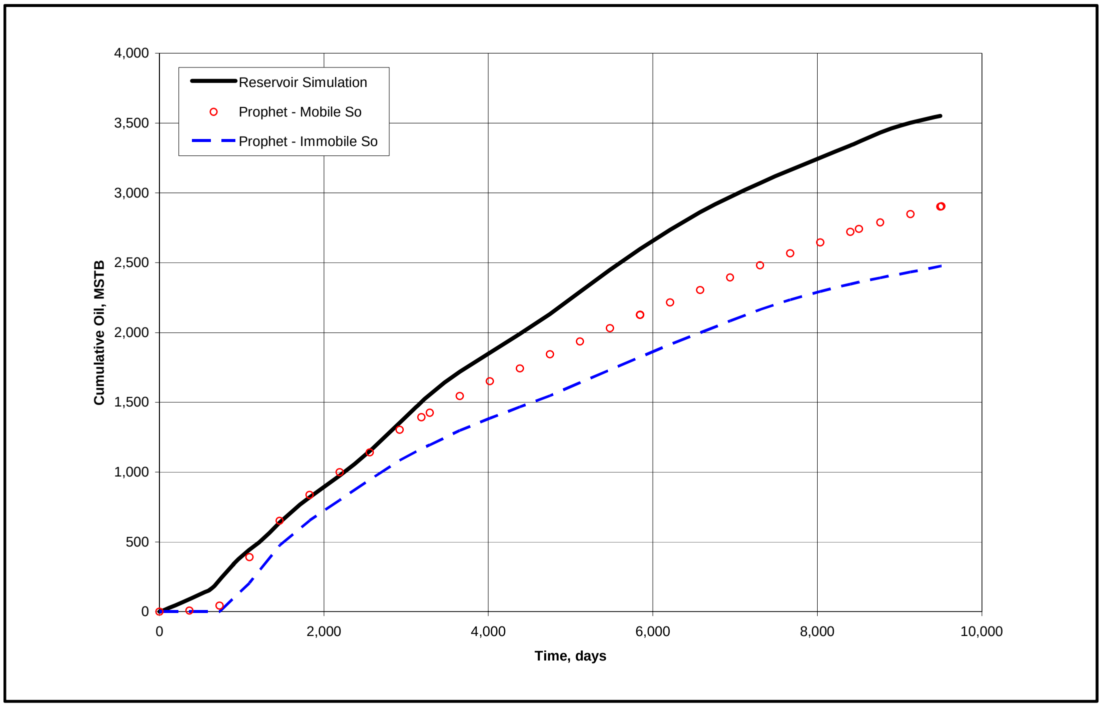


Figure 9. Analysis of Simultaneous MPZ and TZ/ROZ Oil Recovery: Simulation Comparison Results, Wasson Bennett Ranch Unit

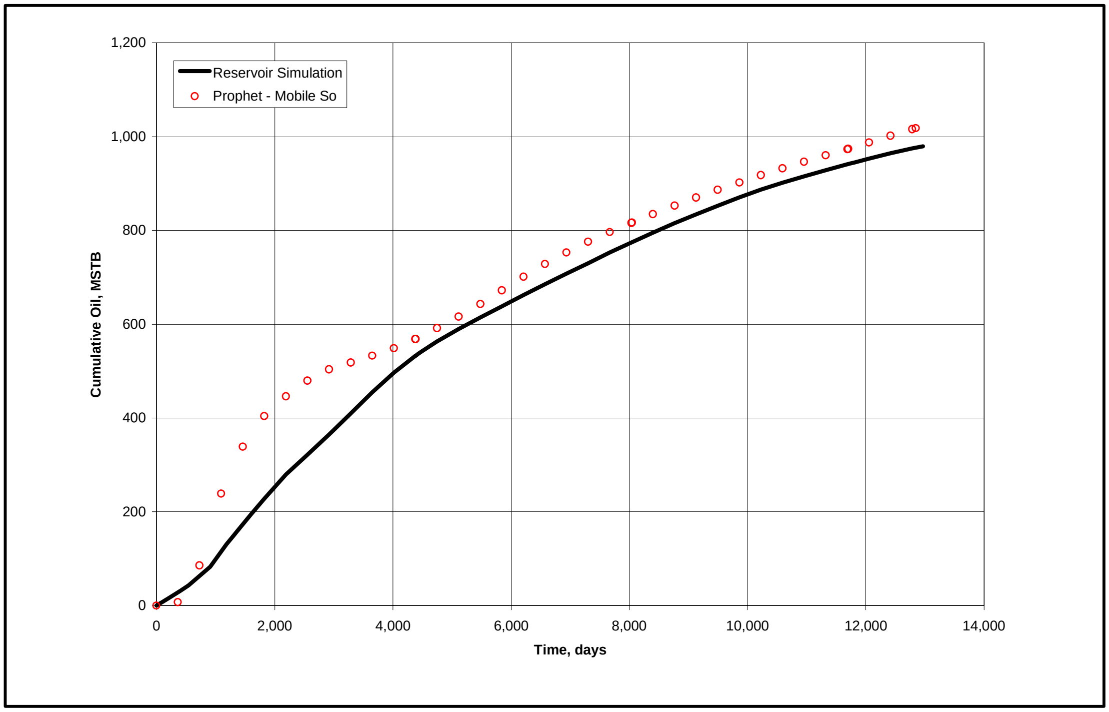


Figure 10. Analysis of Simultaneous MPZ and TZ/ROZ Oil Recovery: Simulation Comparison Results, Vacuum (San Andres/Grayburg)

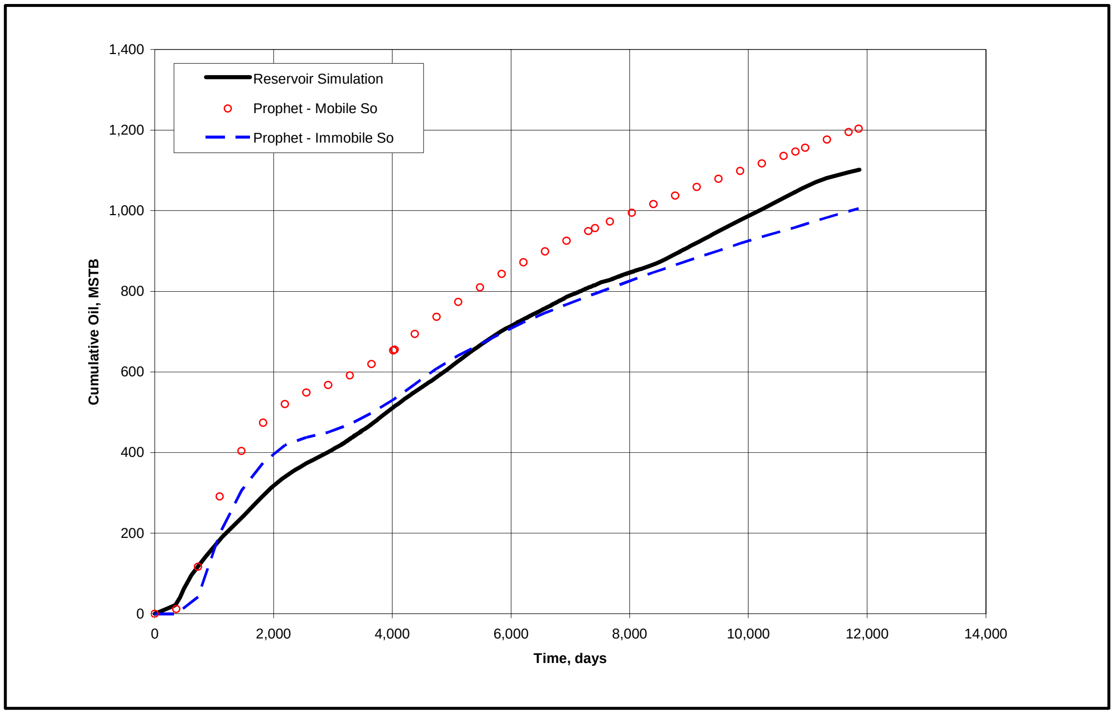


Table 2 provides the model comparisons, with the ultimate oil recovery from these four oil fields scaled to field level. While oil recovery calculations for individual fields vary somewhat, overall the two models provide an excellent match of the aggregate oil production from the four sample oil fields.

Table 2. Comparison of Compositional Model Simulation and *CO2-PROPHET* Model Simulation

Field/Unit	Compositional Model Simulation Field Level Oil Recovery (MMbbls)	*CO2-PROPHET* Model Simulation Field Level Oil Recovery (MMbbls)	% 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 3** 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 3. Results from Two ROZ Completion Schemes (Partial and Full)

Project	Cumulative Oil Production (Mbbls)	Cumulative Gross CO_2 Injection (Bcf)	Gross CO_2/Oil Ratio (Mcf/Bbls)	Cumulative Water Production (Mbbls)	Producing Water-Oil Ratio (Bbls/Bbls)
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 11** 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 4**.

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

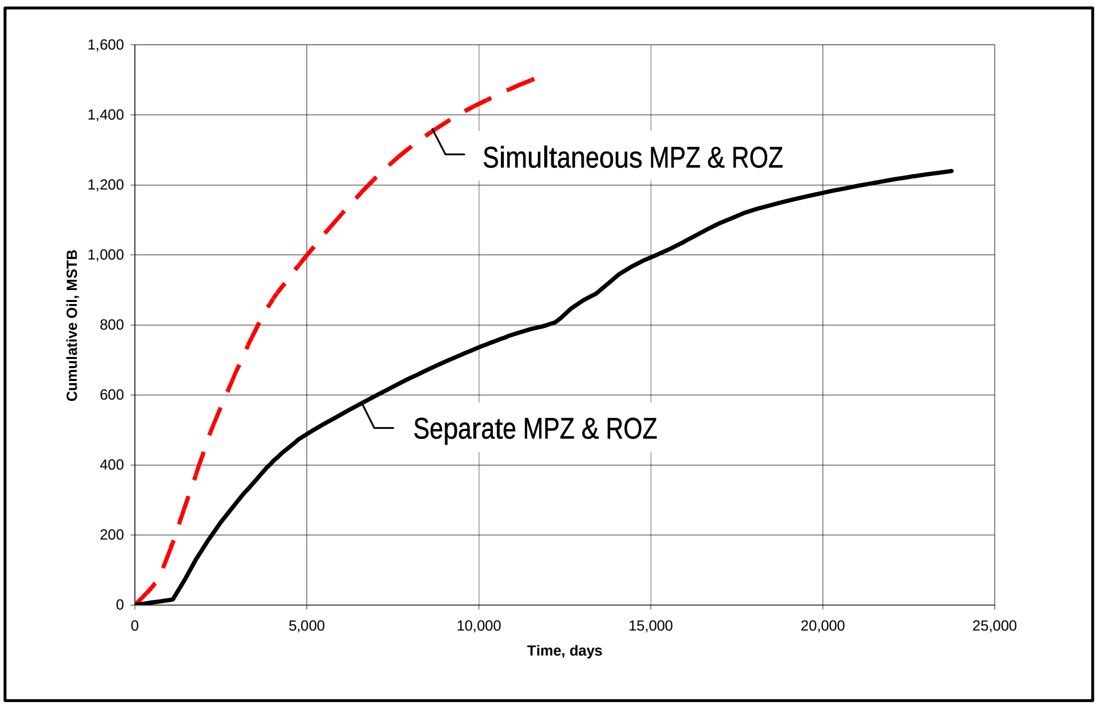


Table 4. Comparison of Separate vs. Simultaneous MPZ and TZ/ROZ CO_2-EOR Flooding: Sample Oil Reservoir

CO_2-EOR Strategy	Duration (Years)	Cumulative CO_2 Injection (Bcf)	Cumulative Oil (MMbbls)	Cumulative Water (MMbbls)
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. MPZ and TZ/ROZ OIL IN PLACE. In Section II, we identified 20 fields in the three Williston Basin oil plays that have potential for significant TZ/ROZ resources. The TZ/ROZ OIP in these 20 fields is estimated at 6.8 billion barrels, which is over three times the OOIP of the MPZ, **Table 5**.

Table 5. Estimates of MPZ OOIP and TZ/ROZ OIP in Three Williston Basin Oil Plays

Play	MPZ OOIP (BBbls)	TZ/ROZ OIP (BBbls)	No. of Fields
1. Greater Billings Nose Area	0.9	3.4	9
2. Nesson Anticline	0.7	1.2	6
3. Northern Tier	0.6	2.2	5
Total	2.2	6.8	20

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 3.3 billion barrels is technically recoverable from the 6.8 billion barrels of TZ/ROZ oil in-place in these three Williston Basin oil plays, **Table 6**.

Table 6. Technical Oil Recovery Totals, Three Williston Basin Oil Plays

Play	Total CO_2-EOR (BBbls)	MPZ CO_2-EOR (BBbls)	TZ/ROZ CO_2-EOR (BBbls)
1. Greater Billings Nose Area	2.2	0.3	1.9
2. Nesson Anticline	0.8	0.2	0.6
3. Northern Tier	1.0	0.2	0.8
Total	4.0	0.7	3.3

To date, no CO_2-EOR projects of the TZ/ROZ have been undertaken in these study fields. As such, no information regarding the potential performance of such a flooding scheme is available to validate the results of this work. Nevertheless, the estimates of TZ/ROZ OIP for these 20 fields may make an attractive recovery target and data collected during the planned Beaver Lodge (Madison) CO_2-EOR pilot flood may add further insight into the potential flood performance of these TZ/ROZ targets.