**The Thesis Committee for Logan Mitchell West**
**Certifies that this is the approved version of the following thesis:**

# Regional Analysis of Residual Oil Zone Potential in the Permian Basin

**APPROVED BY**
**SUPERVISING COMMITTEE:**

**Supervisor:**

Scott W. Tinker

Susan D. Hovorka

Charles Kerans

# Regional Analysis of Residual Oil Zone Potential in the Permian Basin

by

**Logan Mitchell West, B.A.**

**Thesis**

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# Dedication

I dedicate this work to my parents for their continued support even in my struggles and reluctance to fully articulate what I do and why I do so. Thank you for your unconditional love and faith in me. I dedicate this work to my brother, Cane, for your taking an interest in my passion and living yours to the fullest in a way I aspire to. I would also like to dedicate this to my loving and, shall we say, more critically supportive girlfriend Joyce.

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# Abstract

## Regional Analysis of Residual Oil Zone Potential in the Permian Basin

Logan Mitchell West, M. S. Geo. Sci.
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Supervisor: Scott W. Tinker

This study provides independent analysis of Residual Oil Zones (ROZs) in the Permian Basin from a regional perspective, focusing on the formation mechanism and present ROZ locations. Results demonstrate widespread potential for ROZs, defined here as thick volumes of reservoir rock containing near-residual saturations of predominantly immobile oil formed by natural imbibition and displacement of oil by dynamic buoyant or hydrodynamic forces.

Previous work suggests hydrodynamic forces generated by regional tectonic uplift drove widespread oil remobilization and ROZ creation. To test the hypothesis, uplift and tilting are quantified and the resulting maximum regional potentiometric gradient used as a physical constraint to compute and compare predicted ROZ thicknesses from hydrodynamics for several ROZ-bearing San Andres fields with known ROZ thicknesses. Late-Albian Edwards Group geologic contacts, which are interpreted to have been deposited near sea level prior to uplift, are used as a regional datum. Approximate elevations determined for the present datum show ~1800 m of differential uplift since Edwards deposition, with an average regional slope of ~0.128˚. This post-Edwards tilting increased the pre-existing regional structural gradient of the San Andres Formation to ~0.289˚. Predicted ROZ thickness resulting from hydrodynamic forces, which are calculated using the post-Edwards regional structural gradient, is consistent with measured ROZ thickness at several fields. When compared with countervailing buoyancy forces, hydrodynamics is calculated to be the more dominant driving force of oil movement for reservoirs with structural dips less than 1.5˚, which is the common dip for San Andres Formation platform deposits where ROZs have been identified.

To predict the location of ROZs, ROZ-related oil field properties were identified and analyzed for over 2,800 Permian Basin reservoirs. A strong basin-wide correlation between API and crude sulfur content is consistent with the expected outcome of oil degradation driven by oil-water interaction, and supports the use of API and sulfur content as proxies for ROZ potential in the Permian Basin. Spatial analysis of sulfur data shows that the highest probability for ROZ existence exists in Leonardian through Guadalupian-age reservoirs, distributed primarily in shelf and platform areas of Permian structures. Combined, these results support the widespread potential for ROZs across the Permian Basin generated primarily by regional scale tilting and resultant hydrodynamic forces.

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# Introduction

Residual Oil Zones (ROZs) are a topic of growing interest as a potential resource for commercial resource extraction, especially in the Permian Basin (Rassenfoss, 2014). The Permian Basin, located in west Texas and southeastern New Mexico, is one of North America's most prolific oil and gas-producing regions. ROZs are also of interest for the purposes of Carbon Dioxide ($CO_2$) Capture Utilization and Storage (CCUS), as fields actively producing from the ROZ have all employed $CO_2$-Enhanced Oil Recovery ($CO_2$-EOR) (Melzer et al., 2006). Fueling the interest in ROZs is evidence pointing to the potentially extensive presence of ROZs across the Permian Basin (Lindsay, 1998, 2001; Brown, 2001; Koperna et al., 2006; Trentham, 2012). While initial findings suggest that ROZs may be a significant resource, fundamental questions regarding ROZ formation, location, and economic potential are yet to be fully answered.

The study addresses two broad questions: how did ROZs form in the Permian Basin and where might ROZs be located. This work assesses the potential regional extent of ROZs and advances basic understanding of ROZ formation by further examining the hypothesis that ROZs are widespread across the Permian Basin (Koperna et al., 2006; Trentham, 2013) resulting from regional tilting and hydrodynamic processes (Lindsay, 1998, 2001; Brown, 2001; Melzer et al., 2006).

The first section of this thesis consists of a fundamental examination to clearly define a ROZ and the different processes by which ROZs may form. A firm understanding of fundamentals allows for the prediction of ROZ distribution and extent. A brief overview of the Permian Basin and prior studies introduces ROZs in the context of the Permian Basin and looks at past literature through the new perspective of ROZs. These studies provide the basis for the present theory of ROZ formation by hydrodynamic forces generated by regional tectonic uplift.

This work addresses the hypothesis that ROZs have formed by tectonically induced hydrodynamics by quantifying the extent of regional uplift and tilting across the

Permian Basin since the mid-Cretaceous and seeks to determine whether the present theory is physically consistent with observed ROZs. Previous analyses are largely qualitative in nature or consider only present day hydrodynamics (Lindsay 1998, 2001; Brown, 2001; Melzer et al., 2006). Findings regarding the extent of uplift and tilting will allow for better identification of the driver of ROZ formation.

Another aim of this study is to identify the location of present ROZs. Considering a diverse range of potential indicators that should theoretically result from ROZ-forming processes, this work analyzes publically available geological and geochemical attributes of thousands of reservoirs across the Permian Basin to determine what parameters linked to ROZ formation are the most promising indicators of ROZ potential in the Permian Basin and where in the region these indicators are located in the subsurface. For both broad questions covered in this work, the analysis rests on a fundamental understanding of ROZs and looks at the question from a regional level.

Focusing on fundamentals at a regional scale serves two primary purposes. First, the existing hypothesis of basin-wide hydrodynamic displacement rests on the assumption of a regional mechanism for ROZ genesis, one that might not always be evident when approached field-by-field. Secondly, the regional viewpoint offers a unique perspective to ROZs in the Permian Basin. A detailed field-by-field bottom-up assessment of regional ROZ potential requires access and analysis of often-proprietary data for thousands of individual reservoirs each with site-specific geologic complexities that is beyond the scope of this project. The top-down regional approach of this research is feasible using publically available data and is beyond the typical business-scope of individual operators. Thus, this work provides unique regional context for future field-scale studies. Finally, from the perspective of CCUS, a regional assessment is more germane than a limited set of individual field studies in assessing ROZ potential as a meaningful target for large-scale deployment and market for $CO_2$.

The aim of this study is to complement the existing efforts of operators and other researchers by providing quantitative, physical constraints on potential ROZ-forming processes and identifying where ROZs are most likely located, not only for the commonly studied San Andres Formation but the full Phanerozoic stratigraphic section of the Permian Basin. This work is the first to assess ROZ potential across several stratigraphic units and also provides the first regionally extensive quantification of uplift and tilting of Permian Basin strata since the mid-Cretaceous. The hope is that this work will provide additional basic understanding of ROZ formation in the Permian Basin and offer additional background from which detailed field-scale studies can proceed.

At the same time, there are limitations to this top-down regional approach. This work assesses the potential and not necessarily the verified presence of ROZs at any given field or reservoir. Similarly, this study is not designed as an exercise in resource estimation or commercial viability of ROZ exploitation. Such studies will require more reservoir scale-work coupled with these findings and the previous and ongoing work of others to more accurately quantify the potential of ROZs volumetrically. Rather, this work offers a more extensive qualitative determination of how widespread the potential for ROZs in the Permian Basin may be.

## Defining Residual Oil Zone

In the process of defining and describing ROZs, several terms possess variable meanings depending on the author and context. For instance, residual oil saturation ($S_{or}$) and oil-water contact (OWC) refer in the strictest engineering sense to theoretical endpoints. In theory, the $S_{or}$ is the irreducible oil saturation remaining after an infinite amount of flushing by water (Ramamoorthy, 2012). Similarly, the OWC is the capillary pressure level in a reservoir at which oil achieves positive relative permeability and becomes mobile (Brown, 1992). In application, determination of such endpoint values and locations can be difficult and spatially variable. Therefore, terms in this paper are more general and have less strict definitions.

The oil saturation ($S_o$) in a ROZ is locally variable and may be mobile in pockets due to multiple possible factors (Honarpour et al., 2010). Rather than referring to the oil saturation in a ROZ as the $S_{or}$, the oil saturation present at a given time independent of process (Ramamoorthy, 2012), is preferred. This is called the remaining oil saturation (ROS). Similarly, knowing the exact depth of the relative mobility of water is not realistic. Instead, the producing oil-water contact (POWC) refers to the depth at which oil is first produced (Jennings, 1987). Therefore, unless otherwise noted, the terms in this paper are used in an applied context and do not strictly adhere to theoretical principles.

Previous studies have offered a range of definitions of a ROZ (Lucia, 2000; Koperna et al., 2006; Melzer, 2006; Honarpour et al., 2010; Pathak et al, 2012; Trentham, 2013). While these definitions are generally similar, the tendency is towards empirical as well as process- and site-specific definitions. Without a clear and fundamental definition, ROZs may be confused with other occurrences of oil sharing similar traits with ROZs but generated by different processes. A process definition is important for identification and prediction of ROZs. A residual oil zone is defined in this work as ***a volume of rock of significant scale into which oil accumulated and was later naturally displaced, leaving behind a low, largely immobile remaining oil saturation.***

Two important terms in the definition are “significant scale” and “residual”. While water imbibition and displacement of oil to levels of residual saturation can be observed down to the core scale, the emphasis here is on an entire zone or interval of reservoir over which this process has occurred. As the processes driving ROZ formation may act over tens to hundreds of kilometers (km), the effects should be observable at sufficiently large scales. At finer scales, other factors may act as the primary control. On the practical side, exploitation and production from a ROZ will only occur if there is a commercial resource. Therefore, significant scale implies tens of meters in thickness over a field. With respect to “residual”, reservoir conditions and properties can behave dynamically over time and natural processes such as oil displacement may not be entirely efficient. For these reasons, it is possible that a ROZ may have some mobile oil pockets. While a ROZ is generally considered as being immobile, the presence of any mobile oil should not discount a zone from being a ROZ. For this reason, remaining oil saturation and not residual oil saturation is used.

Implied in the ROZ definition is that the oil has accumulated beneath a trap, as has been the case for ROZs of the Permian Basin (Melzer et al., 2006; Honarpour et al., 2010; Pathak et al., 2012). This detail, however, is purposely omitted from the definition. ROZ formation is fundamentally a fluid process made possible by matrix capillary pressure. Traps, especially hydrodynamic traps, can evolve through time. Including “trap” in the term without perfect knowledge of past reservoir conditions might unduly limit recognition of ROZ to areas that may serve as traps in the present but not the past. Similarly, while studies of oil migration indicate that oil migrates as thin strands through the most permeable conduits (Dembicki Jr. & Anderson, 1989; England, 1994; Ganesh, 2012) (Table 1), if such an instance occurred that oil migrated as a large plume through a significant volume of rock, this too would leave behind a large zone of residual oil resulting from imbibition.

Stemming from this definition, the observation of a ROZ is a thick interval of rock with near-residual saturations of oil with limited or no mobility. The oil saturation ($S_o$) of the field prior to production can be best modeled by imbibition, not drainage models (see Appendix I for definitions) (Lucia, 2000). ROZs may exist either below the producing oil water contact (POWC) of a known field ("greenfield") or, if the entire previous accumulation has been swept, as a stand-alone ROZ that offers no primary production ("brownfield") (Melzer, 2006).

ROZ formation occurs when oil accumulated beneath a trap under initial conditions is displaced as reservoir conditions change (Figure 1). Buoyant forces may drive oil to migrate beyond the original spill point or through an imperfect seal. Similarly, changing hydrodynamic forces may sweep oil out of the trap. The one scenario in which a condition change is not prerequisite to ROZ formation is if a seal over a trap is initially leaky but the rate of leakage is slower relative to the rate of oil accumulation such that oil first fills the reservoir before gradually leaking (Figure 2). In each case, reservoir water imbibes back into the reservoir, displacing oil to the point of immobility where it is mostly residually trapped (Figure 1). This process is the same as an engineered waterflood with the primary exception being that natural forces drive the ROZ formation, likely acting over longer time periods with a higher sweep efficiency resulting in a lower overall ROS.

ROZs are the result of fluid dynamics and capillary pressure (Pc). An initial accumulation forms when migrating oil accumulates beneath a trap. Because most reservoir rocks are generally considered water-wet initially (Anderson, 1987), this is considered a drainage process. Once accumulated, the uppermost interval where Pc is the highest and oil moves freely with near zero water mobility is called the main pay zone (MPZ) (Figure 1; Melzer et. al., 2006). Oil in the MPZ can be exploited via primary, secondary, and tertiary production methods. Beneath the MPZ is the transition zone (TZ) where both oil and water are mobile (Arps, 1964; Schowalter, 1979, Schowalter & Hess, 1982; Jennings, 1987). In theory, the TZ can be defined as the interval of a hydrocarbon column extending from the OWC to the point of irreducible water saturation ($Sw_{irr}$) (Valenti et al, 2002). In this paper, though, the TZ is referred to as the interval extending from the level of first oil production to the point where the relative permeability of oil ($K_{ro}$) is substantially greater than the relative permeability of water ($K_{rw}$) that water is generally non-productive. This level is not necessarily the point of theoretical $S_{wirr}$ (Figure 1). Oil in the TZ decreases steadily from the MPZ to the POWC, and while oil may be produced under primary production throughout the TZ, economic considerations may impose an artificial depth limit below which production is not commercially viable (Jennings, 1987). Below the POWC, interconnected oil saturation diminishes to zero at the capillary entry pressure ($P_{ce}$), which is the capillary pressure threshold oil must overcome to enter the reservoir as a connected hydrocarbon body. Beneath the $P_{ce}$ is the free water level (FWL), the level at which the capillary pressure is zero (zcpl) (Lucia, 2007).

The ROZ forms between the paleo and present FWLs where saturations are theoretically reduced to a residual, immobile state as isolated droplets. When a ROZ forms, remobilization and displacement of oil beyond the trap leads to elevation of the FWL and POWC within the reservoir. Consequently, the TZ and MPZ thicknesses decrease (brownfield) or are fully displaced (greenfield). As water imbibes into the reservoir, $S_o$ decreases according to imbibition curves down to the new FWL. Below the FWL, mobile oil is displaced and only the $S_{or}$ theoretically remains. While variable locally, the average $S_o$ in a ROZ should remain relatively constant throughout the interval in contrast to the expected steady decline of a TZ. In this scenario, the transition zone shrinks and, if the reservoir is not fully swept, a portion of the MPZ may remain above (Figure 1). This has been the case for several ROZs identified in the Permian Basin (Figure 4) (Lucia, 2000; Honarpour et al., 2010; Pathak et al., 2012).

Multiple other factors affect and create variability in fluid saturations. These factors include heterogeneities in matrix petrophysical properties, pore throat distribution, and wettability (Christiansen, 2007). Hysteretic effects also play a role as $S_{or}$ increases with increasing initial oil saturation ($S_{oi}$) (Schowalter & Hess, 1982). Furthermore, natural imbibition of water in a reservoir may not necessarily be perfectly efficient in displacing oil. Studies by Krevor (2011), Frykman et al. (2009), and Saadatpoor (2012), amongst others demonstrate the possibility of higher than residual saturations in the imbibed portions of the reservoir due to reservoir heterogeneities and the influence of residually trapped portions of non-wetting fluids on the further movement of the non-wetting fluid. Additionally, the number of pore volumes of water imbibing and potentially passing through a ROZ may not be very large (Trentham, 2012) in contrast to theoretical estimates of $S_{or}$. Due to reservoir properties and saturation history, fluid saturations throughout the ROZ may have more variability and mobility than theoretically expected. In any case, ROZ formation involves a reversal in the fluid entry process that should be reflected in its saturation profile and relative mobility of oil.

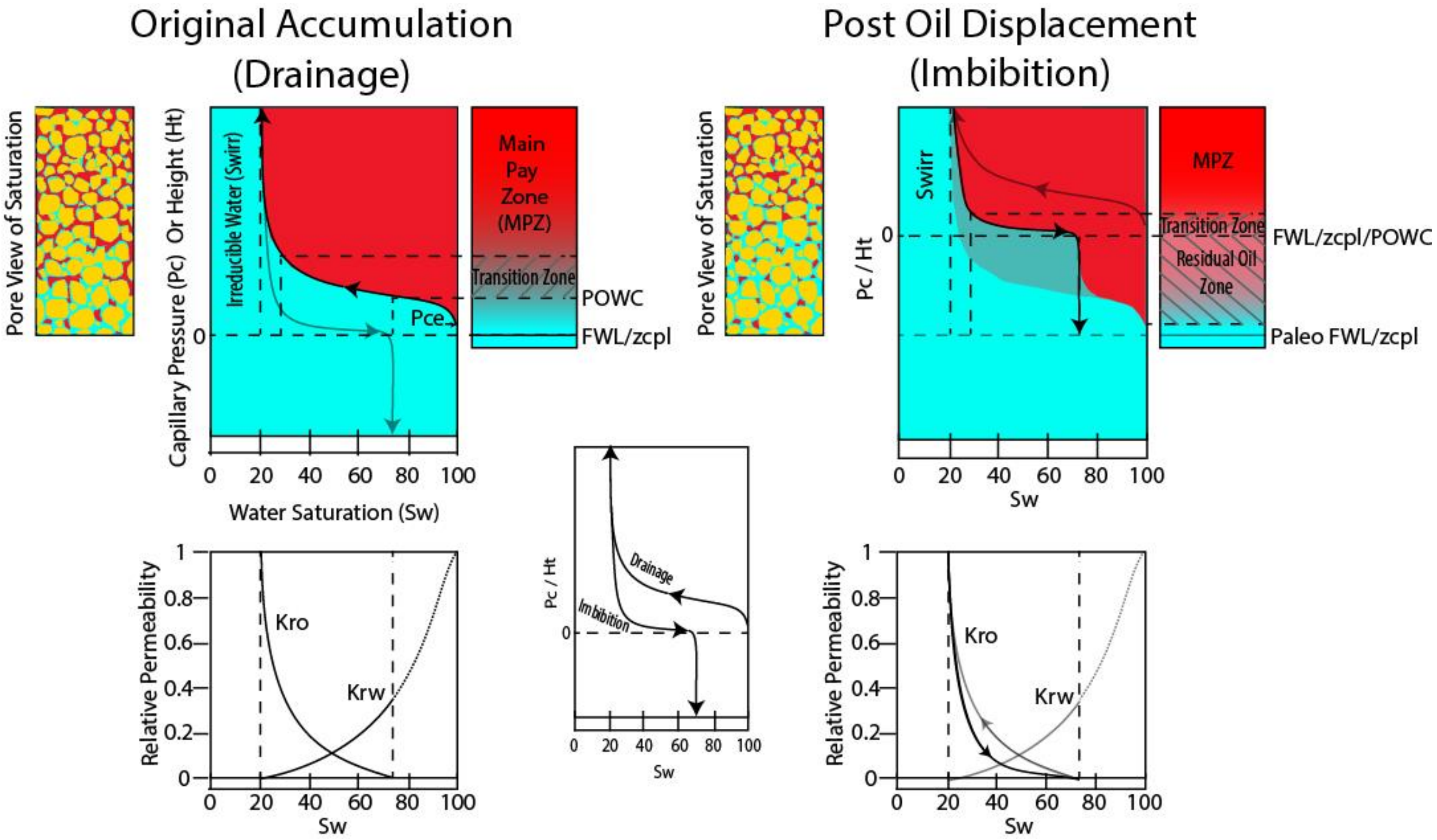


Figure 1: Idealized diagram showing the distribution of oil (red) and water (blue) saturation in multiple views for both the original and post-displacement reservoirs. Beneath are the related relative permeability curves for oil (Kro) and water (Krw). Whereas the original accumulation forms as a drainage process, ROZs are the result of oil displacement, elevation of the FWL/zcpl and POWC, and water imbibition (center). The ROZ forms between the paleo and present FWLs where saturations are theoretically reduced to a residual, immobile state as isolated droplets. Where the reservoir is not fully displaced ("brownfield"), a MPZ can remain as found at several Permian Basin fields (Figure 4). For practical purposes, the top of the TZ is set where Kro >> Krw rather than where Krw = 0. This figure pulls from concepts of Anderson (1987), Arps (1964), Berg (1975), Schowalter (1979), Schowalter & Hess (1982), Lucia (2000), and Christiansen (2007).

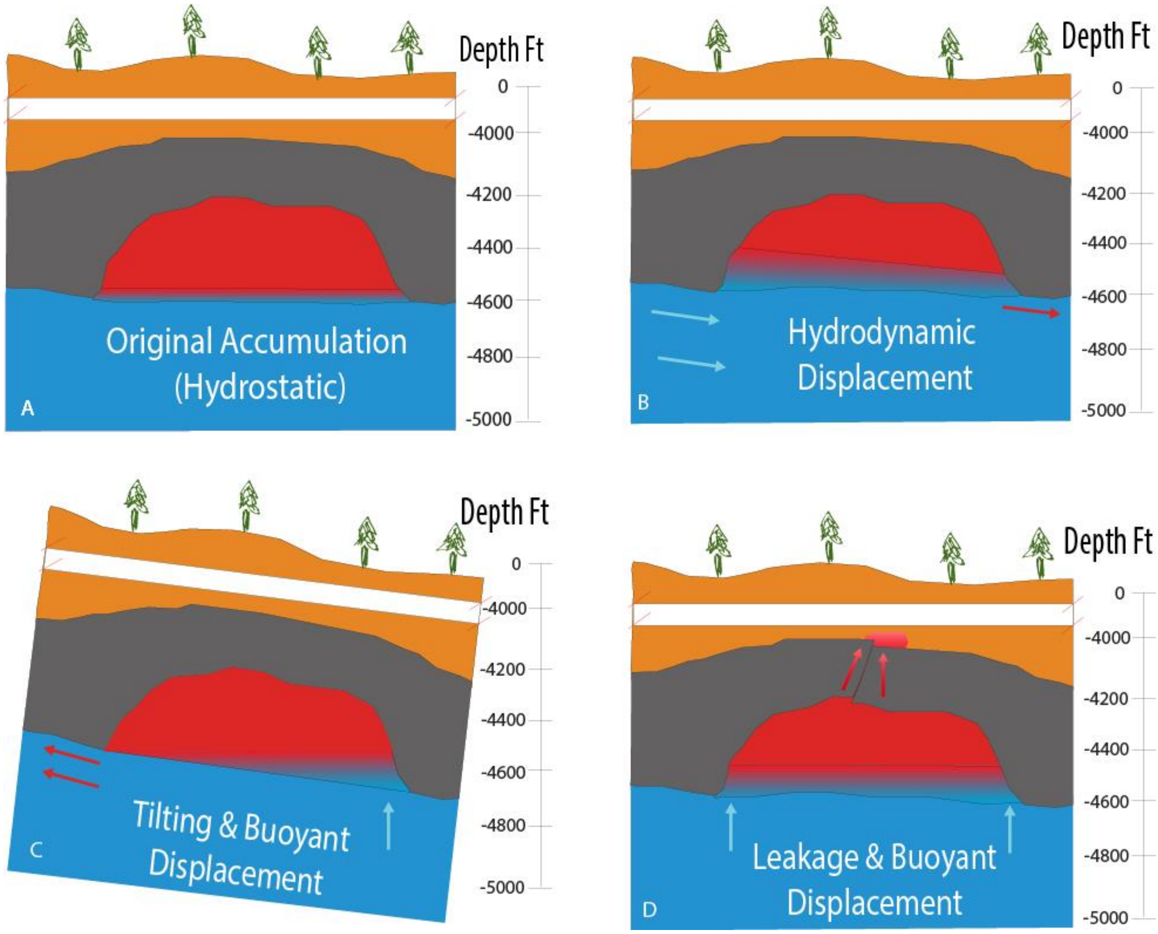


Figure 2: Schematic of the original accumulation (A) and hydrodynamic (B) and buoyancy (C&D) driving mechanisms capable of producing ROZs. The ROZ is outlined in black. Arrows indicate the direction of oil (red) and water (blue) movement. Note the relationships between the FWL and OWC for each mechanism. A tilted OWC and flat original FWL indicates hydrodynamics (B), whereas a flat OWC and either tilted or flat original FWL can indicate tilting (C) or a faulty seal (D), respectively.

There are two driving mechanisms that can account for this observation: buoyancy and hydrodynamics (Figure 2). Buoyancy is the force generally responsible for petroleum migration and is described by:

$$(1)\ Fb = \rho f * Vf * g$$

Where, $F_b$ = the buoyant force exerted on a fluid by the fluid it is displacing (kg), $\rho_f$ = density of displaced fluid ($\frac{kg}{m^3}$), $V_f$ = the volume displaced ($m^3$), and g = gravitational acceleration ($\frac{m}{s^2}$).

In the case of buoyant displacement of oil from where it is trapped in a reservoir, conditions must change such that either trap geometry or seal efficacy are altered, allowing buoyant forces to overcome the capillary and other forces restricting continued upward migration of oil.

Hydrodynamic impacts on multi-fluid systems are also well documented (Hubbert, 1953, 1967; Lerche & Thomsen, 1994; Dahlberg, 1995). Active hydrodynamic systems result in fluid pressure differences, with fluids moving in the direction of higher to lower pressure or hydraulic head. The relative pressure levels can be mapped as a potentiometric surface whose gradient is equivalent to the hydraulic gradient in the reservoir. In a multi-fluid hydrodynamic reservoir, water flows down gradient, tilting fluid contacts (e.g. OWCs) in the down-gradient direction. Hubbert (1953) expresses this as:

$$(2)\ \tan(\theta) = \frac{\partial Z_o}{\partial \mathrm{x}} = \left\lfloor \frac{\rho_w}{\rho_w - \rho_o} \right\rfloor \frac{\partial \mathrm{h}}{\partial \mathrm{x}}$$

where $\frac{\partial \mathrm{Z_0}}{\partial \mathrm{x}} = \text{slope of OWC}\ (\frac{\mathrm{m}}{\mathrm{m}})$, $\theta = \text{OWC tilt angle (degrees, °)}$, $\frac{\partial \mathrm{h}}{\partial \mathrm{x}}$ potentiometric surface gradient $(\frac{\mathrm{m}}{\mathrm{m}})$, $\rho_w = $ water density $(\frac{\mathrm{kg}}{m^3})$, and $\rho_o =$ oil density $(\frac{\mathrm{kg}}{m^3})$. In this equation, $\left\lfloor \frac{\rho_w}{\rho_w - \rho_o} \right\rfloor$ is also referred to as the tilt amplification factor (TAF). The greater the density difference, the smaller the TAF and the tilt of the fluid contact would be.

While both ROZ-forming processes – hydrodynamics and buoyancy – result in the same fundamental observation, there may be a subtle difference that can impact oil saturations. Assuming a predominantly water-wet reservoir, buoyancy driven migration results in spontaneous imbibition of formation waters back into the reservoir as oil evacuates whereas an increase in hydrodynamic forces could result in forced imbibition. Because forced imbibition leads to negative capillary pressures, the ROS from hydrodynamic-driven ROZ formation may be lower than that for buoyancy-driven ROZ formation (Zeidouni, 2014).

While dedicated study of ROZs is in its early stages, the buoyant and hydrodynamic forces that drive ROZ formation are well-studied and well-described phenomena common to many natural petroleum systems (Hubbert, 1953; Berg, 1975; Schowalter, 1979; Lerche & Thomsen, 1994; Dahlberg, 1995). Goebel (1950) & Schowalter (1979) provide examples or note the presence of what is here defined as a ROZ. However, because of oil immobility in ROZs, they have been of little commercial or academic interest until the late 1990s (Melzer, 2006; Trentham, 2012). Since the processes driving ROZ formation are understood and mathematically described, though, characteristics of ROZs may be predictable.

The ability to predict and understand ROZ formation by its driving processes is a critical reason for a fundamental description of ROZs. The importance in understanding which mechanism was the main driver of ROZ formation provides the ability then to predict the potential and key characteristics of ROZs such as thickness and ROS. This also implies that ROZs are not the result of unique circumstances of each hydrocarbon reservoir and might be expected in any basin where geologic or hydrologic conditions have changed since the onset of petroleum migration and accumulation.

While ROZs can potentially form in any basin, not every zone of low $S_o$ encountered will be a ROZ. There are several other reservoir, pore, and basin-scale processes that can result in some characteristics similar to that of a ROZ (Table 1).

The most important differentiation is between a ROZ and a TZ. Both are potentially volumes of low $S_o$, but whereas a TZ is the byproduct of Pc influencing oil accumulation (i.e. drainage) (Christiansen, 2007), ROZs result from imbibition driven by reservoir to basin-scale fluid dynamics. The primary observed difference, then, is the steady, predictable decline of $S_o$ over the TZ compared to the relatively steady average $S_o$ in the ROZ. The other indicator is that oil in the TZ should be mobile whereas oil in the ROZ will almost always be immobile or at least not sustain oil production.

Table 1: Identification and differentiation of processes which can resemble ROZs

| Process | Similarity to ROZ | Differentiation From ROZ |
|---|---|---|
| **Dual Fracture/Matrix Porosity System** | • High water cut where low $S_o$ primary porosity dominates flow and production | • Does not exclude ROZ<br>• Remaining oil may be mobile in secondary porosity<br>• Is reservoir specific |
| **Transition Zone** | • Interval of low-$S_o$<br>• High water production | • Gradual decline of $S_o$ from top to bottom<br>• Oil is mobile<br>• Is a product of initial oil drainage rather than imbibition (reflected in saturation profile)<br>• Thickness controlled by capillary pressure and is predictable from rock quality rather than fluid dynamics<br>• Is reservoir specific |
| **Waste Zone** | • Low $S_o$<br>• Limited oil mobility | • Results from observable facies change in upper extent of reservoir rock (Schowalter & Hess, 1982)<br>• Poor reservoir quality rock<br>• $S_o$ decreases with height<br>• Is reservoir specific |
| **Engineered Waterflood** | • Theoretically at $S_{or}$<br>• Immobile oil | • Anthropogenic<br>• Lower sweep efficiency & higher ROS<br>• Discontinuous due to fingering |
| **Migration Pathway** | • Residually trapped oil | • Contacts limited volume of rock<br>• Discontinuous saturation of rock<br>• Oil saturation fingers<br>• Is largely located beneath a seal |
| **In-situ Generation** | • Potentially low $S_o$ | • Primary migration, not displaced<br>• Single reservoir<br>• Irregular oil saturation<br>• Proximal to organic-rich deposits<br>• Potential oil mobility |
| **Under filled, stratified** | • Potentially low $S_o$<br>• Potential oil immobility | • Primary migration<br>• Drainage saturation profile (possibly stacked)<br>• Potential oil mobility<br>• Single reservoir |

# Background

## Study Area

The Permian Basin is the name given to a geologic basin underlying present day West Texas and southeastern New Mexico (Dutton et al., 2005) and is one of the largest oil producing regions in the U.S., accounting for 13.8% of cumulative U.S. oil production (Dutton et al., 2005; EIA, 2013; TXRRC, 2013).

Existing literature and study on the Permian Basin is extensive. Several publications offer detailed histories and descriptions of the Permian Basin including Hill's (1996) review book and Dutton et al. (2005). To provide context for the evolution of ROZs in the Permian Basin, an abbreviated history of the Permian Basin region is described below as largely distilled from Horak (1985), Hill (1996), and Dutton et al. (2005) (Table 2). This description is in reference to the whole region, and not just the period of Permian Basin formation, which occurred from the Pennsylvanian to the Triassic (Hill, 1996). Preceding the Permian Basin was the Tobosa Basin, from Cambrian through Mississippian (Hill, 1996), and post-dating the Permian Basin was the Comanche Platform and adjacent mini-basins (Kerans, 2002).

During the Pre-Cambrian Greenville Orogeny, mafic intrusions were emplaced that established the grain of what would later become the Central Basin Platform (CBP) (Adams & Keller, 1996), an important structure for future sedimentation and ROZs (Hill, 1996). After rifting and coeval deposition of Cambrian through Mississippian sediments in the then Tobosa Basin, late Mississippian time saw the onset of convergence associated with the Ouachita-Marathon orogeny (Shumaker, 1992). Compression continued through the Pennsylvanian period with much of the accommodation developing with the growth of high-angle reverse faults on adjacent to the developing CBP (Yang & Dorobek, 1995), which remained a local high while the adjacent Midland and Delaware Basins formed to the east and west, respectively (Shumaker, 1992). Other key features during this time were the growth of the Horseshoe Atoll, an isolated carbonate platform in the eastern Midland Basin possessing ROZs; the emergence of the Ozona Arch, another local high located off the southeastern tip of the CBP with potential ROZs; the formation of depositional shelves across the basin (Figure 3) where many ROZs are potentially located; and the development of the San Simone and Sheffield channels to the north and south of the CBP, respectively (Dutton et al., 2005).

Table 2: Chronological timeline of Permian Basin[1] evolution and its relevance to ROZs. Tectonics from Horak (1985). Stratigraphy and ages from Dutton et al. (2005), Phelps (2011), & Walker et al (2012)

| Timeline of Events | | | | Relevant Stratigraphy | | Tectonic Phase | ROZ-Related Events |
|---|---|---|---|---|---|---|---|
| Age | Series/Epoch | Stage | Age | Analysis Group | Relevant Formations | | |
| Paleo-Proterozoic | | | ~2500 | | | **PreCambrian Phase:** Establishes regional grain and zones of weakness that influence later tectonics including plutonism and high angle fualting setting up the future CBP | **Controls:** Basement Initiates some future basement structures affecting future structure, uplift, and fluid flow |
| Meso-Proterozoic | | | ~1600 | | | | |
| Neo-Proterozoic | | | ~1000 | | | | |
| Cambrian | Lower | | ~542 | | | **Passive Margin Phase:** No important structural deformation. Period of "layer cake" sedimentation into broad Pre-Permian (Tobosa) Basin | |
| | Upper | | ~500 | | | | |
| Ordovician | Lower | | ~488 | Ordovician | Ellenburger | | |
| | Middle | | ~ 471 | | McKee-Waddell-Connell-Simpson | | |
| | Upper | | ~460 | | Montoya | | |
| Silurian | Lower | | ~443 | Silurian | Fusselman | | |
| | Upper | | ~ 428 | | Wristen-Silurian | | |
| Devonian | Lower | | ~416 | Devonian | Devonian-Thirty One | | |
| | Middle | | ~ 397 | | | | |
| | Upper | | ~385 | | | | |
| Mississippian | Lower | | ~359 | Mississippian | Woodford | | |
| | Middle | | ~345 | | Lower Mississippian | | |
| | Upper | | ~326 | | Barnett-Mississippian | **Collision Phase:** Formation of PB structures with O-M Orogeny; major deformation; establishes Permian sedimentation patterns | **Controls:** Basement Further development of basement structures and fault zones<br>**Controls:** Stratigraphy Deposition of some future source rocks for known ROZ oils; Development of Horseshoe Atoll where some ROZ are found |
| Pennsylvanian | Lower | Springer | ~318 | Pennsylvanian* | | | |
| | | Morrow | | | Morrow | | |
| | | Atoka (Bend) | | | Atoka | | |
| | Middle | Des Moinesian | ~311 | Strawn | Strawn | | |
| | Upper | Missourian | ~306 | Canyon | Canyon | | |
| | | Virgilian | | Cisco | Cisco | | |
| Permian | Lower | Wolfcampian | ~299 | Permo-Penn | Wolfcampian | | |
| | Middle | Leonardian | ~285 | | Wichita Albany-Abo-Dean | **Permian Basin Phase**: Syndepositional smaller scale deformation and subsidence and maximum burial of Delaware Basin due to sedimentation | **Controls:** Stratigraphy Deposition of ROZ target formations; Some reservoir structures develop via compaction<br>**Controls:** Diagenesis Dolomitization, dolomite & anhydrite cementation<br>**Controls:** Fault & Fracture Syndepositional faulting and fracturing |
| | | | | Yeso* | Clearfork (U & L)-Tubb-Blinebry-Paddock-Yeso-Glorieta-Holt-San Angelo | | |
| | Upper | Guadalupian | ~270 | San Andres** | San Andres | | |
| | | | | Grayburg** | Grayburg | | |
| | | | | Queen** | Queen | | |
| | | | | Artesia | Seven Rivers-Yates-Tansill-Artesia-Salado-Rustler-Dewey Lake | | |
| | | Ochoan | ~260 | | | | |
| Triassic | Lower | | ~251 | | Dockum Group | **Stable Platform Phase**: Continued, gradual deformation of Permian Basin into broad syncline; Limited deposition; tectonic stability; area is positive except for Early and Late Cretaceous with the inundation of the shallow Cretaceous Interior Seaway | Maximum Burial near end Createceous |
| | Middle | | ~245 | | | | |
| | Upper | | ~228 | | | | |
| Jurassic | Lower | | ~199 | | | | |
| | Upper | | ~175 | | | | |
| Cretaceous | Lower | Berriasian | ~145.5 | | | | |
| | | Valanginian | ~140.2 | | | | |
| | | Hauterivian | ~136.4 | | | | |
| | | Barremian | ~130 | | | | |
| | | Aptian | ~125 | | | | |
| | | Albian | ~112 | | Trinity & Edwards Group | | |
| | Upper | Cenomanian | ~99.6 | | Buda | | |
| | | Turonian | ~93.5 | | | | |
| | | Coniacian | ~89.3 | | | | |
| | | Satonian | ~85.8 | | | | |
| | | Campian | ~83.5 | | | | |
| | | Maastrichtian | ~70.6 | | | **Laramide Phase:** Guadlupe Mtns and Delaware Mtns possibly subjected to broad arching with streams directing generally N, W; Potential 1.2 km uplift of Guadalupe Mtns and tilting of Delaware Basin | **Drivers:** Hydrodynamics Potential initiation of uplift, tilting, and hydrodynamics<br>**Drivers:** Buoyancy Potential tilting; Potential reactivation of fault and fracture causing seal failure<br>**Controls:** Basement Potential reactivation basement structures<br>**Controls:** Fault & Fracture Reactivation & initiation of fault and fracture networks |
| Paleogene | Paleocene | Early | ~65.5 | | | | |
| | | Mid | ~61.7 | | | | |
| | | Late | ~58.7 | | Ogallala | | |
| | Eocene | Early | ~55.8 | | | | |
| | | Mid | ~48.6 | | | | |
| | | Late | ~37.2 | | | **Volcanic Phase:** Intrusive and extrusive volcanism between subduction & compression and crustal extension/thinning | |
| Neogene | Oligocene | Early | ~33.9 | | | | |
| | | Late | ~28.4 | | | **Basin & Range Phase**: Transition from compression to extension; NNW normal faulting & Fracturing; Uplift Guadalupe, Apache, Delaware, & Glass Mtns; Increased heat flow during middle phase; | **Drivers:** Hydrodynamics Uplift and tilting of Permian Basin and initiation or increase of hydrodynamics<br>**Drivers:** Buoyancy Tilting of traps; Potential seal failure<br>**Controls:** Diagenesis Dissolution/rpl of sulfates; Precipitation of biogenitic calcite, metal sulfides, native sulfur<br>**Controls:** Recharge/Discharge Growth and subsequent loss of recharge area; development of vertical discharge pathways<br>**Controls:** Basement Potential reactivation of basement structures |
| | Miocene | Early | ~23 | | | | |
| | | Mid | ~16 | | | | |
| | | Late | ~11 | | | | |
| | Pliocene | Early | ~5.3 | | | | |
| | | Late | ~3.6 | | | | |
| Quaternary | Pleistocene | Early | ~1.8 | | | | |
| | | Middle | | | | | |
| | | Late | | | | | |
| | Holocene | | ~12 Ka | | Alluvium | | |

*Time Equivalent Bone Spring & Spraberry Groups Deposited in Delaware and Midland Basins, respectively

**Time Equivalent Delaware Sands (Bryshy/Cherry/Bell Canyon) Deposited in Delaware Basin

[1] Refers to region, not actual period of Permian Basin (Penn-Tri)

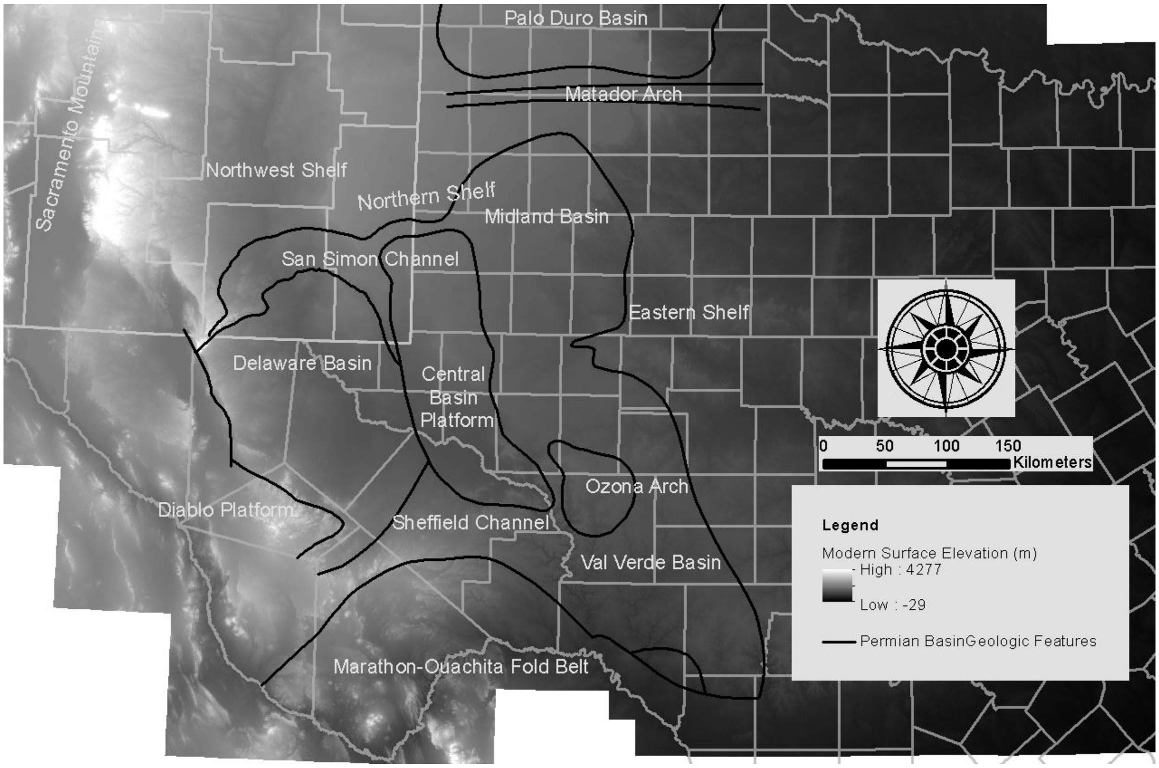


Figure 3: Outline of key structural elements of Permian Basin region at the time of the Permian deposition (Dutton et al., 2005). Background is mosaic digital elevation model (DEM) of surface topography built from ASTER DEM (NASA, 2012) with the outline of Texas and New Mexico counties (gray lines). Note that the Permian Basin refers to the area stretching from the Diablo Platform to the Eastern Shelf and from the Northwest Shelf to the Val Verde Basin. The Matador Arch and Palo Duro Basin are separate. The elevated regions to the west are the Sacramento Mountains. Topographic region from the south of San Simon Channel to top of map is the modern High Plains.

With the major structural architecture well established by the end of Pennsylvanian time (Shumaker, 1992), the greatest amount of sedimentation took place during Permian time when the basin's thickest stratigraphic sections accumulated during the Wolfcampian, Leonardian, and Guadalupian stages (Table 2; Figure 19) as the Delaware and Midland Basins rapidly subsided (Mazzullo & Harris, 1989). With increasing burial, many of the organic-rich sediments entered the oil window, initiating petroleum generation (Hills, 1984) and migration from the basins upwards through slope sediments and fault and fracture zones into traps within the Permian strata (Ramondetta, 1982a) beginning in the Permian and continuing into the Cretaceous (Horak, 1985;

Mazzullo & Harris, 1989; Lee & Williams, 2000). Oil accumulated during this period would later be displaced, forming ROZs.

Sedimentation continued through Permian time as the basins became restricted from the ocean to the south, leading to deposition of thick evaporite sequences of the Guadalupian and Ochoan (Dutton et al., 2005). After Permian time, deformation continued at reduced rates, continuing to shift the structure of the basin, reservoir formations, and future ROZ precursor accumulations. Sedimentation also continued, but with less accommodation. Deposits were largely fluvial-lacustrine (Triassic) and/or not preserved (Jurassic) until the inundation of the shallow epicontinental Western Interior Seaway beginning in the Mid-Cretaceous (Hill, 1996).

Following the Permian deposition and initial generation, migration, and accumulation of oil, came the onset of the Laramide tectonics beginning at ~80 Ma in the Cretaceous (Hill, 1996). While epeirogenic uplift centered to the north in the Colorado Plateau region, compressional stresses are known to have extended across the Permian Basin region into south and central Texas (Budd et al., 2013). Though there is no direct evidence of uplift having occurred at that time (Hill, 1996), the compressional stresses did affect faulting and fracture networks (Budd et al., 2013; Frost et al., 2012; Smith, 2013), which Horak (1985) argues led to ~1.2 km of uplift in central New Mexico. The change in the stress regime and its impact on fracture networks could have increased the hydraulic conductivity of fractured media. Any uplift would have generated the difference in elevation needed to create gravitational potential for water flow, though not necessarily recharge and discharge zones enabling water to flow.

The next major phase is the uplift, tilting, and volcanic activity associated with the extension and rifting of Basin and Range tectonics (Hill, 1996). During this time, the Sacramento Mountains and other coeval ranges formed in central New Mexico, uplifting reservoir formations of the Permian Basin over one km (Horak, 1985). In conjunction with uplift, denudation of any overlying Mesozoic sediments exposed Permian and Pennsylvanian strata, allowing for easy recharge into the respective aquifer units (Lindsay, 2001). Eroded sediments from the highlands were deposited as the Ogallala

Formation that forms the present, minimally deformed landforms of the High Plains (Gustavson & Winkler, 1988) (Figure 3). The Basin and Range period of uplift and any possible uplift associated with Laramide phase tectonics are thought to be the key events in initiating ROZ formation by hydrodynamic forces.

## ROZs in the Permian Basin

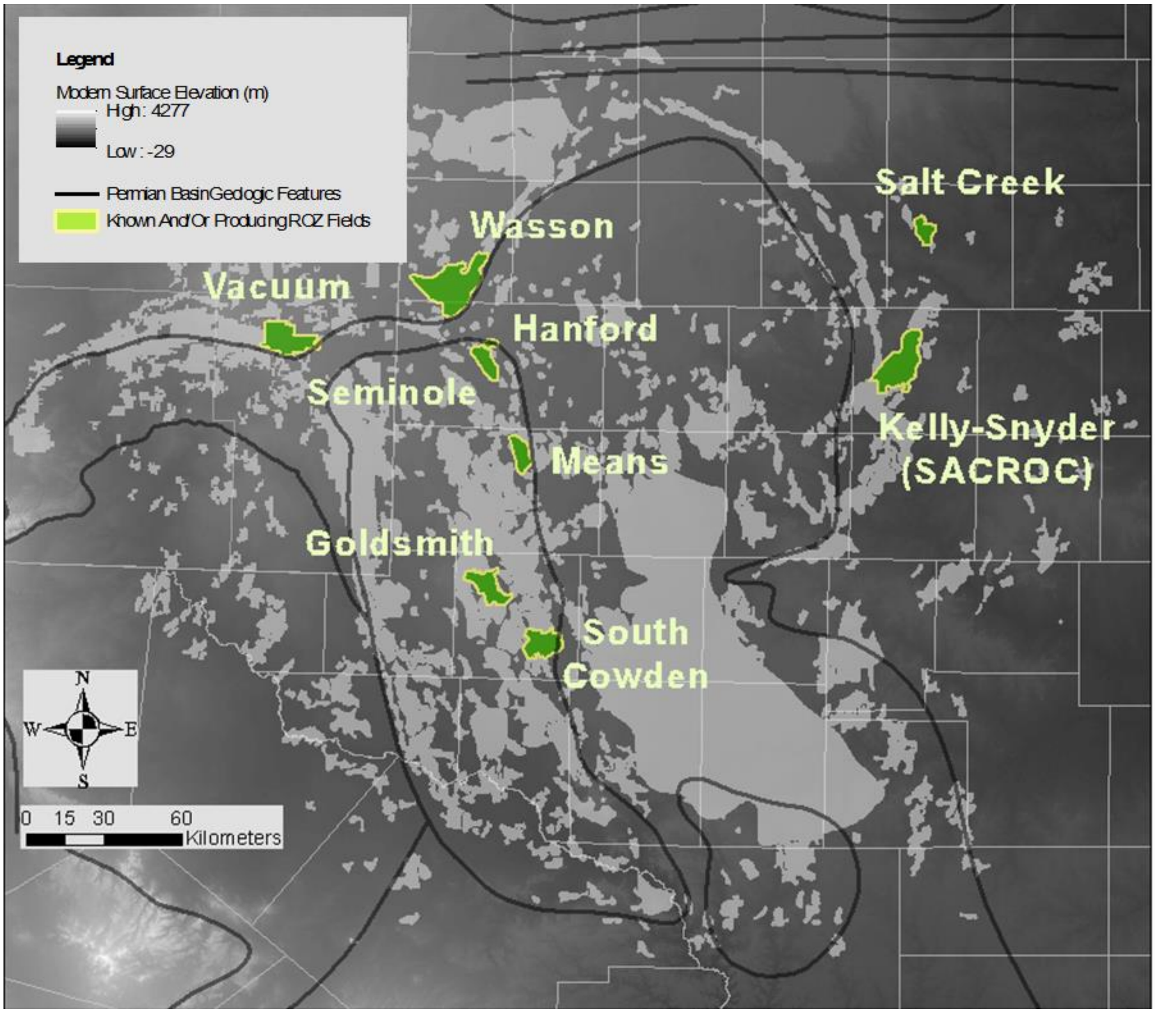


Figure 4: Locations of oil fields with known and/or producing ROZs (Green) overlain on surface topography (Lucia, 2000; Bishop 2004; Trentham, 2012), Permian Basin structural outlines (black) and distribution of oil fields in the Permian Basin (grey; Dutton et al., 2005). Generated using ArcGIS.

The presence of ROZs has been noted in several fields across the Permian Basin and includes fields at which either production from ROZs is ongoing or presence is otherwise known through published work (Lucia, 2000; Brown, 2001; Melzer et al., 2006; Honarpour et al., 2010; Pathak et al., 2012; Trentham, 2012) (Figure 4). An adapted reservoir model from Pathak et al. (2012) of the Means Field San Andres reservoir offers an idea of how a ROZ appears (Figure 5). Important features of this model are the high water saturations in the ROZ, the thickness of the ROZ exceeding that of the MPZ, and the stepped OWC. These or similar features are common across many of the studied ROZs in the Permian Basin.

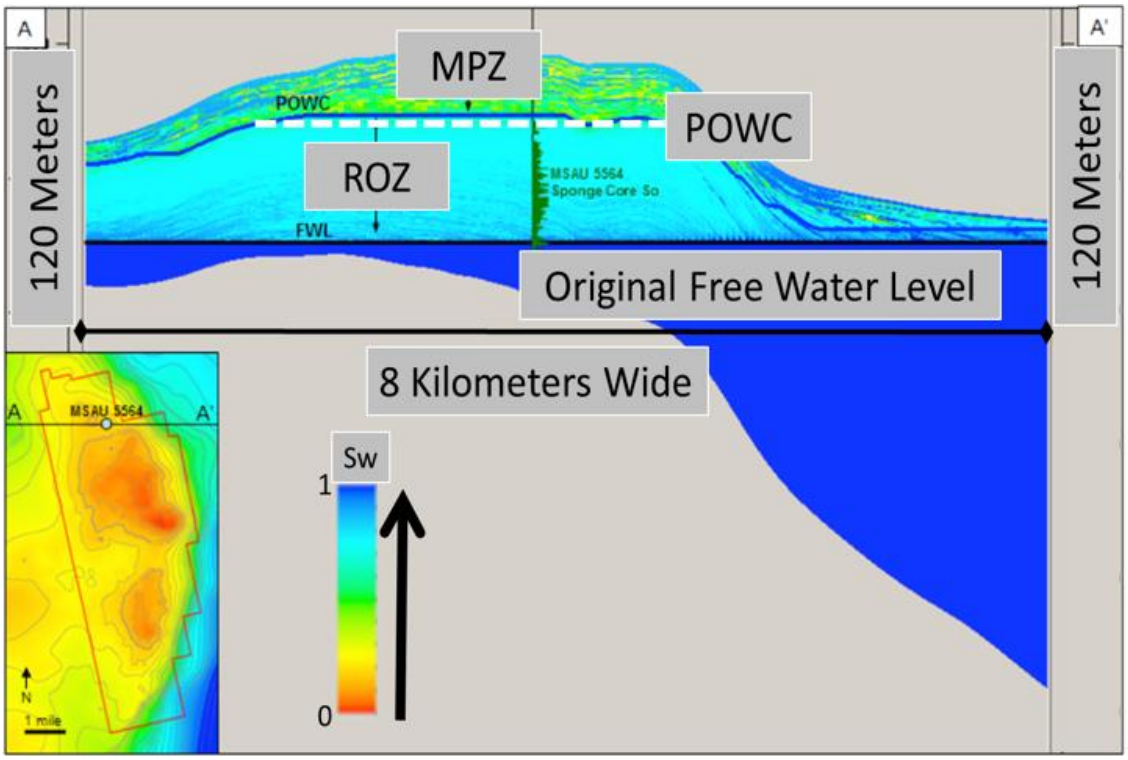


Figure 5: Model of Means Oil Field (San Andres Formation) showing the MPZ underlain by a thicker ROZ. Adapted from Pathak et al. (2012). The colors in the figure represent the modeled water saturation in the reservoir and are inverted with oil saturation. Key features include the ROZ being thicker than the MPZ, a stepped POWC to the east

The fundamental observation expected and identified in studied fields is a thick zone of low to immobile oil saturation that remains largely consistent from the FWL to the bottom of oil saturation and is best described by an imbibition, not drainage curve (Lucia, 2000) (Figure 1). In addition to direct calculations of oil saturations in ROZs, additional indirect indicators of low oil mobility are present in past drilling and field reports. Trentham (2012) notes references to thick sections beneath a mobile, producing zone where oil shows or positive well log calculations produce only sulfurous water when perforated, a sign that oil is both immobile and has interacted with aquifer waters.

Another critical piece in understanding ROZs is the observation that several ROZ fields possess tilted OWCs (Melzer, 2006). Heterogeneities in carbonate reservoirs can result in thick TZs and ostensibly tilted OWCs even in hydrostatic conditions. However, evidence indicates this is not the most likely explanation for many Permian Basin fields. Brown (2001) was one of the first to link ROZs to hydrodynamics. He showed that the tilted OWC at Wasson field and the thick zone of low oil saturation beneath it cannot be explained by reservoir heterogeneities. He and others (Hubbert, 1953; Grauten, 1965; Berg, 1975) attribute tilted OWCs in the Permian Basin to active hydrodynamic conditions, finding the tilt of the Wasson OWC to be consistent in magnitude and direction with the local potentiometric gradient (Equation 2). The existence of hydrodynamic conditions is well known and demonstrated by McNeal (1964), Hiss (1980), Dutton & Orr (1986) and others for regional aquifers replenished by meteoric recharge in uplifted areas to the west and flowing down gradient across the basin.

Trentham (2012) and others have also noted several other pieces of anecdotal evidence common to ROZs of the San Andres Formation. These include anhydrite and gypsum dissolution and native sulfur precipitation, each linked to the influx of undersaturated waters possessing sulfate-reducing bacteria into the reservoir. Other research has also shown that waters for some fields with ROZs are of relatively low salinity (Dutton & Orr, 1986) and have isotopic compositions indicating a meteoric origin (Bein, 1993), far different from the high-salinity connate waters in other San Andres fields (Dutton & Orr, 1986).

The combination of observations at studied ROZs to date has lead researchers to propose hydrodynamic flushing as the primary mechanism of ROZ formation across the Permian Basin (Melzer, 2006). The key observations in relation to this are the tilted OWCs, meteoric-derived formation fluids, and multiple signs of diagenesis throughout the ROZ section. Multiple authors link the establishment of hydrodynamic conditions and influx of meteoric waters to late-stage tectonic activity. Both Basin and Range related extension and uplift if not also Laramide associated uplift might have contributed to hydrodynamic conditions (Hiss, 1980; Hills, 1984; Lindsay, 1998, 2001; Brown, 2001). As regions to the west of the Permian Basin uplifted, denudation of overlying Cretaceous, Triassic, and most importantly Permian salt overburden exposed much of the Permian strata, allowing for recharge (Lindsay, 2001) of meteoric waters into the exposed formations. The subsequent change in hydrodynamics is hypothesized to be the driving force for ROZ formation in the Permian Basin (Brown, 2001; Lindsay, 2001; Melzer, 2006; Trentham, 2012).

There is still some debate as to the relative uplift during each tectonic episode and its influence on regional hydrodynamics. There is even a question of whether any uplift took place in central and southern New Mexico during Laramide activity (Hill, 1996). Horak (1985) suggests over 1.2 km of uplift took place during Laramide events. Eaton (1987) further supports Laramide timing of uplift, proposing the emergence of the Alvarado Ridge (~38-35 Ma) over central New Mexico. Duchene & Cunningham (2006) and Duchene (2013) argue that uplift of the Alvarado Ridge initiated hydrodynamic conditions over the Permian Basin that persisted until extensional faulting starting 29 Ma began reducing the size of the recharge zone and elevation of hydraulic head. On the other hand, the timing of meteoric water interaction and associated dissolution of salts (Anderson, 1981), deposition of native sulfur (Hentz & Henry, 1989), meteoric spar (Hill, 1996), Mississippi Valley Type (MVT) ore deposits (Mazzullo, 1986), late-stage calcite (Scholle, 1992), and quartz and kaolinite (Leary & Vogt, 1990) in Permian-age formations is argued by the respective authors to have occurred in association with Basin and Range tectonics, uplift, tilting, and removal of overburden in the uplifted western regions exposing Permian-age reservoir strata. Regardless of the exact timing of uplift, the regional potentiometric surface and gradient is known to have decreased, as marked by clay deposits formed at the water table in caves of the Guadalupe Mountains that dating shows steadily decline starting at ~14 Ma down to the present level (Polyak, 1998).

While active hydrodynamic systems with meteoric recharge can explain observations of diagenesis and meteoric waters, and active hydrodynamics in Permian Basin reservoirs, they do not directly indicate hydrodynamic displacement of oil as the driver of ROZ formation. Infiltration of meteoric waters can also occur as buoyant displacement of oil leads to spontaneous imbibition of meteoric recharge into reservoirs. This further necessitates the importance of calculating the amount of uplift and tilting and the expected hydrodynamic force in order to test whether quantification of driving forces at a regional level is consistent with what is observed of ROZs and to identify and use proxy data as a means of locating ROZs. The following analysis aims to apply physical constraints to the amount of uplift and tilting.

## Data

Two primary datasets were developed to address the questions of uplift, tilting, and ROZ location. With limited exception, these two datasets are composed of pre-existing data that were not previously assembled as a singular dataset or analyzed in the manner carried out in this research.

### Uplift and Tilting Dataset

In order to quantify the amount of regional uplift and tilting that has occurred since the Mid-Cretaceous, the top-Albian Edwards Group is selected as an original horizontal datum prior to Laramide and later deformation.. The reasoning for selecting this contact is discussed in later sections.

Nomenclature for the Edwards Group is only defined in regions of central Texas and the Edwards Plateau, which do not encompass the entire Permian Basin region. However, there is not a unified stratigraphic chart that attempts to correlate the local nomenclature and stratigraphy between localities from central Texas to central New Mexico. Determining the stratigraphic correlations across this region is not within the scope of this effort. Instead, this work attempted to determine approximate correlations and local geologic contacts (Table 3) based on relative stratigraphic charts and formation dating present in the literature (Table 4).

Data points for each contact were compiled from existing outcrop and subsurface data (Table 4). Outcrop locations were taken from geologic atlases for both Texas (Barnes, 1974) and New Mexico (Scholle, 2003) that are made digitally available. Using ArcGIS software, the selected contact points (Table 3) were identified, extracted, and converted into individual data points (Figure 5). To assign elevation values to the collected data points, several ASTER global digital elevation model (GDEM) (NASA, 2012), were merged into a single mosaic (Figure 3). The contact data points were then overlain on the GDEM mosaic and the raster elevation data for point was extracted to the data point.

Subsurface data were predominantly gathered from existing literature and models (Table 4) detailing the Trinity-Edwards boundary. A limited number of contact points were selected from water well drillers’ reports made available from the Texas Commission on Environmental Quality (TCEQ) based on lithological descriptions available in the literature. These data were assigned approximate spatial data based on the drillers’ reports. The locations and depths reported were then created as a layer and added to the outcrop data. This is the same method used by other sources from which data points were gathered. Subsurface data from other sources were either adapted from figures or taken from models made available by authors upon contact. For figures, the maps were georeferenced, the relevant data points selected, traced, and assigned proper values, and the final data points added to the compiled dataset. For model data, the relevant data points were culled, converted to the proper units and coordinate system, and created as a new layer in the compiled dataset. The Avaya et al. (2009) model data were only available from an interpolated surface model. This surface was similarly converted into data points but comes inherent with original error in the interpolated elevations. Once all data points were collected, normalized, and added into a single database, the points were merged as a single layer (Figure 6).

Once merged into a single layer, the layer was converted into a three-dimensional (3-D) layer using the corresponding elevations of each data point. Data points were analyzed in 3-D view (not presented), as point profiles (Figure 9C), and as interpolated surfaces. Interpolation of the data points was carried out using krigging techniques in the ArcGIS software. Interpolation is most exact where data density is highest (Figure 10), but can be considered acceptably accurate as compared to present day topography. Data error is discussed further in the Methods and Results and Discussion sections.

Both the upper and lower Edwards Group surfaces are used owing to issues with data availability. The surface with the least inherent variability is the upper Edwards Group surface, a regional sequence boundary (Phelps, 2011). However, this surface is absent across most of the Permian Basin region and formations in central New Mexico are generally not subdivided to be precisely time correlative with Texas stratigraphic nomenclature. Data points do exist, though, in the highest sections of the Sacramento Mountains and the southeastern Permian Basin and beyond. Therefore, this surface is used for absolute elevations from which the total differential uplift and associated regional slope are calculated.

The lower Edwards Group contact is present both in outcrop and subsurface across much of the Permian Basin region and was therefore used as the dataset for interpolation. The contact is coeval with transgressing seas and flooding of the shelf (Rose, 1972; Phelps, 2011), which are by nature time transgressive. Also, as a sequence boundary, non-deposition and erosion are possible across the boundary. However, as discussed in greater detail in the Methods and Results sections, this error does not significantly alter results. The purpose of the interpolated surface is to visualize the local changes in elevation across the Permian Basin that are not captured by the straight-line calculations of total relative uplift and tilting from the upper Edwards surface data. Prior analyses have depended on inferred fault offsets or topography as the primary source for elevation uplift and tilting. This dataset offers the most constrained and regionally extensive analysis of the modern day elevation of the surfaces of interest.

Table 3: Contact points used for upper and lower Edwards Group equivalents. Adapted from Barnes, 1974 and Scholle, 2003.

<table>
<tr><th colspan="2">Upper Edwards</th></tr>
<tr><th colspan="2">Texas</th></tr>
<tr><th>Upper Formation</th><th>Lower Formation</th></tr>
<tr><td>Buda-Eagle Mountain Undivided</td><td>Loma Plata</td></tr>
<tr><td>Buda-Del Rio Undivided</td><td>Salmon Peak</td></tr>
<tr><td>Buda-Del Rio Undivided</td><td>Devils Diver</td></tr>
<tr><td>Buda-Del Rio Undivided</td><td>Santa Elena</td></tr>
<tr><td>Buda</td><td>Salmon Peak</td></tr>
<tr><td>Buda</td><td>Santa Elena</td></tr>
<tr><td>Buda</td><td>Loma Plata</td></tr>
<tr><td>Buda</td><td>San Marline Limestone</td></tr>
<tr><td>Buda</td><td>San Marline-Finlay Undivided</td></tr>
<tr><td>Buda</td><td>Segovia</td></tr>
<tr><td>Del Rio</td><td>Segovia</td></tr>
<tr><td>Del Rio</td><td>Devils River</td></tr>
<tr><td>Del Rio</td><td>Edwards LS</td></tr>
<tr><th colspan="2">New Mexico</th></tr>
<tr><td>Mancos Shale</td><td>Dakota Group Tucumari Glencairn</td></tr>
<tr><td>Mancos Lower</td><td>Dakota SS</td></tr>
<tr><td>Mancos Shale</td><td>Dakota Group Tucumari Glencairn</td></tr>
<tr><td>Graneros</td><td>Dakota Group Tucumari Glencairn</td></tr>
<tr><td>Greenhorn-Graneros Undivided</td><td>Dakota Group Tucumari Glencairn</td></tr>
<tr><th colspan="2">Lower Edwards</th></tr>
<tr><th colspan="2">Texas</th></tr>
<tr><td>Walnut Clay</td><td>Paluxy Sand</td></tr>
<tr><td>Walnut Clay</td><td>Glen Rose</td></tr>
<tr><td>Goodland- Walnut Undivided</td><td>Antlers</td></tr>
<tr><td>Goodland- Walnut Undivided</td><td>Paluxy Sand</td></tr>
<tr><td>Comanche Peak</td><td>Paluxy Sand</td></tr>
<tr><td>Edwards LS</td><td>Paluxy Sand</td></tr>
<tr><td>Del Carmen</td><td>Shafter</td></tr>
<tr><td>Del Carmen</td><td>Glen Rose</td></tr>
<tr><td>Edwards-Comanche Peak-Walnut Clay Undivided</td><td>Antlers</td></tr>
<tr><td>Comanche Peak-Walnut Clay Undivided</td><td>Antlers</td></tr>
<tr><td>Finlay</td><td>Cox</td></tr>
<tr><td>Fredericksburg</td><td>Maxon Sand</td></tr>
<tr><td>Fredericksburg</td><td>Trinity</td></tr>
<tr><td>Fredericksburg</td><td>Glen Rose</td></tr>
<tr><td>Fredericksburg</td><td>Antlers</td></tr>
<tr><td>Fort Terret</td><td>Maxon Sand</td></tr>
<tr><td>Fort Terret</td><td>Glen Rose</td></tr>
</table>

Table 4: Data sources used to develop uplift and tilting database

| **Data Sources By Types** | |
|---|---|
| Stratigraphy | |
| Bozniac (1955), Brand & Mattox (1972), Rose (1972), Barnes (1974), Fassett (1974), Kues (1985), Mateer (1985), Mack et al. (1986), Mack (1987), Fallin (1989), Holbrook & Dunbar (1992), Barker et al. (1994), Talbert & Atchley (2000), Lucas et al. (2001), Scott et al. (2001), Scholle (2003), Scott et al. (2004), Mancini & Scott (2006), Blandford et al. (2008), Anaya & Jones (2009), Lucas et al. (2010), Phelps (2011) | |
| Data Contact Points | |
| Upper Edwards | Barnes (1974), Scholle (2003) |
| Lower Edwards | Reeves, R. & Small, T. (1973), Barnes (1974), Fallin, (1989), Blandford et al. (2008), Anaya & Jones, (2009) |

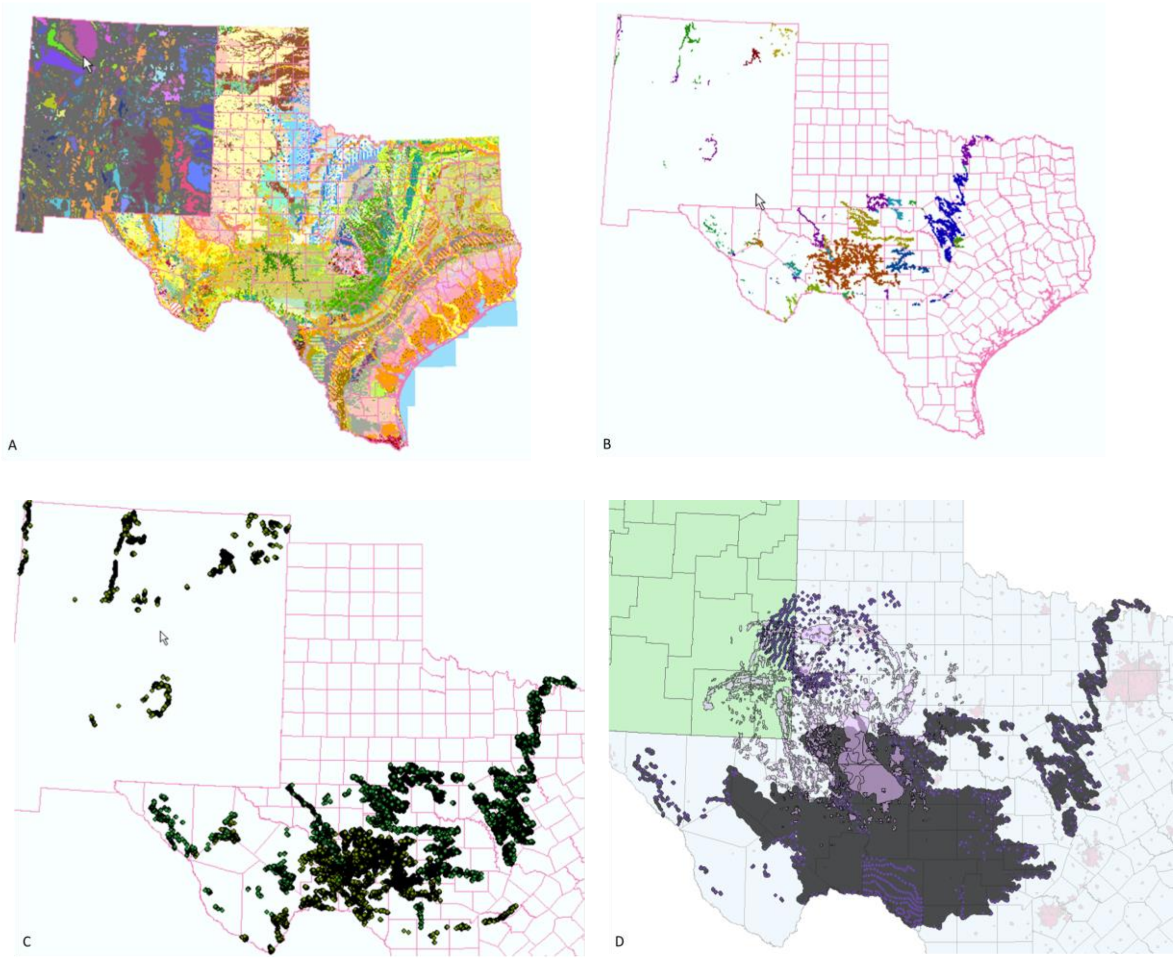


Figure 6: Images showing the steps for uplift and tilting dataset compilation. A) Digitized geologic maps for Texas and New Mexico used to identify outcrops of the upper and lower Edwards Group contacts (B). Extraction of contact lines for upper and lower Edwards. (C) Contact lines converted to point data. (D) Merging of outcrop with subsurface data for lower Edwards Group.

## Oil Field Attribute Dataset

Evaluation of the location of potential ROZs and the appropriateness of regional hydrodynamics as the driving mechanism depend on the availability of oil field reservoir and fluid properties. To assess fluid, reservoir, and ROZ relationships over the entire region, a database was amassed from oil and gas field data from field reports and other sources (Table 5).

Most sources of field data were only available in print or as scanned papers. These data were manually input into a database. After culling for data errors in the original data or manual entry, each field and each stratigraphic/reservoir name was assigned a classifier. These classifiers were then combined to give each reservoir in every field a unique identifier. This included normalizing field and stratigraphic names in addition to eliminating quantitative values that were significant outliers resulting from input error in the original reports. Qualitative data, such as dominant lithology and oil color were assigned quantitative values so that they could also be easily analyzed.

Where data sources already existed in digital form, the data was again culled to normalize names and eliminate outliers. Unique identifiers were used to combine this field data with the database built from manual input into a single data base consisting of over 75 rock and fluid attributes for over 2800 individual reservoirs from separate formations in over 1500 fields. Some attributes were calculated during this work (Table 6). The most significant attribute that relates to work presented in this document is the conversion of water resistivity data to water salinity based on the resistivity value and temperature of measurement. For fields where temperatures were not reported, values were estimated from depth and geothermal gradient from measurements by Ruppel et al., 2005. For all fields where this data was available, the salinity was calculated. Because a central tenant of the theory of hydrodynamic formation of ROZs is the influx of meteoric waters, low formation water salinity may be an indicator of past ROZ forming processes.

In the course of quality control, some subjective decisions were made. Some data points were clear outliers. If the outlier did not correlate with other field data, writing in the field report, or adjacent field data, it was excluded. Some fields were listed with multiple reservoirs. For these entries, the reservoirs were split into individual stratigraphic units and the same data assigned to each except where other data sources listed the fields and corresponding data individually, in which that data was preferred. Similarly, multiple sources listed the same fields but provided different values for the same attribute. The data from these sources were combined into a single reservoir. Where enough data was present, the mode or median value was typically selected as the representative value. Otherwise, a subjective decision was made based on comparison of that data to data from nearby fields. Subjective decisions were also made for some qualitative or identifying information of fields that was incomplete, inconsistent, or in error. Decisions were made typically by comparing data from nearby fields. With respect to depth, some sources listed the depth to the top of the reservoir and others listed to production depth or other well point. Where multiple depths were reported, depth of production was commonly listed as this was the exact depth from which fluid attributes, temperature, and pressure were most likely measured and could be several hundred feet below the top of the reservoir where conditions would be different.

Once compiled, data was analyzed for relationships potentially corresponding to ROZ presence or absence. These relationships were reviewed to resolve what reservoir attributes might best correlate with ROZ potential. This data was also used to determine average, median, and statistical qualities of all available rock and fluid properties for each formation group. Analyses such as the determination of the predicted POWC tilt in a reservoir depend on reservoir conditions. For these analyses, relevant data for reservoir conditions and fluid properties were used to compute the estimated reservoir qualities and, subsequently, the TAF and critical tilt angle. Additional analysis from this database was carried out to either eliminate alternative explanations of observed relationships or assess other potential attributes connected to ROZ but is not present here.

For added functionality, location information was gathered for over 95% of the fields. The location information and database were then merged into ArcGIS and the same reference layer as the uplift data. This spatial comparison of fluid and rock properties across the region provides the capacity for visualizing the location and distribution of ROZ proxy data, and therefore, ROZ potential.

While the data used were all gathered from other sources, the database built is the most robust dataset found to be publically available and enabled statistically significant analysis of data for formations throughout the Permian Basin. Where formations had limited data, they were typically grouped with adjacent reservoirs with similar overall properties for the purpose of both analysis and display.

Table 5: Primary sources used for Permian Basin oil attribute database

| **Primary Sources For Permian Basin Oil Attribute Database** |
|---|
| RGS (1956, 1960, 1967, 1977, 1988, 1995), Herald (1957), Stewart, W., (1964) Barnes, V., (1974), Pierce et al. (1978), SPE (1982a, 1982b), WTGS (1982, 1987, 1990, 1994, 1996, 2005), NPC (1984), NIPER (1992, 2004), Dutton et al., (2005), Manrique et al., (2004) |

Table 6: Data types and amounts compiled for Permian Basin reservoirs

| **Database Attributes** | |
|---|---|
| **Geologic Properties** | Porosity, Permeability, Lithology, Depth, Temperature, Pressure, Coordinates |
| **Fluid Properties** | Salinity, Resistivity, Geochemistry, pH, OWC Tilt, |
| **Oil Properties** | API, Sulfur Content, Color, Base, Viscosity, GOR |
| **Number of Fields** | 1500+ |
| **Number of Reservoirs** | 2800+ |

## Data Quality

In both the elevation and reservoir attribute data sets there are some data quality issues. For the elevation data, there are multiple sources of error. Some error is introduced when overlaying contact location points with the DEM. Most of this error was introduced when the geological atlases were digitized. Because much of the exposures in this region are along bluffs, a shift of only 5 or 10 m horizontally can result in a difference of over 30 m vertically. Additionally, subsurface data from TWDB and TCEQ are largely based on driller's reports, which have their own quality issues with regard to the exact location of well datum elevation, and identification of the contact as lithological descriptions vary immensely between different drillers. In all cases, the data included went through quality control, but this does not entirely eliminate error. The error in elevation data is not systematic and is insignificant over the basin-wide scales of hundreds of kilometers over which it is assessed.

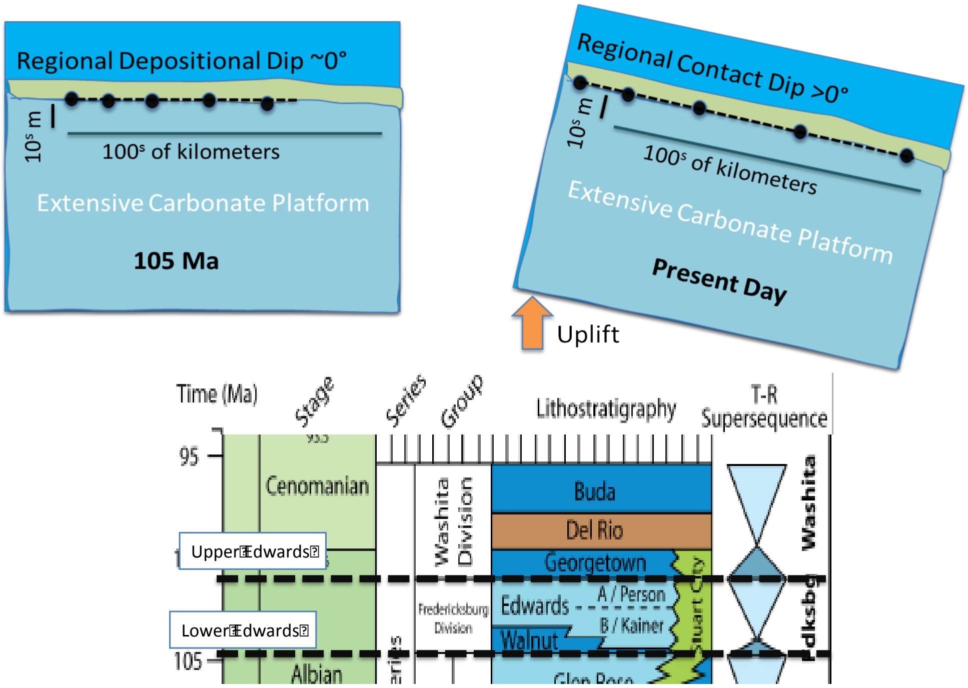
Similarly, there are data discrepancies within the database of reservoir attributes. The sources of error include initial errors in published reports, error during the data entry process, and the discrepancies between multiple reports available for the same field and reservoir that couldn't be removed during data quality control efforts. Analysis on large sets of this data provides robust, broad trends despite local errors. Outliers during analysis noted were double-checked and corrected if needed. In total, this database should be considered as robust as any publically available. Therefore, it is with confidence and limited uncertainty that the results are presented.

## Methods & Results

The two broad questions being addressed are (1) whether hydrodynamics related to late-stage uplift and tilting can account for formation of observed ROZs and (2) where are ROZs located in the Permian Basin. Separate approaches were taken to assess these two issues. Because each subsequent approach follows from prior results, both the methods and results of each are presented together sequentially.

### Quantifying Late-Stage Regional Uplift and Tilting

The key component in testing the hypothesis of tectonically induced hydrodynamic formation of ROZs is determining the actual extent of late-stage uplift and tilting. While the present structure of Permian strata is well studied, the important aspect as it pertains to ROZ formation is how much structural relief can be attributed to Laramide and Basin and Range tectonics. To assess this, the time equivalents of the upper and lower stratigraphic contacts of the Edwards Group (Late Albian, ~105-100 Ma; Rose, 1972; Phelps, 2011) were selected as a proxy datum for paleo-sea levels (Figure 6).



Phelps (2011)

Figure 7: Simplified schematic showing approach of using the bounding surfaces of the Edwards Group – a regionally extensive, conformable, shallow water deposit – as a regional proxy for a pre-tilt flat surface. Any present day tilting is then equivalent to total Late Cretaceous and Tertiary tilting of the Permian Basin.

The Edwards Group and equivalent facies comprise the initial flooding sequence of the shallow-water epicontinental Western Interior Seaway (Figure 7) into the mid-continent. These late Albian carbonate platform tops were selected as a sea level datum for two key reasons: the Edwards Group predates both the Laramide and Basin and Range events (~80-40 Ma) avoiding the uncertainty pertaining to the relative influence each; the Edwards Group and time-equivalent formations are composed of extensive shallow-water carbonate facies, deposited over the Comanche Shelf (Figure 8) (Fisher & Rodda, 1969; Rose, 1972; Kerans, 2002).

On the shelf, depositional topography of the Edwards Group undoubtedly varied locally, but throughout an entire transgressive and regressive supersequence (Phelps, 2011), the faunal and facies relationships indicate consistent shallow water deposition across the spanning over the entire region including the Permian Basin (Rose, 1972; Fisher & Rodda, 1969). The consistent shallow-water lithology indicates that these sediments were deposited regionally within 10 m of sea level. This interpretation is supported by the observation that there are no deep-water fauna or facies transitions, as would be expected if there were a steadily dipping depositional surface spanning hundreds of kilometers.

Over the ~400 km extent of the Permian Basin, even 100 m of depositional topography would amount to a regional dip of 0.014°, which is similar to those for other carbonate ramps and shelves (Read, 1985). Furthermore, the direction of increasing thickness of Edwards equivalent is towards the southwest (Rose, 1972; B) whereas modern topographic gradient is to the southeast (Figure 3). Therefore, without greater detail of the actual depositional topography, this work assumes that the depositional surface of Edwards Group geologic contacts had minimal, shallow regional dip and that the present day relief on the contacts is representative of uplift and tilting that has taken place in the past 100 Ma. The greatest source of error is that the data compiled represents a somewhat time-transgressive surface. However, because the average thickness of the Edwards Group over the region is ~150 m, the error introduced is minimal. Further justification of the use of the Edwards Formation and their equivalents is found in the Discussion on data quality.

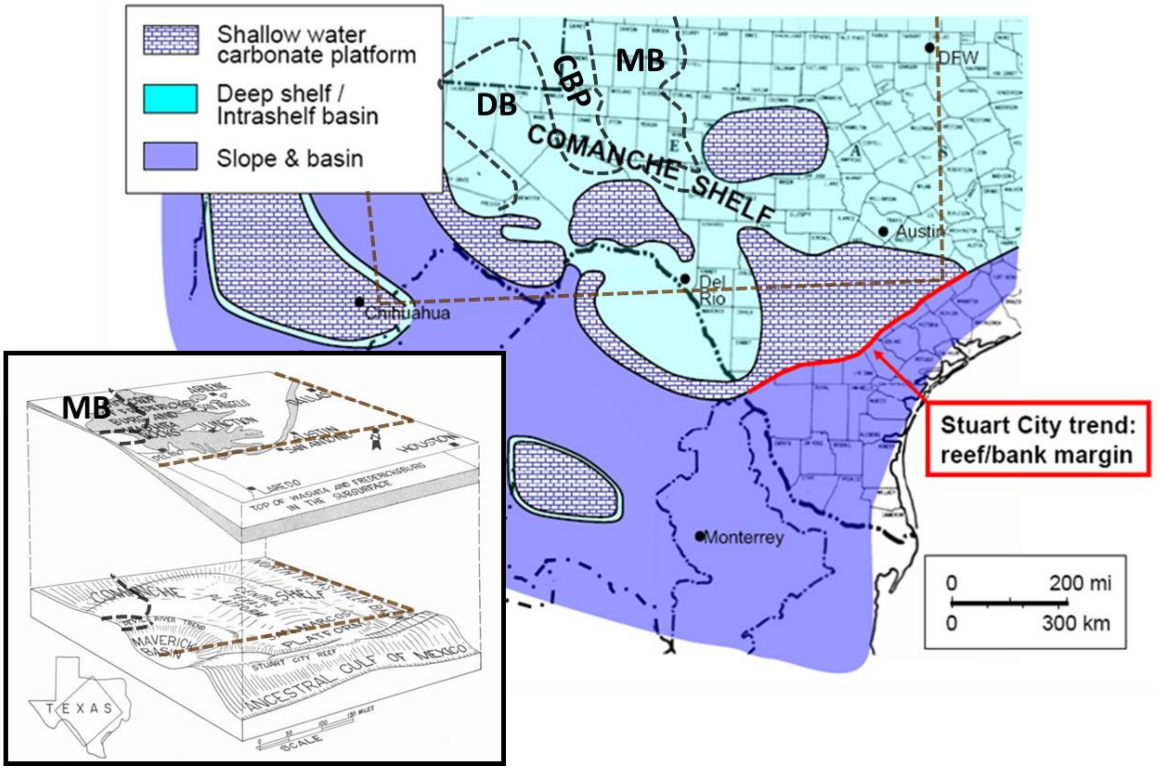


Figure 8: Image depicting the depositional environment during mid-late Albian. Image shows area over Permian Basin to be expansive carbonate shelf (Kerans, 2002). Inset features figure adapted from Rose (1972) indicating the eastern edge of the Midland Basin to be over the Comanche Shelf but largely removed from Cretaceous-age structures. The black dashed line represents approximate edges of Permian structural features Brown dashed line represents approximate edges of interpolated surface structure of the lower Edwards contact (Table 3; Figure 10). Figure used here to indicate that depositional topography over the region of the Permian Basin platform was relatively flat. Beyond the Permian Basin region but within the area investigated for uplift, some present structural relief can be tied to depositional topography (i.e. Maverick Basin), although most of the region is also flat at deposition.

The Data section discusses the construction of the dataset used to assess the present elevation of the Edwards Group surfaces. Both the upper and lower Edwards surfaces are utilized due to data availability. While the upper Edwards contact data points are more aerially extensive, the lower Edwards contact points have greater density and coverage (Figure 9). Thus, the upper Edwards points are used to determine the total differential uplift between the peak elevations of the Sacramento Mountains and the easternmost extent of the Permian Basin. The lower Edwards data points, though time transgressive, are then used to generate the interpolated surface over the Permian Basin, showing the local tilting and variations over reservoir formations.

Using the data set developed for this study, the maximum differential uplift measured from the highest outcrops of the Edwards Group in the Sacramento Mountains to the southeast corner of the Midland Basin is 1800 m (Figure 7). Over a distance of 450 km, this translates to an average slope of 0.128˚ (2.34 m/km) over the entire basin.

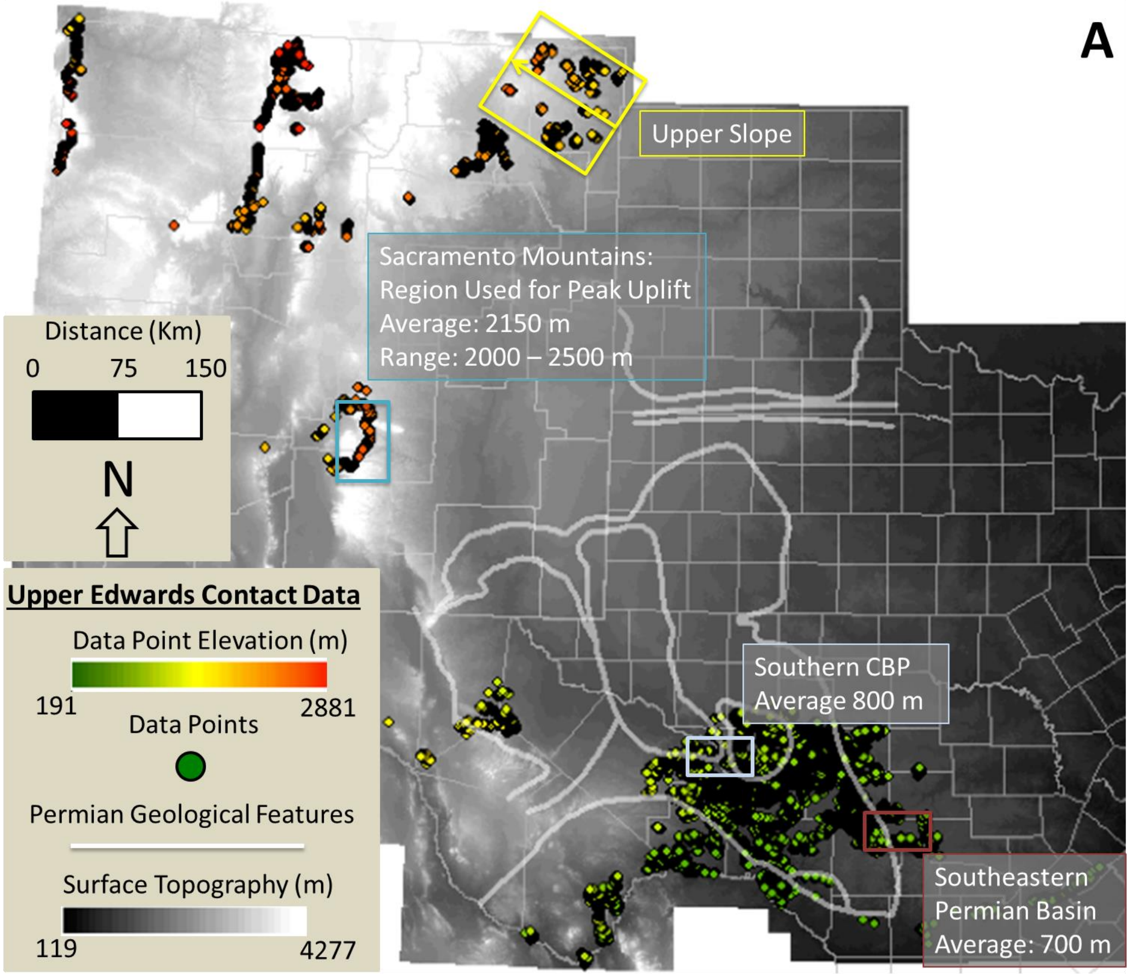


Figure 9: (A) Combined data points for UE contacts colored by elevation. Areas from which total differential uplift and tilting are estimated highlighted by boxed areas (Table 7)

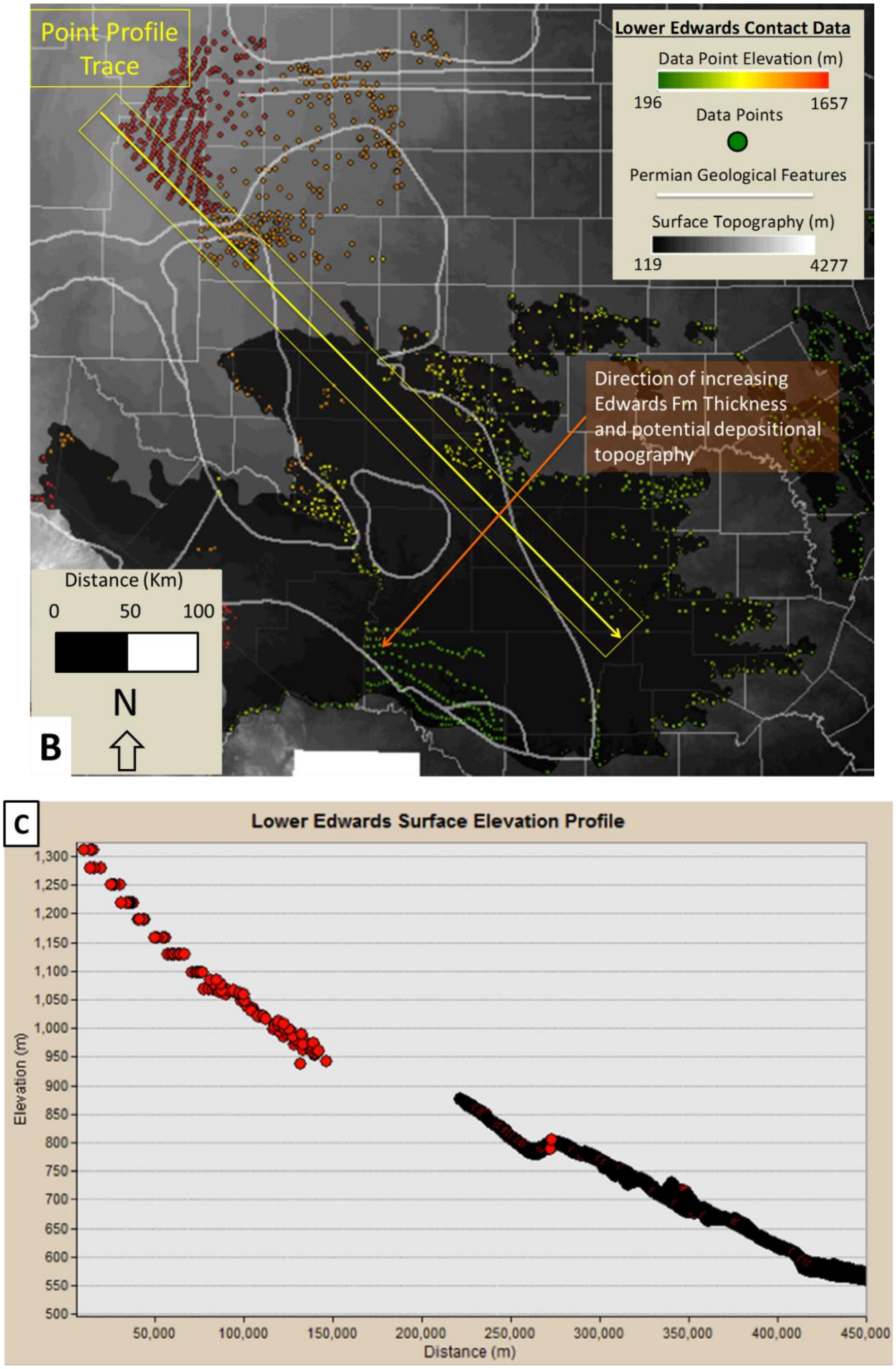


Figure 9: (B) Lower Edwards contact data points colored by elevation. Yellow area is trace of range from which point profile (C) is taken. Elevation of profile ranges from 0-1300 m over 450 km. For data point sources see Table 4.

Table 7: Quantification of differential uplift and tilting across the Permian Basin region from elevation profiles of the upper Edwards (Figure 9). Lower and Upper Slope refer to the slope to the west (Upper) and east (Lower) of the Pecos River hinge point.

| **Variable (Δz/Δx)** | **Value** | **Slope** | **Note** |
|---|---|---|---|
| | | m/km | |
| **Total Uplift (Δz)** | 1800m | -- | Total uplift variable depending on end points selected for upper Edwards. This taken for southeast Permian Basin corner and mean max elevation value (Figure 9A) |
| **Max Regional Tilt** | 0.215° | 3.75 | Assumes max peak elevation and south CBP discharge (9A) |
| **Min Regional Tilt** | 0.128° | 2.23 | Assumes minimum peak elevation and southeastern Permian Basin end points (9A). |
| **Permian Basin Tilt (Lower Slope)** | 0.128° | 2.23 | Taken from lower Edwards surface starting east of the Pecos River (9B) |
| **Upper Slope** | 0.458° | 8.00 | In northeast New Mexico (Union County) from upper Edwards (9A) |
| **Southern High Plains Topographic Tilt** | 0.135° | 2.36 | Taken from Western Escarpment to next erosional point (Figure 11) |
| **San Andres Formation Regional Tilt** | 0.286° | 4.99 | Uses total tilt of 2150 m from Sacramento Mountains to southern tip CBP (9A) |

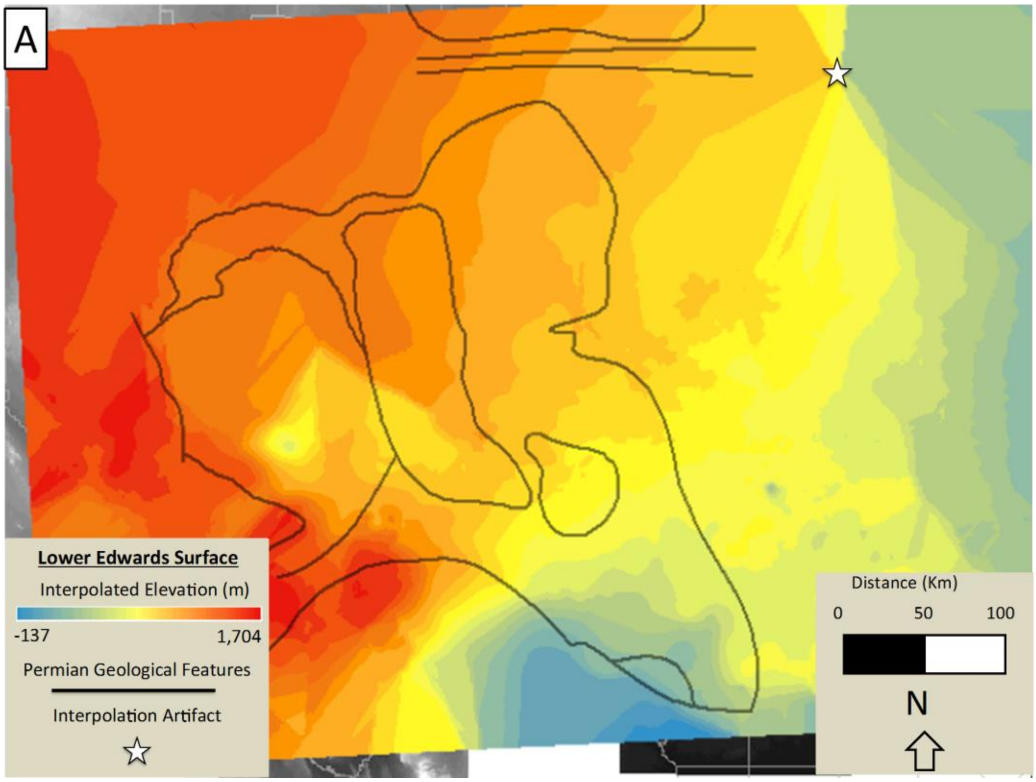


Figure 10: (A) Resulting structural surface of lower Edwards Group data points from krigging using ArcGIS

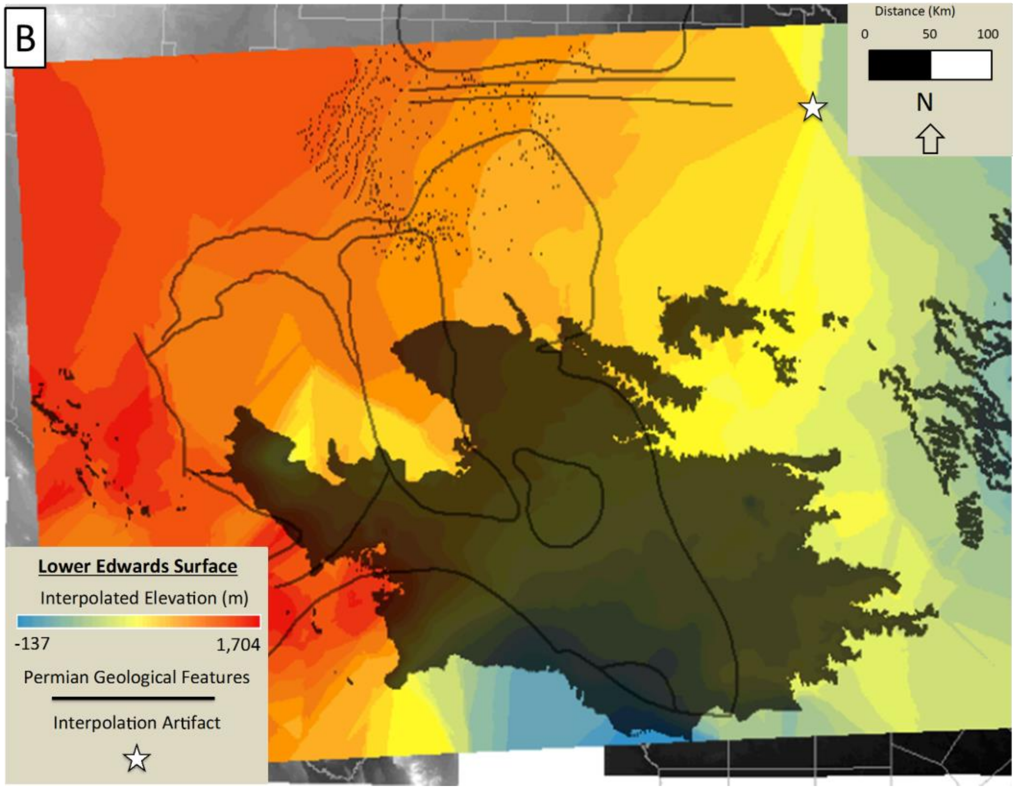


Figure 10: (B) Interpolated surface with contributing data points.

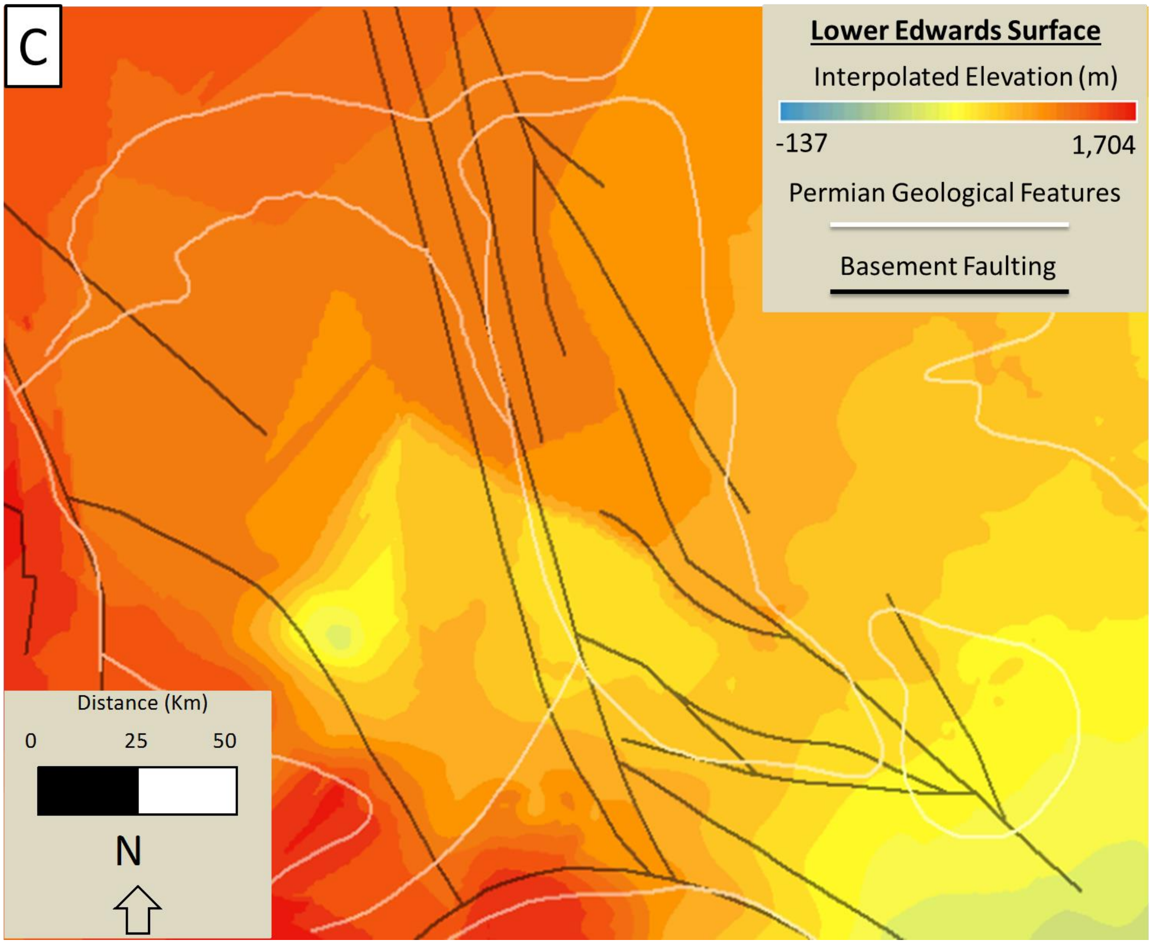


Figure 10: (C) Interpolated surface with overlay of basement faults (Dutton et al., 2005). Basement structures appear to correspond to local variance in lower Edwards surface at many points.

As would be expected of broad regional uplift, tilting is mostly gradual across the Permian Basin with limited deviations (Figure 9 & Figure 10). Aside from areas in the peaks of known major uplift to the west and southwest, the two main breaks in the structural trend occur over the Delaware Basin and south-central CBP (Figure 10C). There is also an increase in slope approaching the Sacramento Mountains (Figure 9B, Figure 9C, & Figure 10) with the hinge corresponding roughly to the Pecos River (Figure 11). West of the Pecos River, the tilt increases to 0.215˚ (3.75 m/km) (Figure 11, Table 7).

Worth noting is the similarity between the Edwards Group and surface topography. The slope profile of the Edwards Group is similar to present day topography (Figure 3, Figure 10). For example, the High Plains region of New Mexico and Texas tilts at 0.135a (2.36 m/km) (Table 7, Figure 11), very similar to the 0.128˚ slope of the Edwards over the same region. The lower Edwards and modern topography are also aligned in the area of sharp change in Edwards Group elevation along the south-central CBP. The sharp face in the interpolated surface (Figure 10C) is expressed at the surface as an erosional scarp (Figure 3).

While the Edwards Group was assumed to initially be flat, Permian formations had pre-Cretaceous structural dips resulting from depositional topography, compaction, and broad scale pre-Cretaceous deformation (Table 2). Therefore, the present day structure on the San Andres Formation drops 2,150 m from the Sacramento Mountains to the southern CBP, a tilt angle of ~0.286º (Table 7). The relation between this regional tilt and ROZs is the potentiometric gradient, assuming that the elevation head (Hubbert, 1953) is the dominant component of regional hydrodynamics and that the slope is measured from the relative recharge and discharge zones. The regional slope (Table 7) of the San Andres Formation can be treated as the maximum potentiometric gradient of the San Andres aquifers and associated oil field POWC tilts prior to the decline of the water table to modern levels.

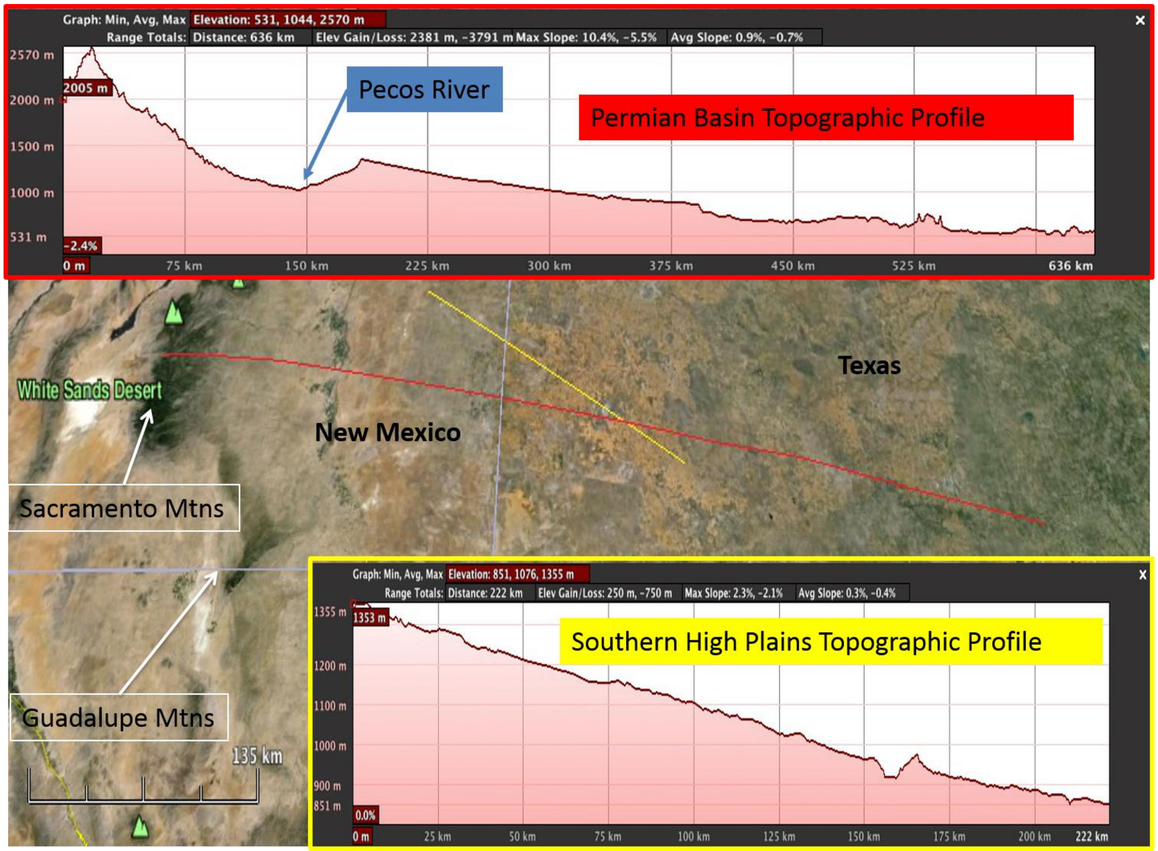


Figure 11: Topographic profiles across Permian Basin (red) and along dip of the Southern High Plains (yellow). Image created from Google Earth™. Surface topographic gradients are approximately the same as dip determined from Edwards Group contacts (Table 7).

## ROZ Thickness Comparisons

Having quantified the amount of uplift and tilting, the next question is whether or not the numbers fit the ROZ observations. Using a simple box model, the tilt of the POWC wedge at several San Andres fields is calculated from the maximum regional San Andres potentiometric gradient (0.289˚) and from the reservoir fluid properties listed in the Permian Basin reservoir database compiled for this study. Fluid properties are adjusted to specific reservoir conditions for each field. Assuming the reservoir filled to spill initially, the area of the wedge formed by the tilted POWC was converted back to a rectangular thickness by keeping the reservoir width and total displaced area fixed (Figure 12; Table 8, fourth column). This predicted thickness was compared with the measured thickness of the ROZ as reported in published sources (Table 8, second column). The predicted ROZ thicknesses for the maximum potentiometric gradient are also compared to predicted ROZ thicknesses for the current potentiometric gradient reported for the fields by Keller (1992) and Brown (2001). Their studies were based on data from pre-production field reports. This analysis offers a first-order assessment of the capacity for past and present hydrodynamic forces to drive the ROZ formation observed in the Permian Basin.

The lack of available specific reservoir data such as stratigraphy, geometry, and spatially distributed rock properties like permeability necessitates the simplicity of this model. Hence, the results should not be expected to predict an exact match. Rather, this model is meant to determine whether estimates are generally consistent with measured ROZ thickness. If predictions were regularly much larger or smaller than actual measurements, it would indicate that the hypothesis that hydrodynamic forces are a primary driver is inconsistent with observations. If this were true, the hypothesis should either be amended to incorporate alternative explanations for ROZ formation (i.e. buoyancy) or account for reservoir-scale controls that might influence ROZ formation more than regional scale forces.

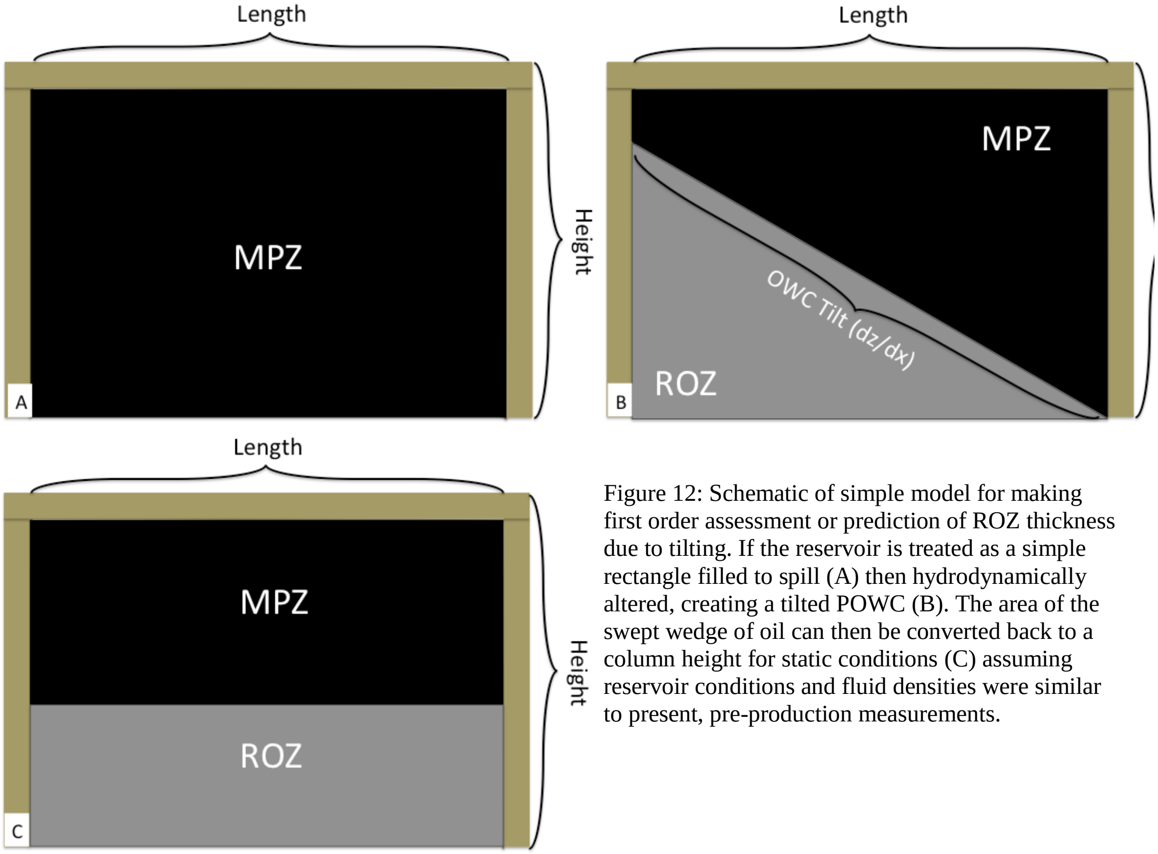


Figure 12: Schematic of simple model for making first order assessment or prediction of ROZ thickness due to tilting. If the reservoir is treated as a simple rectangle filled to spill (A) then hydrodynamically altered, creating a tilted POWC (B). The area of the swept wedge of oil can then be converted back to a column height for static conditions (C) assuming reservoir conditions and fluid densities were similar to present, pre-production measurements.

At every field except for Wasson, the maximum potentiometric gradient predicted ROZ thickness to within 50% of the measured value (Table 8). The average absolute error between the model estimate for the maximum potentiometric gradient and measured thickness as reported or illustrated in field studies is twenty-seven percent. While the Wasson (50%) and Seminole (-45%) fields have the greatest predictive error, they are also unique as the local potentiometric gradients and tilts of their OWCs is nearly perpendicular (Brown, 2001) to the gradient of regional tilt and general fluid flow. These local hydrodynamic and their related stratigraphic controls may account for some of the increased error in these fields.

The maximum hydraulic gradient provides a more accurate estimate of actual ROZ thickness than the pre-production regional potentiometric gradient (McNeal, 1964;

Dutton & Orr, 1986) for all but one of the reservoirs. Therefore, not only are potential paleo-hydrodynamic conditions a viable explanation for ROZ formation, but they may potentially be a better predictor of ROZ thickness than present day hydrodynamics.

Table 8: Results from applying simple model (Figure 12) known and predicted maximum regional hydrodynamic forces to known ROZ fields.

| Field | Measured ROZ Thickness (m) | Predicted thickness from measured POWC tilt (m) [% Error] | Predicted thickness from max potentiometric tilt (m) [% Error] |
|---|---|---|---|
| **Means**[1] | 122 | 27 [-78%] | 116 [-4%] |
| **Seminole**[2] | 99 | 12 [-88%] | 54 [-45%] |
| **Goldsmith**[3] | 46 | 19 [-59%] | 55 [19%] |
| **Wasson**[4] | 84 | 77 [-9%] | 127 [50%] |
| **S. Cowden**[5] | 30 | 40 [31%] | 25 [-16%] |

[1]Pathak et al., 2012, [2]Honarpour et al., 2010, [3]Trentham, 2012, [4]Brown, 2001, [5]Lucia, 2000

## Hydrodynamic Versus Buoyant Driven ROZ Formation and Oil Migration

Just as uplift and tilting can initiate hydrodynamic forces (Figure 2B), they also alter the geometry of reservoir traps. If a reservoir is filled to spill and the trap geometry shifts (i.e. tilts), a new spill point is established, allowing for the buoyant migration of some oil beyond the former spill point and out of the trap (Figure 2C). In the Permian Basin the regional potentiometric gradient runs predominantly down structural dip (McNeal, 1964; Dutton & Orr, 1986), in opposition to up-dip buoyant migration of oil. With the two contrasting forces at play, it is important to determine which force is likely the most dominant in affecting ROZ formation and the migration of any displaced oil beyond the reservoir.

Using the median reservoir oil and brine fluid properties (Table 6) for the San Andres Formation corrected to average reservoir temperature, a graphic method devised by Davis (1987) is employed to determine the dominant force based on Hubbert’s (1953) hydrodynamic equation (Equation 2). Davis (1987) rephrases Equation 2 in terms of the driving forces acting on fluids in the subsurface and their respective horizontal components, which can be used to solve for the structural dip at which competing buoyant and hydrodynamic forces are balanced and expressed as

$$(3) \qquad \tan(\mathrm{S}) = \left\lfloor \frac{\rho_w}{\rho_w - \rho_o} \right\rfloor \frac{\partial \mathrm{h}}{\partial \mathrm{f}}, ,$$

where S is the angle of structural dip (˚) and $\frac{\partial \mathrm{h}}{\partial \mathrm{f}}$ = the potentiometric gradient parallel to the bedding planes ($\frac{m}{m}$), which is the actual value determined from well bore measurements but typically written $\frac{\partial \mathrm{h}}{\partial \mathrm{x}}$ assuming a horizontal bedding plane (Davis, 1987). Equation 3 provides the ability to solve for the critical dip angle of the confining strata for at a fixed TAF for any given potentiometric surface gradient. In terms of Equation 2, if the angle of the tilted POWC is greater than the dip angle of the confining unit, then the oil will flow in the direction of the water drive. If not, oil will move in the opposite direction, driven primarily by buoyancy.

Graphing solutions for Equation 3 at a known TAF with $\frac{\partial \mathrm{h}}{\partial \mathrm{f}}$ along the horizontal axis and S the vertical axis, provides the curve of critical points at which hydrodynamic and buoyant forces are balanced and oil remains stationary (Figure 13). If the intersection of the dip angle and potentiometric gradient falls to the right of the curve, water drive will be the dominant force driving oil movement. Under conditions falling to the left of the curve, oil buoyancy will be the dominant driving mechanism. This calculation is relevant to both the displacement of oil from a reservoir and its movement along the migration pathway.

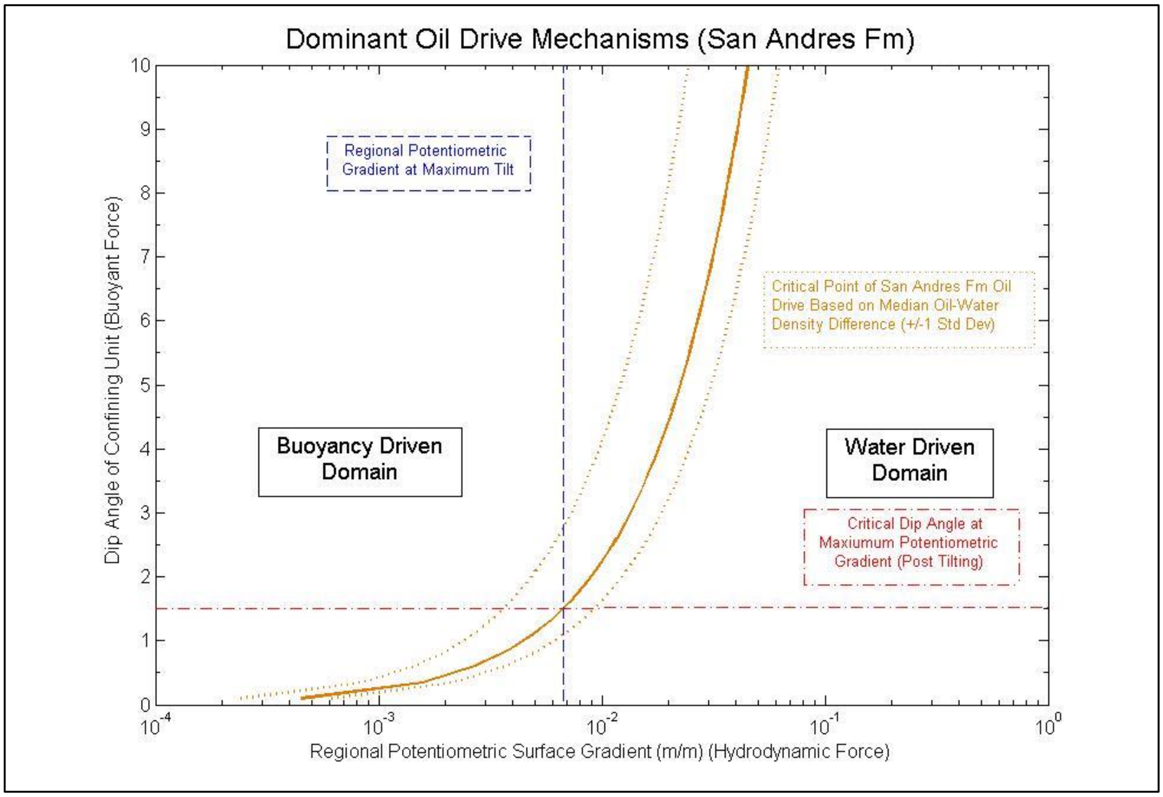


Figure 13: Comparison of the impact of tilting-induced buoyancy against the hydrodynamic gradient for the San Andres Formation using the average contrast in oil-water density. Hydrodynamics control oil migration for conditions right of the curve and buoyancy to the left. Regional conditions are plotted indicating that at the regional level, fields dipping ~1.5˚ or less will have down dip oil migration.

At the maximum potentiometric gradient of the San Andres Formation ($10^{-2.31}$), the critical angle for oil drive is 1.5˚ for median TAF calculations, with a range of ~1.1˚ to 2.75˚ falling within one standard deviation (Figure 13). This means that for any field at which the structural dip of the confining unit or trap is less than 1.5˚ (or <1.37˚ before tilting), oil movement would have been driven by hydrodynamic forces. Buoyant forces would drive oil movement beneath confining structures dipping greater than 1.5˚. Because the San Andres shelf region, where many oil reservoirs are located, has a broad structural dip less than 1.5˚ (Ramondetta, 1982b; Figure 14), hydrodynamic forces should have been the primary mechanism driving ROZ formation and oil migration in the areas where most ROZs have been identified.

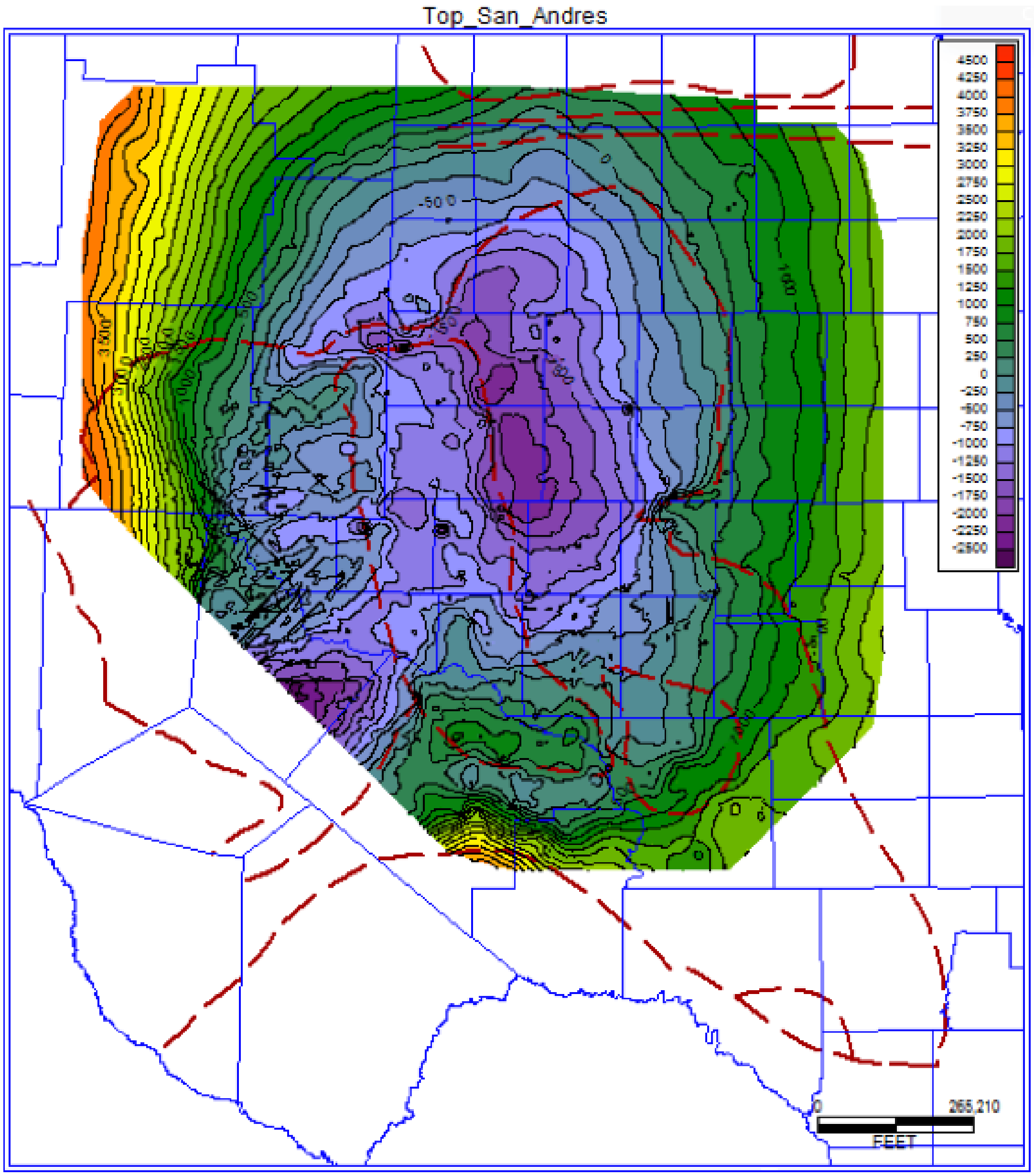


Figure 14: Low-resolution structural map of top San Andres Formation and equivalent formation tops from Carr (2012). Contour Interval is 250 ft. Much of the structure over oil-bearing regions along the shelves and CBP dip at <1.5˚ where hydrodynamic forces would have been dominant at the maximum potentiometric surface gradient. Structural topography largely controlled by underlying features and differential compaction. Structures vary locally and have dips >1.5˚ in places.

## ROZ Proxy Identification and Location

The above results provide additional support for regional hydrodynamics driving ROZ formation. If the oil distribution prior to uplift and tilting was known, this fundamental understanding of ROZ formation indicates that the location of ROZ could be predicted the using a regional groundwater flow model. However, pre-tilt oil distributions remain an unknown and the development of such a model is beyond the scope of this effort as it carries considerable uncertainty when quantifying and predicting the timing of past conditions. Rather than predicting ROZ presence theoretically, this study identifies potential ROZ locations using proxy data.

This study combines empirical evidence from Permian Basin ROZs (see Background) with an understanding of what processes could take place during hydrodynamic formation of a ROZ in potentially meteoric water to define expected attributes of a ROZ (Table 9). Attributes are defined as primary and secondary indicators that are further categorized as direct and indirect. Primary indicators are considered those that are an intrinsic quality of a ROZ. Secondary indicators are characteristics demonstrative of the occurrence of ROZ-forming processes but do not confirm ROZ presence. Primary and secondary indicators can be further divided into direct and indirect lines of evidence. The former are direct observations of ROZ presence (primary) or ROZ-forming processes occurring after oil accumulation (secondary). Indirect indicators are observations that are byproducts of ROZ formation or ROZ-forming processes but not necessarily evidence solely attributable to either. Whereas direct evidence stands alone, indirect evidence is suggestive but not proof.

Table 9: List of characteristics commonly associated with known ROZ fields in the Permian Basin. Based on work by Melzer (2006) and Trentham (2012).

| Indicator | Relation to ROZ | Alternate explanations | ROZ Interpretation/Evidence in Literature | Sources |
|---|---|---|---|---|
| Primary – Direct | | | | |
| Imbibition Profile | Result of displaced oil | None | All known ROZ have imbibition profiles | (Pathak et al, 2012; Honarpour et al, 2010; Brown, 2001; Lucia, 2000) |
| Primary – Indirect | | | | |
| Non-productive oil shows in cuttings | Immobile oil saturation | Transition zone, waste zone, carrier bed, dual porosity system, etc. | No direct studies. Original field reports note non-productive shows in some known ROZ Fields | WTGS Oil & Gas Field Reports (1952, 1957, 1960, 1975, 1998, 2005) |
| Promising log $S_o$ calculations non-Productive | Immobile oil saturation | Calculation error due to heterogeneity, low salinity formation fluid, etc. | No direct studies. Noted difficulty in assessing ROZ saturation from logs and core. | Pathak et al (2012) and Honarpour et al (2010) |
| Secondary - Direct | | | | |
| Oil degradation | Shows oil-water interaction | Interaction could have occurred along migration pathway or in a different trap prior to migration into current reservoir | Linked to interaction with meteoric water, especially in sulfate rich environments | Ramondetta, 1982; Smith, 1968; Jones & Smith, 1965 |
| Secondary - Indirect | | | | |
| Tilted OWC | Hydrodynamics | Frozen-In, Pre/Post Emplacement/Capillary Pressure | Arguments for hydrodynamic, frozen-in, and rock-property explanations of tilted OWC exist in literature. Most recent and common literature points to hydrodynamics, directly refuting other possibilities. | Frozen-in: Keller (1992), Wilson (1977)<br>Hydrodynamics: Hubbert (1967), Gratton & Lemay (1968), McNeal (1964), Hiss (1980), Brown (1992, 2013) |
| Native Sulfur | Byproduct of oil biodegradation by imbibing meteoric waters | Abiogenic or related to upwelling from basin | Formed as byproduct of biogenic sulfate reduction then oxidation | Hill (1996), Leary & Vogt (1990), Hentz & Henry (1989), Zimmerman & Thomas (1969) |

Table 9 (continued)

| Indicator | Relation to ROZ | Alternate explanations | ROZ Interpretation/Evidence in Literature | Sources |
|---|---|---|---|---|
| Secondary - Indirect | | | | |
| Evaporite Dissolution | Meteoric water diagenesis during hydrodynamic sweep | Predates or unrelated to ROZ | Occurs during influx of undersaturated meteoric waters | Hill (1996), Leary & Vogt (1990), Hentz & Henry (1989), Zimmerman & Thomas (1969) |
| Solution enhanced fractures | Meteoric water diagenesis during hydrodynamic sweep | Predates or unrelated to ROZ | Nothing found in literature | |
| Secondary dolomitization | Late-stage diagenesis by meteoric waters and microorganisms during biodegradation and hydrodynamic sweep | ROZ-dolomite correlation is coincidental or dolomite is precursor to ROZ | Literature suggests that periods of dolomitization are syn- and early post-depositional and is supported by isotopic analysis. Altered “secondary” dolomites noted as forming in conjunction with exposure and mixing with during Permian. However, lab experiments show possibility of microbial-supported precipitation of dolomite crystals in groundwater conditions similar to ROZ mixing zone | Leary & Vogt (1990); Lucia (2004); Garcia-Fresca (2011); Roberts (2004, 2012); Saller & Henderson (1998); Mazzullo (1986) |
| High dissolved $H_2S$ | By product of oil biodegradation in presence of $SO_4$ | $H_2S$ derived from oil-sulfate reactions in the deep basin and migrated up with oil, not formed in situ | Literature shows that $H_2S$ is byproduct of biogenic sulfate reduction in oil-water mixing zones | Hill (1996), Leary & Vogt (1990), Hentz & Henry (1989), Zimmerman & Thomas (1969) |
| Potentiometric surface | Shows hydrodynamics | Shows for today, not past, not great enough regional level to explain height of certain ROZ | Uplift initiated at latest by 18 Ma and is direct source for potentiometric gradient | McNeal (196); Dutton & Orr (1986) |
| Hypogenic karsting | Evidence of fresh water and H2S | Is thought to have migrated up from the basin. Not necessarily related. | Some literature shows it tied to sulfate reduction in basin, but same processes are known to occur in ROZ fields | Hill (1996); Leary & Vogt (1990) |

Table 9 (continued)

| Indicator | Relation to ROZ | Alternate explanations | ROZ Interpretation/Evidence in Literature | Sources |
|---|---|---|---|---|
| Secondary - Indirect | | | | |
| Dolomite etching | Presence of undersaturated fluids | Could have occurred outside of ROZ formation | Timing indicates dedolomitization affiliated with Cenozoic meteoric water influx | Lindsay (2001); Leary & Vogt (1990) |
| Low salinity formation waters | Meteoric water | Infiltrated during previous, non-ROZ forming process such as exposure and vertical infiltration rather than | Original formation seawater to supersaturated brines (Stueber et al, 1998; Dutton & Orr, 1986). Low salinities due to meteoric water influx (Dutton & Orr, 1986; Hiss, 1980) | Bein & Dutton (1993); Stueber et al (1998); Dutton & Orr (1986); Bein et al (1991); Dutton (1987) |
| Other Observations | | | | |
| Depositional Environment | Predominantly open marine | | | |
| Sequence stratigraphy | Thicker cycles | | | |
| Flow Properties | Fewer "baffles to flow" | | | |
| Mineralogy | "Double dose" dolomitization | | | |
| Lithology | Unaltered limestone beneath ROZ | | | |
| Petrophysics | Commonly better porosity and permeability than MPZ | | | |

Primary indicators all relate to oil saturation. The direct indicator would be an imbibition $S_o$ profile. Indirect observations are byproducts of low, immobile oil saturations including non-productive zones with oil shows, or zones that had been calculated as oil-bearing from well logs. The direct secondary indicator is evidence of oil degradation based on oil composition analysis, which results from the interaction of oil and water. Indirect secondary indicators for ROZs are formed by hydrodynamic forces, often in the presence of some meteoric water can be split into byproducts potentially reflective of hydrodynamics, diagenesis, or oil degradation though none can stand alone as evidence of oil-water interaction.

While there are several potential indicators of ROZ or ROZ-forming processes observable in Permian Basin reservoirs, not all indicators have readily available data and not all data are tied to strong indicators of ROZ presence. Of the categories for secondary, indirect evidence, the two most widely available are related to hydrodynamics and oil degradation. The qualities of hydrodynamic-related indicators as evidence of ROZ are less reliable. For example, measurements of salinity or resistivity are highly variable within a reservoir and even more variable across a broad region. Using a single value for a field is not necessarily representative of fluid properties and higher salinities do not exclude the possibility of water imbibition or injection into a reservoir. On the other hand, tilted POWCs common to ROZs in the Permian Basin can be strong evidence for hydrodynamic affects, but they are not recorded for every field, can be subjective depending on the operators definition of the OWC (i.e. POWC, economic OWC, etc.), must be determined prior to production, and should ideally be distinguished as the byproduct of hydrodynamics and not reservoir heterogeneity alone. For this reason, the indicators selected as proxies in this study are those pertaining to oil degradation.

Oil degradation is a suitable indicator for several reasons. In contrast to observations of diagenesis or hydrodynamics, which can take place in the absence of oil, oil degradation implies that ROZ-forming processes have occurred after or during the initial accumulation of oil into the reservoir. Previous work and the results discussed from this work suggest that hydrodynamic forces formed ROZs in the Permian Basin.

Therefore, oil degradation should be notable in the Permian Basin anywhere ROZ-forming processes have occurred but not in reservoirs remaining in static conditions contacting only connate brines.

Honarpour et al. (2010) and Cassidy (2013) demonstrate that ROZ oils are degraded. Ramondetta (1982a) provides the most extensive and direct analyses of oil degradation in the Permian Basin. Focusing on San Andres oils of the Northern Shelf, including Wasson, Ramondetta (1982a) concludes that meteoric groundwater infiltration attributed to hydrodynamics introduced sulfate-reducing bacteria into the reservoir. These bacteria anaerobically consume lighter hydrocarbons utilizing sulfates in the matrix as an oxygen source. Byproducts of this process include reduction of calcium sulfates ($CaSO_4$) to native sulfur (S), production of hydrogen sulfide ($H_2S$), precipitation of calcite ($CaCO_3$), and increased concentration of sulfur components in the crude oil (Equation 4).

$$(4) \qquad CaSO_4 + H_2O + \text{Hydrocarbon} + \text{Bacteria} \leftarrow\rightarrow CaCO_3 + CO_2 + H_2S + S$$

Each of these byproducts has been noted in various Permian Basin reservoirs including the dissolution of sulfates (Lucia, 2000; Vogt & Leary, 1990), presence of high sulfur, high aromatic oils (Jones & Smith, 1965; Smith, 1968; Belt & McGlasson,1968), presence of high dissolved $H_2S$ (Melzer, 2006), and the precipitation of biogenic native sulfur (Hentz & Henry, 1989; Ruckmick, 1979) and biogenic calcite (Tinker & Mruk, 1995; Scholle et al., 1992) replacing sulfates and sometimes trapping oil inclusions (Wiggins, 1993). Oil degradation, however, need not only occur via anaerobic biodegradation. Oil degradation can occur from both water washing and biodegradation (Bailey et al., 1973; Palmer, 1991; Head et al., 2003). In both cases, degradation proceeds through exposure of the oil zone to flowing and or meteoric waters as occurs in the Permian Basin.

While oil degradation is shown to affect ROZs in the Permian Basin, direct evidence of oil degradation in the form of compositional analyses is not available for a number of fields. Therefore, this work uses indirect evidence of oil degradation as its proxy for ROZ formation. Oil degradation can affect oil characteristics in multiple ways (Table 10). The alteration attributes most commonly recorded in oil field reports are crude oil gravity and sulfur content. If oil degradation is indeed occurring across the Permian Basin, it should be noted in API and the weight percent sulfur (wt%S). Ramondetta (1982a) demonstrates this relationship for a limited number of Northern Shelf San Andres oils. This study expands on his work and that of Jones & Smith (1965), using the database of Permian Basin reservoirs prepared here to look at the relationship across all Permian Basin reservoirs.

Table 10: Oil attributes that are affected by biodegradation. Adapted from (Bailey, 1973; Ramondetta, 1982a; Palmer, 1991)

| Oil Attribute | Expected Change in Quality |
|---|---|
| **Sulfur (S) (wt%)** | Increase |
| **Oil gravity (API)** | Decrease |
| **Viscosity (cp)** | Increase |
| **Asphaltenes** | Increases relative to saturated and aromatic content |
| **Acidity (oil pH)** | Increase |
| **Carboxylic acids & Phrenoids** | Increase |

In the Permian Basin, a strong correlation between API and crude sulfur content (Figure 15A) is consistent with the expected byproduct of oil degradation and is evidence supporting their use as proxies for ROZ potential in the Permian Basin. For this work, sulfur content is taken as the primary indicator as it is more reflective of degradation and potentially less affected than oil gravity by other reservoir parameters or oil source.

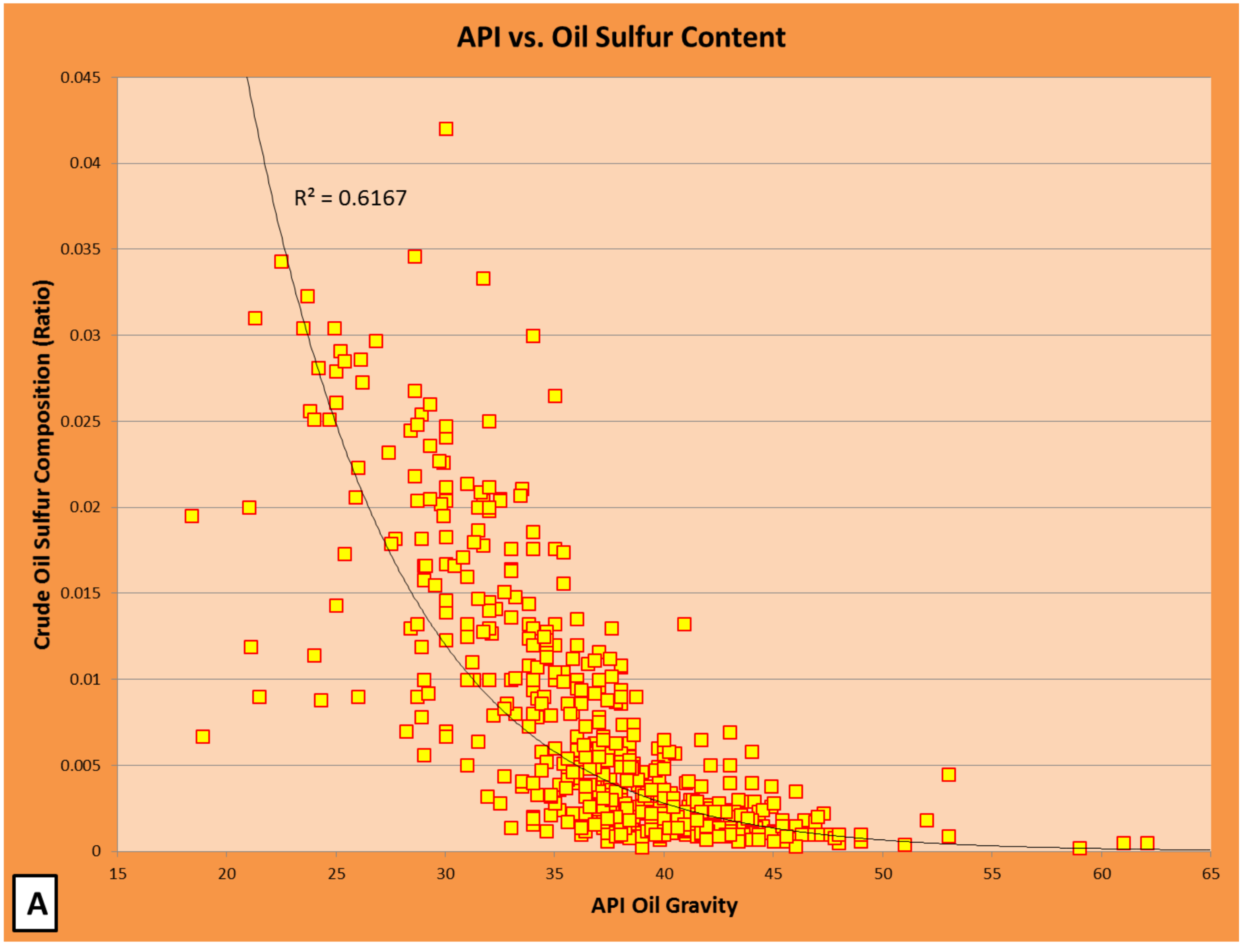


Figure 15 (A) API oil gravity plotted against crude oil sulfur content (weight ratio) for all Permian Basin fields. Data shows strong inverse trends indicating the likely occurrence of oil degradation.

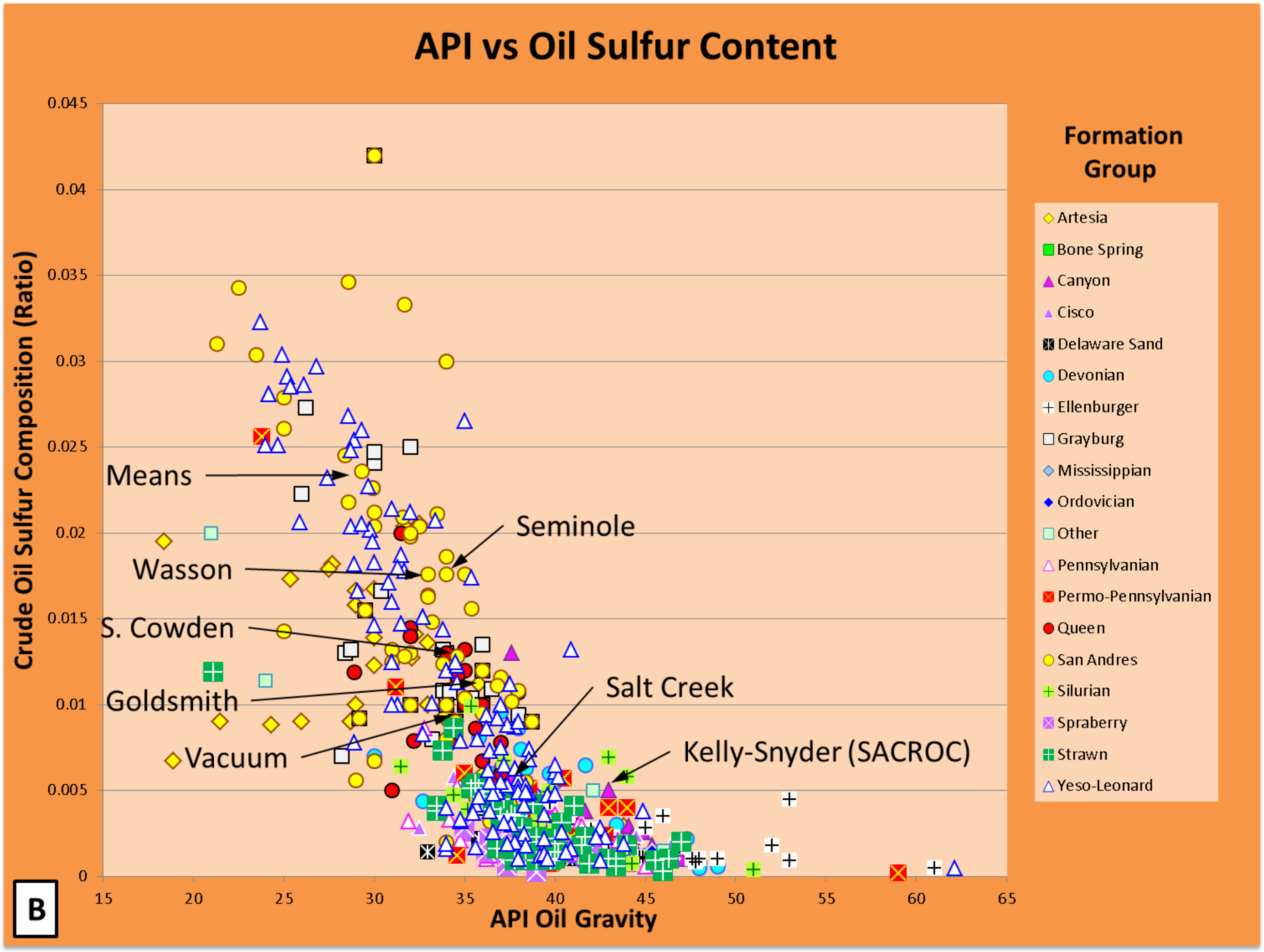


Figure 15 (B) Subdivides data points from (A) by formation. Known fields with ROZs are labeled.

Not only is there a strong correlation, but also oils containing higher percentages of sulfur are also predominantly from a limited subset of reservoir formations (Figure 15B; Figure 16). The sulfur-rich oil formations include almost all Permian formations of Leonardian and Guadalupian age. Other formations may have sulfur-rich fields (Figure 15B), but they are outliers. Additionally, regardless of the data source, known and suspected fields with ROZs all show similarly high sulfur content (Figure 15B, Figure 16). Based on this analysis, the key ROZ target formations extend from the Leonard through Guadalupian strata.

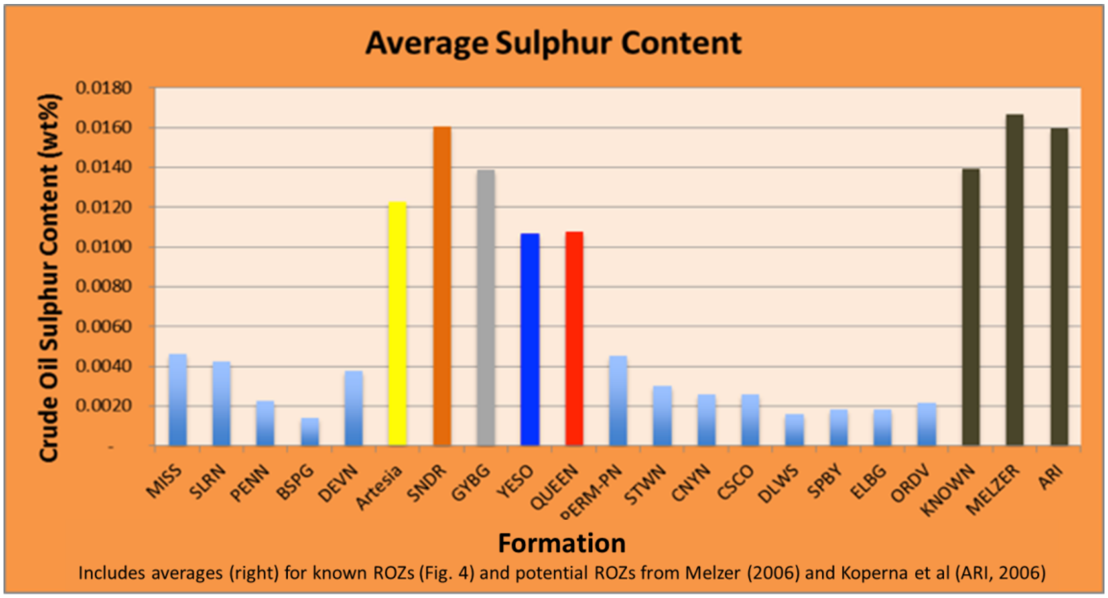


Figure 16: Average sulfur content of crude oil by formation groups (Table 2). Colored columns indicate those with highest sulfur and most likely to contain ROZs. Right three columns represent average wt% S for reservoirs with known or suspected ROZs (Figure 4; Melzer, 2006, Koperna et al., 2006).

This study also provides spatial analysis of ROZ proxies. For the database of reservoir properties, location data were assigned to each unique field wherever possible to allow for graphical display. Using ArcGIS, reservoir data were integrated with geospatial data for field locations from the Preferred Upstream Management Practices (PUMP) database (Dutton et al., 2005) whose polygons were converted to points. For fields not in the PUMP files, location data were obtained from field reports, well permitting forms and reports, the Texas Railroad Commission, and the Texas Railroad

Commission (2014). Together, over 2800 reservoirs were used in geospatial analysis of the reservoir data.

Sulfur content displayed spatially for both the San Andres (Figure 17A) and Yeso Group (Figure 17B) show that the regions with the highest probability of ROZ presence are predominantly along the paleo-shelf and inner-shelf environments mostly on the Northern and Northwestern Shelves and along certain portions of the Central Basin Platform. These findings are similar to those of Jones & Smith (1965) but are more detailed, robust, and consider wt% S in a new context. While the occurrence of sour crudes is widespread, the figures show that ROZ potential in these regions is not ubiquitous and varies between formations. Based on the proxy evidence presented here, it is apparent that ROZs are likely widespread over the Permian Basin but are restricted both stratigraphically and spatially. While ROZs are not ubiquitous, the findings of this work demonstrate the potential for ROZ in several formations never before investigated for ROZs. It is important to note, though, that the occurrence of high sulfur content and low API is only a proxy for ROZ forming processes, neither guaranteeing nor excluding the possibility that ROZ has formed.

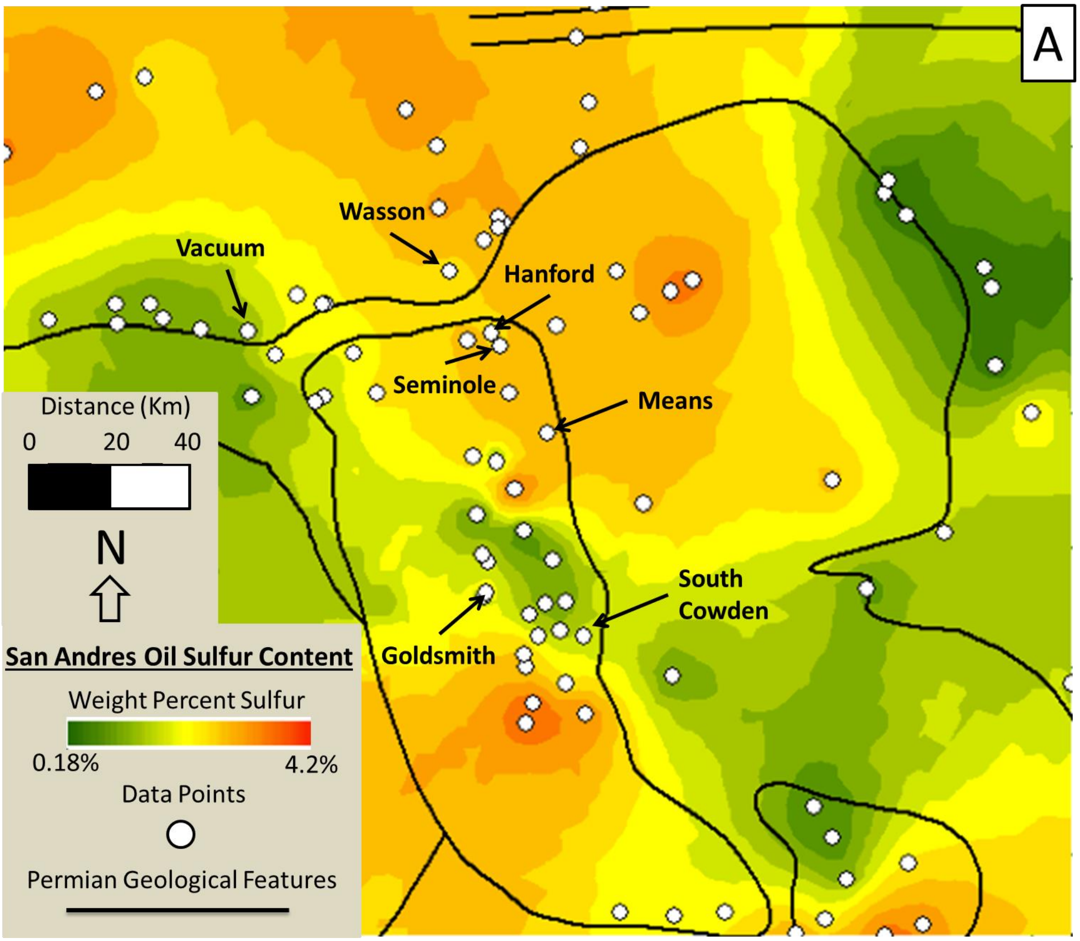


Figure 17A: Interpolated surfaces of sulfur content for San Andres Group (Table 2) reservoirs generated for this study. Increasing warmth of colors signifies increasing sulfur content in crude oils, and therefore, higher probability of ROZ presence. Results show that higher sulfur content is more widespread in San Andres than Yeso Group (17B). For both reservoirs, higher sulfur content is common on Central Basin Platform and Northern & Northwestern Shelves and less so in the basins, indicating a higher potential for ROZ presence in those regions. Fields with known ROZs in the San Andres are labeled for reference.

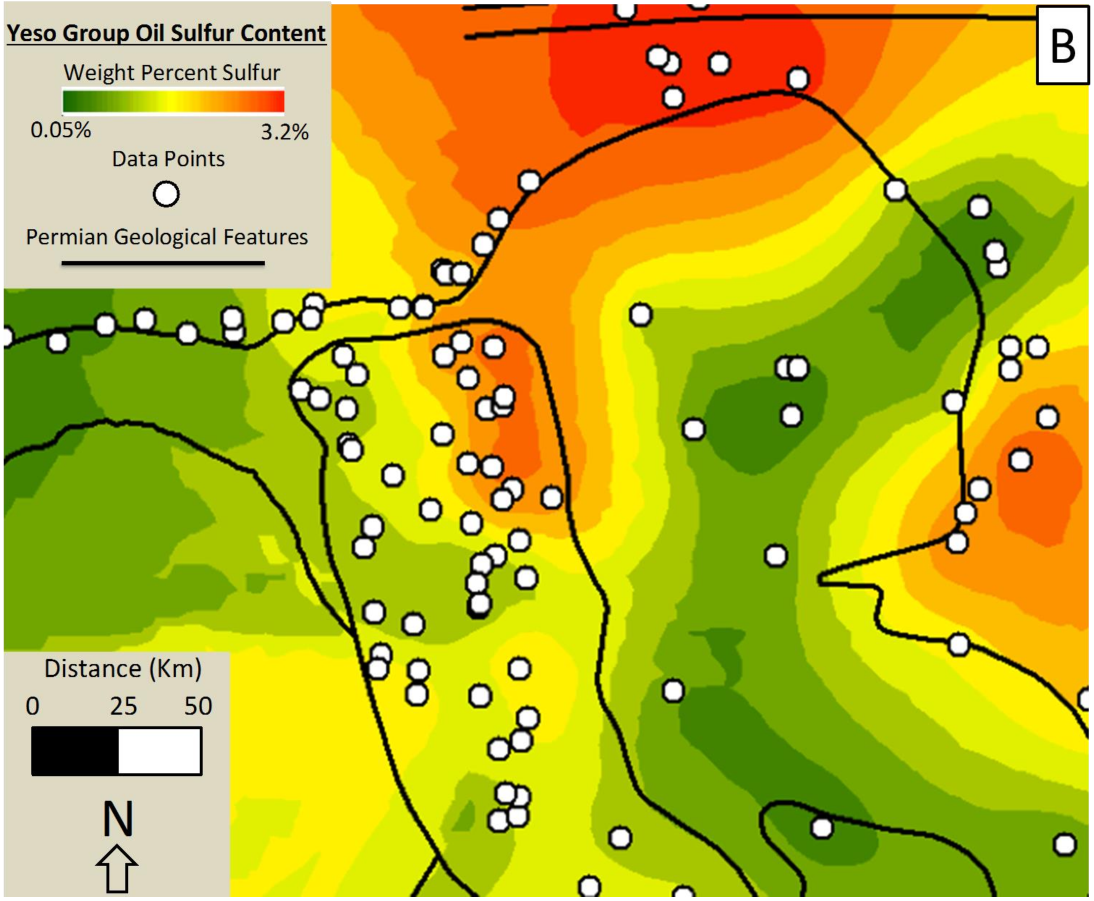


Figure 17B: Interpolated surfaces of sulfur content for Yeso Group (Table 2) reservoirs generated for this study. Increasing warmth of colors signifies increasing sulfur content in crude oils, and therefore, higher probability of ROZ presence. Results show that higher sulfur content is widespread but less so than in San Andres Group, notably along the northern Delaware Basin margin and western Central Basin platform.

## Discussion

Results from the analysis of tectonic influence on hydrodynamics and the location of ROZ proxies appear to complement and support previous findings that ROZ has formed across the Permian Basin due to hydrodynamics. Not only might ROZs be extensive, as defined in this work, they may also be predictable, as a more detailed understanding of factors controlling ROZs in the Permian Basin evolves. While the results of this study are suggestive of extensive ROZ presence, there are several uncertainties that must be addressed, in particular the quality of data and assumptions used in this analysis. Even accounting for the uncertainty, the approach of this study focuses on several first-order factors driving regional processes.

To further progress understanding and prediction of ROZs at smaller scales would require additional understanding of controls affecting ROZ formation and their relative influence. Discerning the role that fault and fracture networks, stratigraphy, and timing, amongst other controls, have on ROZ formation should be resolved in order to advance understanding, prediction, and estimation of ROZ potential in the Permian Basin. Despite the major issues for further study, results provided in this work further support the likelihood of ROZs being widespread across the Permian Basin. A global potential for ROZs also exists, which would have important implications for CCUS.

## Data Assumptions

### Uplift and Tilting

The basis for calculations regarding uplift and tilting is that the upper and lower contacts of the Edwards Group were deposited approximately flat on the scale of the entire shelf and that time transgression present in the contact selection does not introduce significant error. As acknowledged in the Data section, this assumption is not perfect. Depositional topography undoubtedly varied, and while the contact selection was meant to align with second-order supersequence boundaries (Phelps, 2011), time discontinuity does exist across the data points. These imperfections introduce error into the calculations. However, the kilometer-scale of interest for this work is orders of magnitude greater than the error inherent in the assumptions ($10^s$ m). Furthermore, as mentioned, the consistency of shallow water fauna and facies in the Edwards Group deposits indicates that these boundaries are not hugely time transgressive. This amount of error is acceptable for the first-order level observations and conclusions drawn from the results.

Inconsistencies and discrepancies are present in the literature with respect to stratigraphy and ages. Therefore, the selected contacts do not represent a perfect time correlative surface. However, the error presented by this is not significant on the basin-wide scale of this analysis. Furthermore, the analysis carried out but not presented here shows no significant or systematic error in the data at the regional scale. Local error does exist, but is less than one percent of the regional change in elevation.

Data error and discrepancies in the interpolated surfaces appear minimal. As expected, interpolated surfaces are most precise and accurate where data density is highest. In areas where data density is lower, the accuracy and precision decline but are generally consistent with trends in the overlying topography (Figure 3). The primary exception is the data artifact in the northeast section of the lower Edwards surface (Figure 10B). Otherwise, the lack of data constraint in some uplifted regions like the Guadalupe Sacramento Mountains results in the surface trend being correct, but the actual slope in the highest regions being lower than topographic slope.

### Sulfur as a Proxy

Selecting sulfur, and to a lesser extent API, as the proxy data for ROZ generates some uncertainty. Kerogen type and thermal maturation, reservoir mineralogy and temperature, and the length of time and rate of oil degradation are all factors influencing the amount of sulfur in crude oil. Also, sulfur data are measured in oils from the MPZ and not ROZ. To the first concern, areas with higher relative amounts of sulfate in the matrix lithology are noted to have higher sulfur contents (Jones & Smith, 1965; Smith, 1968; Ramondetta, 1982a). That is why this work does not equate sulfur concentration as a one-to-one proxy for ROZ. The important factor is that the greatest control on sulfur variability is oil degradation. Regions without oil degradation should have low crude oil sulfur concentration. With respect to sampling oils only from the MPZ, while oil degradation is concentrated along and beneath the OWC, convection of oil as well as imbibition and diffusion of water into the MPZ still exposes MPZ oils to degradation, as shown in these data.

The greatest potential for error may come with reservoir temperature. At the current geothermal gradient, reservoirs extending down through the Devonian all have average temperatures below the empirical 80˚C threshold for biodegradation of oil meaning that any degradation in deeper layers should also be apparent in the sulfur content of the oil. However, if the peak periods for oil degradation occurred during periods of elevated temperatures, it is possible that deeper formations (pre-Leonard) may not have had suitable conditions for biodegradation. Even so, oil degradation in hydrodynamic systems would still proceed via water washing.

## Reliability of Field Indicators

There are a few issues of interest when addressing oil field indicator reliability. Despite extensive quality control carried out in compiling the database of oil field properties, error in data input, original sampling, and data recording can all occur. These errors are likely limited in number and extent, however. Additionally, reservoir data may be reported as a single measurement, which may or may not be reflective of the field-wide average. Even so, the database compiled here represents as robust and accurate a compilation as is certainly publically and likely privately available for the Permian Basin. Because analysis is carried out on large numbers of reservoirs at a time, error is not expected to impact conclusions.

Even without occasional errors in the database, none of the data accrued is a direct indicator of ROZ. Therefore, no single data point or even combination of data points can guarantee the presence or absence of a ROZ. For instance, data from the Foster

San Andres and Grayburg reservoirs have API, wt%S, oil color, and water salinity values comparable to other fields with ROZs. Furthermore, the presence of native sulfur in core samples undoubtedly indicates the interaction of oil with meteoric groundwater. However, Trentham (2013) considers the Foster Field as one of the few he has studied in the San Andres that do not appear to have a ROZ. Assuming this to be true, Foster represents an example of a false positive. The indicators are present but ROZ is not. False negatives can also occur. Indicators reported for the Salt Creek Pennsylvanian reservoir have higher API, lower sulfur, and don't report a tilted OWC, yet Salt Creek is reported by Bishop (2004) as having a ROZ. Therefore, absolute decisions should not be made from these indicators. For this reason, this work maps regions where ROZ is most likely rather than naming individual fields.

False positive and negative outcomes from indicators also reinforce the importance of defining ROZ in this paper. Stripping the definition down to the fundamental cause and effect of a ROZ avoids the inclusion of descriptions or driving mechanisms, which might be too exclusionary. By also setting a general scale for ROZ, the definition also avoids situations such as that at Foster field. There, indicators show that imbibition has occurred but only over one or two meters, which is neither enough to clearly distinguish ROZ from a TZ nor an amount worth specifically producing. The potential for proxy data to result in false positives and negatives is reason to continue to study ROZs and develop an improved understanding of ROZ indicators across the Permian Basin.

## Controls on ROZ Formation

### Basement Structure

Basement structures can affect geological processes during deposition and deformation. The location of basement faults (Figure 10C) in juxtaposition to the interpolated lower Edwards surface indicates the potential for basement structure to have affected uplift and tilting as well as potential ROZ distribution in the Permian Basin (Hills, 1984; Dutton et al., 2005). Over most of the Permian Basin, the structure gently slopes to the southeast, but there is a notable region of depression in uplift over parts of the Delaware Basin and southern CBP. The northern edge of the depression correlates with outcrops of the Edwards Group and a depression in present day topography. Rather than conforming to the outline of Permian structures or mirroring structural contours of Permian strata (Figure 14; Figure 18), which are attributable to shallower underlying structures, the edges of this region of depression are aligned with pre-Cambrian fault lineaments (Figure 10).

Assuming that this area was not an area of depression prior to Edwards Group deposition, based on no noted major facies changes or formation thickness, the depression suggests that deformation of the Edwards surface is due to structural controls such as the reactivation of deep-seated faults during Laramide and/or Basin and Range tectonics rather than draping over pre-existing Permian depositional topography.

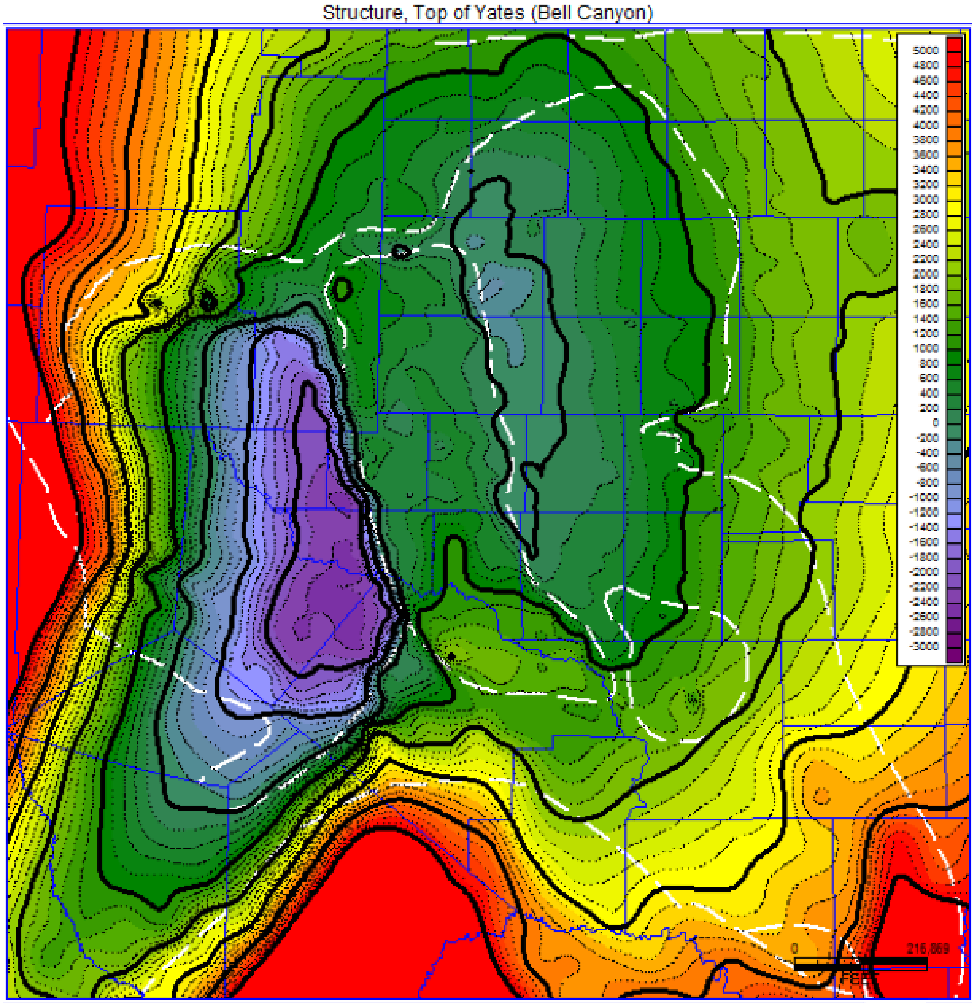


Figure 18: Structural map of present day top of the Yates Formation and equivalent points (Carr, 2012). Contour interval 200 ft. White dashed line is outline of Permian Basin structures. Local highs appear in the northwest corner and southern heel of the CBP.

Reactivation of the basement structures could have impacted the relative uplift of the region in multiple ways. One possible explanation is that movement occurred along the basement faults as the blocks rotated or were dropped down relative to adjacent basement structures either under shear stress from compression or in order to accommodate northeast-dipping uplift in front of the Diablo Platform and east-southeast dipping uplift off the Sacramento Mountains. Another possibility is that the depression is associated with collapse rather than uplift. Dissolution of evaporites is a well-documented occurrence across the Permian Basin region (Anderson, 1981; Baumgardner et al., 1982, Johnson, 1989), including in the region of the Delaware Basin underlying parts of this area of depression (Anaya & Jones, 2005). Smith (2013) and Zahm & Kerans (2010) demonstrate that in upper Edwards equivalent deposits over along the Ouachita-Marathon front even where pre-existing structures are not through going, they are still the principal cause of secondary fault and fracture zones. These basement-controlled zones of weakness can provide vertical pathways for fluid migration and may have influenced the presence of thick Quaternary infill of collapse structures such as the Monument Draw Trough that are found directly above high-angle faults in the western CBP (Figure 19). Anderson (1981) interpreted this as a result of basement weakness that translated into overlying evaporites, which were then dissolved by rising groundwater.

These basement faults may influence more than just upper Permian salt dissolution. Spatial interpolation of sulfur data for both the San Andres Formation and Yeso Group (Figure 17) shows a northwest-southeast trending decline in sulfur concentration across the central CBP, similar to the same region of sharp deviations in the Lower Edwards interpolated surface that are collinear with known basement faults (Figure 10C). The potential for basement structures to influence local and regional structures and fluid flow make them an important factor to consider in further assessing ROZ development in the Permian Basin.

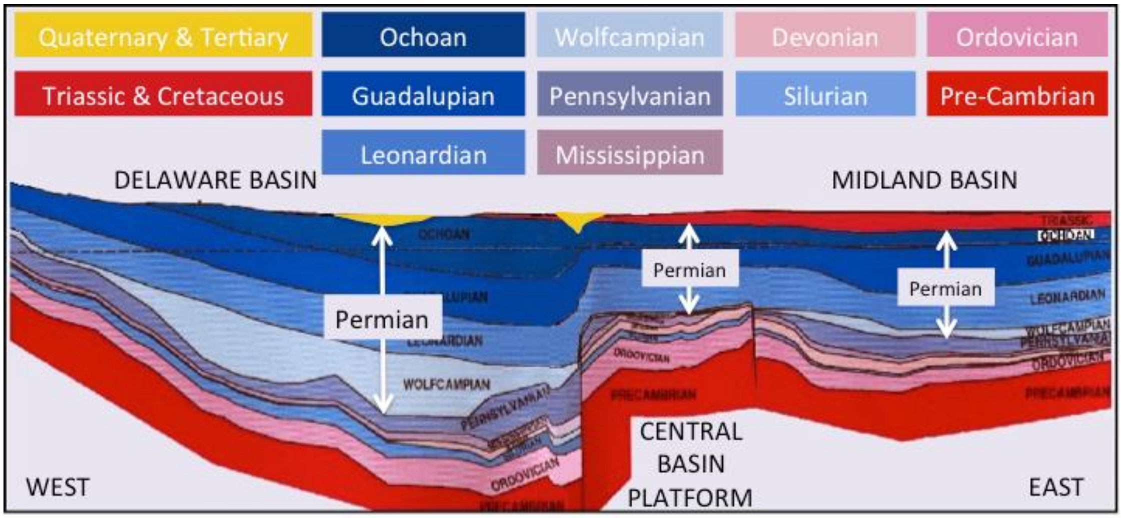


Figure 19: Schematic cross-section of Permian Basin showing relative stratigraphic thickness. Worth noting is the association between surficial collapse and infill with underlying fault structures that provide zones of weakness for vertical fluid migration. Figure modified from Lindsay (1998).

## Fault and Fracture Networks

Fault and fracture networks are another factor likely affecting ROZ formation. Permian Basin carbonate reservoirs typically have low primary porosity and permeability and secondary porosity and permeability typically plays an important role in fluid flow both at the reservoir and regional level (Mayer & Sharp, 1998; Dutton et al., 2005). Fracture zones, in particular, appear to be an important control in generating preferential flow paths.

Regionally, fault and fracture networks in the Permian Basin associated with basement structures (Smith, 2013; Zahm & Kerans, 2010) or formed syndepositionally have remained important from the time of their formation to the present (Budd et al., 2013; Frost et al., 2012; Mayer & Sharp, 1998; Kosa & Hunt, 2006; Scholle et al., 1992). Where cements at some point may have closed fracture networks in time, changing stress regimes have reopened them (Horak, 1985; Budd et al., 2013), allowing them to enhance fluid flow down to the reservoir scale.

Important to ROZ formation may be that syndepositional faults and fractures appear most common to the outer shelf and platform margin depositional environments. These are the same areas where ROZ proxy analysis indicates are the most likely targets. From the Guadalupe Mountains to the CBP, syndepositional fault and fracture networks appear to be primary pathways for the migration and interaction of both meteoric groundwater and oil, contributing to the conditions for hypogenic karstification, which is responsible for shaping Carlsbad Caverns and other large cavernous zones along the shelf. While oil is not going to be trapped in an open cavern, the role and ability of fault and fracture networks to preferentially transport formation fluids similarly makes them important to oil migration and ROZ formation because they can concentrate flow to local areas, impacting the regional potentiometric gradient around them.

### Stratigraphy

While this work has treated reservoir rocks as homogeneous layers, heterogeneity is the rule rather than the exception for the Permian Basin. As such, oil migration, accumulation, and aquifer flow are all greatly affected by the local and regional stratigraphy. The nature of ROZs, too, is intimately controlled by stratigraphic changes in lithology, mineralogy, and petrophysical properties.

Stratigraphy ties to ROZ in multiple ways. Oil accumulation in the Permian Basin is intimately tied to stratigraphy. Several San Andres and Grayburg fields are formed wholly or in part as stratigraphic traps, generally controlled by the presence of porosity occluding sulfates (Craig, 1990; Keller, 1992; Ramondetta, 1982). Additionally, stratigraphic and petrophysical heterogeneity controls preferential flow paths of fluids through the reservoir. For multiple fields in the Permian Basin, particular lithology or distinct stratigraphic and hydrogeological units appear to lend themselves to ROZ formation (Melzer, 2013, personal communication). Similarly, stratigraphic changes in lithology and mineralogy will result in different wettabilities, which in turn affect the capillary pressure as well as residual and remaining oil saturations during oil drainage and imbibition. Another influence stratigraphy has on ROZ development is on potentiometric gradients. Hubbert (1953) & Dahlberg (1995) describe how, in hydrodynamic settings, the transition from high permeability facies to low permeability facies and back results in a steeper potentiometric gradient across the low permeability zone leading to the formation of hydrodynamic stratigraphic traps along a flow path. Brown (2013) suggests this as potentially playing an important role in the occurrence or Permian Basin ROZs. Based on these reasons, gaining a better understanding of what stratigraphic controls are most important and how they influence ROZ formation will be essential in assessing the viability of ROZ for production.

### Diagenesis

Intertwined with fracture networks and stratigraphy is diagenesis in its role of forming preferential flow paths. Hill (1996) and Mazzullo & Harris (1989) summarize the major stages of diagenesis affecting Permian Basin reservoirs. As it pertains to ROZ, two critical stages are initial dolomitization and telogenetic dissolution.

Dolomitization is important to ROZs both because the dominant lithology of ROZs is dolomite and dolomites in Guadalupian reservoirs tend to possess the best flow properties. Dolomitization of the Permian Basin is well documented. The prevailing model of dolomitization is one of multiple episodes of reflux dolomitization occurring early during the depositional and burial history commonly coincident with periods of exposure and restriction of concentrated seawater over the platform (Saller & Henderson, 1986; Lucia, 2004; Saller, 2004; Garcia-Fresca et al., 2012). Generally, while dolomitization is porosity destructive in platform interior deposits of Guadalupian carbonates in the Permian Basin, subtidal deposits generally have their porosity enhanced (Saller, 2004). Along the CBP, ROZs are found in porous subtidal dolomitized mudstones (Leary & Vogt, 1990).

Similar to early dolomitization, late-stage dissolution has also enhanced porosity and permeability in many fields with ROZs. Lucia (2000) connects the dissolution of sulfates to increased production across the South Cowden field, which is itself the result of interaction with inflowing meteoric groundwater (Leary & Vogt, 1990; Mazzullo & Harris, 1989; Hill, 1996). While some precipitation of calcite and authigenic clays or silica results from the same processes, sulfate dissolution is the most prevalent and creates important secondary porosity that further enhances fluid flow and more dissolution (Lucia, 2000). The difference with late-stage dissolution is that it may be coincident with ROZ-forming processes and is therefore not necessarily an initial control on ROZ formation but can certainly be a factor on the present nature of ROZs in addition to being an indication of potential ROZ presence.

### Recharge & Discharge Zones

In contrast to reservoir and local flow controls affecting ROZ, recharge and discharge zones play an important role at the basin scale and greatly affect hydrodynamic forces responsible for ROZ formation.

For the Permian Basin, degraded oils are concentrated within reservoirs in the Leonardian and Guadalupian-age formations. This observation gives further credence to the hypothesis of hydrodynamically driven oil displacement. The strata exposed in the recharge zone along the flank of Sacramento Mountains are the same Leonardian through Guadalupian formations showing widespread degradation (Figure 16). That the target ROZ formations have large recharge zones while other formations do not may be one control on genesis of ROZ in different strata.

Discharge zones also play a role in controlling hydrodynamics and the migration of displaced oil. The elevation of the primary discharge zone sets the slope for the regional potentiometric gradient, and without a means of discharge, regional hydrodynamic flow will not occur. For past Permian Basin aquifers, however, the nature of discharge is still subject to some speculation. For the main ROZ target formations, present day outcrops exist shortly to the east of the Permian Basin range (McNeal, 1964) and are one means of discharge. It is unclear where the main discharge regions were in the past. As discussed above, basement structures and vertical fault and fracture networks can also serve as discharge pathways. In addition to dissolution, other evidence for the vertical migration of fluids, including oil, are sulfur deposits from oil biodegradation situated over known fault blocks (Ruckmick et al., 1979; Hentz & Henry, 1989) and large-scale collapse and fill features such as the Wink Sink (Baumgardner et al., 1982; Johnson, 1989). Trentham (2012) uses evidence of biogenetic native sulfur deposits to suggest that some oil displaced during ROZ formation may have escaped to form the large sulfur deposits in the Fort Stockton area. Given the intensity of basement faults around the CBP, their relation to vertical fluid migration, and the noted reopening of fracture zones during Laramide and Basin and Range tectonic episodes, it is probable that significant quantities of oil leaked from ROZ target formations into overlying strata along vertical discharge pathways.

## Timing of ROZ Formation

Predicting ROZ formation and the present state of ROZs in the Permian Basin requires grasping the full genesis of ROZs in the context of Permian Basin evolution. The temporal component of factors driving and controlling ROZ formation is critical in understanding the present state of ROZs.

Relative to most geologic processes that occur on a timescale of millions of years, hydrodynamic conditions can change almost instantaneously. At the Cairo Field in Arkansas, a ROZ formed in no more than 12 years due to hydrodynamics resulting from aquifer drawdown at an adjacent field (Goebel, 1950). While natural hydrodynamic conditions are more dependent on geologic and climatic conditions that operate on longer timescales, the gap still highlights the difficulty in accurately assessing the hydrodynamic conditions that existed at the time of greatest ROZ formation.

For Permian Basin ROZs, timing is important for understanding when ROZ formation began, for how long the processes have been active, and to understand the peak hydrodynamic force. These are intertwined and depend on the timing and rate of uplift, tilting, denudation, and extensional faulting thought to have broken up the recharge zone and lowered the potentiometric gradient (Lindsay, 2001).

The potentiometric surface is known to have been higher in the past (DuChene & Cunningham, 2006; Duchene, 2013), but how high depends on the timing of peak uplift and exposure of the recharge zone relative to extensional faulting. Peak hydrodynamic forces assumed in this work could be overestimated if the potentiometric surface began falling before maximum uplift. The timing of peak hydrodynamic forces is also necessary in understanding the length of time over which they acted, which could potentially impact the sweep efficiency of formation waters through ROZs and is tied to ROS and the condition of oil as degradation acting over longer time periods could lead to the formation of heavy oil and solid bitumen. The only timing that is constrained is the lowering of the water table (Polyak, 1998) and that is only for certain regions. The lack of timing constraints makes building historical regional groundwater flow models difficult.

Timing impacts the migration of oil into reservoirs as well as out from ROZs. Lowering the potentiometric gradient can mean transitioning from hydrodynamic to buoyancy driven oil flow and allow for remigration of oils into the reservoir (Figure 13), a theory supported by Lindsay (2001). The timing issue is further complicated by the possibility of large increases in the geothermal gradient preceding Basin and Range uplift. Depending on the timing of ROZ formation, this change in reservoir temperatures could have led to additional oil generation and emplacement in ROZs.

## Implications for Regional ROZ Potential

The results of this study provide independent analysis of ROZ formation from a unique regional perspective that supports and complements past and ongoing efforts indicating that ROZs are widespread across the Permian Basin, most likely formed dominantly by hydrodynamic forces. Providing physical constraints to the regional processes confirms what reservoir-scale observations indicated and provides a context in which ROZ occurrence might be predicted. Furthermore, by determining a viable proxy for ROZ in the Permian Basin, this work offers a first glimpse at the potential for ROZ presence beyond the San Andres and Grayburg reservoirs. Findings indicate that ROZs may be present in multiple formations not yet considered.

The presence of ROZ indicators in multiple formations besides the San Andres and Grayburg, though not unexpected, provides additional credence to the hypothesis that they are regional, hydrodynamic-linked phenomena. More importantly, to the extent that previous estimates (Koperna, G. et al., 2006) are correct, they are made only from known oil fields for the San Andres and Grayburg. Both the possibility for ROZ greenfields and the finding here that ROZ presence is potentially widespread in other formations indicates that current predictions for the Permian Basin ROZ resource may be an underestimate.

The consistency of these findings with previous work furthers the impetus for additional study into ROZs. This work has shown that, fundamentally, ROZs should be predictable and it is the expectation here that more information and additional understanding about ROZs will lead to better predictability of their location and nature across the Permian Basin. Based solely on the fact that every field in the region has been tilted, every field has the potential for ROZ formation. A better understanding of controls should indicate to what extent this is true.

## ROZs and CCUS

While not a major focus of this study directly, an important indirect implication is the potential for ROZs as a target for CCUS. Though ROZs have, to this point, been explored and exploited solely for commercial purposes, the potentially vast scale of ROZs in the Permian Basin and the value of $CO_2$ for EOR make ROZs attractive options for CCUS. Similar to conventional EOR, ROZs offer the potential for economic returns using $CO_2$. Given the potentially lower ROS in a ROZ compared to waterflood MPZ, the ratio of $CO_2$ injected per barrel oil produced could be higher. Although lower $CO_2$ usage efficiency may lower the net economic return, it increases the likelihood that ROZ exploitation is carbon neutral or negative over the lifetime of the project. Net $CO_2$ storage over the life cycle of a project provides added appeal as a CCUS project that not only can partially offset the system costs, but simultaneously provide environmental benefits at a meaningful scale. It is worth noting that the active hydrodynamic conditions in some ROZ fields could lead to displacement of injected $CO_2$ beyond the trap, which is a valid consideration to be taken into account before initiating injection at any given site.

Aside from purely CCUS considerations, ROZs are also beneficial analogue for the relative importance of residual trapping for $CO_2$ storage in dynamic reservoir conditions. Despite persistent hydrodynamic forces affecting oil accumulations for millions to tens of millions of years, the ROS trapped in the reservoir still represents a considerable fraction of the original accumulation. While the geochemical properties of oil and CO2 are different and will react differently with formation fluids, ROZs as a general analogue are promising for the storage of $CO_2$ in the subsurface over geologic time periods.

## ROZs Around the World

Finally, ROZs are the result of natural processes that should be common to many dynamic basin. While dedicated study of ROZs has, to date, been focused on the Permian and, to a lesser extent, the Big Horn and Williston Basins, ROZs are unlikely to be confined to these regions. Table 11 lists several other basins around the world where published conditions and characteristics indicate ROZ potential.

Table 11: Worldwide basins exhibiting potential for ROZs. This list is not exhaustive.

| Basin Name(s) | Location(s) |
|---|---|
| **San Juan, Williston, Big Horn, Permian** | United States |
| **Western Canada** | Canada |
| **Junggar, Tarim, Qaidam** | China |
| **Zagros Foreland** | Iran, Iraq |
| **Maracaibo** | Venezuela |
| **Barrow, Canning, Cooper, & Vulcan** | Australia |
| **Baltic Sea** | Lithuania |
| **N/A** | North Sea |
| **N/A** | Barents Sea |
| **N/A** | Papua New Guinea |

## Conclusion

Defined here fundamentally as ***a volume of rock of significant scale into which oil accumulated and was later naturally displaced, leaving behind a low, largely immobile remaining oil saturation***, residual oil zones (ROZs) are implicitly predictable at the regional scale according to the principles of buoyancy and hydrodynamics. Based on this understanding, this study takes a unique regional approach in the analysis of potential ROZ presence across the Permian Basin, assessing the viability of the present hypothesis for ROZ formation and identifying the formations and areas with the highest potential for ROZs.

This work quantifies the regional uplift and tilting hypothesized to have driven hydrodynamic formation of ROZs. Differential uplift over the Permian Basin is over 1800 m, resulting in a maximum potentiometric gradient in the ROZ-bearing San Andres formation of 5 m/km. The hydrodynamic forces generated by this maximum potential gradient predict ROZ thickness within 30% of measured values for multiple San Andres fields and are more accurate at predicting ROZ thickness than current hydrodynamic conditions. Hydrodynamic forces are shown to be a more dominant driving force of oil movement than countervailing buoyancy forces over regions covering most known oil reservoirs in the San Andres Formation. Based on this evidence, hydrodynamics can be considered a physically viable explanation of ROZ formation in the Permian Basin.

Through development and analysis of a robust Permian Basin reservoir attribute database and methodical description of expected ROZ characteristics, oil degradation is determined to be the optimal indicator of ROZ potential based on data availability, reliability, and the fact that oil degradation is a direct indicator of oil-water interaction in the reservoir. In addition, the finding of a strong correlation between API and crude sulfur content is consistent with the expected byproducts of oil degradation and supports use of these two particular indicators as proxies for ROZ potential in the Permian Basin. Analysis of the distribution of these proxies in the Permian Basin indicates that, though not ubiquitous, the potential for ROZs extends predominantly across Leonardian and Guadalupian-age reservoirs. Georeferencing of the reservoir attribute database and spatial display of ROZ proxy data shows that the potential areas of ROZ presence are widespread across multiple formations, which suggests that present estimates of the ROZ resource in the Permian Basin may be low. ROZs are not unique to the Permian Basin and should likely be expected in dynamic, hydrocarbon-bearing basins across the world. While significant additional work remains to understand factors controlling the nature of ROZs, the potential resource size makes them an important possibility for both commercial exploitation and CCUS development.

## Glossary

Biodegradation – The degradation of crude oil in a reservoir by microbes. Generally associated with the exposure of oil to moving water containing microbes after oil accumulation. Impact of biodegradation is increase in oil density, viscosity, and non-hydrocarbon compounds such as sulfur (Bailey, 1973a).

Brownfield – A ROZ where free water level is at the top of the reservoir and there is no MPZ, only RO (Melzer, 2006).

Capillary Pressure (Pc) – Difference in pressure between the interface of wetting and non-wetting phases (Donaldson & Djebbar, 1996). The Pc increases with the height of a hydrocarbon column as buoyancy increases.

Drainage – The process during which the saturation of the non-wetting phase increases. With respect to ROZs, drainage is the process by which oil first accumulates in a reservoir, resulting in a particular oil saturation curve dependent on capillary pressure (Christiansen, 2007).

Enhanced Oil Recovery (EOR) – Oil recovery technique in which substances not typically present in a reservoir are injected to aid in production of additional oil (Lake, 1989). For ROZs, the injection of carbon dioxide ($CO_2$-EOR) is the preferred recovery option.

Greenfield – ROZ that underlies existing MPZ (Melzer, 2006).

Hydraulic Head – The flow force of water. Is the sum of the elevation head and pressure heads and representative of the fluid potential energy measured by the height to which water will rise in a well from some point at depth (Dahlberg, 1995). Water flows in the direction of high head to low head (Hubbert, 1953). Measured in height.

Imbibition – The process during which the saturation of the wetting phase increases. With respect to ROZs, imbibition is a secondary process that has occurred after initial oil accumulation as water reenters the reservoir, displacing oil and forming a ROZ. Imbibition results in a particular oil saturation curve dependent on capillary pressure, initial oil saturation, and other hysteretic effects. Note that water reentry into a mixed-wet or oil-wet reservoir where it is not necessarily the primary wetting phase is commonly referred to as imbibition by convention (Standnes, 2001; Zhang et al, 2006) and is used similarly in this paper.

Main Pay Zone (MPZ) – Upper extent of some reservoirs where oil moves freely with near zero water mobility (Melzer, 2006). The entire MPZ will produce under primary and secondary production only the upper portions of the TZ will do the same. Sustained oil production is only possible in the ROZ through EOR operations.

Oil Water Contact (OWC) – The capillary pressure level in a reservoir at which oil achieves positive relative permeability and becomes mobile (Brown, 1992).

Potentiometric Gradient – The gradient of the potentiometric surface from any point (Hubbert, 1953). The gradient over a certain length is representative of the hydraulic head across that length. Measured in height by length (m/m).

Potentiometric Surface – The surface representative of the hydraulic head of an aquifer determined to a specific elevation based on the elevation head at which the measurement is taken and the pressure head causing water to rise (Hubbert, 1953). Measured in height.

Producing Oil Water Contact (POWC) – The depth at which oil is first produced (Jennings, 1987).

Remaining Oil Saturation (ROS) – Fractional pore volume occupied by oil in part of a reservoir at a given point in time (Ramamoorthy, 2012). Is used here to reference the oil that exists in a part of the reservoir, and is preferred to *residual oil saturation* because it is not bound to a process.

Residual Oil Saturation ($S_{or}$) - the irreducible oil saturation remaining after an infinite amount of flushing by water (Ramamoorthy, 2012).

Residual Oil Zone (ROZ) – A volume of rock of significant scale into which oil accumulated and was later naturally displaced, leaving behind a low, largely immobile remaining oil saturation. ROZs result from imbibition processes and possess variable but steady average oil saturation throughout (This Paper).

Transition Zone (TZ) – In theory, the TZ is the interval of a hydrocarbon column extending from the OWC to the point of irreducible water saturation (Valenti, 2002). In practice, the TZ is the relative interval extending from the level of first oil production to the point where water is generally non-productive given the large difference in relative permeability between oil and water. In contrast to a ROZ, the TZ is the product of drainage processes and possesses a predictable, steadily declining oil saturation.

Water washing – Stripping of oil components by waters (generally fresh) flowing past oil once it is accumulated (Lafargue & Barker, 1988). Water washing degrades oils by stripping more soluble compounds and commonly results in more sulfurous, heavier oils with lower solution gas oil ratios (GOR) (Bailey, 1973a).

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## Vita

Logan West was born in Little Rock, Arkansas, where he attended Little Rock Central High School. It was during his freshman year of high school when Logan had his first taste of the science of geology during a two-week program in the geological orientation of Arkansas. After high school, Logan enrolled at Princeton University where he explored a variety of fields. However, the allure of learning more about geology swayed him into taking the Geology Department's freshman seminar. Logan graduated with a Bachelor's of Arts in Geosciences from Princeton University in 2007, completing a thesis on the mineralogy of soil samples in the Canadian Arctic, a potential analogue to an ancient Martian environment. After college, Logan worked in community development in Chicago and taught English to college students in Beijing before becoming a Visiting Scholar at Tsinghua University. While at Tsinghua, Logan worked with the Tsinghua-BP Clean Energy Research and Education Centre as well as the World Resources Institute to conduct research on carbon capture and storage (CCS). Desiring to further develop his technical skills, Logan returned to the US to pursue a Master's degree at the University of Texas at Austin, concentrating in Geology with the Gulf Coast Carbon Center. He continues to reside in Austin, Texas and plans to pursue a PhD in Geology with the University of Texas at Austin.

Permanent email: logan.m.west@utexas.edu

This thesis was typed by Logan West.