Residual Oil Zone Exploration: Rethinking Commercial Reservoir Models and the Residual Oil Zone "Cookbook"

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INTRODUCTION

Fluid buoyancy principles have driven exploration strategies since the origins of the oil industry. It has led to subsurface structural concepts and updip pinchout stratigraphic models that pervade not only our prospect ideas but also our mapping concepts and software models. When one thinks about exploring for residual oil, whose presence originally required oil buoyancy but, due to post entrapment tectonics is no longer required, it is naturally difficult to abandon those concepts in favor of alternative methodologies emphasizing the presence and properties of immobile oil.

In order to develop the new strategies for locating and high grading residual oil opportunities, it is important to recognize that most basins in the world have had multiple stages of tectonic activity. If a tectonic stage, either local or regional, followed the original entrapment stage, residual oil zones will result. What have been called "mother nature's waterfloods" can be caused by several processes[1], local, regional or basinwide tilt (Type 1), leaky or breached seals (Type 2), or laterally flushed (Type 3). All can have repeated episodes that can create more than one pore volume of water sweep but Type 3 can create multiple volumetric sweep which, in one situation, was hydrologically modeled at 17-50 pore volumes[2] in 15 million years. Certainly there are other situations where PV sweep exceeds 100 like in some of the fresh water ROZs in the Rockies in the United States.

The exposure of hydrocarbons to water is a process that has been studied by many researchers. Solubility (diffusity) of the various components in oil is therefore known and can significantly impact the properties of residual oil, especially if the water is moving. Therein lies the importance of the above mentioned pore volume sweep. Finding the situations where pore volume sweep is limited may prove to be critical to finding oil that contains the necessary light ends to allow gas expansion drive or low minimum miscibility pressures (MMP). The results of the San Andres ROZ oil characterizations have found that the changes in oil properties are, in general, insufficient to preclude commercial exploitation by either EOR or depressuring production methods.

This report summarizes some of the findings of ten years of research on the subject of residual oil. The studies were prompted by the recognition that 200-400' thick sections of residual oil lie beneath several oilfields in West Texas. When it was determined that the residual oil saturation averaged similar values to the swept zones in their main payzone (MPZ) waterfloods, it led to the idea that CO_2 EOR could be successful in the ROZs, just like it was in their MPZ waterflooded zones. CO_2 EOR pilots were initiated in the Seminole San Andres Unit (SSAU) by Hess Corporation and in the Wasson field to the north in Yoakum County. The pilot project successes have led to full field deployment of the CO_2 floods throughout the two fields. Meanwhile, other fields in the Permian Basin area of West Texas and Southeastern New Mexico (Permian Basin region) investigated the zones beneath the oil/water contact and many operators have now extended their floods deeper into the ROZ.

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[1] Melzer, L.S. (2006), Stranded Oil in the Residual Zone, U.S. Department of Energy Report, February 2006, http://www.melzerconsulting.com/pdf/ROZ_Melzer_Document_51.pdf

[2] Trentham, R.C, Melzer L.S., Vance, D. (2012): Identifying and Developing Technology for Enabling Small Producers to Pursue the Residual Oil Zone (ROZ) Fairways of the Permian Basin, San Andres, Jun 2012, RPSEA Grant Final Report, http://www.rpsea.org/0812319/

The success of the ROZ EOR projects spurred the research reported herein. A new theory to replace the transition zone concept was necessary to explain the ubiquity and thickness of the ROZs. The U.S. Department of Energy sponsored the first work wherein three origins of ROZs were proposed[3,4] as well as an effort to quantify the ROZ resource beneath 50+ fields in the Permian Basin. The Research Partnership to Secure Energy for America sponsored two more projects where 1) the laterally swept origin of ROZs were modeled for a particular case in west Texas[5] and 2) an effort to investigate the science of ROZ formation and map the ROZ fairways of sweep was conducted[6].

What was envisioned only as a commercial exploitation strategy via EOR methods (particularly CO_2 EOR) made a huge turn in 2013. The development of horizontal drilling and well stimulation advances in shale reservoirs over the previous two decades led to the concept that if these methods worked in ultra low permeability shales, why couldn't they work in low permeability carbonates? In that spirit, Manzano, LLC drilled and hydrofractured a 4500' lateral in the San Andres formation in Lea County, New Mexico with the idea that the reservoir would be low permeability. Production of 2000+ barrels of water per day changed that view but, to their credit, they continued to produce until the reservoir pressures dropped approximately one-third and oil and gas began to be produced. The well was located within the mapped ROZ fairway in the midst of vertical (non-commercial) dry holes so analysts began to believe that the oil was, at least in part, residual oil liberated by gas expansion as the reservoir pressures fell. The exploration "play" expanded to large regions of the ROZ fairways. Because of the ROZ fairway mapping and the well locations where no mobile oil has been produced (ROZ 'greenfields'), the ability to identify the commercial nature of the ROZ play has become obvious and spread to other counties with ROZ fairways. Recognition of (i.e., ability to discriminate) this commercial recovery process is being incorporated into past and on-going plays such as the Mississippian Lime and Hunton dewatering plays in Oklahoma and Wichita Albany play in West Texas.

This report is intended to assist explorationists with finding and characterizing ROZs in their oil basins. Many of the conclusions herein have been drawn from the San Andres formation of the Permian Basin in the southwestern United States but with a watchful eye to the Wyoming and the Rockies[6, Chapter 9.2] (central U.S.). ROZs have also been found in the southern Williston Basin[6, Chapter 9.3] and will most certainly be present in many basins around the world. It is important to mention that carbonate reservoirs have been central to the ROZ research to date but clastic reservoirs can also contain ROZs; however, much more work needs to be done there.

Finally, most of the tools utilized in the search for ROZs are highlighted here and their particular application in finding and characterizing ROZs. Some of the more qualitative tools have to be relied upon since even the latest generation of wireline logs cannot help with characterizing the compositions of the oil which are so critical to determining the MMP and gas expansion properties of the oil.

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[3] Melzer, L.S. (2006), Stranded Oil in the Residual Zone, U.S. Department of Energy Report, February 2006, http://www.melzerconsulting.com/pdf/ROZ_Melzer_Document_51.pdf

[4] Melzer, L.S., Koperna, G.J., & Kuuskraa, V.A. (2006), "The Origin and Resource Potential of Residual Oil Zones," SPE paper 102964, w/, presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Tx Sept 24-27, 2006.

[5] Trentham, R.C., Melzer, L.S., Vance, D., et al (2012): Identifying and Developing Technology for Enabling Small Producers to Pursue the Residual Oil Zone (ROZ) Fairways of the Permian Basin, San Andres, Jun 2012, Research Partnership to Secure Energy for America Grant Final Report, http://www.rpsea.org/0812319/

[6] Trentham, R.C., Melzer, L.S., Kuuskraa, V.A., Petrusak, R, Vance, D. et al (2016), Identifying and Developing Technology for Enabling Small Producers to Pursue the Residual Oil Zone (ROZ) Fairways in the Permian Basin San Andres Formation, Research Partnership to Secure Energy for America Final Report (In Review).

IDENTIFYING KEY INDICATORS OF ROZs: THE ROZ"COOKBOOK" (*Authors: R.Trentham and L.S. Melzer)*

1.1 STEP-BY-STEP GUIDE

The following step-by-step guide is provided in an attempt to assist a company in an evaluation to determine:

1) whether a Residual Oil Zone (ROZ) might exist beneath their producing field,
2) where a ROZ might exist outside of the limits of a field, and then
3) determine what are the properties of the fluids and rocks within the ROZ that might be exploited with EOR or depressuring production methods.

STEP #1: Gather a Multi-discipline Team for the ROZ Study to Possess Talents that Include at a minimum:

- Reservoir Engineering
- Geoscientist
- Petrophysicist

Depending on the particular situation, a geophysicist may prove valuable.

STEP #2: Documenting Existing Data

- For a Field Specific Study
  - Review existing well files for mud logs and sample logs that penetrated below the "established" oil/water contact (hereinafter referred to as the ROZ[7]). Look also for:
    - Drill stem tests (DSTs), water chemistry analyses, any attempted completions within the ROZ interval.
    - Any changes in reservoir mineralogy and connate water chemistry noted between ROZ and main pay zone (MPZ).
    - Wireline logs from the same time frame and estimate the oil saturation (S_o) in the ROZ.
    - Find any surviving cores and/or core reports that might penetrate below the OWC. If found, attempt to estimate the S_o and the thickness of the ROZ. One should not be necessarily dissuaded by S_o values <20% due to the unavoidable loss of oil due to the coring process[8] when utilizing conventional coring methods.

[7] We choose to use this term in lieu of "transition zone." In no way should this be interpreted to suggest that capillary and surface tensional forces are not at work but is intended to incorporate the broader concept of a natural waterflood that could have been at work below an oil/water contact in a field. This ROZ definition becomes more apparent in the steps that follow where one is looking for residual oil without an overlying main payzone.

[8] Core taken at depth under pressure will naturally lose fluid pressure as the core is pulled to the surface and exposed to atmospheric pressures. Any entrained gas in t drive to expel most of the natural gas and a portion of the liquid. The

        - Considering the possible differences between the MPZ and ROZ water compositions, pore geometries, mineralogy, and oil saturations, attempt to establish a formation water resistivity value (Rw) for the ROZ.
        - Collect field cuttings and/or cleaned samples for wells drilled thru ROZ. These can be soaked with a solvent to discover the presence of residual oil even in old cuttings.
        - Collect all field reports including unitization studies if available and, in addition all "anecdotal" information from field, professional and service company personnel, active and retired as well, that pertains to the ROZ. A documented tilted oil/water contact is especially valuable.
    - Locate, review and reprocess (if necessary) any seismic data for the field
- For a Field Area Study
    - Incorporate any available field area seismic data into a field, regional or basin-wide structural maps and thru-going stratigraphic cross sections of main pay, ROZ, and formation below the ROZ horizon[9]. Revise if appropriate.
    - Expand field specific study area to look for evidence of "sweep" in the ROZ in regional data.
    - Put together a field area or regional groundwater (flushed fairway {Type 3 ROZ} or vertical sweep {Type 1 or 2 ROZ}) model[10] for the interval of interest.
    - Collect all "anecdotal" information from field, professional and service company personnel (including active and retired) that pertains to experiences below the MPZ (the ROZ).
- For a Basin-wide Study
    - Find and study the latest basement map for the entire Basin in which the oilfield resides.
    - Find and study the latest basin-wide structural maps on key formation marker tops.
    - From the literature and above information, attempt to reconstruct the basin-wide post depositional, post oil emplacement tectonic history.
    - Attempt to construct a regional paleo structural map for the oil emplacement time frame.
    - Attempt to reconstruct basin-wide facies maps for the formation(s)/interval(s) of interest. Of special interest are intervals with wide scale lateral continuity.
    - Estimate the potential for post emplacement sweep, and, from the basin-wide studies, what tectonic and structural changes have occurred from then to present that would influence paleo trap sweep and, for Type 3 ROZs, OWC tilt.
    - Reconstruct the lateral and vertical extent of several paleo entrapments using wells that drilled through the formation(s)/interval(s) of interest.
    - Refine facies model map for the Basin to field areas of special interest.

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degree of liquid loss is difficult to estimate but will be a function of entrained gas, viscosity of the oil as well as the porosity and permeability of the rock

[9] Note the fact that modern day structure may have no bearing on the presence of a ROZ since post entrapment tectonics can cause an ROZ to be in a low structural position

[10] Melzer, L.S. (2006), Stranded Oil in the Residual Zone, U.S. Department of Energy Report, February 2006, http://www.melzerconsulting.com/pdf/ROZ_Melzer_Document_51.pdf

- Tie the above model to the porosity and permeability data (knowing that there are facies/environment of deposition changes diagonally across specific fields).
- Attempt to find a relationship among the field specific fluid properties and rock porosity – permeability - facies that would suggest what intervals/sub-areas exist for optimizing higher ROZ S_o values.

STEP #3: Screen Out Unlikely or Poor ROZ Candidates and Identify Promising Candidates

Some formations or areas within a Basin and even some entire Basins will be poor candidates for ROZ presence. If the anecdotal data from well logs, DSTs, mudlogs etc. do not indicate possible ROZs, the field areas or even entire basins should be eliminated from the need of acquiring new data. Note, however, that it is an unusual basin that does not have tectonic events after hydrocarbon accumulation in the original (paleo) traps. The later stage tectonics create the ROZs.

Any evidence pointing to the presence of ROZs with significant in-situ oil saturations (i.e., greater than 25%) should be ranked and advanced to the stage of attempting to gather additional data.

STEP #4: Gathering New Data

After accomplishing the data review and mapping exercises, there will likely be sub-areas within the field area that have higher expected ROZ potential. Target it/them first with an eye on an initial "science well" for the best sub-area. If possible, target a location where some primary production might be possible at the top of the ROZ. Try and relegate land and operational factors to secondary status.

- Data to be Acquired <u>with</u> a Newly Drilled Well:
  - Mud Logs from reputable company with lithology, gas chromatography (GC) components up to C-5 or 8, H_2S and CO_2 sensors, drilling time, porosity, fluorescence, and cut. Require mudloggers to note the presence of native sulfur.
  - Whole (conventional) core (sidewall cores are often less representative) with routine core analysis (porosity, permeability, So and Sw) and detailed core descriptions
  - Full, modern suite of wireline logs to include DLL or DIL, sonic, compensated density/porosity, and pulsed neutron density/porosity and any other special formation particular logs such as PE, spectral gamma etc. Note that the porosity in the ROZ can be classified as secondary in nature hence lower computed porosity values from the sonic log.
  - Get a formation imaging (FMI) log over the same interval as the core.
  - Run drill stem tests (DSTs) or, at least, repeat formation tests (RFTs) to acquire oil/water/gas samples. Analyze water samples from different depths.
  - Conduct lab analyses of oil and gas samples to reconstruct in-situ oil compositional analysis
  - From formation temperature and compositional analysis, compare against MPZ fluids from nearby fields in the same formation (if possible), estimate ROZ oil saturations, gas/oil ratios (GORs) and minimum miscibility pressures (MMPs).
  - Cross-correlate the mud- and wireline logs with core results, depth correcting where necessary.

- With modern fast drilling technologies, high quality 10' samples are not possible. Consider using a solvent (e.g., the "Weatherford" technique) to leach oil from samples and use UV light to create a relative fluorescence scale.

- Data to be Acquired Without a Newly Drilled Well:

  - Select a promising area that possesses one or more deep wells drilled though the formation(s)/interval(s) of interest.
  - Obtain access to the well or wells to reestablish the nature of the interval of interest in the well (e.g., cased or open hole). Pulsed neutron logs are especially useful for So calculations and can be used even in cased holes.
  - Re-enter the well
  - Run the above described logs in the case of an open-hole interval
  - Acquire a pulse neutron log in the case of a cased interval of interest.
  - If a completion is attempted, collect and analyze water samples.

Once in possession of the new data set from new or reentered well(s), reevaluate the sub-area for desirable MPZ and/or ROZ targets and, as desirable targets are identified, identify new sub-area(s) and consider a second "science well" with duplicative data as identified above but substituting the FMI as a proxy for the conventional core data set.

STEP #5: Optional Vertical Well Completion

If primary production is promising, select multiple sets of perforations to

1) Acquire ROZ oil/water/gas samples from deep within the ROZ.
   a. Water samples – compare to old pre-water flood MPZ samples if available.
   b. Oil samples, if possible
   c. Gas samples, if possible
   d. Bottom Hole Shut in Pressures
2) Compare above water chemistry to MPZ formation water chemistry from nearby fields and also to modern water flood water chemistry to check for possible vertical cross flow or mixing
3) Evaluate whether to perforate the ROZ in a higher position to check for varying fluid properties with depth into the ROZ.
4) Proceed with the attempt to establish primary production on top of the ROZ and acquire and evaluate fluid properties as above.

1.2 TABLE OF EVIDENCE FOR A ROZ AND EXPLANATIONS

The following table (1.1) lists the various field activities during the drilling and completion of a well with the classic interpretation vs. the interpretation related to a ROZ occurrence and the explanation to that new interpretation.

TABLE 5.1 - Summary of "Classic" Observations of ROZ's and the ROZ-based Revised Interpretation of the Observations				
ACTIVITY	**EVIDENCE**	**CLASSIC INTERPRETATION**	**ROZ INTERPRETATION**	**ROZ EXPLAINATION**
Drilling	Oil on pits	Transition zone/MP remnant oil	Presence of ROZ highly likely	Oil wet reservoir. Oil is released during drilling. Often seen in Roz's
	Drilling Break	Aquifer / No Significance	Good Reservoir	Open marine environment. Good cycles and flow units.
Mud Logging	Cut in samples	Transition Zone / MP Remnant	Oil saturation present	Residual Oil Saturation is present
	Dull gold Fluorescence in samples	Transition Zone / MP Remnant	"Water washed" oil	Indicative of Mother Nature's Waterflood. Reduced Saturation of oil.
	Odor in samples	Transition Zone / MP Remnant	Oil saturation present	Indicative of Mother Nature's Waterflood. Reduced Saturation of oil.
	Gas show	Not expected. From Oil Zone above if present.	Oil saturation present	Indicative of Mother Nature's Waterflood. Reduced Saturation of oil.
	"Free" Sulfur crystals	Suggest at or below O/W contact	Mother Natures Waterflood	Result of activity of Sulfate Reducing Bacteria. Indicates Meteoric Derived Flushing.
	Sulfur and Anhydrite	No significance	Mother Natures Waterflood	Result of activity of Sulfate Reducing Bacteria. Indicates Meteoric Derived Flushing.
	Sulfur and Calcite	No significance	Mother Natures Waterflood	Result of activity of Sulfate Reducing Bacteria. Indicates Meteoric Derived Flushing.
DST	Sulfur or Black Sulfur water	Not unusual / No significance	To be Expected.	Result of activity of Sulfate Reducing Bacteria. Indicates Meteoric Derived Flushing.
	Salty Sulfur water	Not unusual / No significance	To be Expected	Result of activity of Sulfate Reducing Bacteria. Indicates Meteoric Derived Flushing.
	Lower Salinity than expected	Not unusual / No significance	Meteoric Derived Flushing.	Indicative of Mother Nature's Waterflood. Meteoric Derived Flushing.
	"Skim" of Oil	Not unusual / No significance	To be Expected. Never significant oil	Oil Wet reservoir. Small amounts of Oil is released during pressure drop.
	Good to Excellent Pressure	Not unusual / No significance	To be Expected	ROZ is not in pressure cmmunicationwith a Main Pay
Logging	Rw different than MP	Not unusual / No significance	ROZ water chemistry different than MP	Rw is different because the meteoric derived sweep is composed of lower salinity water
	So > 30% in calculations	Might be productive	ROZ. Residual to waterflood and MNW	Rw is different because the meteoric derived sweep is composed of lower salinity water
	Different M an N than MP needed	Not unusual / No significance	fabric destructive dolomitization in ROZ only	Rocks have undergone a second diagenetic event
	Excellent Porosity in dolomite	Not unusual / No significance	Open Marine + Sweep associated dolomitization	Thicker open marine cycles and Secondary dolomitization in ROZ during sweep
	"Looks *like a Winner*"	set casing	ROZ can have appearance of producable on completion	ROZ thicker cycles, secondary dolomitization, salinity differences make calculations difficu
Core Analysis	5 - 40% oil saturation	Zones with higher water saturation non-productive	Saturations expected following MNW	Expected So after Mdeteoric Derived Sweep
	Oil Wet Core	Consider log analysis	Sweep related fabric destructive dolomitization >> Oil wettin	Expected after Sweep related fabric destructive dolomitization
	Open marine facies	Not unusual / No significance	Good Quality reservoir, thick cycles and flow units	ROZ's tend to be found in more open marine settings
	SHR near base and/or top	Suspect oil/water contact(s)/water washing	Water Washing from Meteoric Derived Flushing	Multiple SHR Zone suggest Multiple O/W contact, both Paleo and recent
	Better Porosity and Perm than main pay	Not unusual / No significance	Good Quality reservoir, thick cycles and flow units	ROZ's tend to be found in more open marine settings
	Sulfur Crystals	Diagenesis - no interpretation	Free sulfur often found in ROZ	Converrsion by Sulfate reducing bacteria results in free sulfur
	Sulfur and Anhydrite	Diagenesis - no interpretation	Free sulfur often found in ROZ	Converrsion by Sulfate reducing bacteria results in free sulfur
	Sulfur and Calcite	Diagenesis - no interpretation	Free sulfur often found in ROZ	Converrsion by Sulfate reducing bacteria results in free sulfur
	Spotty Oil Stain	Consider Log Analysis	Intervals with low perm in ROZ	Intervals with low perm in ROZ can have remnat high saturations
	Leached molds	Not unusual / No significance	Leaching during MNW	Leaching during MNW
	Leached Fracture	Not unusual / No significance	Leaching during MNW	Leaching during MNW
	Fabric Destructive dolomite	Not unusual / No significance	Secondary dolomitization in ROZ during sweep	Secondary dolomitization in ROZ during sweep
	Limestone below oil stained interval	Not unusual / No significance	Zone is below Swept ROZ	Zone is below Swept ROZ
Completion	large volumes of fluid (sulfur water)	expect a decrease in water production over time	Large volumes of water cut on IP indicates an ROZ	Swept down to residual to waterflood, good porosity and perm in open marine
	Less than 5% oil	expect an increase in oil production over time	>85% water cut on IP indicateds an ROZ	Swept down to residual to waterflood
	Good Pressure	Not unusual / No significance	ROZ not drained, to be expected	Thinner cycles in MP don't reduce pressure in ROZ
	Lower Salinity than expected	Suspect water flow	Meteoric Derived water	Meteoric Derived water has lower salinity
	Different Scale than in Main Pay	Suspect water flow	Different water chemistry	MNW changes water chemistry significantly

1.3 ROZ PROPERTIES/EVIDENCE OF PRESENCE OF A ROZ

The following is an expanded explanation of the data presented in Table 1.1: A Summary of "Classic" Observations of ROZs and the ROZ based revised Interpretation of the Observations." Much of this data began as "anecdotal" information gleaned from conversations with a number of experienced Permian Basin geologists and engineers along with some personal experiences. These professionals, upon being introduced to the concept of ROZs, related their many experiences with ROZ characteristics that were not well understood to them at the time (going back to the 1950's), but which now can be clearly "fit" into the concept of ROZs. Each of the oil field personnel spoken to has had moments where poorly understood data led one to spend money needlessly; eventually to shrug their shoulders and walk away from a well that they felt "should have produced oil." Those wells were frustrating failures based on our understanding at the time. Most of those experiences were caused by the presence of residual oil and would be likely ROZ CO_2 flood candidates today.

1.3.1 Drilling

1.3.1.1 Oil on the Pits

Oil on the pits is something expected when drilling through a main pay or new field discovery, but it is almost counterintuitive when drilling thru a Residual Oil Zone (ROZ). However, since many ROZs are oil wet and contain, by definition, between 20-40% oil saturation, the process of drilling actually releases oil from the rock and a sheen of oil will often appear on the pits. An example of this is the Gulf #1 N. E. Elida Unit, Section 1, T4 S, R32 E in Roosevelt County. Oil was observed on the pits leading to an expectation that this would be a new field discovery. However, when cores were taken and drill stem tests (DSTs) run it was determined that there was insufficient cause to set pipe and attempt a well completion. This is a classic response for a "greenfield" ROZ. In this Gulf #1 N. E. Elida Unit, there was reported stain in samples between 3730-4030' depth. Cores were taken from 3506-3565' and recovered dolomite with no oil shows, core taken from 3706 – 3765' which had a slight show oil in fractures, core was taken from 3880-3920' and recovered limestone with "bleeding" heavy oil, core recovered from 3908-3921' had So = 30% in the bleeding oil interval, the core taken from 3954-4012' recovered limestone with no shows. A DST run from 3702-3765' recovered 126' of drilling mud, 819' of salty sulfur water. A DST run from 3876-3920' recovered 59' of drilling mud, 84' of slightly gas cut sulfur water. A DST run from 4060-4250' recovered 45' of drilling mud. The well was plugged and abandoned (P&A'd) without further testing of the San Andres.

1.3.1.2 Drilling Break

As ROZs are often in the subtidal to deeper, more open marine portions of the San Andres, the intervals tend to have thicker, more porous cycles, cycle sets, and flow units when compared to the thinner more heterogeneous, and less porous cycles and thinner flow units in the Main Payzones (MPZs). The MPZs also tend to have a higher proportion of tidal flat facies which drill slower. Therefore, the ROZs often drill considerably faster than the MPZs (if present) or the tidal flat capped non-pay above the greenfield ROZs.

1.3.2 Mudlogging

1.3.2.1 Oil Cut In Samples

As with oil on the pits discussion, ROZs contain, by definition, between 20-40% oil saturation so it would be logical to assume that there should be oil in samples seen during examination at the well site. The oil may not have the “flash” cut or “streaming” spread often seen in main pays, but ROZ will ALWAYS have some demonstrable cut in fresh samples. Unfortunately, with the modern drilling technology, describing 10’ samples has become virtually impossible. It is important, however, to make an effort to make as complete a description of the samples as possible.

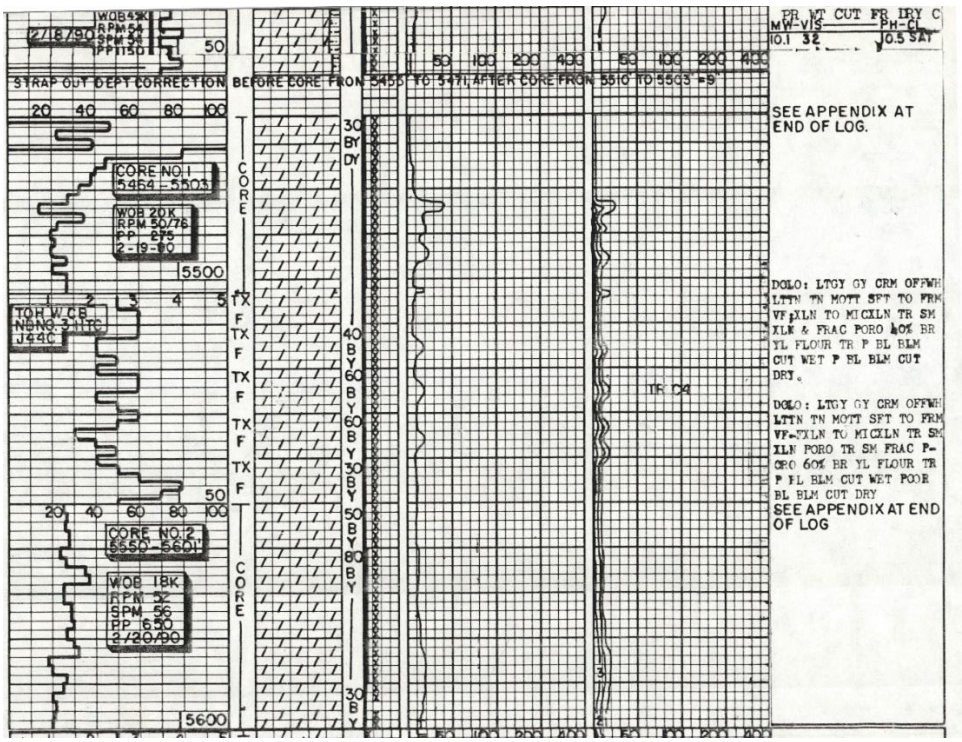

Figure 1.3. Anschutz #1 Keating Mudlog of interval identified as a greenfield ROZ (5500 – 5550) showing 30 – 60% bright gold fluorescence. The cored intervals above and below were identified as being greenfield ROZs.

As ROZs can vary from <100’ to >300’ thick, modern mudlogs may evaluate the ROZ in only 2 to 3 samples. Working with the mudlogger to understand the invaluable nature of ROZ sampling, and capturing all data for the ROZ interval is critical.

1.3.2.2 Dull Gold to Bright Yellow Fluorescence in Samples

The mudlog shown above, Figure 1.3, is from the Anschutz #1 Keating in Gaines County. The well was cored from 5454-5503’ and 5550-5601’ and the presence of residual oil (a greenfield ROZ) evident in the cored intervals. Between the cored ROZ intervals, the well was drilled and the type of odor, cut and fluorescence classically expected from a greenfield ROZ well was documented.

As with oil on the pits discussion, ROZs contain, by definition, between 20 -40% oil saturation so it would be logical to assume that there should be oil in samples seen during examination at the well. Oil may not be as "live" as in the MPZ, and may not exhibit the "gold" fluorescence throughout as seen where there is >75% oil saturation. Oil in ROZs has undergone "Mother Nature's Waterflood (MNW) and associated anaerobic bacteria action; the lighter aromatic hydrocarbons may be diminished or absent. This will result in the "Dull" as opposed to "bright" fluorescence. This is, however, still an indicator of the presence of an ROZ. Make sure the mudlogger records accurately the type and intensity of fluorescence.

1.3.2.3 Odor in Samples

Odor will likely be apparent in fresh drill cuttings, aka "roughneck" samples. As with discussions above, ROZs contain sufficient oil saturations so that it would be logical to assume that there should be an oil odor in samples seen during examination at the well. As discussed, the oil may not be as "live" as in the MPZ oils, and may not exhibit the sharp an odor. Since the oil in ROZ has undergone MNW and associated anaerobic (sulfate reducing) bacterial action, and there may be a sulfurous odor to the samples as there is most often a salty sulfur or black sulfur connate water associated with the presence of the water flooded ROZ. This is also an indicator of the presence of the ROZ. As a cautionary note, the sulfur odor may overwhelm the oil odor and be reported as such on the mudlogs. If drilling a new well, one should make sure the mudlogger records these observations.

1.3.2.4 Gas Shows

It might be assumed that because of the MNW, there would be little if any gas present in the ROZ and therefore in the roughneck samples. There is demonstrable proof from a large number of ROZs that there is gas in the ROZ oil especially in the upper portions. GOR's of 500 – 1000 can be expected in many upper ROZs. This is gas that remains in the oil (having never been depressured) or has migrated into the ROZ oil after the meteoric sweep had been diminished by the subsequent tectonics (in the Permian Basin it would be the Basin and Range faulting) that reduces the hydraulic head. The presence of only C1 gas (methane) shows is not generally representative of an ROZ. The presence of an observable C2-C5 composition in the gas is most often present on the Gas Chromatograph. In a new well, make the mudlogger aware that gas shows above C1 are to be expected in the ROZ.

1.3.2.5 "Free" Sulfur Crystals

Free sulfur crystals are typically not present in the MPZs; they are seen only in association with the ROZ. The crystals can range from doubly terminated crystals to botryoidal void filling masses. Because of the bio-geochemical reactions that take place in the ROZ during the meteoric derived sweep, free sulfur can be found in leached fossils, fractures, vugs and, occasionally, interparticle porosity. The Redox based biogenic reaction is**:**

$$CaSO_4 + HC \Longrightarrow CaCO_3 + H_2O + H_2S$$

Where "HC" is the general term for the flushing hydrocarbons.

The H_2S can be oxidized back to elemental sulfur (S^0) and is seen where the ROZ hydrodynamics are not present.

The sulfur crystals are typically found within the ROZ but can also be present in the upper water zone at or below the paleo oil/water contact(also called the base of oil saturation or BOSO) immediately below

the ROZ. Occasionally the free sulfur is seen in the very lowermost MPZ or in the tight cap above a greenfield ROZ. Some workers have reported using the presence of native sulfur in cuttings as an indication that they have reached the oil/water contact in major fields and, as a result, cease drilling any deeper.

1.3.2.6 Sulfur and Anhydrite

Sulfur crystals are typically seen associated with anhydrite in the ROZ. The sulfur and associated anhydrite crystals can range from terminated crystals to botryoidal and void filling masses, Figure 1.4. Because of the bio-geochemical reactions that take place in the ROZ during the meteoric derived sweep, sulfur and anhydrite can also be found in fractures and vugs. Sulfur and anhydrite associations are typical as void filling minerals. At depths less than 2500', the anhydrite can be in its hydrated form (gypsum).

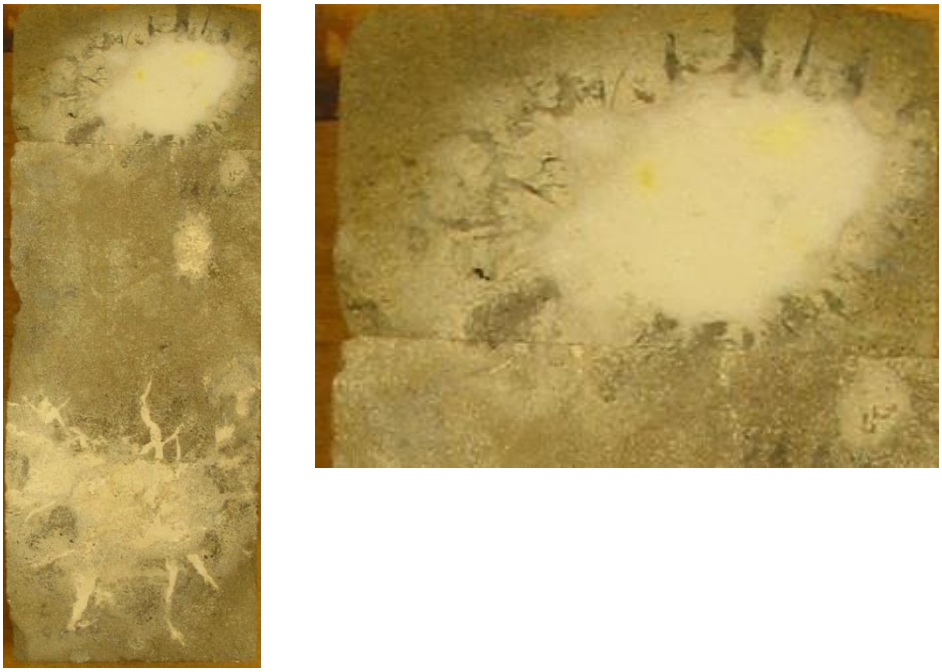

Figure 1.4. Sulfur and gypsum in hydrated anhydrite nodule in Burlington Resources #51 Reese, Upton County, TX. Note that the nodular anhydrite has been re-hydrated to gypsum in this example from a San Andres reservoir at +/-2350'.

1.3.2.7 Sulfur and Calcite

Sulfur crystals are typically seen associated with calcite in the ROZ. The sulfur and calcite crystals can range from terminated crystals to botryoidal and void filling masses, Figure 1.5. Because of the bio-geochemical reactions that take place in the ROZ during the meteoric derived sweep, sulfur and calcite can be found in fractures and vugs. Sulfur and calcite associations are typical as void filling minerals.

Figure 1.5. Sulfur and Calcite in leached void in Chevron H. S. A. #1548, Ward County, TX. Unlike sulfur associated with anhydrite, sulfur crystals associated with calcite often have well defined crystal faces.

1.3.3 Drill Stem Tests (DSTs)

1.3.3.1 Sulfur and Salty Sulfur Water

Sulfur water, black sulfur water, or salty sulfur water are typically recovered on DSTs in ROZs in both brownfield and greenfield reservoirs. As discussed above, the Gulf #1 N. E. Elida Unit #1, Section 1, T4 S, R32 E in Roosevelt County is such an example. Here there is a classic response from a greenfield ROZ and now easily recognized as diagnostic of the presence of a ROZ. In this Gulf #1 N. E. Elida Unit, a DST run from 3702-3765' recovered (rec) 126' of drilling mud, and 819' of **SALTY SULFUR WATER**. A DST run from 3876-3920' rec 59' of drilling mud, and 84' slight gas cut **SULFUR WATER**. A DST run from 4060-4250' rec 45' drilling mud with no water.

For the same reasons that one finds sulfur crystals or sulfur in association with calcite or anhydrite in the ROZ (see above), sulfur water is typical of the ROZ even when the ROZ is in a brownfield where the original connate water in the MPZ was "salt water." Be aware, however, that sometimes the sulfur components in the water may be ignored and are not recorded in the DST report since they were considered negative indicators of mobile oil presence.

1.3.3.2 Lower Than Expected Salinity

There have been a number of operators who have reported that the water in the ROZs has lower salinity than that reported in the MPZ prior to the institution of the waterflood. In addition, there is evidence

from at least two San Andres fields that the waters within the ROZ have decreasing salinities with depth in the ROZ. With the lateral sweep (Type 3 ROZ) origins, somewhat lower salinities are expected and are the result of the long term meteorically derived flushing in the ROZ. Unless the ROZ proximity is close to the water source and in a high permeability aquifer, the salinities will reflect mixed zone values and a strategy to find higher salinity ROZs is recommended. As the lateral sweep model suggests, the ROZ and MPZ originally had similar salinities before MNW and ROZ waters modified over geologic time. The different salinities lead to different Rw values and complexities in Sw calculations. It is important therefore, to analyze or, at least attempt to account for, the ROZ waters and determine the correct Rw profile for the ROZ. The aforementioned "bow" shape porosity profile would suggest that the maximum porosity would reflect the lowest water salinity values. Coincidentally, it suggests the maximum late stage diagenesis which can be reflected in prevalent intervals of sucrosic dolomite.

More discussion related to Rw will follow in Section 1.3.4.1.

1.3.3.3 "Skim" of Oil

In many DSTs, small quantities of oil will be produced. Because the ROZ oil saturations are at residual to waterflood values and these carbonate reservoirs retain only "wetted" oil, it would be expected that there might only be very small quantities of oil made on a DST. However, a better representation of the predictability of the interval would be obtained by using results from the sample chamber as a measure of the true potential to produce oil. The DST chamber sample normally represents the best example of oil, gas, and water production from the reservoir.

1.3.3.4 Good To Excellent Pressure

Two factors are important here. First, because the paleo trap and subsequent natural waterflood have always been at pressure, one would expect the ROZ oil to be virgin and like the oil in the MPZ. It is important to keep in mind and as discussed previously, two processes could alter the ROZ oil composition, i.e., diffusity into the water and microbial selective extraction. But, otherwise, one would expect the ROZ oil to retain the same composition as the oil in the MPZ.

The second factor is one to consider in brownfield situations. Because there are thinner cycles with more heterogeneity in permeability in the MPZ, and in the non-productive "tite" intervals often present above the ROZ in greenfields, one could expect low ratios of vertical to horizontal permeabilities (Kv/Kh) and minimal pressure reduction in the brownfield ROZ. The pressures expected for a greenfield ROZ would almost certainly represent the regional pressure of the reservoir provided there is/has been no production from or water disposal into the interval in the immediate vicinity. Noted exceptions exist but pressures recorded in DSTs of the brownfield ROZ in producing fields often have near virgin reservoir pressures.

In many producing fields that have had long production histories from the MPZ, but no withdrawal from the ROZ, the ROZ generally has essentially virgin reservoir pressures. Situations have been found, however, where there has been some drawdown of pressure, although this is probably confined to the proximal contact of portions of the ROZ where historic completions have treated into the ROZ interval(s). In regions with a long history of primary production without water flooding, some pressure reduction in proximal ROZ intervals can be expected. This can, of course, affect the gas in solution in the residual oil if the drawdown has been significant.

1.3.4 Logging

1.3.4.1 Water Resistivity (Rw) Different than Main Payzone

Traditionally, a method used for determining the Rw in a producing field, in a potential new field, or new pay discovery, was to use the produced water chemistry, typically from a DST, of the interval below the O/W contact. In the case of an underlying ROZ, this can be problematic. In that case, the necessary assumption is that the ROZ Rw is the same as the Rw in the connate water in the main payzone. Considering the water sweep, especially in Type 3 ROZs, the water chemistry in the ROZ will have changed as a result of the lateral, meteorically derived sweep. The fact that the meteorically derived sweep has had no impact on the water chemistry in the sweep isolated MPZ, the ROZ Rw will be different than in the MPZ. In those situations where the source of water is nearby or in situations with highly permeable reservoirs, the pore volume sweep is mature and the water may be brackish or even fresh as it is in some Wyoming fields.

A related and common historical assumption was to assume that an Rw for a MPZ could be "back-calculated" using the resistivities at a depth below the "Pay" (MPZ) where the workers assumed that the zone was 100% wet. Back-calculating the Rw for the Pay using this method to determine the Sw for the pay will likely be in error for Type 3 ROZs due to the differing water chemistry in the ROZ. In different words, the Rw derived from that ROZ will generate a misleading Sw for the MPZ as there is/was different salinities in the MPZ and the ROZ. There are additional factors too; the activity of the flushing and anaerobic processes along with the presence of the sulfur may also confound the use of a simple Archie's equation calculation.

1.3.4.2 Oil Saturations Varying Greatly from +/- 30%

One very large challenge for operators over the years has been obtaining a reasonable value for residual oil saturations. This is true when considering an EOR project, adjusting injectors for flood pattern modifications, and now for depressuring projects The growing set of data for water and oil saturations (Sw, So) derived from cores in the ROZ tend to be similar to the saturations found as residual oil saturations to waterflood in the well swept zones within waterfloods. However, a number of operators have reported that attempts to calculate Sw from logs in both greenfield and brownfield ROZs can result in variable Sw values that do not match the adjusted Sw and So measured from the core. One operator reported that three different petrophysicists calculated three different Sw values for the same well. There is a growing consensus that this is a function of the variable salinities, the presence of sulfur rich waters, native sulfur, and variable M and N values input into Archie's equation.

One operator, anecdotally, has reported variations in both saturations and water chemistry during the development of a San Andres CO_2 ROZ flood on the eastern side of the Central Basin Platform. To date, there is no widely accepted solution to this Archie's calculation problem and operators have resorted to core and even chemical tracer injection techniques[11] to gain confidence in oil saturations.

One other possible explanation is the presence of spotty higher oil saturation in the tighter portions of ROZs. Variable oil saturations have been seen in core where, instead of a uniform reduction of saturation occurring in the interval, there are dual porosity/permeability systems and the oil has not been uniformly swept from the interval. What has been also observed is that the baseline oil saturation seems remarkably consistent and varying between 30-40% if the formation waters are saline (not fresh

[11] For example, Chemical Tracers, Inc.

or brackish). These values have led to the proliferation of CO_2 EOR projects being extended deeper into the ROZ and two new greenfield ROZ EOR projects.

1.3.4.3 Different M and N Values than Main Payzone (MPZ)

As mentioned above, (Archie formula) calculations of Sw's from wireline logs for ROZs can lead to misleading values. Many factors are at work as discussed above so it is not entirely known at this time how to make correct adjustments. It is true that different analysts utilize different values for M (cementation factor {varies around 2}) and N (Saturation exponent (generally = 2}) than those values utilized in the MPZs.

1.3.4.4 Excellent Porosity in the Dolomitic ROZs

Within the San Andres formation of the Permian Basin, the ROZs are often in the subtidal "sea level high stand" sections and not in the supratidal (sabkha) or deeper clay rich, limey dolomites. These subtidal zones can be very thick They can also appear in very porous, thinner cycles, cycle sets and flow units. The MPZs, on the other hand, are generally thinner and more heterogeneous, are less porous cycles and thinner flow units than observed in the ROZs. The MPZs also tend to have more tidal flat (sabkha) facies and disseminated anhydrite which result in lower average porosities on logs, and permeabilities and porosities in core. The ROZs, in a fashion, were originally similar to the MPZs but have undergone the pervasive, late stage dolomitization that the MPZs never witnessed. To repeat, this ROZ process is a late stage, secondary dolomitization associated with the meteoric derived flushing that the MPZs have not experience due to their isolation from the sweep. The thicker, more open marine packages, coupled with the flushing related secondary porosity development, results in a consistently better quality reservoir in the ROZ relative to the MPZ. This is most often manifested in a classic "bow" shaped porosity within the ROZ section where the best porosity is likely where the late stage dolomization overprint is best developed.

1.3.4.5 "Looks Like a Winner"

There is a wealth of anecdotal reporting of drilling, mudlog and electric log data all pointing to mobile oil presence suggesting that a greenfield ROZ well is a "winner" and should be cased and successfully completed as a producer. As has been pointed out above, a combination of factors can lead to the erroneous conclusion that a greenfield ROZ will be a new field or new pool discovery. When taken in the context that both the MPZs and ROZs have residual oil and mixed or predominately oil wet characteristics, it is not surprising that these mistakes occur. Careful evaluation is needed to determine the potential produceability of a well that has been swept by Mother Nature's Waterflood using the parameters discussed above. A classic example of this type of mistake is the Anschutz #1 Keating well in Gaines County.

The Mudlog shown in Figure 1.6 is from the Anschutz #1 Keating in Gaines County. The well was cored from 5454-5503' and 5550-5601' and the presence of what we know today as a greenfield ROZ documented in the cored intervals. While drilling between the two cored ROZ intervals from 5500-5550', the samples contained 30-60% bright gold fluorescence, and good to excellent porosity. Sample shows on the mud log were apparent to a depth of 5750'. The Neutron Density and Resistivity logs were run and the water (oil) saturation calculations pointed to the presence of mobile oil and a decision made to case and complete the well. The well was perforated, acidized and tested over a three month period. The recovery was 8 barrels of oil and +/-3700 BW before the well was plugged. This only one of many similar expensive mistakes of attempting completions in the ROZ.

Now, 20 years later, the Tall Cotton ROZ CO_2 greenfield project was initiated just over 1 mile to the southeast of the Keating well and is now producing EOR oil after several months of CO_2 injection. Kinder Morgan recognized the potential of CO_2 flooding the ROZ knowing none of the 16 producing wells in the Tall Cotton project would have produced any meaningful primary oil.

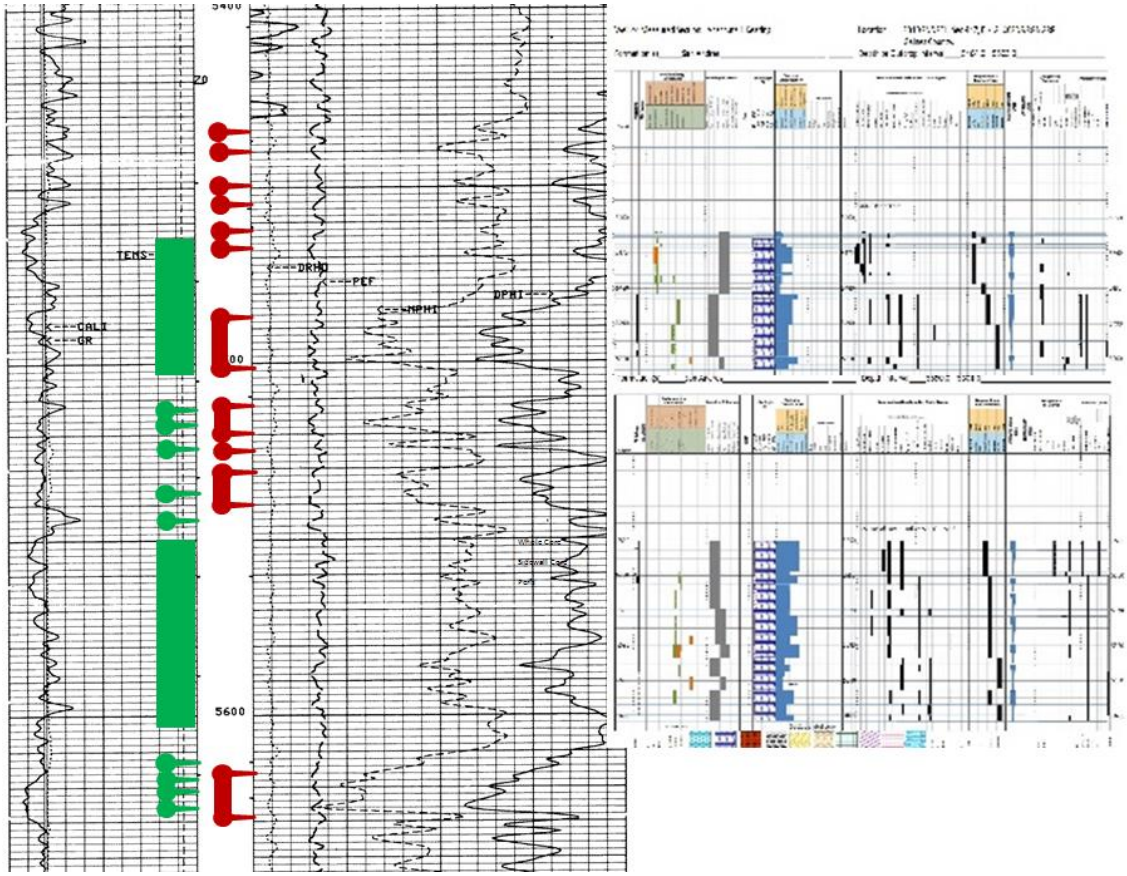

Figure 1.6. Well log and core description for the Anschutz #1 Keating, Gaines County, TX. The GREEN intervals are recovered core, both whole core (solid bar) and sidewall (spikes), and the perforated intervals are shown in RED. The perfs above the cored ROZ intervals tested the very shallow subtidal to intertidal "cap" on top of the deeper subtidal ROZ.

1.3.5 Core Analysis

1.3.5.1 Five To Forty Percent Oil Saturation

During the study of a CO_2 EOR project in the ROZ in the Goldsmith-Landreth San Andres Unit (GLSAU)[12], nine cores were recovered sampling both within the MPZ and the ROZ intervals. Standard core analyses were conducted and the So of the MPZ and ROZ compared. As the Goldsmith Field was an older field

[12] Trentham, R.C., Melzer, L.S., Kuuskraa, V.A., Koperna, G.J (2015), Using Next Generation" CO_2 EOR Technologies to Optimize the Residual Oil Zone CO2 Flood at the Goldsmith-Landreth Unit, Ector County, Texas, U.S. Dept of Energy Project Award 3 DE-FE0005889, Sept 2015 (in review).

with a 40+ year waterflood history, the MPZ saturations (So) had been reduced to "residual to waterflood." When compared to the So for the MPZ, the So for the ROZs were almost identical, ranging from 25% to 45%, Figure 1.7. As the ROZ had only been water flooded by natural processes, we can state that "Mother Nature's Waterflood" resulted in a sweep efficiency quite similar to that found in a highly successful, mature and modern waterflood.

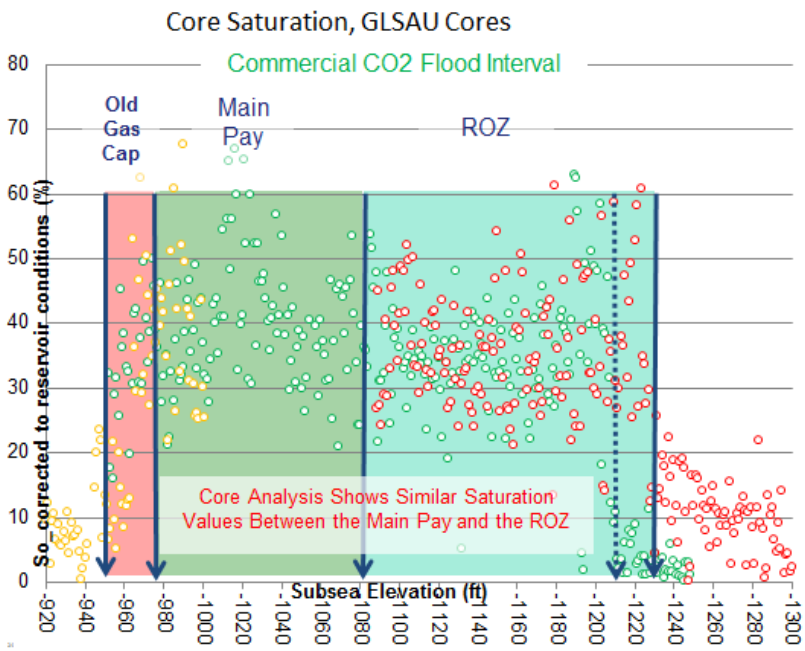

Figure 1.7. Plot of core oil saturation data for a number of wells in the Goldsmith-Landreth San Andres Unit (GLSAU) plotted vs. depth. Note the close relationship between the MPZ "residual to waterflood" (25 – 50%) saturations and the residual to Mother Nature's Waterflood saturations in the ROZ, also 25-50%.

1.3.5.2 Oil Wet Core

There has been an evolution over time concerning the wettability understandings in the large carbonate fields and reservoirs in the Permian Basin (PB). During the early decades of development in the PB, it was assumed that all reservoirs were water wet. Over time, average initial oil saturations were often shown to be 80-85% and it was revised to understand that most carbonate reservoirs are, at least, partially oil wet and, in more recent years, recognition that some cases are predominately oil wet. The new understandings of the anaerobic processes involved in the natural waterflooding and resulting overprint of dolomitization lead to the belief that the oil wetting characteristics in the ROZ are enhanced. Further, based upon the evaluation of ROZ cores, ROZs in the San Andres carbonates appear to be mostly oil wet. Considering the history of our reservoir education, it is not surprising that this remains highly controversial but, specifically, the evidence from the brownfield ROZ developments tends to support the San Andres ROZs being predominately oil wet. This also helps with the observations that the residual oil saturations values to the natural water flood can remain at a level comparable to the flushed zone oil saturations in man's waterfloods.

1.3.5.3 Subtidal Shallow Carbonate Shelf Facies

As discussed above, the ROZs tend to be developed in the subtidal portions of the San Andres where anhydrite and muddier (limey dolomite) facies are less common, these intervals can have thicker, more porous cycles, cycle sets and flow units when compared to the thinner more heterogeneous, and less porous cycles and thinner flow units in the Main Payzones. The MPZs also tend to have more tidal flat facies which result in lower average porosities on logs, and permeabilities and porosities in core. For further insight and discussion, see the Regional Geology section above.

1.3.5.4 Solid Hydrocarbon Residue (SHR) Near Base and Top of ROZ

Solid Hydrocarbon Residue (SHR), aka 'bitumen' or 'tar,' is often found at the traditional oil/water contact (OWC) in fields and at multiple points in fields where there are multiple oil/water contacts. These might not be expected to be found in the interval below the OWC contact if an ROZ were not present. Therefore, the SHR would be found at the paleo OWC contact in either a greenfield or a brownfield and at intervals within the paleo-oil column if multiple paleo OWC contacts were present.

1.3.5.5 Better Porosity and Permeability than MPZ

The ROZs, similar to the MPZs, have been dolomitized. The ROZs however, have undergone a late-stage, secondary dolomitization associated with the meteorically derived flushing that the MPZs have not undergone. The thicker, more open marine packages, coupled with the flushing related secondary porosity results in better quality reservoir in the ROZ (see Open Marine discussion above).

1.3.5.6 "Free" Sulfur Crystals

As discussed above, free sulfur crystals are typically seen only associated with the ROZ. The crystals can range from doubly terminated crystals to botryoidal to void filling masses. Because of the bio-geochemical reactions that take place in the ROZ during the meteoric derived sweep, free sulfur can be found in leached fossils, fractures, vugs and, occasionally, in interparticle porosity. As discussed above, the simplest form of the redox based biogenic reaction is:

$$CaSO_4 + HC \Longrightarrow CaCO_3 + H_2O + H_2S$$

Where HC represents the general term for hydrocarbons in the flushing oil

1.3.5.7 The H_2S is Occasionally Oxidized Back to Elemental Sulfur (S^0).

The sulfur crystals are typically found within the ROZ but also are present in the water zone/paleo oil/water contact immediately below the ROZ and in the lower MPZ and tight cap above a greenfield ROZ. Some workers have reported that they use the presence of native sulfur as an indication that they have reached the oil/water contact in major fields.

1.3.5.8 Sulfur and Anhydrite

Also as discussed previously, sulfur crystals are typically seen associated with anhydrite in the ROZ. The sulfur and anhydrite crystals can range from terminated crystals to botryoidal and void filling masses. Because of the bio-geochemical reactions that take place in the ROZ during the meteorically derived sweep, sulfur and anhydrite can be found in fractures and vugs. Sulfur and anhydrite associations are typical of void filling minerals.

1.3.5.9 Sulfur and Calcite

In a similar fashion as above, sulfur crystals are also seen associated with calcite in the ROZ. The sulfur and calcite crystals can range from terminated crystals to botryoidal and void filling masses. Because of the bio-geochemical reactions that take place in the ROZ during the meteorically derived sweep, sulfur and calcite can be found in fractures and vugs. The sulfur and calcite associations are also typical of void filling minerals.

1.3.5.10 Spotty Oil Stain

The presence of spotty high oil saturation in the tighter portions of ROZs has been occasionally noted in core, Figure 1.8. These spotty high oil saturations have been seen in core where, instead of a uniform reduction of saturation occurring in the interval, there are dual porosity/permeability systems (large burrows for example) and the oil has not uniformly invaded the reservoir (paleo trap).

Figure 1.8. Spotty oil stain in tighter portion of burrowed open marine wackestone, Chevron H. S. A. #1548, Ward County, TX. Near base of ROZ.

This could lead to erroneous values of interpreted oil saturation, especially if plug analyses are performed and the plug is recovered from the higher oil saturated interval. The higher oil stain also could be found in the porosity/permeability fraction where there is lower permeability and the reservoir was therefore isolated from the meteorically derived sweep. The higher permeability portions would be swept to residual oil saturations to waterflood.

1.3.5.11 Leached Moldic Porosity

Below the ROZ, coincident with the transition from dolomite above to limestone below, the open marine fossils such as fusulinids will be complete, with preserved internal structures in the limestone.

However, in the pervasively dolomitized ROZ, the fossil grains will be leached partially or completely. In some cases it is apparent that the grains were leached – then filled partially or entirely with anhydrite- then the fusulinid molds partially or completely leached again. There is often a "dolo-trash" of small crystals found at the bottom of the leached fusulinids indicating that the molds have had multiple periods of filling and leaching. This is interpreted to be related to the meteorically derived flushing.

1.3.5.12 Leached Fractures

There are examples of leached fractures in the ROZ where there is no crystal growth or oil stain/SHR on the fracture faces, Figure 1.9. This suggests that the fractures have been leached after Mother Nature's Waterflood. The conclusion is that they are related to the continuing meteorically derived flow that maintained the tilted oil/water contacts in the field discovery era oil column.

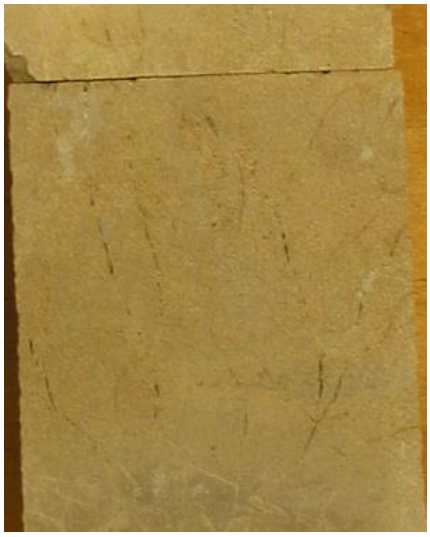

Figure 1.9. Leached fractures in core. The fractures are post oil emplacement as the faces of the fractures are "clean" with no oil stain.

1.3.5.13 Fabric Destructive Dolomitization

The transition between Fabric Destructive Dolomite in the ROZ and the Fabric Selective Dolomite in the partially dolomitized "limestone" below the ROZ has been shown, at least in one case, to occur within one foot distance in the vertical core, Figure 1.10. In the GLSAU in the Goldsmith field, the interval below the transition matrix is a mix of the original lime mud, and euhedral dolomite grains. Above the transition, the dolomite is almost all fabric destructive, with mostly subhedral to anhedral crystals with only a few relic euhedral crystals, and little, if any, calcite. This is good evidence that the fabric destructive dolomitization is associated with the meteorically derived flushing event, and not associated with the early dolomitization event that resulted in the deposition of the euhedral crystals seen below.

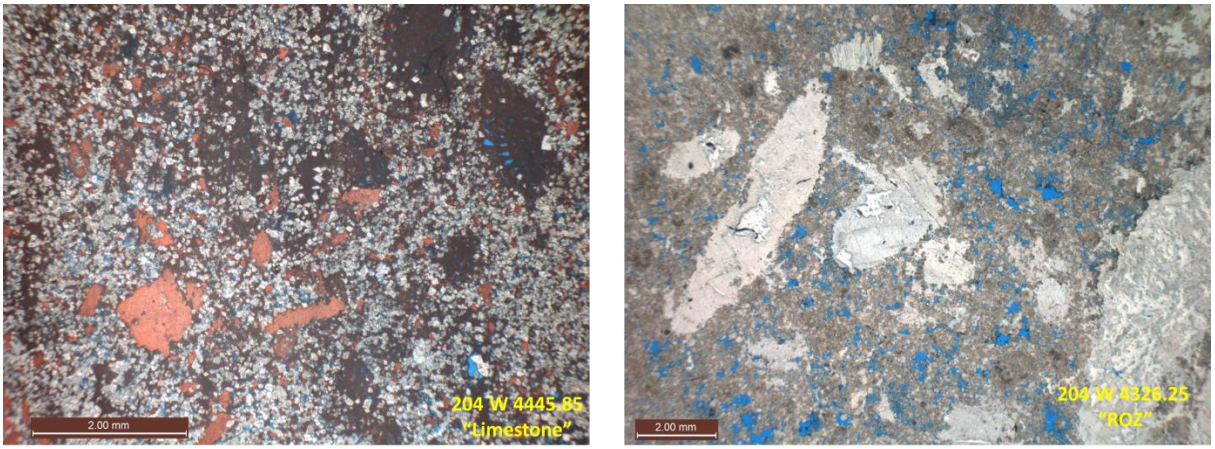

Figure 1.10. Comparison of (A) Limestone below ROZ with small euhedral dolomite crystals (white crystals) fusulinids with preserved internal structure, and patchy calcite (pink) cement, #204 W GLSAU, depth 4445.85, with (B) subhedral to anhedral dolomite with fusulinids replaced with anhydrite from ROZ, depth 4326.25.

It should be mentioned here again that it is this reservoir characteristic which leads to the subdued nature of the "bow" shape in the sonic logs which has been historically interpreted at evidence of secondary porosity. The authors would prefer to relate the effect to the higher sonic velocities of the more pervasive dolomite although recrystallization is clearly involved.

1.3.5.14 Dense Limestone Below the Base of the ROZ

The "limestone" (usually a limey dolomite) below the basal ROZ transition contains complete calcitic or aragonitic fossils, often fusulinids with complex internal structures, and other fossil grains. The low permeability matrix (<0.1 millidarcies) is a mix of the original lime mud, and euhedral dolomite grains. These small dolomite crystals are most often doubly terminated and appear to have been non-displacive grains. These grains are believed to be associated with the early dolomitization event of the shallow shelf but were deposited in the deeper water section of the formation.

This limestone below the transition is typically recorded on the porosity logs as only partial dolomite (some separation is often seen on the neutron-density log curves but not the amount of separation seen when the rock is 100% dolomite). The PE curve also records a value that falls between the 3.1 (barnes/electron) of dolomite and 5.1 of limestone in contrast to the 3.1 values above.

1.3.6 Completion

1.3.6.1 Large Volumes of Fluid (Sulfur Water)

ROZ wells are capable of producing large volumes of water during DSTs or upon completion. Examples of this are some of the Tubb Formation Carbonate wells in the North Ward Estes (west side CBP) area where large volumes of water were reported on initial production potentials (IPP's), Table 2. Although sulfur water or salty sulfur water are not reported as such on completion reports, many of the drill stem tests (DSTs) of the interval reported salty sulfur water or simply calling it sulfur water.

H. S. A.	1561	IPP 10 BO, 126 MCF, 4591 BW
H. S. A.	1564	IPP 9 BO, 10 MCF, 3133 BW
H. S. A.	876	IPP 13 BO, 88 MCF, 2185 BW
H. S. A.	1164	IPP 25 BO, 24 MCF, 4165 BW

Table 1.2. IP's for selected Tubb Carbonate completions, North Ward Estes area.

For example, the Gulf #319 G.W. O'Brien DST of the Tubb interval (5850-5911') recovered 210' of gas cut mud (GCM) & 360' salty sulfur water. The large volumes of fluid being produced are indicative of the reservoir permeability enhancements associated with Mother Nature's Waterflooding.

1.3.6.2 Less Than 5% Oil Cut During Completions

Some wells can be identified to have been completed in intervals that bridge through the MPZ and ROZ. The upper portion of the ROZ has been transitionally swept and with increasing sweep with greater depth (the upper "bow"). These completions will reflect higher oil saturations than residual to waterflood and will often produce some oil upon completion. However, the oil cut will typically be low since the zones yielding oil are the higher elevation and lower permeability (tite) zones. There are a number of examples with oil cuts in the 5 to 25% range in the upper ROZs (commonly referred to as the upper Transition Zone (TZ) or the upper portion of the "bow" shaped porosity curve. Depending on the depth of the perforations, these wells also typically make large total fluid volumes, produce mobile water (and oil wet intervals) and will, over time, see continued increases in water cut until the well is abandoned. The exception to this are wells where the pressures are being significantly reduced and there is gas and some oil breakout and a corresponding increase in oil production. Vertical wells often do not see this significant reduction in reservoir pressure while horizontals, with their excellent drainage efficiency, can be very effective in causing the large water production and needed pressure reductions. A 1/3rd reduction in reservoir pressure is needed in the typical horizontal San Andres well to begin any oil production.

1.3.6.3 Virgin Reservoir Pressures in the ROZ

Because there has been no extra stage of dolomitization in the MPZs (no lateral sweep) and they most often possess thinner cycles with more lateral and vertical heterogeneity in permeability, they are very different reservoirs than the underlying ROZs. The brownfield ROZs are also generally isolated from the pressure variations that have occurred in the MPZ production phases. And, of course, the pressure determined for a greenfield ROZ would be expected to represent the regional pressure of the reservoir unless, perhaps only possibly affected by nearby disposal wells.

In several cases, experience has shown that the pressures recorded in DSTs of the brownfield ROZs (associated with overlying MPZs) are very near the expected reservoir pressures. However, this can be more problematic if the ratio of vertical to horizontal permeabilities (Kv/Kh) of the reservoir system and MPZ/ROZ transition interval is near unity. In many of the examined producing fields that have had long production histories from the MPZ and, especially those with implemented waterfloods, the ROZs have essentially virgin reservoir pressures. A few cases have shown that there is some effect from drawdown of pressure or injection from above but is generally confined to the uppermost portion of the ROZ.

1.3.6.4 Lower Salinities than MPZ Connate Waters

San Andres formation water salinities can vary from the Central Basin Platform (CBP) to the Northwest Shelf (NWS), and from area to area on the CBP and NWS. However, there is a growing body of evidence that salinities can be considerably different from the MPZ to the ROZ in a brownfield, and even vary

vertically within a single greenfield or brownfield. As discussed in the Rw section above, and when the water chemistries in the ROZ are affected as a result of the lateral and meteorically derived sweep, one would expect that the sweep will have had no impact on the isolated MPZ water chemistries. The salinities in an ROZ will therefore be different than that of the MPZ and vary within the ROZ by being less saline associated with the higher porosities.

1.3.6.5 Different Scale Deposits than in the MPZ

As discussed, San Andres water chemistries in the MPZ and the ROZ are often considerably different. They can even vary vertically within the ROZ. As the water chemistries vary, the interactions of the waters when commingling the zones can lead to scaling issues. Because of the liberation of sulfur by the microbes, the ROZ water are likely to be saturated with sulfates (SO_4) while MPZ waters are not. It stands to reason then that the scaling tendencies and treatments for inhibition of scale in the zones will differ as well. In many brownfield EOR projects, the CO_2 injection wells will be separate for the MPZ and ROZ. The producing wells are usually comingled. The commingled production naturally mixes waters and can cause scaling in the wells. The sulfate scaling tendencies are exacerbated. Careful attention must be paid to the scale treatment program as there is evidence from a number of CO_2 flooded fields where inattention to scale issues severely restricted production. Only when an ROZ-specific scale program was introduced did the wells reach optimum production. Water alternating gas (WAG) injection waters utilized in the MPZ, have had, in most cases, decades to equilibrate with the connate waters in the MPZ. However, as the waters produced from, and injected into the ROZ will be different than both the connate waters and the flood waters in the MPZ, scale treatments in the ROZ will need to be carefully crafted for a totally different set of produced waters.

1.4 COMMERCIAL BASELINE COMMENTS RELATED TO ROZ EXPLOITATION

The commercial exploitation of naturally formed ROZs has been underway since the late 1990s. Several major oil companies recognized that extraordinary thicknesses of residual oil were beneath their oilfields and began the characterization of the intervals. In particular, Hess Corporation at the Seminole San Andres Unit in Gaines County of West Texas recognized 300’ of oil shows within a nearly pure interval of dolomite beneath their on-going CO_2 flood.

What has opened the door to the production of oil from the ROZ has been the recognition that the San Andres ROZ oil is, in most ways, analogous to the oil in the MPZs and thereby exploitable by the same EOR methods. In addition, the residual oil saturations to waterflooding (Sorw) values are also comparable. CO_2 EOR projects, proven successful in the MPZs after man’s waterfloods, could therefore be extended below the oil/water contact into the ROZ. And, given the success of those vertical extensions, an effort to explore and characterize the ROZs around the Basin and in other Basins became a priority.

It was soon recognized that a new model was needed for the origins beyond the widely recognized transition zone (TZ) model. The TZ model fell short of a plausible theory for several reasons. It could not explain the 300’ and sometimes 400’ of residual oil present below MPZs. It again fell short explaining the greenfield ROZs where there was no overlying mobile oil zone. Thirdly. It could not explain the tilted

oil/water contacts beneath the major San Andres oilfields[13]. Once a geological cross section could envision the sweep[14], the ROZ studies naturally morphed into proving the viability of the lateral sweep model and mapping of the sweep fairways.

Once the greenfield fairways were mapped and ROZs characterized, it became possible to recognize that it was indeed immobile oil that was being produced by the new horizontal wells. It was clear that, in order to produce the oil, the reservoir pressures had to decline in order for the solution gas to expand and liberate oil. What was surprising to most analysts was the commercial nature of those wells. A one-mile long lateral could provide estimated ultimate recoveries of 250,000 barrels (bbls) and be commercial at $40/bbl oil and this, from a zone that would produce essentially no oil under primary production.

With the new realizations of oil produced using the horizontal well depressuring production method, comes the knowledge that the industry has been producing residual oil in mixed or predominately oil wet reservoirs for a long time. In fact, compositional models with their relative oil/water and gas permeability algorithms should have alerted the industry to this fact. Perhaps what was missing was the hesitancy of industry to accept mixed- and predominately oil wet reservoirs. Or, stated another way, the industry was awaiting a diagenetic signal that our reservoirs could be oil wet. The microbial activity described herein is such a signal and the delayed recognition of that key biogeochemical process is due to the fact that those processes are not active in mobile oil zones where they are negligible (inhibited).

We close this chapter by restating the importance of the advances in the drilling, completion and EOR technologies that have overwhelmed the U.S. oil industry in the past two decades. But it has also taken the combination of advances in drilling, completion, EOR and reservoir characterization to make it happen. Those innovations have again rewritten the ground rules for the oil and gas industry.

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[13] 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.

[14] Lindsay, R.F. (2001), "Meteoric Recharge, Displacement of Oil Columns and Development of Residual Oil Intervals in the Permian Basin," West Texas Geological Society Fall Symposium, Pub 01-110, Oct 2001, p. 189.