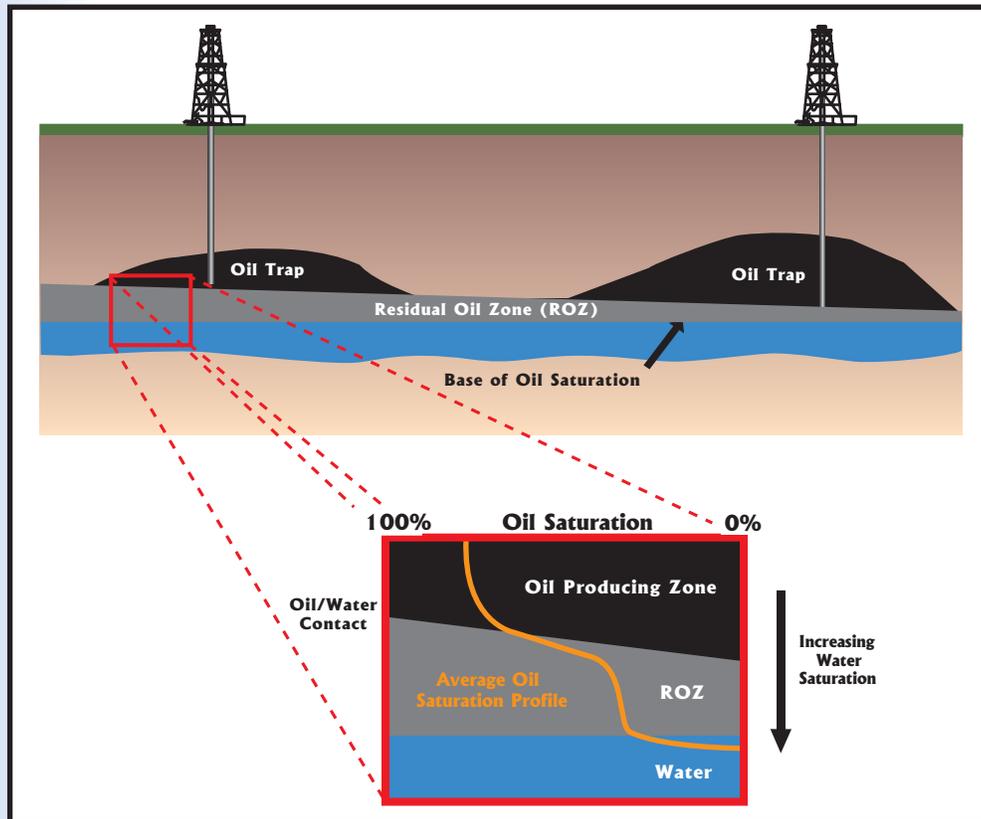


STRANDED OIL IN THE RESIDUAL OIL ZONE



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

Prepared by
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Much of the analysis in this report was performed in late 2005. The domestic oil resource recovery potential outlined in the report is based on six basin-oriented assessments released by the United States Department of Energy in April 2005. These estimates do not include the additional oil resource potential outlined in the ten basin-oriented assessments or recoverable resources from residual oil zones, as discussed in related reports issued by Department of Energy in February 2006. Accounting for these, the future recovery potential from domestic undeveloped oil resources by applying EOR technology is 240 billion barrels, boosting potentially recoverable resources to 430 billion barrels.

Disclaimer

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Executive Summary

The presence of an oil bearing transition zone (TZ) beneath the traditionally-defined base oil-water contact (OWC) of an oil reservoir is well established. What is now clear, and as established by this study, is that, in certain geologic and hydrodynamic conditions, an additional residual oil zone (ROZ) may exist below this TZ. This zone may be extensive, thick, and filled with a residual oil that may be recoverable using CO₂ enhanced oil recovery (EOR). These thick residual oil zones exist where nature has waterflooded the lower portion of an oil reservoir.

Past investigations of the origins and presence of these naturally-formed ROZ's have been hampered by two limitations: a general lack of interest in these intervals, as they would add little or no additional oil during primary and secondary production; and, clear preference for avoiding drilling into these residual oil transition zones to avoid or reduce the production of water.

Topics Addressed by the Study. The advent of advanced tertiary oil production technology now enables previously waterflooded oil zones (with low oil saturations) to be further exploited, particularly using CO₂-EOR. Yet, the residual oil saturation and reservoir properties in naturally-created ROZ's are like those in the waterflooded intervals of the main pay zone (MPZ). As such, new interest is emerging to better understand the nature, size and recoverability of the "stranded oil" in these transition and residual oil zones.

To facilitate and further support this new interest in the ROZ, this study addresses three topics:

- 1) The study reports on the results from three on-going CO₂-EOR projects that examine the technical and commercial merits of CO₂ flooding in ROZ's;

- 2) The study discusses the origin of ROZ's of abnormal thicknesses, considerably beyond those formed by capillary pressure; and
- 3) The study proposes additional research and investigations that would provide improved estimates of this sizable, previously unaccounted-for oil resource within already-discovered domestic oil fields.

Current ROZ Field Projects. Three residual oil zone CO₂-EOR projects are underway in the Permian Basin of West Texas. They are: Occidental's Transition Zone project in the Denver Unit of the Wasson Field; Amerada Hess' Residual Oil Zone pilot in the San Andres Unit of the Seminole Field; and Occidental's Main Pay and Transition Zone project in the Bennett Ranch Unit of the Wasson Field.

The first of the ROZ projects is in the Denver Unit and was initiated in 1991 by Shell, then the operator, using six-patterns. The Project has since been expanded several times to other areas of the Denver Unit. The oil production data shows distinct oil response from the ROZ to injected CO₂. The operator reports that the CO₂-to-oil ratios are reasonably consistent with the results being achieved by the CO₂ flood in the MPZ. With a well-documented, thick residual oil (transition) zone interval, the oil target is substantial. The study estimates an oil in-place (OIP) of over 500 million barrels in the upper portion of transition and residual oil zones of the Denver Unit. A portion of this resource is already being produced using CO₂-EOR.

The second ROZ project is Amerada Hess' 500 acre San Andres Unit ROZ Phase 1 pilot, located in the Seminole Field, south of the Denver Unit. This ROZ project was started in 1996, with deepening of four of the existing injection wells and all of the 15 production wells. CO₂ injection and oil production from the ROZ have been conducted in parallel with the ongoing CO₂ flood in the MPZ, with the oil production from both intervals commingled. While this complicates the analysis, the operator reports, and the data clearly indicate a very positive oil response from the ROZ (the *Oil and Gas Journal's* 2004 EOR Survey reports 1,400 barrels per day of incremental oil production from the ROZ Phase 1 project). A second ROZ development phase has been approved

for the Seminole Field, and a third is being discussed, but is hampered by limited availability of CO₂ supplies.

The third ROZ project is a Shell-initiated CO₂-EOR effort at the Bennett Ranch Unit of the Wasson Field. The original CO₂ flood design called for deepening of wells to include both the MPZ and 75 feet of the residual oil (transition) zone. Because of low oil prices in the mid-1990s (during the initiation of the CO₂ project), the deepening of wells was eliminated from the overall project. In late 2003, Occidental carried through on the original CO₂-EOR plan by deepening a number of the wells into the ROZ. The company is now co-developing the ROZ and the MPZ in half of the overall CO₂-flooded area. An additional expansion of the Bennett Ranch ROZ project is currently planned for 2006.

Given the successful results from the above significant ROZ CO₂-EOR field demonstration projects, the topics of the origin of ROZ's and their oil production potential deserve further exploration and discussion.

Origins of Abnormally Thick ROZ's. All reservoirs have oil-to-water TZ's, of varying thicknesses, that owe their origin to capillary forces. These forces cause gradational changes in the oil and water saturations beneath the main pay zone. While these traditional residual oil zones can be successfully CO₂-flooded, and could be included within the CO₂-flooded intervals, the incremental production from capillary pressure-based TZ's may be relatively modest.

Much larger residual oil targets may exist in ROZ's of non-capillary origin. These much thicker and more extensive ROZ's stem from the displacement of oil previously trapped in an oil reservoir, such as those documented in the thick ROZ intervals observed at the Wasson Field (Denver Unit) and the Seminole Field (San Andres Unit).

These non-capillary ROZ's have three origins. Each of these requires that an oil trap be originally formed and that the oil reservoir subsequently be subjected to one or more of the following post-emplacement geologic or hydrodynamic situations:

ROZ Type 1. Regional tilt of a basin;

ROZ Type 2. Breach of the reservoir seal with secondary healing, and/or;

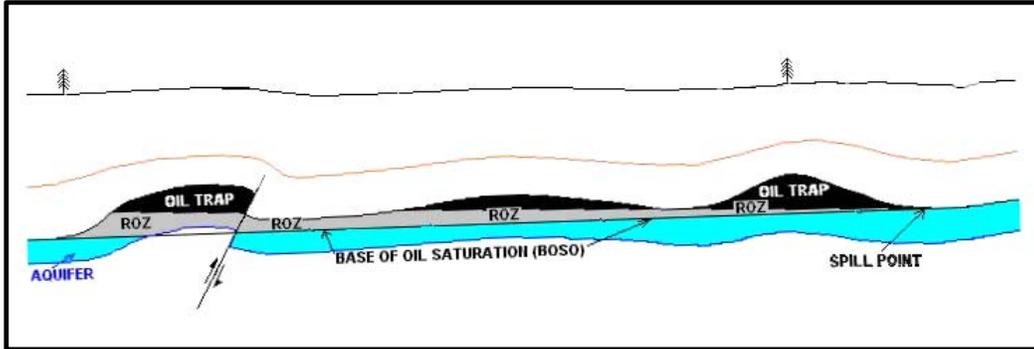
ROZ Type 3. Changed hydrodynamic conditions within the underlying aquifer.

The three ROZ types are shown schematically in Figure EX-1. Note that each of the three types of ROZ's can be viewed as resulting from "mother nature's" waterflood.

ROZ Types. Type 1 ROZ stems from a gravity-dominated shift of the oil and water contact. As such, Type 1 ROZ can contain significant intervals of residual oil, if the field is large and/or if the regional tilt is considerable. OWC dips of 50 to 200 feet per mile are fairly common for oil reservoirs in tectonically active oil basins. Many basins display "late-stage" tilting; however, the potential of "late-stage" tilting adding sizable and new oil to the overall ROZ resource is considered to be fairly minor.

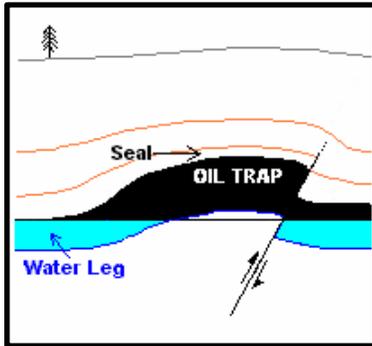
Figure EX-1: Illustrations of the Origin of Three Types of ROZ

TYPE 1 ROZ: Original Accumulation Subject to a Westward Regional Tilt Forming a ROZ

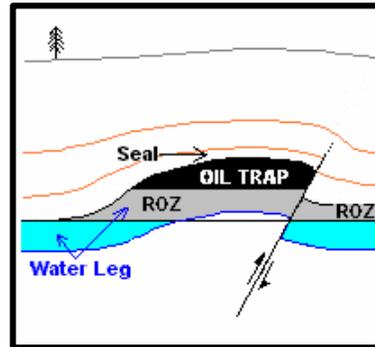


TYPE 2 ROZ: Original Accumulation with a Breached and Repaired Seal Forming a ROZ

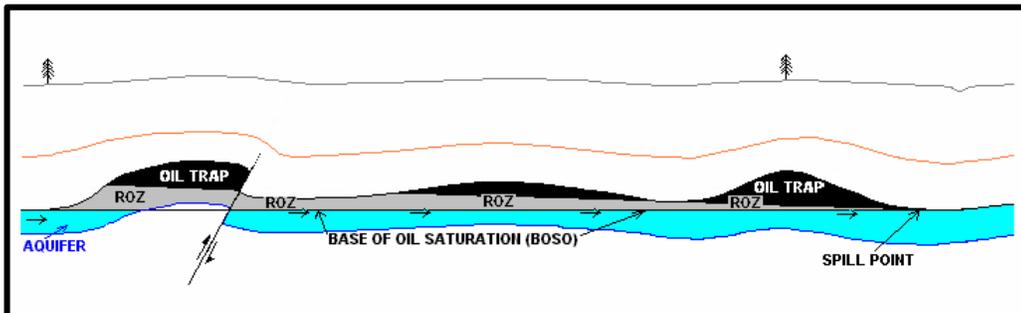
ORIGINAL TRAP



POST-BREACH TRAP



TYPE 3 ROZ: Change in Hydrodynamic Conditions, Sweep of the Lower Oil Column and Oil/Water Contact Tilt Forming a ROZ



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The Type 2 ROZ intervals are oil traps that were once larger, in which, due to breaching of the reservoir seal, some or all of the original hydrocarbons have escaped. Geochemical and/or biological processes may have resealed the reservoir and if the new oil column is less than the original one, a substantial ROZ will be present. Type 2 ROZ intervals are probably quite common, but evidence of their existence is only indirect. For example, relict tar mats or gilsonite veins may be indicators of catastrophic changes in the OWC within a reservoir. This study finds that many basins and reservoirs show these characteristics. However, documentation of these subsurface conditions in the literature is rare.

The third and most likely source of ROZ's (Type 3 ROZ) is from changed hydrodynamic conditions within the aquifers of an oil basin. The changed conditions may be due to nearby or distant uplift of the formation, providing a water source (elevated piezometric pressure) and changes in the discharge pressure due to erosional or tectonically-induced pressure relief. Documentation is again scarce, but several examples of significantly thick ROZ intervals have been recently explained by such hydrodynamic conditions. The Northern and Central Basin Platform areas of the Permian Basin and the Panhandle and Hugoton Fields in the mid-continent are two cases in point.

Hydrodynamic effects on the OWC of an oil reservoir were reported by H. King Hubbert in the 1950s, though little significance was given to this early work. The little attention it did receive was by the geologic community, interested in exploring for hydrodynamic traps where normal structural and stratigraphic trapping mechanisms could not explain the observed oil accumulations.

The hydrodynamic forces on a reservoir can be shown to create a tilt of the OWC, described by the following equation:

$$\text{Oil-Water Contact Tilt} = dz/dx = - (dp/dx) * (\rho(w)/(\rho(w) - \rho(o)))$$

Where: dp/dx = Pressure (Potentiometric) Gradient of the Aquifer
 $\rho(w)$ = Density of the Water in the Aquifer
 $\rho(o)$ = Density of the Oil in the Reservoir

Using the above equation, the tilt of the OWC is directionally downward in the direction of flow and is a function of the pressure gradient and the relative densities of the water and overlying oil. This type of ROZ is, in the opinion of the study, the explanation for the thick ROZ intervals at Seminole (San Andreas Unit) and Wasson (Denver and Bennett Ranch units), as well as for the thick ROZ intervals in other oil fields in the Permian Basin and in other domestic oil basins.

Identification of Tilted Oil-Water Contacts. Since tilted OWC's are a key indicator, reexamination of oil fields with this attribute is a key step for identifying potentially thick ROZ's. Fortunately, OWC contouring is a basic input for efficient exploitation of an oil field and maps exist for most major oil fields. Where present, the tilt of the OWC can be readily derived from these maps. In cases where field wide unitization has occurred, the maps are filed in the public record as part of the exhibits supporting the unitization petitions to State regulatory agencies.

The OWC tilt at the Seminole and Wasson fields provides the first evidence of the presence of changed hydrodynamic conditions within the underlying aquifer. The second indication is from the mapping of the abnormally thick ROZ (confirmation of ROZ thickness was established by the operators using rigorous core and laboratory testing which provided detailed vertical profiles of the residual oil saturations for the ROZ in these two fields).

Thus, data on the presence of a "tilted" OWC and the top of the ROZ are often readily available for most large oil fields. However, determining the commercially viable base of the ROZ interval is more problematic. Very few cases exist, like at Seminole and Wasson, where core data have been acquired to establish the base and degree of oil saturation of the ROZ. In other situations, the base of oil saturation can be

approximated by the loss of oil shows within the drill cuttings or by the use of borehole logs, if sound data on water salinities (resistivities) exists. Another technique, called the Hingle Plot, which takes advantage of the divergence of the ratio of formation resistivity to rock density above and below the base of oil saturation, may be used to estimate the base of the ROZ. In this technique, the base of oil saturation is defined as the depth at which small oil saturations no longer affect formation resistivities, which may be below the commercially attractive interval.

Preliminary Estimates of TZ and ROZ Size and Potential. Given the data and information on tilted OWC's and supporting reservoir data available for the Permian Basin, the study sets forth a first order estimate of the size of the "stranded oil" target in the TZ and ROZ. For this, the discovered oil fields within the North and Central Basin Platform areas of the Permian Basin were examined to identify oil fields with tilted OWC's. First, the study estimated the OIP in the capillary pressure-created TZ below the traditionally selected OWC. The study then calculated the updip thickness of the ROZ wedge based on the degree of tilt. It then assigned a residual oil saturation to the ROZ consistent with the post-waterflood residual oil saturation in the MPZ. Next, the study assumed that the porosity and selected other reservoir oil in the ROZ interval are the same as in the MPZ and that the ROZ only exists within the defined limits of each field.

This methodology was first applied to two of the fields undergoing oil recovery from the ROZ, namely the Wasson and Seminole Fields. The preliminary estimate is that these two oil fields hold approximately 4 billion barrels of oil in the TZ and ROZ. Using a similar methodology, the study next examined a sample of seven additional Permian Basin, San Andres oil reservoirs, namely; Adair, Cowden (N&S), Fuhrman-Mascho, Means, Reeves, Seminole East and Yellowhouse. For these nine fields, the study estimates that the OIP in the TZ/ROZ is over 8 billion barrels, with nearly 3 billion barrels being potentially recoverable.

Using the preliminary OIP estimate in the nine sample fields and extrapolating this data to all of the examined tilted water-oil contact San Andres oil fields in the

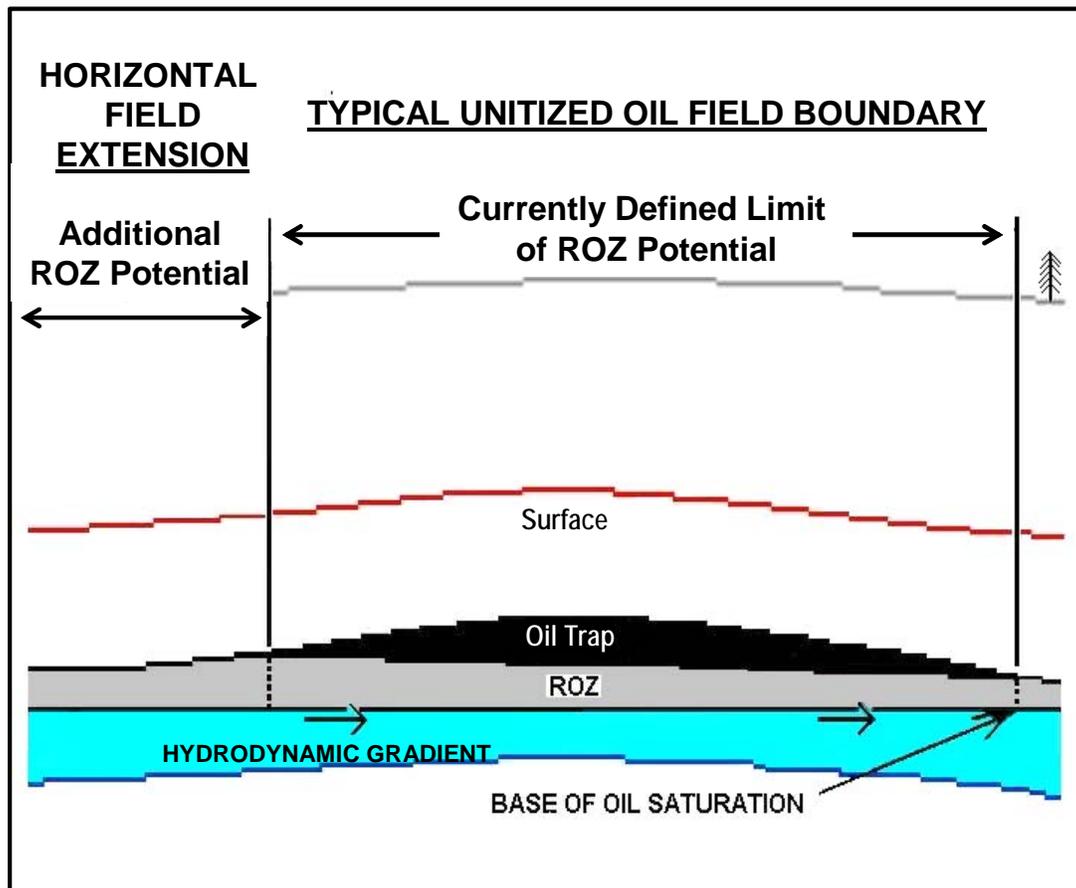
Permian Basin, the study sets forth an overall estimate of 15 billion barrels of OIP in the capillary pressure-created TZ's and the "naturally-created" ROZ's of the Permian Basin.

Additional residual oil opportunities should exist in the oil basins of Wyoming, Montana, North Dakota, and the Texas portion of the Hugoton Basin, based upon analogous geologic conditions. California, Utah, Colorado, and Alaska may also have opportunities for ROZ's and possess the potential for exploitation of these oil zones using CO₂ flooding. Other oil basins need further investigation to determine whether residual oil zones are present to any major degree.

So far, the study has examined the ROZ potential only within the boundaries established for existing fields. Figure EX-2 illustrates that an extension of the ROZ, especially in the up-gradient direction, likely exists and could provide huge additional residual oil resources outside established field boundaries.

Next Steps. Obtaining sufficient reservoir data for defining the size and productivity of the ROZ will be challenging. However, there will be great value from undertaking this task, as it will add previously undocumented oil to the Nation's resource base. A first step would be conducting a series of regional and basin studies. Ultimately, field-by-field analyses will be necessary and will require many years of effort, as field operators acquire the additional data needed for this evaluation. These regional and field-specific studies are the logical next steps toward understanding the full potential of ROZ resources and how they might contribute to future domestic oil production.

Figure EX-2: Illustration of the Presence of ROZ Beyond the Traditional Field Boundary



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Linkage of ROZ and Geologic Storage of CO₂. Recovering oil from the ROZ will require affordable, “EOR-ready” CO₂. Should research lead to new, cost-efficient CO₂ capture technology from electric power plants, large volumes of “EOR-ready” CO₂ will become available and the CO₂-EOR candidate fields (and their ROZ intervals) will become preferred sites for storing and sequestering CO₂. A combination of basic research, reservoir modeling studies, and field demonstration projects will be required to pursue this new domestic oil production opportunity and meet the needs for additional geological settings for storing CO₂. Understanding the role of hydrodynamics in the ROZ will be one of the key issues for establishing “permanence” for sequestration of CO₂ in this geologic horizon. A better understanding of the spatial distributions of ROZ intervals and their underlying aquifers will help locate new ROZ resources and will also assist in furthering the understanding of underground CO₂ storage sites, even where recoverable oil resources do not exist.

I. Background

The unexploited potential of residual oil intervals, below the traditional reservoir oil-water contact (OWC), is both a challenge and an opportunity for an oil industry and a nation facing declining domestic oil production. Fortunately, carbon dioxide (CO₂) enhanced oil recovery (EOR) has emerged as a viable technique for recovering residual oil left behind (“stranded”) after waterflooding, in light oil reservoirs below 3,000 feet in depth. With recent progress in CO₂ flooding technology and availability of affordable supplies of CO₂, it could become feasible to target “stranded” oil in low to moderate (\pm 30%) residual oil saturation settings. Based on the detailed geological and reservoir analysis performed for this study, we now also know that these residual oil saturation settings can be the result of both industry’s efforts and “nature’s waterflooding”.

Outline for Report. This report will address the residual oil resource created by “nature’s waterflooding”. It will review three ongoing field demonstration projects that are recovering residual oil from the transition zone (TZ) (the portion of the reservoir below the traditional OWC). It will also discuss typical attributes and origins of naturally-formed residual oil zones (ROZ’s), including their ubiquitous nature. Finally, the report will propose methodology for further understanding and, ultimately, exploiting this huge remaining, undocumented domestic oil resource.

Identifying Residual Oil Transition Zones. Why has the residual oil zone been overlooked so far? One of the first steps in defining a newly discovered oil reservoir is to determine the depth at which oil production turns predominantly to water and to establish the “traditional” OWC at the base of the main oil column. This information helps confine well drilling to depths at or above this “traditional” OWC. For the purposes of this report, the “traditional” OWC is defined as the depth above which oil is produced relatively water-free.

Capillary forces present in all reservoirs create transitions of oil and water saturation within a depth interval that is somewhat uncertain but usually modest in

thickness. As such, the definitions or criteria for the OWC and the base of the oil zone vary among fields. However, when unitizing a field for waterflooding, the determinations of producible oil and OIP require a consistent methodology and clear determination of the OWC. In this report, we will accept the OWC definitions used by the operators in the unitized oil fields, will report them as presented, and will not attempt to adjust them from field to field.

Once the OWC is determined, the great bulk of wells are drilled above this depth to assure relatively “water free” completions. As such, the definitions of the base of the traditional oil column, the OWC, and the top of the ROZ (within a given oil reservoir) are quickly established. What is lacking is information on the extent, richness, and thickness of the oil and water bearing interval below the OWC, the ROZ.

Certain stacked-pay reservoirs offer opportunities to examine the nature of the ROZ in the TZ. In stacked-pay reservoirs, when drilling through a shallower producing zone, information may be gained about the portions of the reservoir below the traditional OWC. In some cases, a producer would find that his assumptions about the original definition of the OWC were wrong and the existing wells would be deepened. Additionally, in these stacked pay conditions, additional properties of the TZ may be gained from logs taken through these lower reservoir intervals.

Most reservoirs have what the reservoir engineering profession calls a “capillary-based transition zone”. Given constant vertical reservoir properties, the water saturation increases linearly to 100%, usually over a relatively narrow twenty to fifty foot interval. To devise methods for estimating this “traditional” TZ and its oil saturation, capillary forces have been extensively studied in the laboratory.

On occasion, exceptions to the relatively thin, capillary-based transition intervals have been noted, particularly when a TZ was shown on logs to be anomalously thick. But generally, not much additional attention was given to these thick intervals, since only the oil column to the depth of the OWC was considered commercially viable to produce. For the capillary-based TZ oil intervals below the OWC, it was concluded that

production would be dominated by water and that potential reserves from primary or secondary (waterflooding) recovery would be small.

II. New CO₂-Enhanced Oil Recovery Opportunities in Mature Fields

During the 1960s and 1970s, industry began to address the potential for enhanced (tertiary) exploitation of the oil remaining in the reservoir after waterflooding. Many injectants were tested in laboratories that were designed to change the properties of the residual oil, making it more mobile within a reservoir. Large-scale commercial experiments started in the early 1970s. Two types of EOR found widespread application: steam injection and CO₂ flooding. These two methods are highly complementary. Steam flooding has been successfully used in basins with very heavy (viscous) oil at shallow depths, less than 3,000 feet. CO₂ flooding, on the other hand, has emerged as the fastest growing method for exploitation of lighter, less viscous oils, in reservoirs more than 3,000 feet in depth.

Overview of CO₂-EOR. CO₂ flooding proved its commercial viability in the late 1970s, as a result of the SACROC and North Cross projects in the Permian Basin becoming known. During the early 1980s, numerous companies made large investments in the infrastructure for CO₂ flooding and the CO₂-EOR industry has continued to grow since that time.

CO₂ flooding has been shown to be successful in producing oil from water swept intervals in numerous field projects. Although residual oil saturations to water flooding in the swept intervals were low, at $\pm 30\%$ of the pore space, CO₂ injection enabled operators to recover an additional 10% to 15% over the original oil in-place (OOIP).

Industry realized that CO₂'s higher mobility and lower sweep efficiency (than water) would reduce its contact with or sweep of the reservoir. Thus, to achieve these favorable oil recoveries, CO₂ had to be effectively displacing most of the residual oil it contacted.

As these findings emerged, the thought occurred to some that the ROZ beneath the main oil column might also be a target for CO₂ flooding. Thus, the concept of CO₂ flooding of ROZ's emerged. Three significant field projects have served as the pioneers for testing this concept.

Wasson Field (Denver Unit) ROZ Activities. The first example of a CO₂ flood in the residual oil zone was Shell's Transition Zone pilot begun in 1991. Shell had observed that an anomalously thick ROZ lay beneath the San Andres reservoir oil column within their Denver Unit in Yoakum County, Texas. The interval possessed oil saturations that varied from 85% at the top and 0% at the base, over a 300-foot vertical interval. A large portion of the interval had oil saturations above 30%, which Shell believed to be similar to the residual oil saturation to the waterflood within the swept portions of the main pay interval. Since CO₂ flooding was already being used to add incremental oil recovery in the previously waterflooded main pay intervals of this Unit, the hypothesis was that the residual oil (transition) zone could also be flooded using CO₂.

Shell's field research pilot, called the TZ Sweetspot CO₂ flood, began evaluating the oil recovery potential from the upper 150 feet portion of the transition zone. In the midst of this initial field research, Shell's assets in the Permian Basin were combined with Amoco's assets to form Altura Energy, Ltd. Still, Shell's work provided valuable information for delineating the residual oil (transition) zone (see Figure 1 of the Appendix, *Denver Unit Transition Zone Map Showing Phased Areas*, and Reference 1).

Under Altura Energy, evaluation and operation of the ROZ pilot in the Denver Unit continued. Recognizing the commercial success of the ROZ pilot, Altura expanded the pilot area to the Phase 1 ROZ area and had plans for further expansion to the Phase 2 area. Altura was then purchased by Occidental Petroleum in 2000. Under Occidental's management, the Denver Unit transition zone CO₂ flooding project was expanded into the Phase 2 area and then further expanded into Phases 3 and 4. Phase 5, 6, and 7 of developing the ROZ resource in the Denver Unit are still several years away.

Reporting of the results from the Phase 1, 2, and 3 ROZ efforts (by Shell, Altura and Oxy) has been limited to internal reports for owners of the Denver Unit. However, in recent months, Shell has made several presentations that confirm that the Denver Unit TZ performance is meeting pre-divestiture expectations.

Seminole Field (San Andres Unit) ROZ Activities. Operating concurrent with the residual oil (transition) zone pilots at the Denver unit is Amerada Hess' ROZ pilot at the Seminole San Andres Unit (SSAU). The ROZ work at SSAU has seen some limited public exposure, most notably at the 2001 CO₂ Flooding Conference in Midland, Texas (Reference 2). In this conference, Amerada Hess reported on the presence of the ROZ at the Seminole Field and provided a progress report on the performance of the four-pattern CO₂ pilot. Recent discussions with Amerada Hess suggest a Phase II expansion of the pilot is being planned (Reference 3) and discussions are underway for a third possible expansion.

Wasson Field (Bennett Ranch Unit) ROZ Activities. The third ROZ project is a Shell initiated CO₂-EOR effort at the Bennett Ranch Unit of Wasson Field, initiated in 1995. The original CO₂ flood, launched in 1995, called for deepening of wells to include both the main pay zone and 75 feet of the residual oil (transition) zone. But, because of low oil prices in the mid-1990s, the deepening of the wells was eliminated from the project. In late 2003, Occidental carried through on the original CO₂-EOR plan by deepening a number of the wells into the ROZ. The company is now co-developing the ROZ and the main pay zone in half of the overall CO₂ flooded area. Additional expansion of the Bennett Ranch ROZ project is underway.

Several other ROZ projects exist in the Permian Basin. While none of these have been documented in the literature or reported at a conference, ROZ pilot projects are known to exist at ExxonMobil's Means San Andres Unit in Andrews County, Texas (Reference 4) and the Salt Creek Field in Kent County, Texas (Reference 5).

With the advent of higher oil prices and the encouraging results from CO₂ flooding of the residual oil zones at the Denver and Seminole San Andres units, a closer look at the stranded oil potential in the ROZ is warranted.

The first part of this report sets the stage for this closer look by presenting the geological and engineering knowledge gained from the companies conducting ROZ field projects. The second part of the report examines the origins of ROZ's and proposed key parameters for identifying candidate oil fields. The third part of the report discusses other oil fields and basins where this unexploited ROZ resource is likely present. Lastly, the report provides recommendations for future work for defining the magnitude and productive potential of the oil resource from CO₂ flooding the ROZ.

III. Commercial Demonstrations of Oil Response in Residual Oil Zones

The Permian Basin of West Texas has two important features that have motivated research and field tests of ROZ's. The first is the well-established CO₂ infrastructure including pipelines and processing plants that allow economic delivery and recycling of CO₂. The second is the presence of a thick ROZ that can exceed 200 feet in many reservoirs (Reference 6). These ROZ field pilots could be co-developed with CO₂ projects within the main oil pay intervals, such as at Occidental's Wasson Denver Unit (DU) and Amerada Hess' Seminole San Andres Unit (SSAU).

The CO₂ floods in the main pay zone (MPZ) of these two oil fields have produced over 12% of their OOIP during the tertiary phase. Both projects are still active and successful after twenty years of operation, even though oil production has been slower than anticipated (SSAU has an average porosity of 12% and an average permeability of 9 millidarcies). The DU has an average porosity of 12% and a slightly lower permeability of 8 millidarcies. Figure 2, *Porosity-Permeability Crossplot for San Andres CO₂ Floods in the Permian Basin*, illustrates a rock property comparison of numerous Permian Basin San Andres CO₂ projects.

A. Amerada Hess's Seminole Field, San Andres Unit. The Seminole San Andres Unit is situated on the northeast limit of the Central Basin Platform in Gaines County, Texas about 60 miles NNW of the city of Midland (Figure 3, *Geographical and Geological Setting of the Wasson and Seminole Fields, Permian Basin*). The field was discovered in 1936 and unitized in 1969. The 15,700-acre unit began the CO₂ flood in 1983. The production history of the Seminole field is shown in Figure 4, *Production History of the Seminole San Andres Unit (SSAU)*.

The MPZ for the unit averages 195 feet in thickness (Reference 7). Within the pilot ROZ area, the MPZ averages 160 feet of gross thickness and 126 feet of net thickness. The MPZ originally had 1 billion barrels of OIP. The ROZ in the pilot area

has a gross thickness of 246 feet and 197 feet of net pay. As shown in Figure 5, *SSAU MPZ & ROZ Cross-section and Zonal Attributes*, the ROZ has slightly higher porosity and has streaks of higher permeability than the MPZ. The estimated oil in-place for the ROZ has a range of 0.4-1.1 billion stock tank barrels (STB). The ROZ has an average initial oil saturation of 32% of the pore space versus an initial oil saturation of 84% in the MPZ.

Figure 6, *Pilot Area for the SSAU ROZ Phase I Pilot*, shows the Initiation of the ROZ pilot commenced in April of 1996, with four injection wells deepened to include the ROZ. Fourteen producing wells were also deepened with one sponge core taken through the ROZ. Oil and water production lines were installed, electric submersible pumping equipment was placed in all production wells, and a lease production facility was established, all in 68 days. CO₂ injection began in July 1996. CO₂ injection was made both into the MPZ and the ROZ. Estimates of CO₂ injection into the ROZ were made by periodically using injection profile logs. The high CO₂-to-oil ratio of the pilot (according to the operator) is only partially indicative of the pilot ROZ performance, due to conformance issues with CO₂ injection into the ROZ. However, oil response to CO₂ from the ROZ has been clearly established. In the five years from implementation, oil production has increased to 1,400 barrels per day and watercuts have returned to pre-project MPZ levels after opening the ROZ interval which had not been produced in the 60-year history of the field.

Figure 7, *Composite Production Curve and Watercuts for the SSAU ROZ Phase I Project*, illustrates the aggregate response for the ROZ pilot area. MPZ-only oil production was determined on an individual well basis. MPZ production dominated well and project performance until the ROZ oil response caused a significantly improved watercut (Figure 8, *SSAU ROZ Phase I Performance Separating ROZ and MPZ Response*).

Amerada Hess also presented two oil production forecasts based on CO₂ utilization calculated on an instantaneous rate as well as a cumulative basis. Both resulted in similar numbers and are shown in Figure 9, *SSAU ROZ Phase I Performance and Forecast*. Note the high CO₂ utilization factor attributed to the pilot. Although data is not definitive, utilization factors of twice those normally seen in the

MPZ may be appropriate. However, loss of CO₂ updip outside the pilot area may also explain the apparent poorer CO₂ utilization factor. Still, the pilot has clearly demonstrated the ability to mobilize oil from the ROZ. In response to the success of the pilot flood, Amerada Hess has recently begun expanding the capacity of the gas processing plant and is preparing to circulate authorization for expenditures (AFE's) to expand the area of ROZ testing.

B. Oxy Permian's Denver Unit. The Denver Unit (DU) lies on the southern limit of the Northwest Shelf region of the Permian Basin in Yoakum County, Texas, about 80 miles NNW of the city of Midland (Fig 3). As seen in Figure 10, *Wasson Field Area with San Andres Formation Producing Units and Attributes*, it is one of seven units of the huge Wasson Field that covers over 68,000 acres and holds an estimated 4.5 billion barrels of OIP. Oxy Permian's Denver Unit lies within the southeastern portion of the field and is the largest of the units.

Shell initiated the first ROZ pilot field in 1991, with a six pattern CO₂ flood within an area of the Denver Unit called the transition zone sweetspot (TZSS). This is the portion of the unit where the combination of rock properties and in-place residual oil is rich and thick. The success of the pilot led to a 21-pattern expansion, with the entire project adopting the name, Transition Zone Sweetspot CO₂ demonstration project (see Figure 1). As in the initial pilot areas, the upper 150' of the zone was chosen to concentrate CO₂ injection (Figure 11, *Example Log from the Transition Zone Pilot at the Denver Unit*).

The oil saturated zone beneath the MPZ in the pilot area consists of a 300 feet thick interval using the traditional OWC as the base of the main pay. The water saturation ranges from a low of 20% at the top to near 100% at the base. Figure 12, *A Sample Denver Unit Log Illustrating the TZ and Properties*, provides a modern geophysical well log to illustrate the TZ interval in comparison to the MPZ (Reference 1).

Oxy Permian estimates that the OOIP for the combined DU and ODC Unit in the TZ is over 830 million barrels. They note that exploitation of this resource can take

advantage of the existing well, production, distribution, and gathering lines. In addition, the CO₂ pipeline and processing infrastructure has already been built and justified for the overlying MPZ. The required activity for the TZ project includes deepening of injectors and producers, reopening of temporarily abandoned wells (due to the mature nature of patterns within the MPZ CO₂ flood), and some drilling of new wells, just like the MPZ floods and the TZ flood utilized CO₂ water-alternating gas (WAG) injection.

Much like Amerada Hess's experience at SSAU, Oxy Permian has observed a somewhat higher utilization of CO₂ per barrel of oil. The recovery factor is from 10% to 16% of what would be called OOIP in the MPZ. But since the in-place oil within the ROZ is actually a lower figure (due to higher original water saturations than in the MPZ) the conventional terminology needs some explanation. Figure 13, *Oil Recovery Concepts from the Transition (Residual Oil) Zone, Denver Unit, Texas*, discusses the problem of defining recoveries from residual oil intervals, especially when using the hydrocarbon pore volume (HCPV) convention.

The incremental oil response from the Denver Unit ROZ pilot and demonstration areas are provided for the first three areas, the original TZSS, implemented in 1995, the Phase 1 area, implemented July 1997, and the Phase 2 area which was implemented in 2002. The TZSS has 103 million barrels of OOIP and an estimated ultimate recovery of 14 million barrels. The overall response of the TZSS area is shown in Figure 14, *Denver Transition Zone Sweetspot Oil Response*. The figure provides the waterflood baseline, the MPZ response, and the MPZ modeled response. It also shows the TZ prediction and the performance data through the time of this analysis and report. The cost of the TZSS project is \$7.14 million, providing an internal rate of return for the project of 20%, during a period of lower oil prices.

The oil response curve for the second area, the Phase 1 project, is shown in Figure 15, *Denver Transition Zone (Ph I Area) Oil Response*. For Phase 1, as with the other areas, CO₂ injection and oil production are separately monitored. In this area, most of the additional in-fill wells were drilled early enough to set a production baseline that minimizes the complications of extracting true incremental ROZ response. The figure shows a March 2005 "look back" at the incremental oil response. Clearly, the

establishment of the pre-implementation baseline is a key feature of the analysis. The Oxy Permian chosen baseline, shown in the figure, has an 11% annual decline, based on computer simulation. The forecast of oil response from the 1996 model runs (utilized for the project justification) is also shown and matches well with the performance to date.

The oil response in the third project area, Phase 2, is shown in Figure 16, *Denver Transition Zone Phase 2 Oil Response*. Although the area is less mature, it also clearly shows incremental oil response to the injection of CO₂. The project included thirty-four deepened producers, fifteen deepened injectors, three producer conversions, and five new producing wells.

The three ROZ demonstration projects involving CO₂ flooding demonstrate the technical potential for exploiting zones that would not produce primary or water flooded oil in any significant volumes. The forecasts of oil response at the onset of injection were hampered by the lack of analog floods by which to make experience base predictions, necessitating an almost complete reliance on computer simulations. The match of modeled response to actual data, as observed in Figures 14-16, has been exemplary and is a tribute to the assembled reservoir teams, both past and present.

C. Other Examples in the Permian Basin. Shell's confidence in the economic viability of flooding the transition zone was further demonstrated in 1995 with plans for implementation of the Bennett Ranch CO₂ flood (Reference 8). The original plan called for deepening the injection and production wells to include 75 feet of the TZ, making it the first CO₂ flood that would include the ROZ in the overall flooded interval. However, due to low oil prices, the wells were not deepened and only the MPZ was flooded in the initial implementation. In late 2003 the ROZ was added and is now co-developed with the MPZ. Today, about half of the CO₂ flooded patterns are now being co-developed. Figure 17, *Bennett Ranch Unit (Wasson Field) Oil Forecast*, presents a look at the past and forecasted production for the 8-pattern CO₂ flood. Figure 18, *Bennett Ranch Unit (Wasson Field) Oil Response*, illustrates the results at the Bennett Ranch Unit Project. Additional expansion at Bennett Ranch is underway.

Other projects that have evaluated ROZ's with pilots are ExxonMobil's Means Unit and Salt Creek Units. Data is unavailable for these projects. They are discussed only to illustrate the wider industry acceptance of the technical viability of CO₂ flooding of ROZ intervals.

IV. Geological Origins of Residual Oil Zones

A. Definition of Terms. The term *residual oil zone (ROZ)*, though preferred herein, has a commonly used alternate term, *transition zone (TZ)*, as used by Oxy Permian in the Wasson area. Although generally synonymous, the two terms have a subtle but significant difference.

All oil reservoirs have an interval of tens of feet below the normally-defined 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 TZ's and water-wet rocks providing thinner ones. Rocks can also exhibit mixed wettabilities with small pores exhibiting water-wet properties and intermediate to large pore sizes showing an oil-wet properties. In these situations, the oil saturation profile and thickness could show considerable spatial variability reflective of lateral variations in rock (and pore) types.

The term transition zone (TZ) is commonly used for a cross-sectional profile that uniformly grades from the maximum oil saturation of the oil column; say 85% as was observed at the Seminole Field, to zero. The TZ includes an upper interval that produces water and oil at a low water cut. In contrast, and as used herein, the term residual oil zone (ROZ) includes the middle and lower portions of the overall TZ from which water is primarily produced. TZ's can also include intervals like these shown in Figure 19, *Seminole San Andres Residual Oil Saturation Profile*, where the gradational decline in oil saturation is interrupted by a mid-region of relatively constant oil saturation.

The reason that the term residual oil zone (ROZ) rather than the transition zone (TZ) is preferred in this report is to clearly note the abnormally thick ROZ's that exist for reasons beyond normal capillary effects. For example, if the original oil entrapment possessed a thick oil column in its geologic past and the lower portion of this oil column

was invaded by water, the displaced interval would leave an oil saturation much like that attributed to the remaining oil saturation in a swept zone in a water flood (Sow). Such is the case at the SSAU. These types of reservoirs can have anomalously thick ROZ's and could contribute considerable additional EOR reserves above and beyond those from the MPZ's.

B. Original Oil Entrapment. The mechanics of original oil migration and entrapment have long been studied by the oil industry for identifying new oil fields and for minimizing the risk of exploration. Considerations such as the presence of source rock for hydrocarbon generation, thermal burial histories to allow in-situ refining of organic materials, presence of structural or stratigraphic traps, seal integrity and the like are all factors governing the accumulation of oil in the subsurface.

For the purposes of discussing the origins of ROZ's, we use a hypothetical hydrocarbon accumulation, such as the one shown on Figure 20, *Original Oil Accumulation under Static Aquifer Conditions (A Hypothetical Example)*. This original trap accumulation can, on occasion, be shown to have been affected by subsequent forces such as regional or local basin tilt, seal breach, or a change in the hydrodynamic regime in underlying regional aquifers. Examples abound where the oil trap can be rendered temporarily or permanently ineffective by geologic faulting and, at other times, portions of the oil column can be postulated to have been redistributed due to reservoir tilt or hydrodynamic displacement. Such forces are known to have occurred, sometimes many times during the geologic history of an oil reservoir (Reference 9).

With forces that can displace the original oil emplacement, one could expect that opportunities for residual oil zones would be common. The now established technical and economic success of CO₂ flooding ROZ's now creates the need to: 1) categorize the important causes of residual oil zones, 2) examine evidence of such forces at work, and 3) fully examine opportunities for EOR within these ROZ's.

This section of the report examines the three origins for ROZ's.

C. Basin Tilt. Figure 21, *Original Accumulation subject to a Westward Regional Tilt & Forming a ROZ*, illustrates an original oil entrapment with a hydrocarbon spill point on the east. The entrapment is subsequently subjected to a regional westward basinal tilt of approximately 40 feet per mile. This hypothetical situation preserves the identical spill point for the original hydrocarbon accumulation and illustrates that the oil column has been thinned on the west side leaving behind a zone of “water swept” oil. The base of oil saturation has also been tilted and is therefore not horizontal. The OWC is controlled by gravity alone and is horizontal. The resulting ROZ is wedge shaped with the updip side being thicker.

The naturally water swept interval is somewhat analogous to oil produced by a natural water drive reservoir wherein the invaded zone leaves behind a residual oil saturation to water (S_{ow}). It is equally analogous to the swept zones in a pattern waterflood. The relative displacement curves for oil and water are the tools by which the industry estimates the displaced oil in these situations. The remaining (or residual) oil left behind is the target oil which can be produced using CO₂ flooding.

D. Breached and Reformed Reservoir Seals. Figure 22, *Original Accumulation with a Breached then Repaired Seal & Forming a ROZ*, presents a second source of ROZ's. Here, the original oil entrapment is breached. This can occur, for example, by buildup of fluid pressures during the formative reservoir stage, the escape of a portion or all of the hydrocarbons, the subsequent healing of the seal, and the re-entrapment of hydrocarbons. If the second entrapment contains a thinner oil column than was originally present, a ROZ would be present. Proving the transient loss of seal integrity would be difficult, but recent work by the USGS (sponsored by the U.S. Department of Energy) on fracture characteristics might provide some interesting insight on contributory mechanics. Additional observations regarding the presence of tar mats within the reservoir column could also be an indicator of loss of seal integrity during the geological history of a reservoir.

In this second ROZ formation case, the base of oil saturation, the TZ, and the OWC would be horizontal. Gas-to-oil ratios of these reservoirs are often anomalously

low due to the weaker seal capacity. Tar mats and other solid hydrocarbons present within the oil column may provide evidence of such a process.

E. Altered Hydrodynamic Flow Fields. Examination of basin aquifers has been rare, as evidenced by few references in the petroleum geology literature. However, one notable exception is the collection of studies devoted to understanding hydrodynamically trapped hydrocarbons (examples of which are References 9-11). In this body of work, the understanding of currently active aquifer flowfields can lead to finding and describing accumulations that are not explained by normal subsurface structural closure theory. Reference 11 provides a particularly insightful discussion of what has been called hydrodynamic traps and the reader is referred to this work for detailed discussions of not only oil but also gas traps subject to hydrodynamic forces. The above body of geologic work is devoted to exploration objectives or, alternatively stated, is concerned with where the hydrocarbons migrate when subject to hydrodynamic flow. The study of transition and residual oil zones has a different emphasis - - finding the original geologic settings for the migrated hydrocarbons. Almost no references were found to assist in this endeavor. However, three notable exceptions, References 6, 9, and 10 relate to this third class of ROZ origin, altered hydrodynamic flow fields.

Figure 23, *Change in Hydrodynamic Conditions, Sweep of the Lower Oil Column, Oil -Water Contact Tilt, and Development of the Residual Oil Zone*, shows the same original entrapment seen in Figure 20 but uses a west-to-east hydrodynamic flowfield to explain the tilted OWC. Here, the OWC is also tilted, but in this case it's due to the hydrodynamic forces on the oil column. Reference 11 provides analytical methods to determine contact tilts based upon the flowfield and densities of the oil and water.

Since many oilfields were unitized for water flooding, rigorous calculations of oil-in-place were necessary which would require detailed structural contouring of the OWC. We use two examples, shown in Figure 24, *Seminole (San Andres) Field Oil-Water Contact Structure Map – Adapted from Texas Railroad Commission Unitization Filings, 1969*, and Figure 25, *Wasson Field Oil-Water Contact Contour Map – Texas RR Commission Filing, Oct 1964*, from two CO₂-EOR ROZ projects to demonstrate the

detailed work that has been performed. This work was filed for public record during the respective unitization proceedings during the 1960's.

Unitization agreements (and exhibits thereto) are often matters of public record through the state oil and gas regulatory agencies and thus can serve as a valuable source of OWC tilt information. With such information and knowledge of the oil and water densities, one can calculate the hydrodynamic flow field responsible for the contact tilt beneath the oil leg through use of the following formula:

$$\text{Oil-Water Contact tilt} = dz/dx = - dp/dx * (\rho_w/(\rho_w - \rho_o))$$

Where: dp/dx = Pressure (Potentiometric) Gradient of the Aquifer
 ρ_w = Density of the Water in the Aquifer
 ρ_o = Density of the Oil

One must exercise care to avoid assuming that the documented OWC tilt is due to current hydrodynamic gradients. The tilt can be safely assumed to be the result of the maximum gradient, but past and/or current gradients may be lower. Time varying gradients may play into the distribution of the oil saturations in the ROZ. An example and further speculation on this topic will be presented later.

F. Establishing Key ROZ Reservoir Properties. Establishing the OWC contact is possible for most major oil fields. However, determining the thicknesses of the ROZ is more problematic. Very few cases will be found like the Seminole and Wasson fields wherein core data was acquired to establish the base of oil saturation. In other situations, this base can be approximated by the loss of oil shows within the drill cuttings or sample cuts or by the use of borehole logs if reliable data on water salinities (resistivities) is present. Another technique called the Hingle Plot and discussed later, takes advantage of the divergence of the ratio of formation resistivity to density above and below the base of oil saturation. But in this technique, the base is often redefined to be the depth at which low oil saturations no longer affect formation resistivities. Since this oil saturation is generally below 20%, the lower interval may not be commercially productive even using EOR.

Produced water cuts are extremely high throughout the ROZ (95-100%) and, since perforations are typically spread out along thick depth intervals, no confidence is placed in utilization of water cut data for determination of the base of oil saturation.

One final point about the Type 3 ROZ is that it does not necessarily have to possess a retained oil column, as shown in the figure. In this case, the entire original trap may now be a ROZ. This situation may be especially prevalent where high hydrodynamic gradients are present and low relief structural traps have been completely flushed. Reference 12 indirectly alludes to these types of oil traps being present in the Billings Nose area of western North Dakota.

G. Ranking of Importance of ROZ Origination Mechanics. Hydrostatic equilibrium conditions for permeable rocks in most basins are often assumed but are probably quite rare. Such things as pore fluid expulsion during burial and sediment consolidation argue for development of updip directed flow conditions and permeable flow paths. After basin stabilization, meteoric (surface) water influx to the same reservoir formations that produce at depth some distance away is the more typical case. If the same formations have a lower elevation discharge point on the opposite side of the Basin, then the potentiometric field is set up for hydrodynamic flow. Erosional effects on the discharge outcrops can also set up aquifer flow. In some cases, near-stagnant flow fields can effectively provide near hydrostatic equilibrium conditions, however thermal gradients may also be present that promote aquifer circulation.

An interesting case is when an oil basin has subsided and oil migrates into the traps forming the original accumulations. Tectonically active basins provide two necessary criteria for subsequent development of hydrodynamic flow. First, the tectonics dramatically increase the probability of aquifer charge areas and, secondly, provide the opportunity for an alteration of hydrodynamic conditions from the original oil accumulations. The changed conditions cause the displacement of the oil when the flow field is altered. The displaced oil leaves behind the residual oil zone.

Figure 26, *Examples of Hydrodynamic Traps*, illustrates three examples of subsurface conditions leading to displaced and hydrodynamically trapped hydrocarbons. This example (Reference 12) is the exploration driven objective, but the obvious conditions of hydrodynamic trapping require displacement of oil from up-gradient traps. Looking for the source of the oil for the hydrodynamically displaced (in this case hydrodynamically trapped) oil is now pertinent. New exploration methods are needed to optimally search for these ROZ's.

The ubiquitous and sometimes changing hydrodynamic conditions in the subsurface create the necessary conditions for ROZ development. This leads one to conclude that the most common source of ROZ formation is hydrodynamics. This will certainly be the case for tectonically active areas where the conditions are favorable for post-accumulation oil displacement due to hydrodynamic gradient changes.

Local or basin-wide tilt is another common attribute of basin settings and sedimentary environments. It too is related to tectonics so the opportunity for reservoir tilting to be commonplace is also present. However, the degree of tilting may be so slight that commercially significant ROZ development due solely to local or regional tilt is fairly small. Combination of hydrodynamics and formation tilt are probably common and establishing the dominant parameter may prove to be difficult. Sorting through pre-conceived conclusions regarding origins of OWC tilt may prove necessary.

Finally, breached seals of original hydrocarbon accumulations are probably quite commonplace in the subsurface. However, the importance of this ROZ type currently ranks low, due to lack of data. Should the reforming of the seal occur during the continuing oil migration phase, the trap could refill to capacity (spill point) so that the ROZ is refilled with oil. If resealing occurs such that only limited influx of oil is present, a ROZ would be present. No examples of this ROZ reservoir type were found in the literature search, but many undoubtedly exist.

V. Evidence for Additional ROZ's in the Permian Basin

Figure 27, *Distribution of Tilted Oil-Water Contacts in the Northern Shelf and Central Basin Platform Areas of the Permian Basin*, is taken from Reference 6 wherein the author made a thorough study of tilted OWC's in the northern carbonate shelf areas of the Permian Basin. He concluded that many northern shelf San Andres fields have OWC tilts of hydrodynamic origin. However, the author added that not all of the OWC tilts can be *solely* attributed to a hydrodynamics, especially on the Central Basin Platform.

Origins of Tilted OWC's. This landmark work, along with Reference 10, make a strong case that the Middle Tertiary uplift in central New Mexico elevated the San Andres outcrops changing the subsurface San Andres reservoir hydrodynamics. This created large hydrodynamic gradients through the formation in this region of the Permian Basin, causing OWC tilt and sweeping substantial oil out the downdip spill point at the northeastern tip of the Ownby field (Figure 28, *Wasson Field Area Oil-Water Contact Structural Contours*). This process was shown earlier in Figure 23.

Figures 29, *Post-Subsidence Phase of Permian Basin Development*, 30, *Initial Uplift (Maximal Recharge) Phase in the Permian Basin*, and 31, *Extensional Phases and Reduction of Hydrodynamic Gradients in the Permian Basin*, taken from Reference 10, are attempts to reconstruct the actual cross-sectional model of the Permian Basin illustrating the post accumulation starting point, key phases of uplift, flushing and ROZ development. This work presented for the first time a theory that a stage of extensional development during the mid-to-late Miocene Period then created a second phase of hydrodynamics by reducing both the volumetric input and hydrodynamic pressures as recharge zones were isolated and disconnected to the Permian Basin.

Since the ROZ wedge development is a function of: 1) the original oil entrapment and column, and 2) the maximum gradients subjected to the original entrapment, the

reduction of pressure and gradients will make subtle changes to the oil saturation in the TZ. Perhaps also, it affects the amount of geologic time to which the rock is subjected to flushing mechanics. It is speculated that this may be a feature providing some possible insight as to the differences in water saturation profiles as observed between the SSAU and Denver Unit ROZ's. However, Oxy Permian suspects that the rock properties in the ROZ interval may be responsible for the ROZ profile at Wasson (Denver Unit) appearing more transitional than the ROZ at SSAU. More work will be necessary to explain those differences.

A large number of laboratory examinations of transition zones beneath OWC's are evidenced in the petroleum engineering literature. Reference 13 is an example and provides a particularly germane analysis for Permian Basin San Andres reservoirs illustrating examples of water saturation profiles due to vertical water influx to oil zones. Capillary forces control the drainage and imbibition profiles. Normal thicknesses of these TZ's are consistently shown to be less than 50 feet from the OWC to the base of oil saturation. The ROZ examples presented for the Permian Basin cannot be fully explained by capillary forces alone. However, the oil saturations in the upper and basal portions of the transition zone are likely explained by capillary effects, as can be observed in Figure 19.

During the literature search, two notable papers were found that examine TZ's and conclude that significant reserves can be added to a field's production history (References 14, 15). However, the definition used for the top of the TZ for both papers is where water-free oil can be produced. We thus need to refer to the difference between our definition of the top of the ROZ (base of commercial oil) and their definition of the TZ. Nonetheless, methods for estimating those resources can be quite useful for purposes discussed herein, were treated in some detail in Reference 14, and will be discussed in a later section of this report.

Contrasting ROZ Oil Saturation Profiles. The residual oil zone (ROZ) profile at the Wasson field is often referred to as a transition zone (TZ). This terminology describes the relatively uniform gradational nature of the water (or oil) saturation profile. However, we have seen that the zone is 300 feet thick on the southwest side which clearly argues for an origin other than normal transition zone capillary forces. On the

other hand, the ROZ profile at the Seminole unit is substantially different in its vertical profile character where a thick middle zone of nearly constant oil and water saturation is present. But, both the Wasson and Seminole fields are observed to have tilted OWC's implying past or current hydrodynamic forces at work. Horizontal water influx and flushing of oil is therefore a requirement to explain both the tilt and the thick ROZ profile.

One explanation of the SSAU profile could be the cessation or dramatic reduction of hydrodynamic forces. Alternatively, the more gradational Wasson field profile could be explained by a gradual or successively staged reductions of hydrodynamic gradients and downward migration (with commensurate pressure reductions) of oil into the flushed zone. Alternatively, one might suspect a time dependent factor on the reduction of oil saturation, i.e. perhaps the longer the exposure to water flushing, the lower the oil saturation. This could be due to diagenetic effects on the rock of prolonged exposure to water. More work is needed to develop a more confident explanation of the profile differences.

One curious feature of the Seminole field bears mentioning. There is a teardrop shaped region in the northern portion of the field (see Figure 24) that has an anomalously deeper OWC than the rest of the field. It is as though this portion of the field was isolated from the hydrodynamic effects that swept the oil from ROZ. This adds some further weight to the theory of rapid reductions of hydrodynamic gradients at SSAU.

Preliminary Estimate of ROZ Resources. Figure 27 shows that a large number of oil fields in the Central Basin Platform and Northern Shelf areas of the Permian Basin have tilted OWC's and these may contain ROZ's. While it is somewhat premature to quantify the magnitude of this resource, a very cursory attempt to do so has been undertaken, as follows:

- First, the producing area of each oil field is tabulated.

- Next, a crude estimate of the wedge thickness (net pay) of the ROZ is made using the observed tilt in the OWC, as shown on Figure 27, and the down-gradient length of the field.
- Next, for simplicity, the average properties of the MPZ (except for net pay and oil saturation) are assigned to the ROZ interval. The oil saturation in the ROZ is set at swept zone residual oil saturation.
- With this data in hand, the OOIP of the ROZ is calculated for each field.
- Then, using regional data for the Permian Basin on capillary pressure, the OOIP in the upper transition zone is estimated for each field.

Combining this data and methodology, the study estimated the TZ/ROZ OOIP for the nine example tilted OWC fields in the Permian Basin fields. Then, using “a rule of thumb” that says one-third of the OOIP in the TZ/ROZ can be technically produced, the study estimated technically recoverable resources for these nine fields.

Using this simple approach, the OOIP in TZ/ROZ for these nine fields (represented by tilted OWC’s on Figure 27) is estimated at over 8 billion barrels, with a recoverable resource of nearly 3 billion barrels. These nine fields are a sample of the fields within the hydrodynamic fairway of the Permian Basin. While only speculation at this point, the Permian Basin oil fields may hold 15 billion barrels of resource in-place in the TZ’s/ROZ’s of the San Andreas formation, 5 billion barrels of which may be technically recoverable.

VI. Evidence for ROZ's in Other Basins

The study conducted a cursory review of the literature to locate references to fields in basins other than the Permian Basin that might possess evidence for ROZ's. Even though the geologic and engineering literature on this topic is limited, several citations noting the association of tilted OWC's and/or post accumulation tilts on oil-bearing formations were found for significant domestic oil producing regions. This suggests that further work on this topic will likely be rewarded.

Potential for ROZ's in Rocky Mountain Oil Basins. The literature search identified that the Rocky Mountain uplifts had created innumerable fields in Wyoming with tilted OWC's. Literature for the southern Williston Basin in Montana and North Dakota, summarized in Reference 12 and shown in Figure 32, *Regional Structure of the Mission Canyon Fm. and Location of Important Oil Fields and Greater Billings Nose Study Area, Williston Basin*, identified an entire region, the Billings Nose Area, where the extensive displacement of oil by hydrodynamic forces has been documented in considerable detail. The work was performed from an exploration emphasis, thus residual oil zones are not explicitly identified but clearly must be present.

Figure 33, *Sequence Of Oil Migration And Accumulation In The Billing Nose Fields, Williston Basin*, displays the displacement of oil accumulations via hydrodynamic forces and the documented invasion of fresh or brackish water into connate formation waters for the Billings Nose Area. Aquifers outcropping on the Big Horn and Black Hills uplifts are the likely charge for the displacement process. The likely discharge is through the Paleozoic subcrop and into the Jurassic age rocks that are exposed on the east side of the Basin, beneath the glacial tilt in central North Dakota.

The Frannie oil field in the Big Horn Basin shown in Figure 34, *Frannie Oil Field, Big Horn Basin Illustrating the SW Oil-Water Contact Tilt of ~600 ft/mi*, is another example of a tilted OWC caused by hydrodynamic forces. The Big Horn Uplift is a short

distance to the northeast of the field and the OWC tilt is substantial, at 600 feet per mile to the southwest. As might be expected, water in the Tensleep formation of the field is relatively fresh at 3400 parts per million.

Potential for ROZ's in Mid-Continent Oil Basins. A literature review of the Permian Panhandle and Hugoton oil and gas fields of the western Anadarko Basin (Reference 16) offers insight into hydrodynamic oil and gas migration due to piezometric changes in distant erosion outcrops. The postulated source of the waters explaining the observed tilts in oil-water and gas-water contacts is the deep Anadarko basin connate waters that ultimately find their way to the Permian-age outcrops in eastern Kansas.

The literature states: "evidence of post-accumulation tilting, in the form of uneven fluid contacts has been observed in the original development of the (oil) field." This tilting leads to either Type 1 or Type 3 ROZ development. The author makes strong inferences that the oil and gas migration from the Panhandle field was due to hydrodynamic processes related to the reduction in aquifer pressure as a result of post-Laramide (uplift and) erosion and removal of Cretaceous strata and Permian seals causing the regional decrease in formation pressures.

Potential for ROZ's in California Oil Basins. Another area of recent tectonics is the San Joaquin Basin in California. Figure 35, *E. Coalinga Extension Oil Field, San Joaquin Valley, CA Showing Northward OWC Tilt of ~90 ft/mile*, shows one documented tilted OWC field in Fresno County with a south to north dip of 90 feet per mile. The ROZ was also not identified but should reside on the south end of the field. The waters of this field are also very fresh.

Potential for ROZ's in Canadian Oil Basins. The Norman Wells field of northwest Canada contains references to both a tilted OWC and an "undersaturated" TZ, as shown in Figure 36, *Hydrodynamic Tilt and Transition Zone at the Norman Wells Field, British Columbia*. This field is also proximal and southwest of the Franklin Mountains, an uplift with hydrodynamic flow and OWC tilt of 300 feet per mile to the southwest.

Potential for ROZ's in Other Oil Basins. An interesting example of apparent structural tilt causing a ROZ is in the Sadlerochit reservoir of the Prudhoe Bay Field in Alaska (Reference 17). The final significant structural movement in the area occurred during Tertiary time when the entire area underwent northeastward tilting that resulted in a significant redistribution of hydrocarbons in the Penn-Triassic reservoirs. Residual oil saturations in cores taken below the current OWC give evidence of the tilting and oil migration that occurred ostensibly due to the structural tilt. The southeastern area of the field has residual oil saturations that occur between the present OWC and the base of the formation, indicating an upward migration of the OWC. The zone of residual oil saturation below the OWC thins to the west (occurring only in the upper part of the water leg).

The last example presented herein is a withdrawal-induced OWC tilt at the Cairo field in Union County, Arkansas. The Cairo field was discovered eleven years after the Schuler field, located two miles to the southwest, was found and extensively produced. Drilling at the Cairo field determined that the oil and water withdrawals at the Schuler field were responsible for changed hydrodynamic conditions and the resulting southwest tilt of the OWC, as shown in Figure 37, *Migration of Oil in the Cairo Field, Arkansas*.

The most common feature of the fields identified with tilted OWC's and ROZ's is that they are located in basins near uplifts. The Permian Basin and Billings Nose areas represent both the lowest degrees of tilt and ROZ's most distant to the uplift (~150 miles). Another observation found without exception is that the hydrodynamic flow is away from the uplift (source of water) and the OWC tilts down and away from the uplift. Where noted, the thickest part of the ROZ wedge is toward the uplift. The other common feature of the identified fields is the presence of fresher waters in the formation

than the original connate water. Ostensibly, and supported in detail by the Billings Nose work, we would expect that the nearer the uplift, the fresher the water. All of these observations are consistent with either a hydrodynamic or basin tilt origin for ROZ's.

VII. Recommendations for Identifying and Quantifying Significant ROZ Resources

Based on work to-date, tectonically active basins may have the highest likelihood of holding significant ROZ resources. As such, research into understanding the geological and tectonic history of significant oil basins will aid in identifying additional areas with significant ROZ resources. Those with geologically recent uplifts will likely prove optimal. Fields located downdip of water release from surficial outcrops of the key formations should further optimize the search. As was the case in the Permian Basin, one ROZ discovery in a basin will establish that the basin mechanics may be favorable and will help identify other fields with thick ROZ's. Likewise, demonstration of the producibility of the ROZ, as in Denver and Seminole San Andres Units, will ultimately be essential. Clearly much work remains.

A. Proposed Priority Basins. An initial priority of basins with potential for ROZ resources is provided in Figure 38, *Prioritization of Future Effort to Identify and Quantify ROZ Resources*. This rating of basins and areas within basins, for the presence of ROZ is premature, but may help identify and motivate next steps.

As shown in the figure, the Permian Basin is rated by itself in Tier 1. Following close behind are ten basins that can be classified as post oil-emplacement, tectonically active areas. An additional seven basins are currently ranked in Tiers 3 and 4 (Please note that the list and the ratings are incomplete and very preliminary).

B. Approach for Future Work. The future search for ROZ resources should incorporate geological and hydrological considerations. Similar methodology was used for deducing the destination of the displaced and hydrodynamically trapped hydrocarbons in the earlier work by Berg (Reference 12). The geological history of the region also plays an important role, as shown in the cross-sections presented in Figures 20-22.

Quantifying the potentially recoverable ROZ resources is a priority that needs addressing. Even after adjusting for OOIP (Figure 13), applying “rules of thumb” for recovery of the resource will have limitations as reservoir response will vary for the range of reservoir properties that exist in the targeted oil fields. The Amerada Hess and Occidental teams have extensively used reservoir modeling to understand and estimate expected oil recovery in their projects. The utility of such methods is demonstrated in Figure 9 and Figures 14-16. Development of similar modeling approaches for other basin and reservoir situations is a necessity. Continued interaction with Amerada Hess and Occidental, to understand their experience with reservoir modeling and the characterization of their ROZ resources, would prove extremely useful.

Ultimately, the acquisition of geophysical logs for fields with identified ROZ's will be necessary. Formation resistivity (or conductivity) logs can be used where solid data exists on water salinities, enabling reliable calculations of oil saturations. Current operators of identified fields may possess “LAS format” digital logs that will expedite both data acquisition and subsequent analysis. Use of the resistivity log and a presentation technique such as the Hingle plot (Reference 15), as shown in Figure 39, *Use of the Hingle Plot Technique to Determine the Base of Oil-affected-Resistivity (BOSE)*, can assist with defining the thickness of the ROZ. Sample logs should also be acquired to confirm the presence and depth of oil shows. Public filings of unitization records at State regulatory agencies may contain key information on the extent of the tilt of the OWC, the base of the MPZ, and the top of the ROZ.

Regional hydrological modeling work should be included in future studies, as both relic and modern hydrological regimes could play important roles in determining ROZ locations and thicknesses.

Future work should also expand the concept and extent of the ROZ, from just beneath the oil column of a field's outline to its full lateral extent. Figure 40, *“Unconventional” Oil: ROZ Potential*, takes the first step of looking outside the boundary of a defined field area in the upgrade direction. Previously, such expanded areas were excluded from development because they would be uneconomic during primary recovery and waterflooding.

The more extensive lateral locations of the ROZ may not be limited to contiguous situations. For example, the hypothetical traps identified in Figure 26 likely have, as their source of oil, upgradient structural traps. In fact, Reference 12 alludes to several structural traps that were drilled in the area and found to possess excellent shows of oil in the drill cuttings but were classified as wet and non-commercial. Such “barren” traps might ultimately prove to be the source of the displaced oil. Examples of such traps are present in the Permian Basin and give additional confidence to the speculation that significant additional oil could be produced from the ROZ, given ample CO₂ supplies, a healthy oil price environment, appropriate incentives, and a focused technology research and development effort.

Existing fields have a clear economic advantage for pursuing the stranded oil in the ROZ, in that they possess an existing-well infrastructure for deepening wells and emplacing CO₂ facilities, as well as many of the needed fluid handling facilities. “Fields” or areas with no main pay interval obviously do not. While this may present a barrier to development, it may also provide opportunities for aggressive and innovated companies that wish to pursue new domestic oil recovery opportunities.

VIII. Conclusions

The existence of opportunities for significant future oil recovery from residual oil zones (ROZ's) is the thesis of this report. The Seminole/San Andres, Wasson/Denver and Wasson/Bennett Ranch units in West Texas are using CO₂-EOR to recover residual oil saturation in transition zone (TZ) intervals that are 75 to 300 feet thick. As such, these units and their larger oil fields hold vast previously undeveloped oil resources. Other attractive ROZ targets still remain undeveloped.

Overall, over 8 billion barrels of oil exist in the ROZ of nine significant Permian Basin oil fields: Wasson, Seminole, Adair, Cowden (No. & So.), Fuhrman-Mascho, Means, Reeves, Seminole East, and Yellowhouse. Furthermore, 3 billion barrels of this TZ/ROZ resource in-place may be recoverable. Overall, it is estimated that the Permian Basin may hold 15 billion barrels of resource in-place in the TZs/ROZ's of the San Andreas formation, of which 5 billion barrels may be recoverable.

The ROZ likely owes its origin to one of three factors: 1) regional tilting of the basin and resulting tilt of the OWC, 2) temporary seal breach and refilling of a reservoir, and 3) displacement of oil via temporal changes in the hydrodynamic (aquifer) flow fields beneath or within the oil reservoir. Sources 1 and 3 are controlled by post oil-accumulation tectonics and may give guidance for identifying ROZ's in other basins with analogous tectonic conditions.

Finally, the report sets forth a methodology for a wider characterization and more intensive search for ROZ resources. The proposed approach would use available hydrologic and tectonic data to identify priority basins and screen the most likely areas for ROZ's within these basins. The search should then quickly move to geophysical log acquisition, ROZ profile reconstruction, interactions with the operators of ROZ demonstration projects, and reservoir modeling. Quantifying the magnitude of the ROZ resource, its recoverability and its economic feasibility should be priority tasks,

considering the energy and security value of the resource as well as its role as a potential sink for CO₂ storage.

This work will likely have many auxiliary benefits. Research on the ROZ will further our understanding of the mechanics of oil emplacement, displacement and recovery. Unfortunately, our understanding of aquifer involvement in those processes is still embryonic. Hydrodynamics will also be one of the key issues for establishing “permanence” in CO₂ geological sequestration in any underground setting. A better understanding of the spatial distribution of aquifers would not only assist in locating ROZ oil resources but would also assist in certifying and expanding opportunities for storing CO₂.

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