Residual Oil Zones: The Long term Future of Enhanced Oil Recovery in the Permian Basin and Elsewhere*

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Abstract

Residual Oil Zones (ROZ's) have for 60 years intrigued both explorationists and production engineers and geologists. ROZ's have very similar core, cuttings, fluid and log properties as producing wells in modern waterfloods, and typically produce large volumes of water but little if any oil on tests. They are the result of "Mother Nature's Waterflood" during the Cenozoic, as tectonically driven lateral flushing has swept oil and connate fluids out of the lower portions of Permian Basin oil reservoirs.

Over the past two decades, a number of operators have demonstrated that ROZ's beneath existing fields are economically viable targets for EOR. These ROZ's are only producible with tertiary recovery methods (CO2 and, presumably, Chemical) and it is estimated that there are >10 Billion barrels of recoverable reserves in the ROZ's in the upper Guadalupian carbonate reservoirs in the Permian Basin alone. "Greenfields" are areas with no associated Main Pay zones, where significant thicknesses of ROZ's exist. Large areas on the northern Central Basin Platform and the Northwest Shelf are believed to be underlain by San Andres Greenfields. These areas also have multi-billion barrel potential and can serve as sites for combined CO2 EOR and Carbon Sequestration.

There are additional ROZ's in other producing intervals in the Basin which await documentation. Substantial ROZ's are believed to also exist in other basins in the U.S.. Regional and reservoir modeling of this natural waterflood process is ongoing.

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“Residual Oil Zones: The Long Term Future of Enhanced Oil Recovery in the Permian Basin and Elsewhere”.

Dr. Bob Trentham, University of Texas of the Permian Basin.

The 100 Billion Barrel Question

- For decades, when asked, geologists would say there were +/-100 BB OOIP in the Permian Basin and that we have produced roughly ~1/3 of that total.
- 75 MYA the answer to that question may have been 300 BB OOIP.
- Today, with our new understanding of the potential extent of, and oil saturation within, Residual Oil Zones (ROZ's) the answer lies somewhere between those numbers.
- How did we get here from there?
- Throughout Mother Nature's Waterflood.

Size of the Prize

56 fields in five major Permian Basin oil plays that have potential for significant TZ/ROZ resources were identified by Advanced Resources Intl.

TZ/ROZ OOIP in these 56 fields is estimated to be 30.7 Billion Barrels.

Field/Unit	MPZ OOIP (BB)	TZ/ROZ OOIP (BB)	No. of Fields	No. of MPZ Fields with CO2-EOR Projects	No. of Fields with TZ/ROZ CO_2-EOR Projects
1. Northern Shelf Permian Basin (San Andres)	13.0	13.2	13	5	1
2. North Central Basin Platform (San Andres/Grayburg)	2.9	2.6	6	2	1
3. South Central Basin Platform (San Andres/Grayburg)	9.9	7.9	16	5	0
4. Horseshoe Atoll (Canyon)	5.4	2.9	10	4	2
5. East New Mexico (San Andres)	2.3	4.1	11	2	0
Total	**33.5**	**30.7**	**56**	**18**	**4**

Koperna, et, al., 2006

Technically Recoverable Resources from the MPZ and ROZ

Advanced Resources International, Inc.

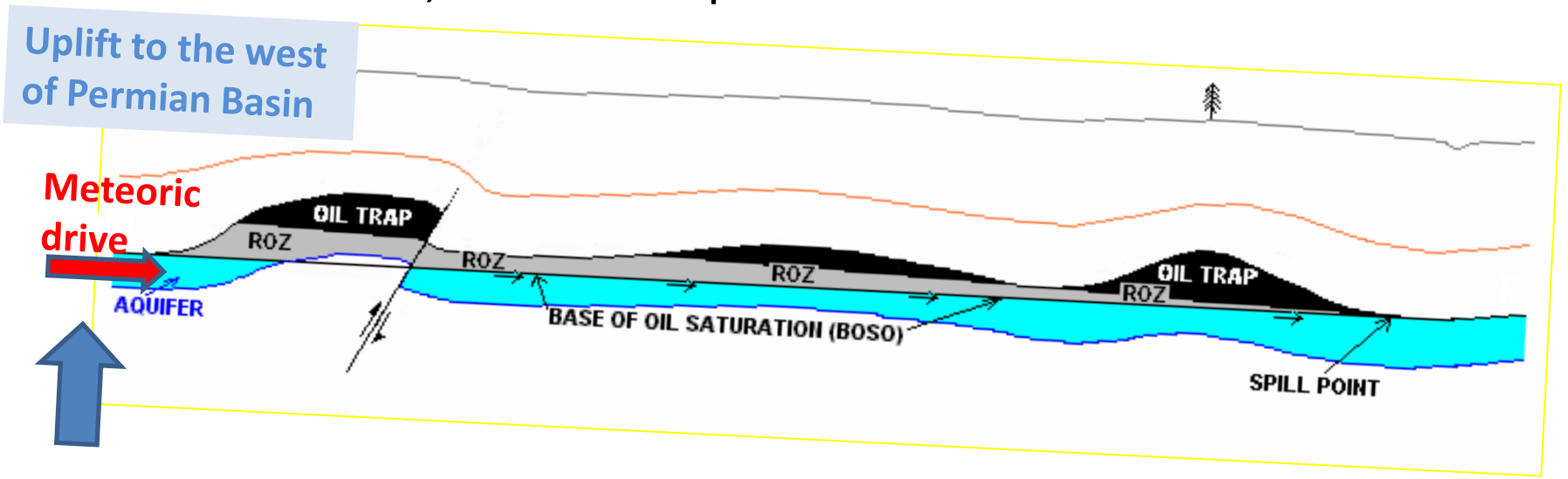
Based on reservoir modeling of applying CO_2-EOR to the TZ/ROZ resources, ARI estimates that there are 11.9 Billion BO is technically recoverable from the 30.7 Billion BO of TZ/ROZ oil in-place in these five Permian Basin oil plays.

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

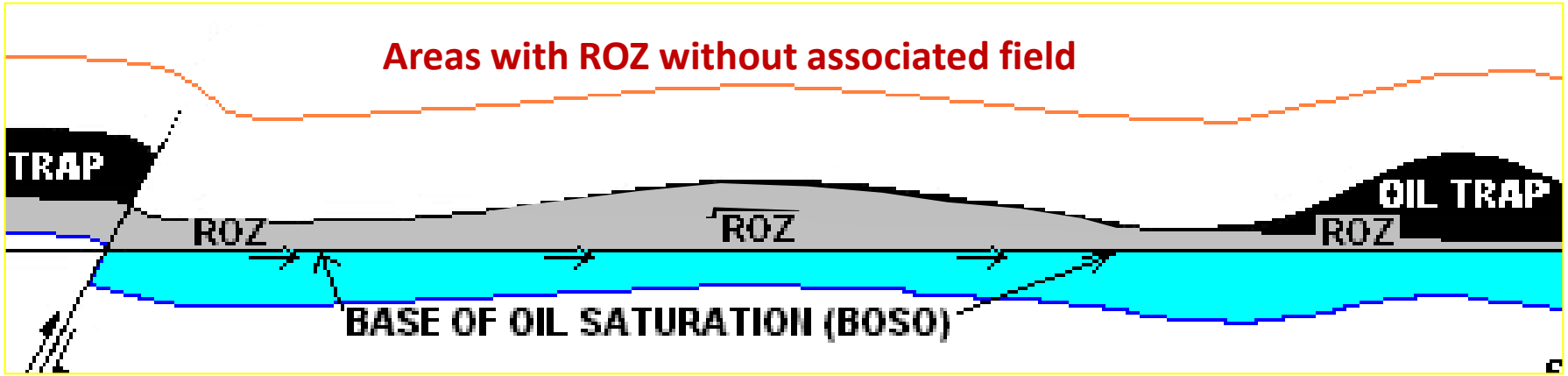
Koperna, et, al., 2006

Mother Nature's Waterflood

Changes in Hydrodynamic Conditions, Sweep of the lower part of the Oil Column, and Development of a Residual Oil Zone.



Dynamic System



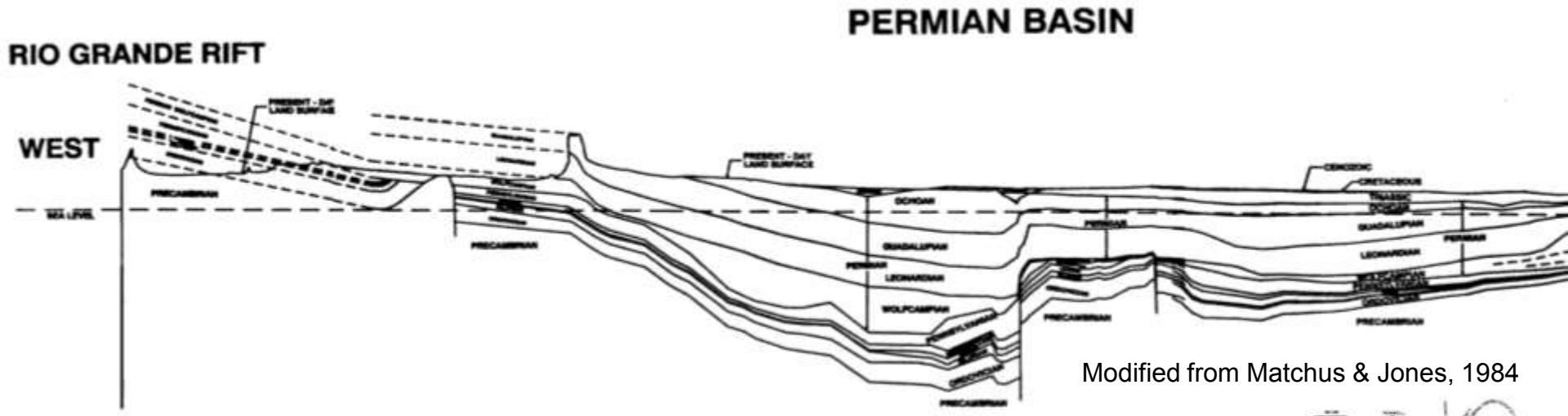
Timing of Post Permian Tectonic Overprint and Meteoric Flushing

Quat	Pliocene - Pleistocene - Holocene	-5 Ma to Present	Base level downcutting of ancestral Pecos River. At ~600 Ka Capitan Aquifer hydrologically connects with Pecos River at Carlsbad. Possible draining of lower Carlsbad and Lechuguilla Caverns.
Cenozoic	Late Miocene	-12 to -5 Ma	H2S ascends into Guadalupe Mtns from basin. Sulfuric acid caves develop from Se to NE, enlarge and cut across older thermal caves.
	Early Miocene	-25 to -12 Ma	Rio Grande Uplift accelerating. Maximum uplift of Guadalupe Mtns block begins (~20Ma). Delaware Basin geothermal gradient reaches 40-50°C/km. "Second" maturation and migration of hydrocarbons. H2S produced where hydrocarbons react with evaporites. Thermal caves developing. Dewatering Calcite spar fills basin and range fault zones.
	Oligocene	-40 to -25 Ma	Trans-Pecos Magmatic Province: Tertiary intrusives and extrusives to SW, dikes in Delaware Basin.. Transition from volcanic to Basin and Range in Delaware Basin Delaware Basin tilts eastward and heats up. "Second" maturation and migration of hydrocarbons. H2S produced where hydrocarbons react with Castile anhydrite. Begin Rio Grande Uplift in late Oligocene.
	Paleocene	-65 to -58 Ma	Laramide uplift continues into Early Tertiary. Older caves get enlarged and connected.
Meso	Cretaceous-Gulfian	-95 to -65 Ma	Late Cretaceous Laramide Orogeny begins. Guadalupe and Apache Mtns. Lifted 1000's of feet above sea level.
Paleo	Guadalupian	-255 to -251 Ma	Seven Rives Yates and Tansill Backreef, Capitan Reef, Delaware Mountain Group Deposition. Early dolomitization in Apache and Glass Mountains.

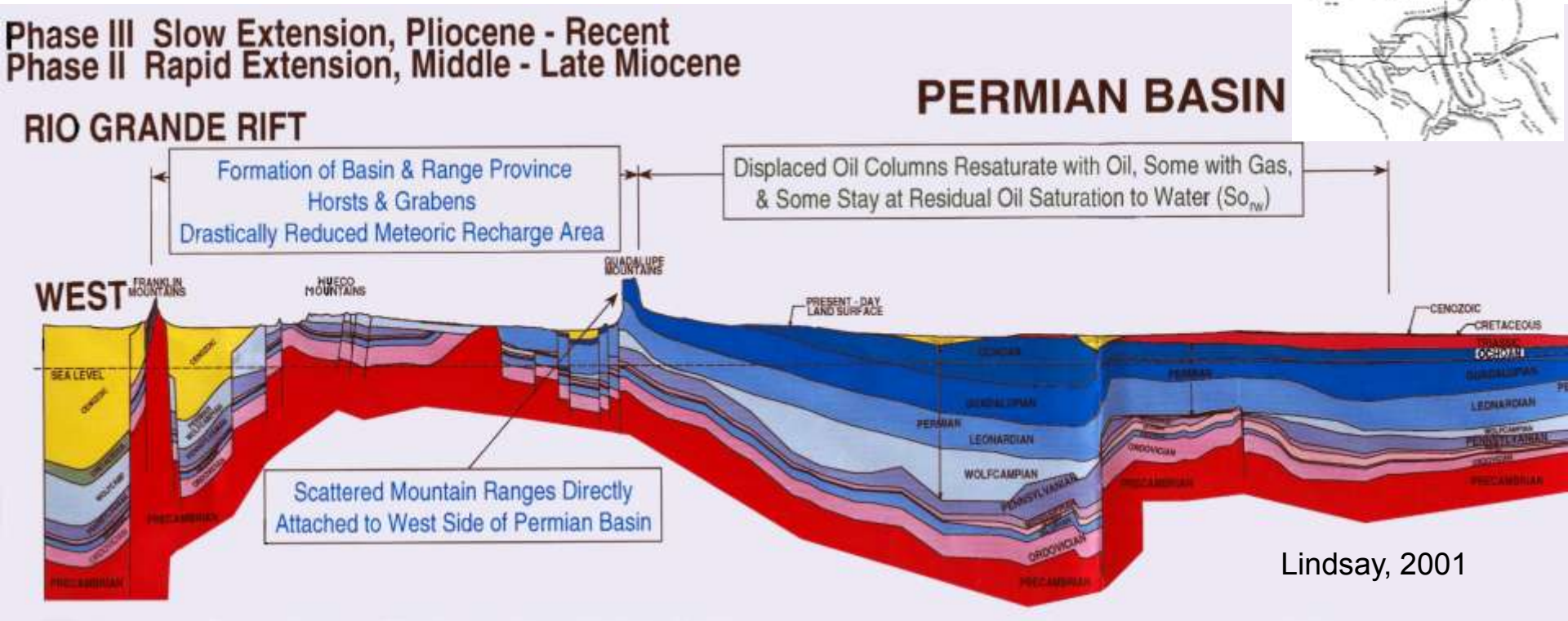
The top of the San Andres was uplifted over 7000' by the tectonism. A gradient of ~80' mile exists today between the Guadalupe Mountains (+6000') and the Central Basin Platform (-1000').

Modified from Hill, 1996

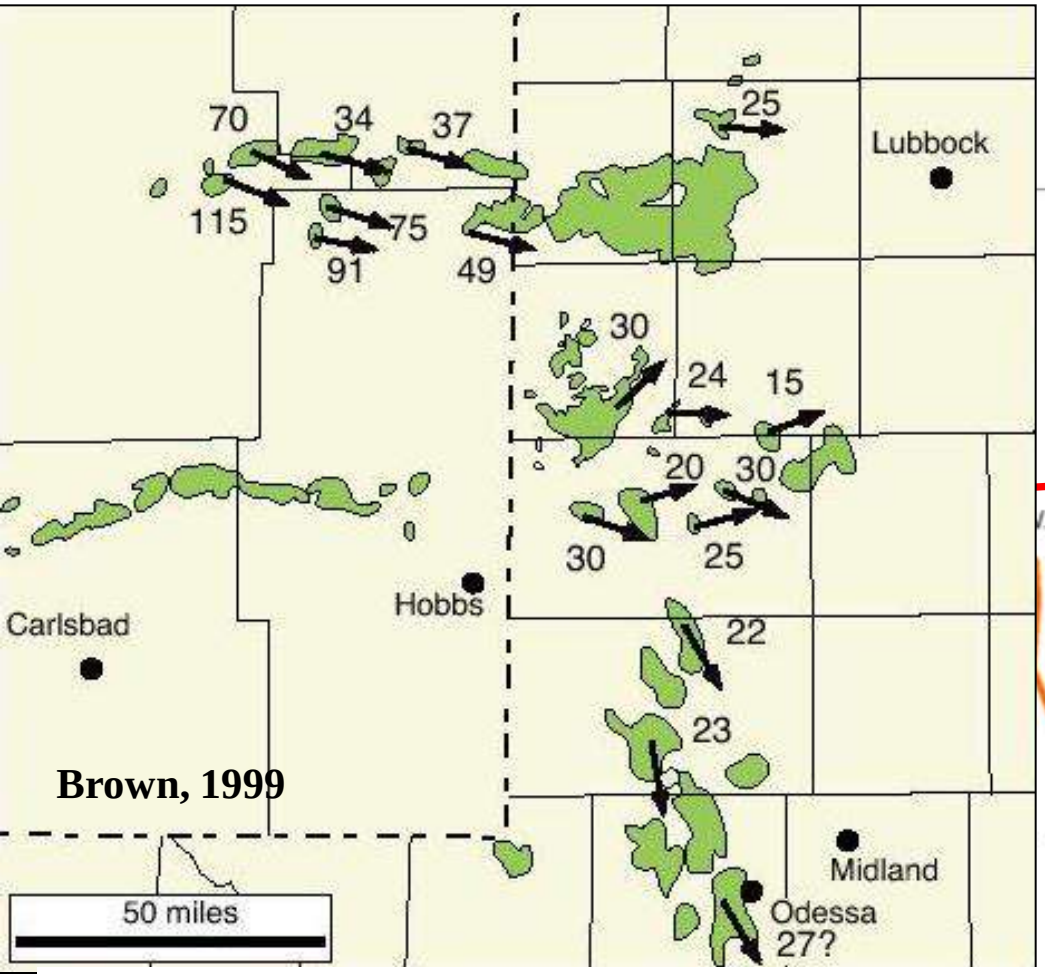
Bob Lindsay, correlated outcrops to Guadalupian fields, identifying the flushing pathway of "Mother Nature's Waterflood" and framed it's history.

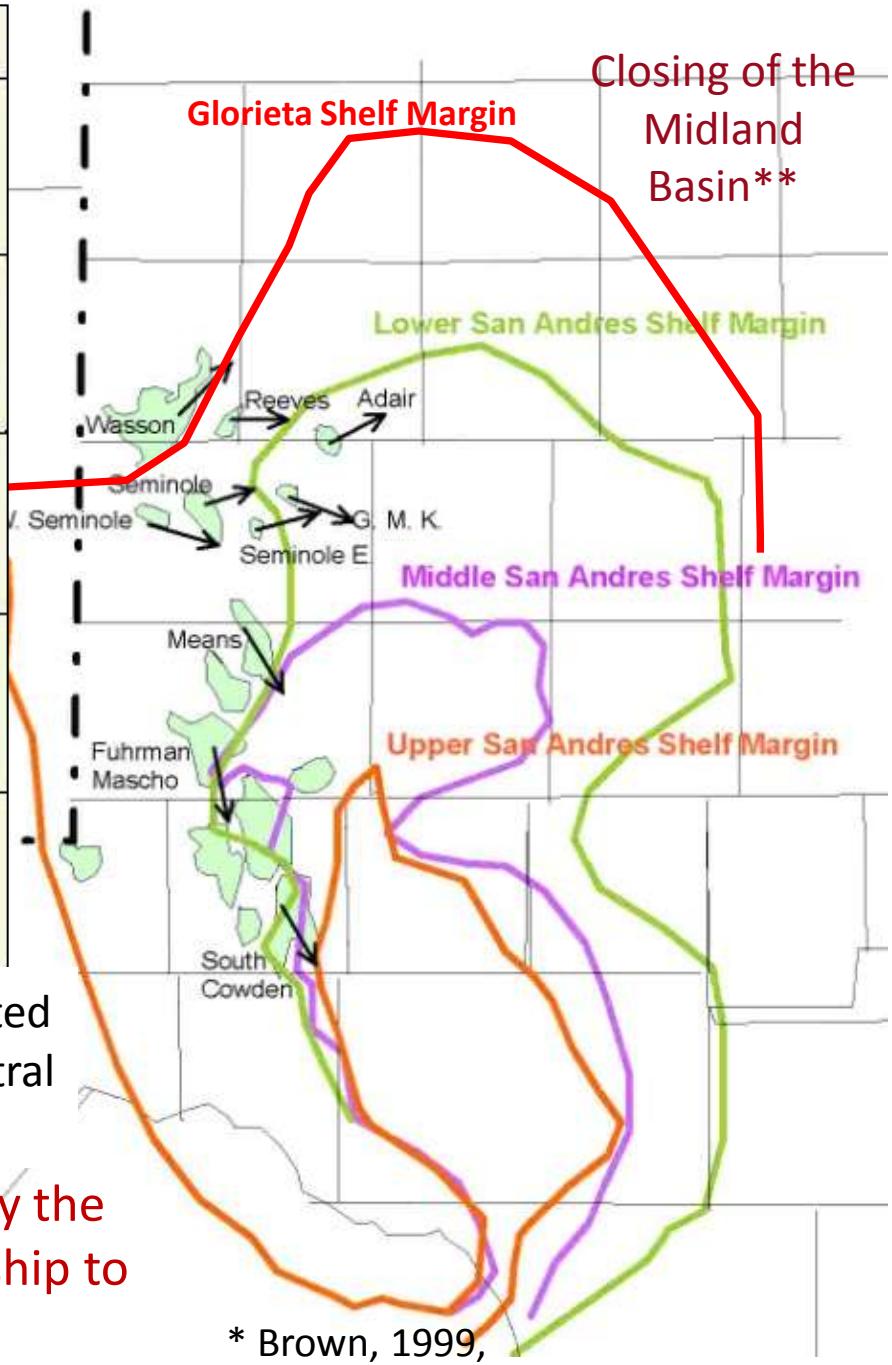


Modified from Matchus & Jones, 1984



Lindsay, 2001

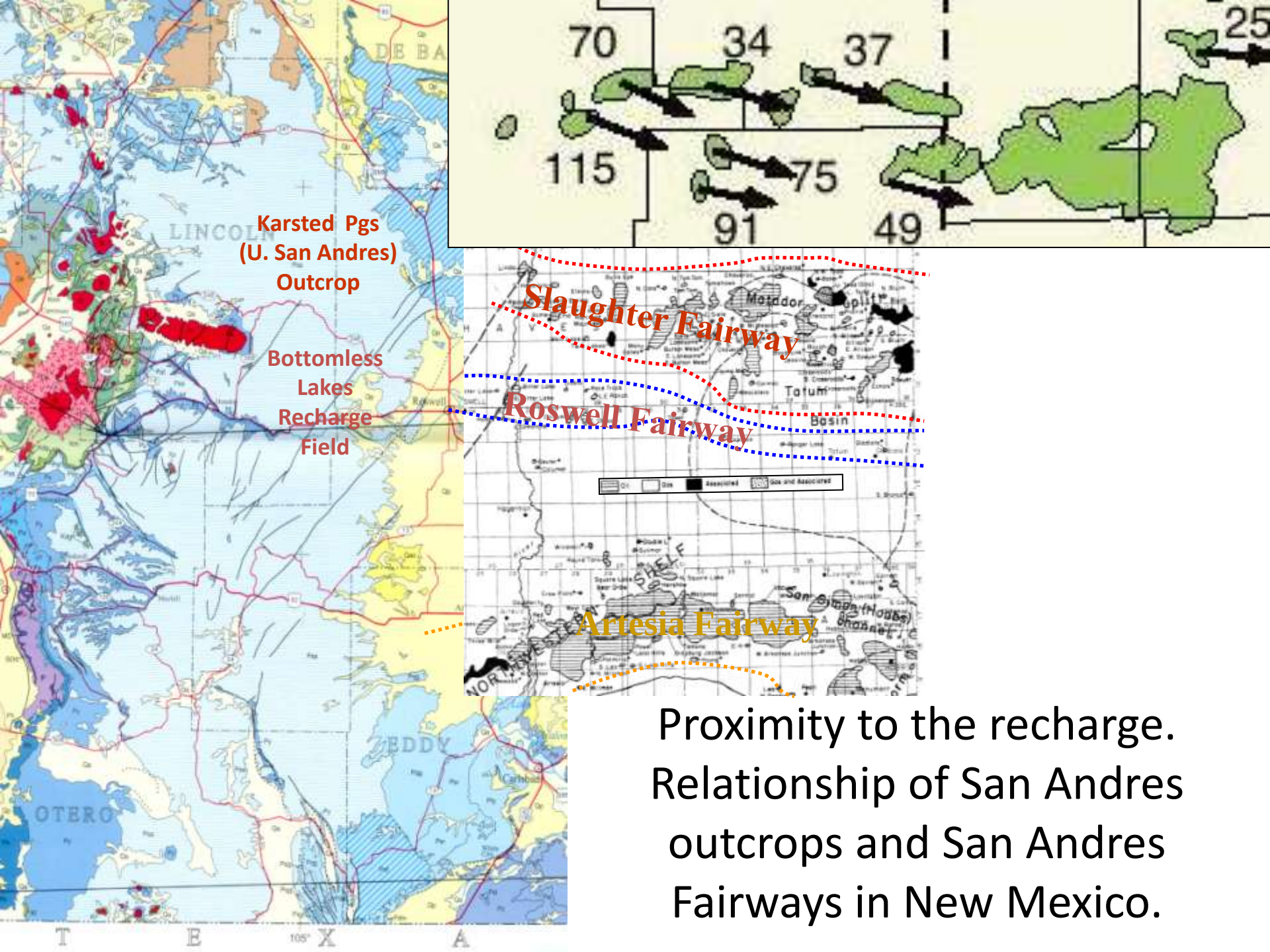




Alton Brown documented the distribution of Tilted Oil-Water Contacts in the Northern Shelf and Central Basin Platform Areas of the Permian Basin*

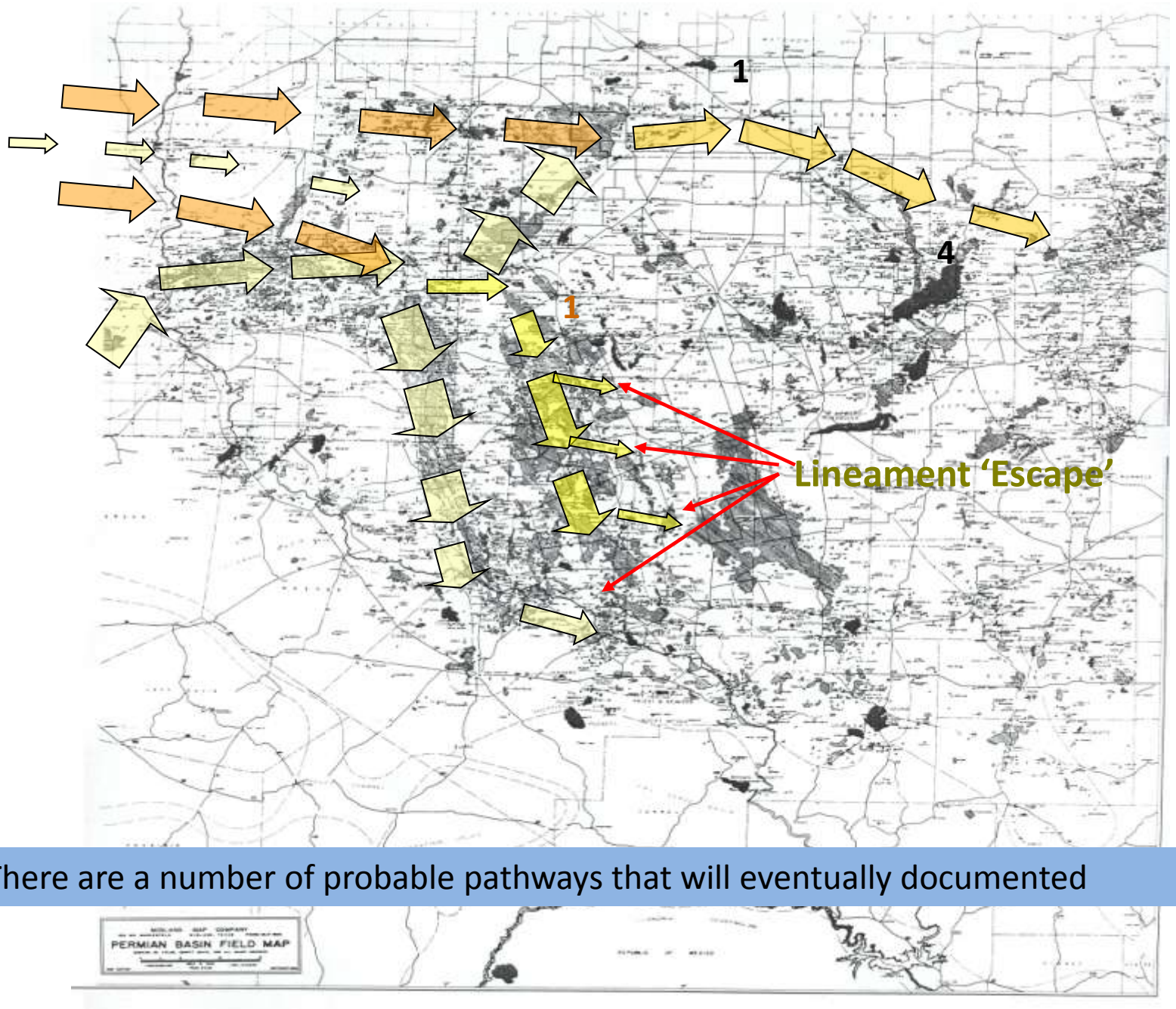
The direction of OWC tilt may be influenced by the age of the producing interval and it's relationship to the shelf margin.

* Brown, 1999,
** Ward et al, 1986



Proximity to the recharge. Relationship of San Andres outcrops and San Andres Fairways in New Mexico.

THEORIZED (U. PERMIAN) HYDRODYNAMIC FAIRWAYS



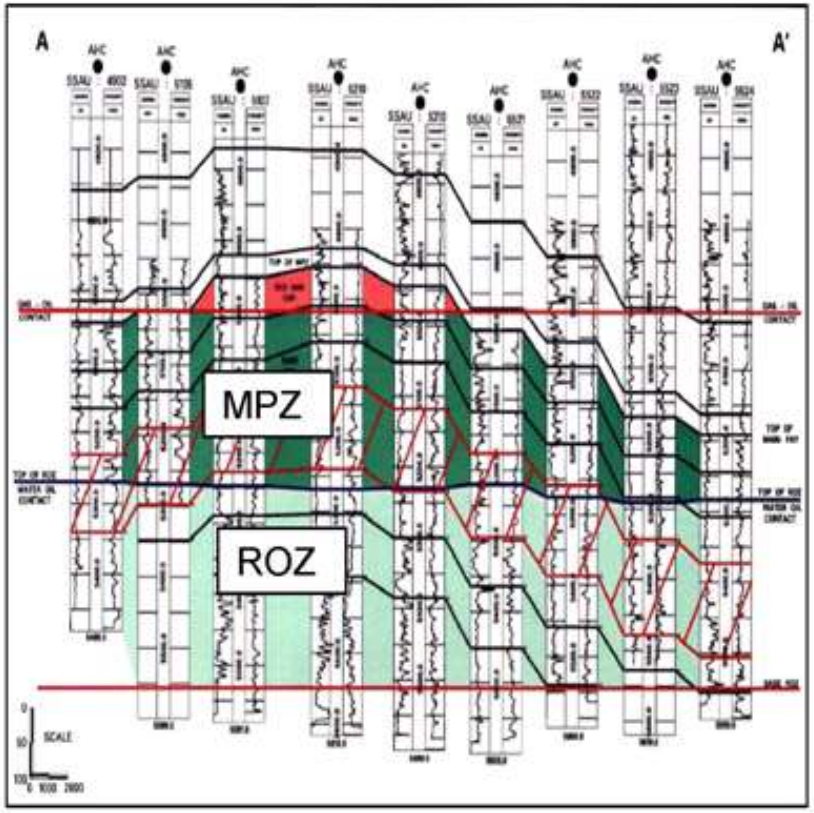
There are a number of probable pathways that will eventually documented

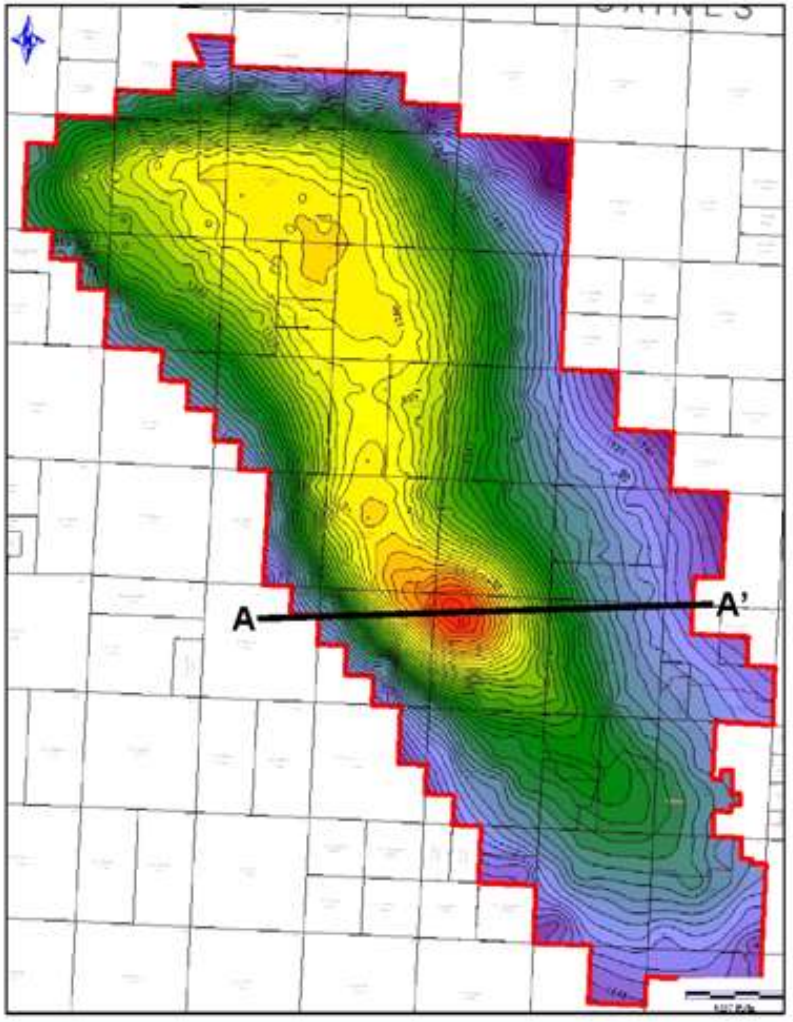
The Gold Standard

Seminole San Andres Unit

SSAU Structure Map & Cross Section

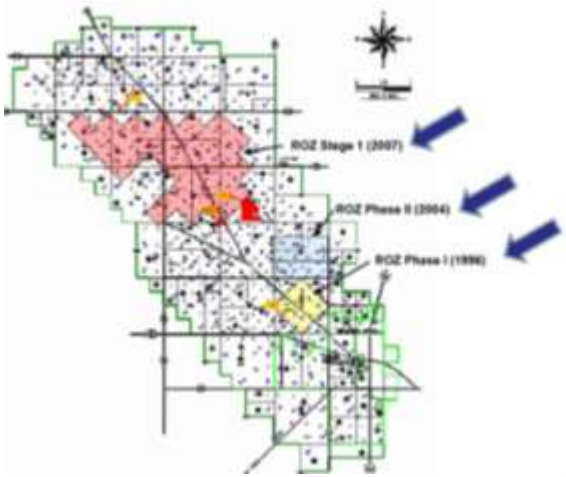
	Net Thickness	Average Permeability	Initial Oil Saturation
Main Pay Zone (MPZ):	126'	9 md	84%
Residual Oil Zone (ROZ):	213'	12 md	32%





HESS

Reservoir Description	Limestone and dolomite deposited in a shallow carbonate ramp environment
Fluid Type	Saturated black oil
Drive Mechanism	Gas in solution and gas cap during primary. External energy from water and CO2 injection during secondary and tertiary recovery.
Develop. History	1936 Discovery 1936 First Production 1969 Unitized/Waterflood 1983 MPZ CO2 Flood Begins 1996 ROZ Phase 1 Pilot 2004 ROZ Phase 2 Pilot 2007 ROZ Stage 1
Cumulative Production	675 MMBO, 40 MMBOE NGL, 702 BCF HC Gas
Current Rate	19.6 MBOPD, 200 MMCFD CO2+HC 25,500 MBOEPD (Oil+NGL+Gas)



Seminole Water Saturation Profile.

Producing O/W Contact

Base of Oil Saturation

Conventionally Productive Oil Zone

Transition Zone (TZ)

Residual Oil Zone (ROZ)

Average Oil Saturation Profile

Height

0 20 40 60 80 100

Water Saturation (%)

Anecdotal Evidence

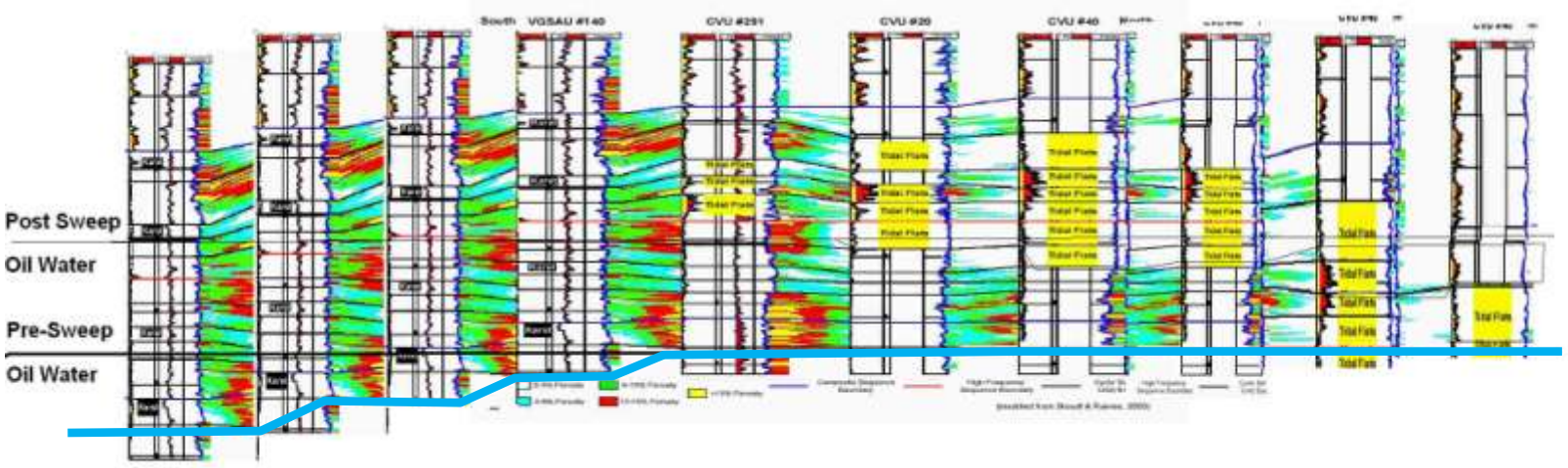
- Info from a growing number of exploration wells documents what can be interpreted as ROZ's where the tests were unsuccessful as there was no associated primary production. Data from a number of explorationists and review and reinterpretation of research articles on Permian Basin fields, suggest a set of common ROZ characteristics:
  - Sample shows of oil and/or gas throughout the ROZ interval,
  - Sulfur water or salty sulfur produced on DST's or attempted production tests, not salt water,
  - Cores with 20-40% oil saturation,
  - Log calculations that suggest producible hydrocarbons,
  - IP's similar to mature waterflood.

  - Evaporites may be dissolved or altered in the lower part of the main pay.
  - The presence of sulfur crystals associated with gypsum/anhydrite/calcite in the ROZ,
  - Solution enhanced fractures in lower portion of the ROZ
  - Enhanced porosity and permeability in the ROZ relative to in the main pay zone as the result of meteoric dissolution of sulfates.
  - Pervasive "late" dolomitization indicating meteoric sweep.
  - "Tight" high So intervals near the BOSO transition.
  - Sequence stratigraphic boundaries to top and bottom of ROZ.
  - Possible oil and water chemistry differences between main pay and ROZ.

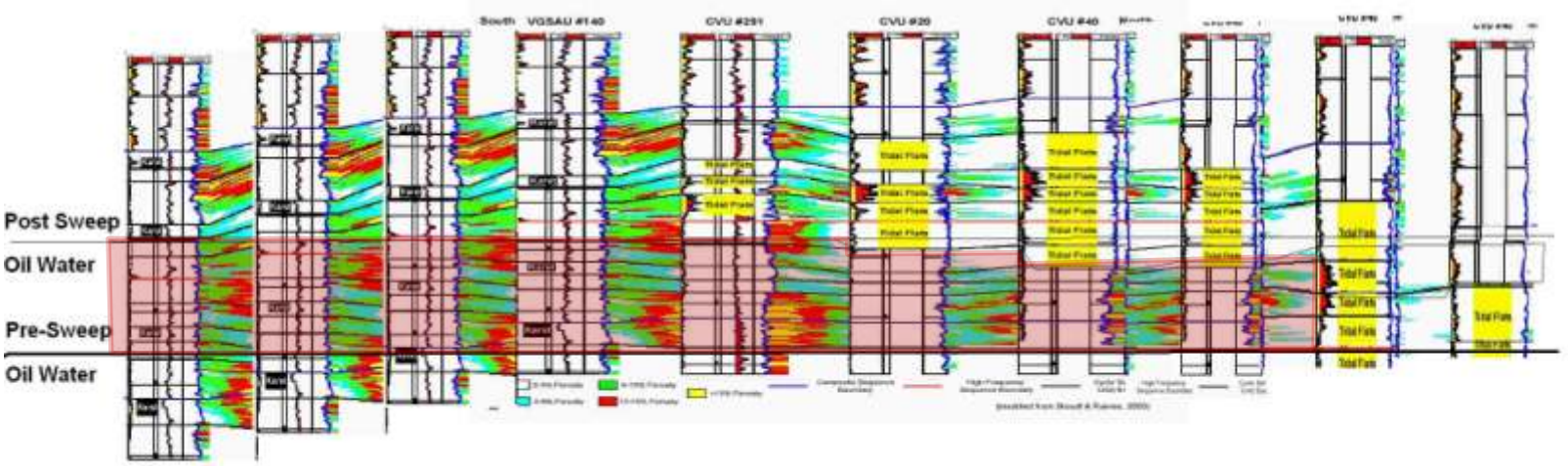
The new Residual Oil Zone Paradigms

- Large intervals and areas have been swept by the tectonically driven "Mother Natures Waterflood" which occurred post basin subsidence and oil emplacement.
- Thick intervals within the ROZ's intervals have the same saturation characteristics as mature waterfloods (30-40% Sorw).
- Tests of ROZ's produce high percentage of water on DST's or completions, but not a "deal killer".
- ROZ's often are interpreted/calculated as producible in Exploration Wells, and Primary and Secondary Production Environments:
  - Good Odor, Cut, Fluorescence, and Gas in samples
  - 20 -40 % oil saturations in core
  - Calculate as oil productive on logs
- The "faux-productive" appearance of ROZ's with significant thicknesses (50 to 300') of CO2 EOR producible hydrocarbons and 20-50% So exist beneath both producing fields (Brown Fields) and in areas where there is no, or a minimum, producible oil column (Green Fields).

Pre Laramide
Original Oil Water contact at base of present ROZ



Post Basin and Range - Flow units, deeper in the reservoir and with higher permeability are swept

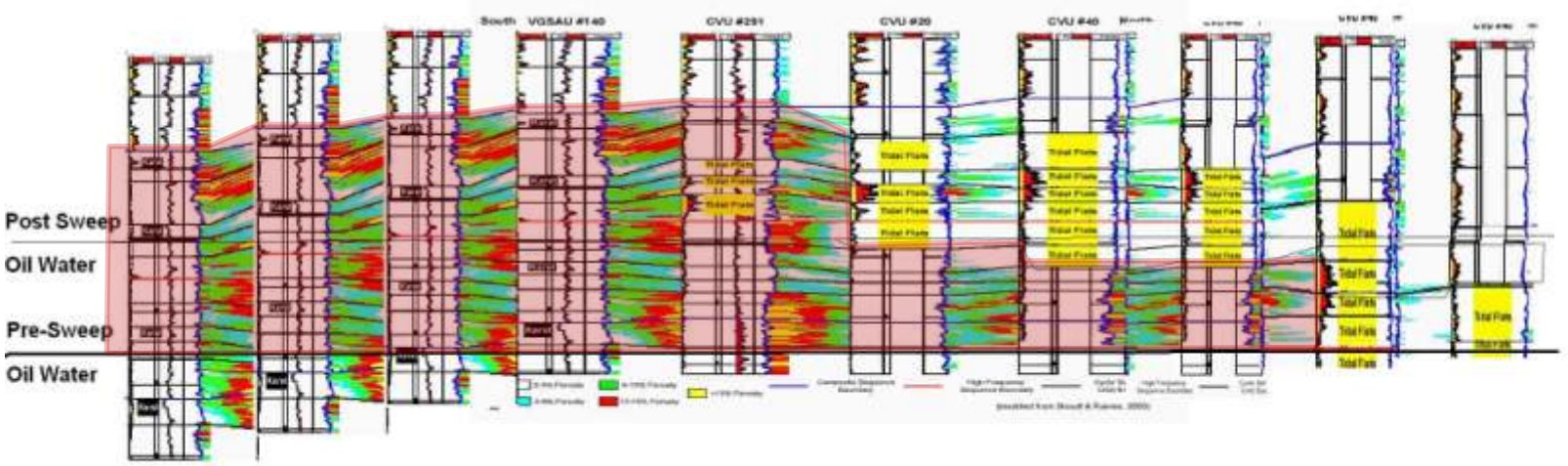


Field Wide - Tidal Flat/Sabkha provide updip permeability trap.

MP - Flow units within Main Pay unaffected by Meteoric derived sweep.

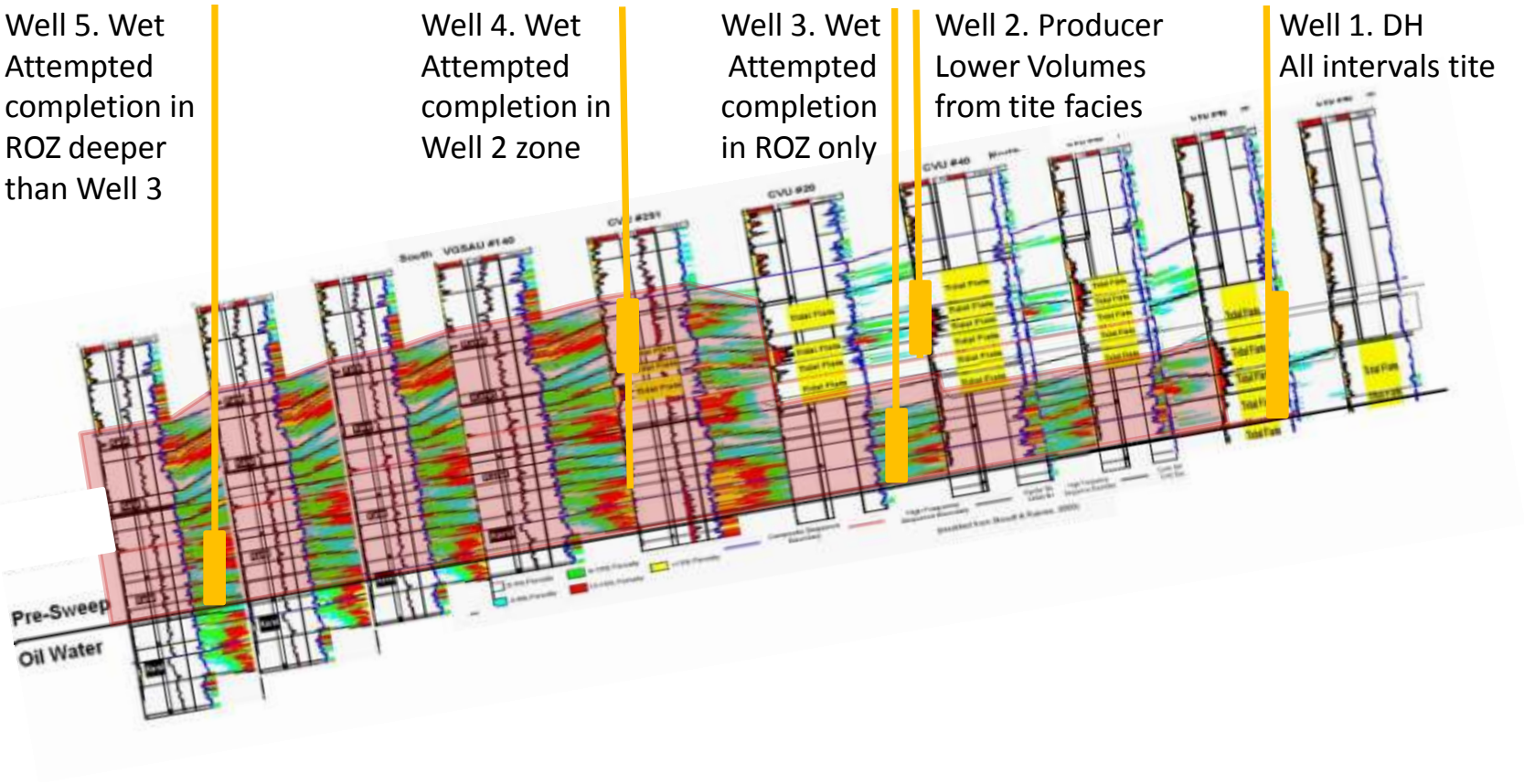
ROZ - Updip shallow subtidal and intertidal will produce low volumes/ low water cut
Downdip higher energy shelf produces “Mature Waterflood” oil cuts and volumes

Post Basin and Range
Most higher permeability Flow Units are Swept



Field Wide - Tidal Flat/Sabkha provide updip permeability trap.
Main Pay- Either thin producing interval or no associated producing interval
ROZ - Updip shallow subtidal and intertidal will produce low volumes/ low water cut
Downdip higher energy shelf with “Mature Waterflood” oil cuts & large volumes

Post Basin and Range
Updip shallow subtidal and Intertidal are productive, downdip swept with mature waterflood IP's



Wells drilled in different portions of the interval will have different recoveries.

W. A. Estes “Holt” Field (actually Glorieta)

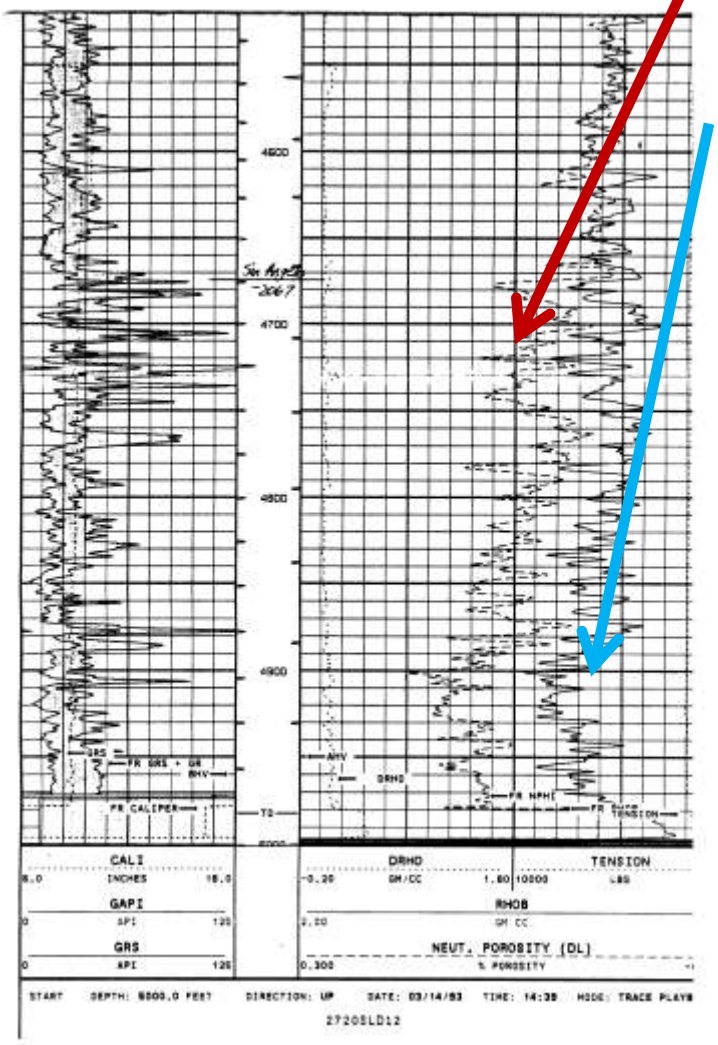
Discovered in 1991, produced over 1MMBO from a small closure with “tight” tidal flat and shallow subtidal carbonates.

Why did it take so long to discover it?

It’s a cap for a thick porous dolomite considered to be the “pay” in the area. The interval had shows & calculated as productive, DST’s a skim of oil and lots of sulfur water, tested a few times and left alone.

What is going on? It’s postulated that the lower, porous portion was swept and only the tight, up-dip facies were left with >70% S_o.

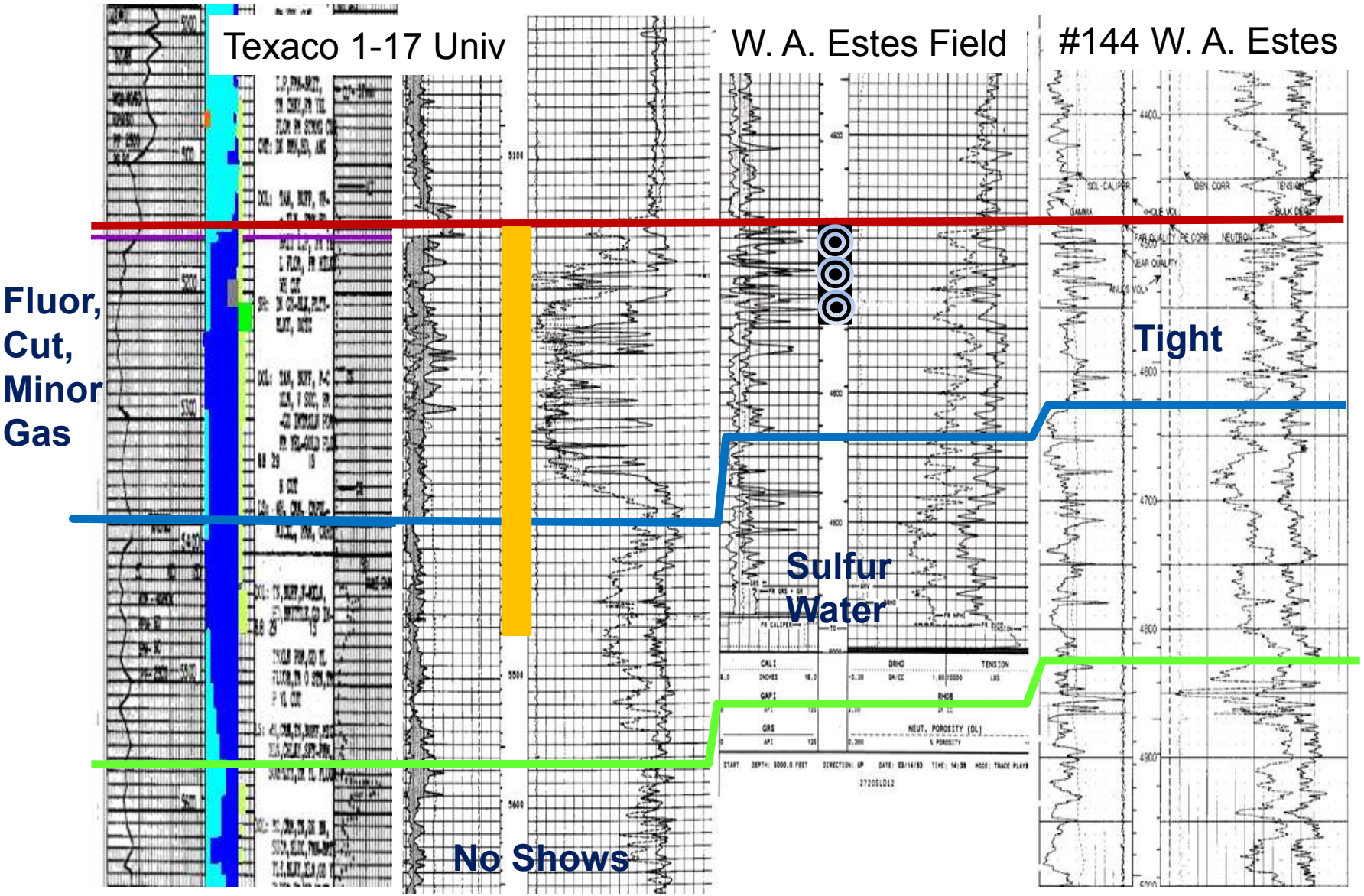
Thick, porous ROZ with CO2 potential?



The pay is the upper Glorieta/San Angelo. The more porous lower section calculates as productive on logs and is oil stained BUT 100% sulfur water productive.

Outer Shelf to Tidal Flat

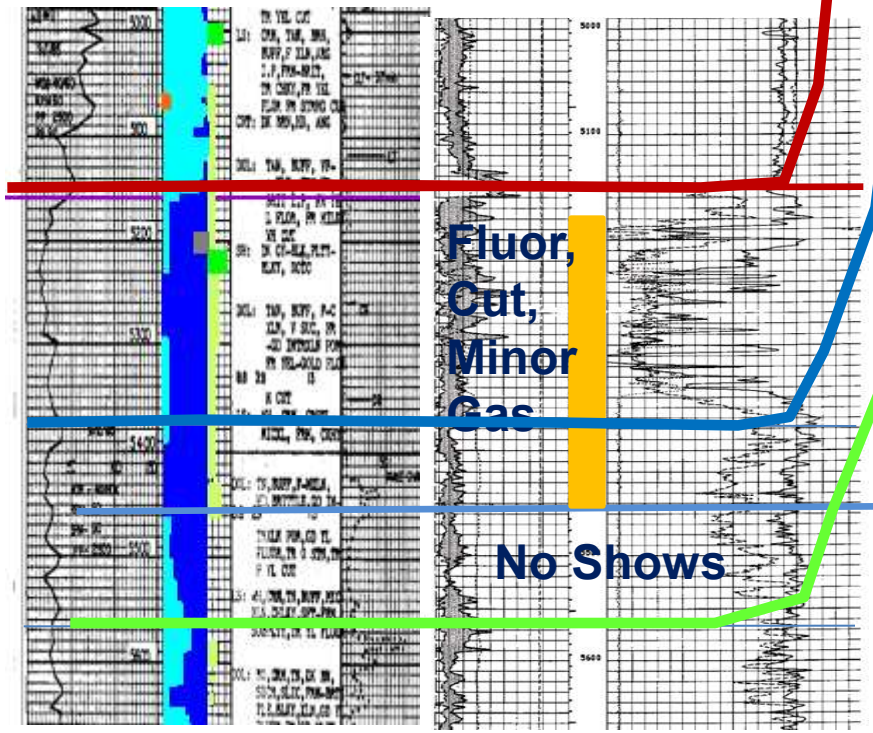
The updip section thinned by pre San Andres tilt and Erosion

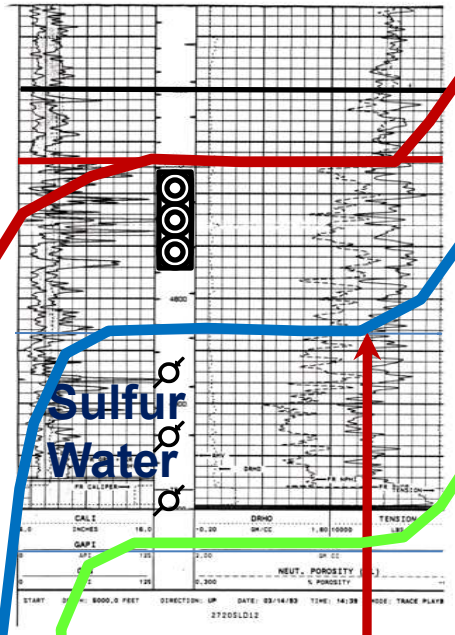


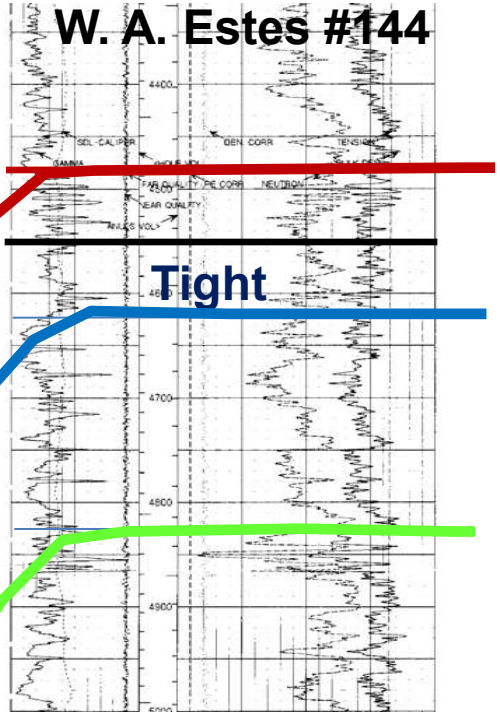
Texaco #1-17 Univ

W. A. Estes Field

W. A. Estes #144







Tight

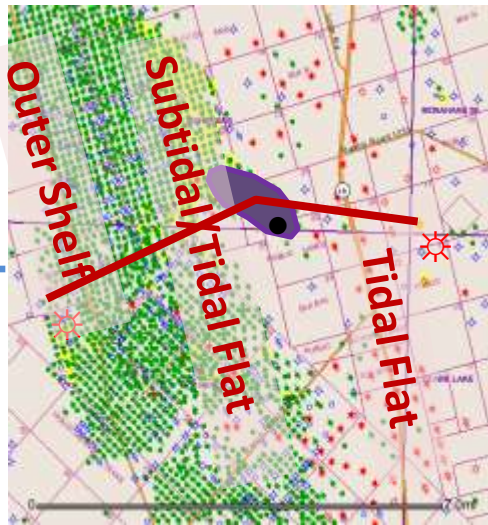
Sulfur Water

Fluor, Cut, Minor Gas

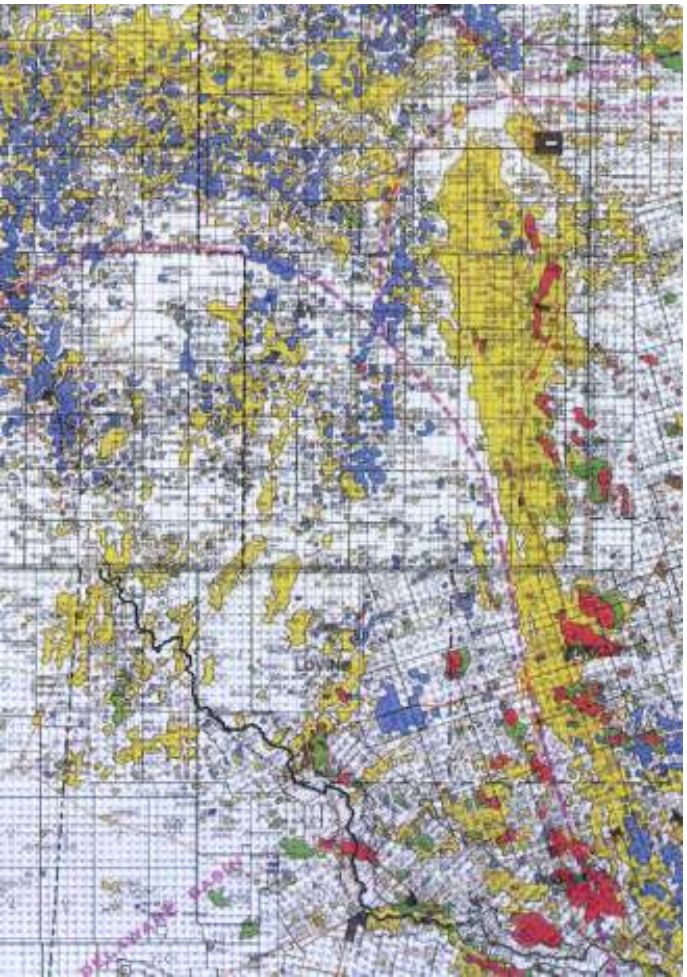
No Shows

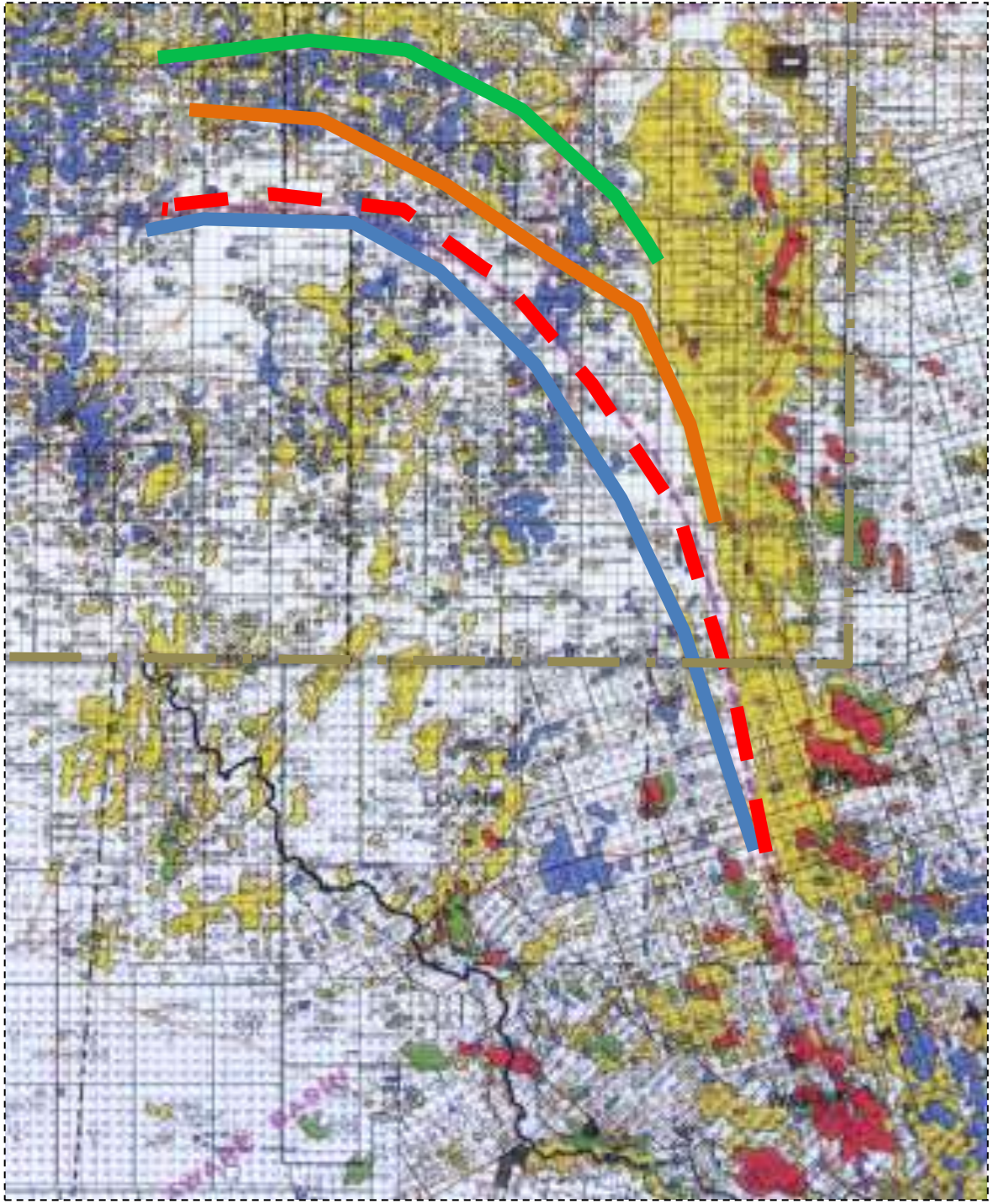
ROZ Maximum 550' !

Base ROZ ?



What is the impact of the prograding Capitan Reef ?





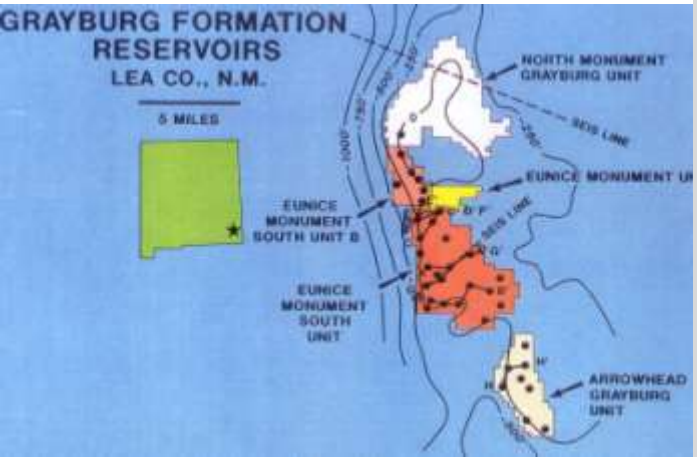
Eunice Monument/South Monument

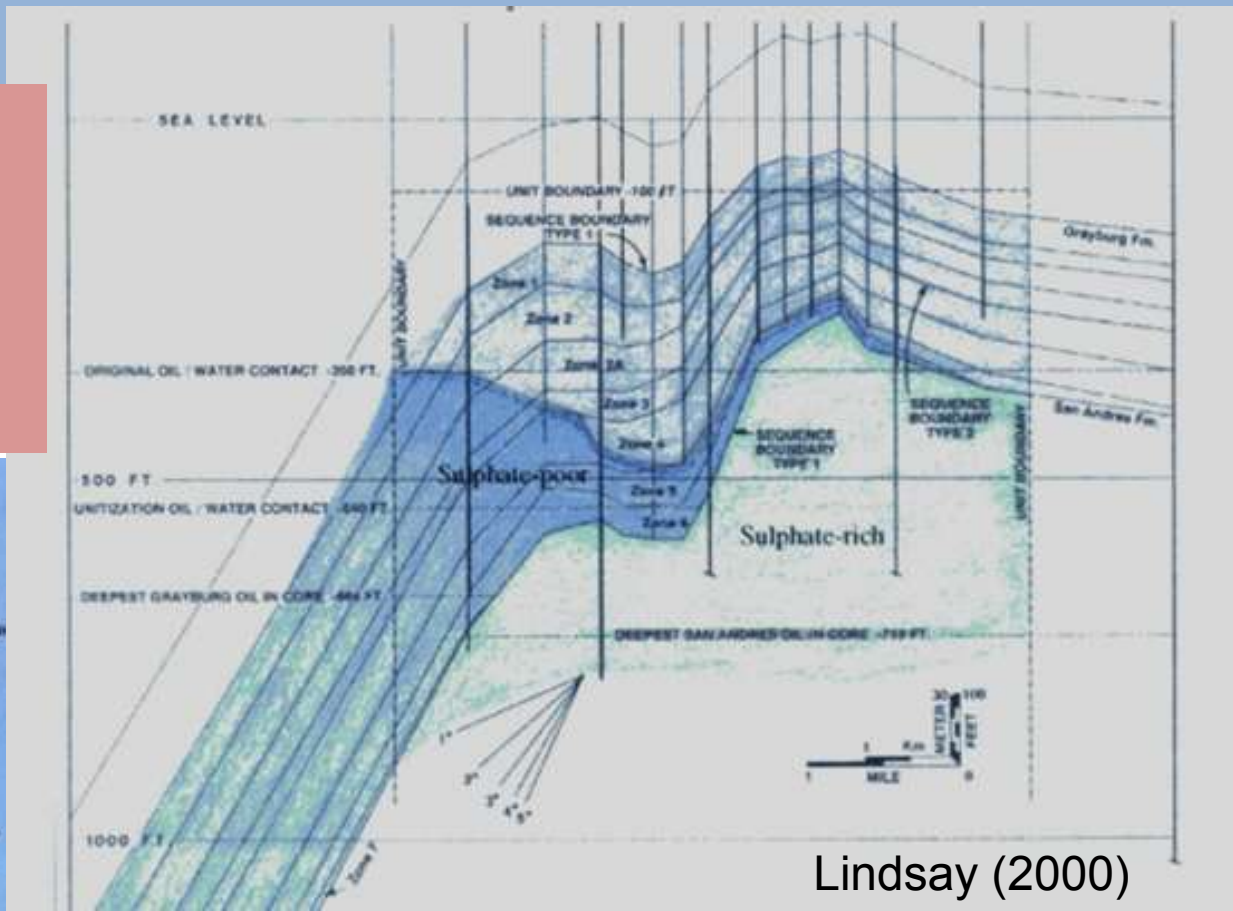
- Grayburg productive with NaCl rich connate water
- San Andres mostly wet with sulfate rich connate water
- Two different sources for the connate waters
- Thickness of San Andres swept reservoir?
- **Eunice Monument South Unit** Productive from the Grayburg with minor production from the underlying San Andres Formation–
- Discovery Oil/Water contact -350’
- Unitization Oil/Water contact -540’
- Deepest Grayburg Oil in core -664’
- Deepest San Andres Oil in core -719’
- >300’ thick SADR w/oil saturation below O/W in Eunice Monument

North Monument Grayburg, Eunice Monument, Eunice Monument South "B", Eunice Monument South, and Arrowhead Grayburg Unit .

- area combined total of 57 square miles.
- Lindsay suggests the sulfate poor edge water is recharged from the Guadalupe Mountains thru the Goat Seep Reef. The Sulfate-rich bottom water drive in the San Andres is recharged from the Sacramento Mountain thru the evaporite rich San Andres. **Eunice Monument South Unit.** The edge water was pulled into the oil leg since production was established in 1929 (from Lindsey, Chevron in-house pubs).
- Structural closures formed by re-activation of existing deep seated faults which folded and fractured the Permian. The structural event increased closure on the reservoir and trapped a larger oil column.

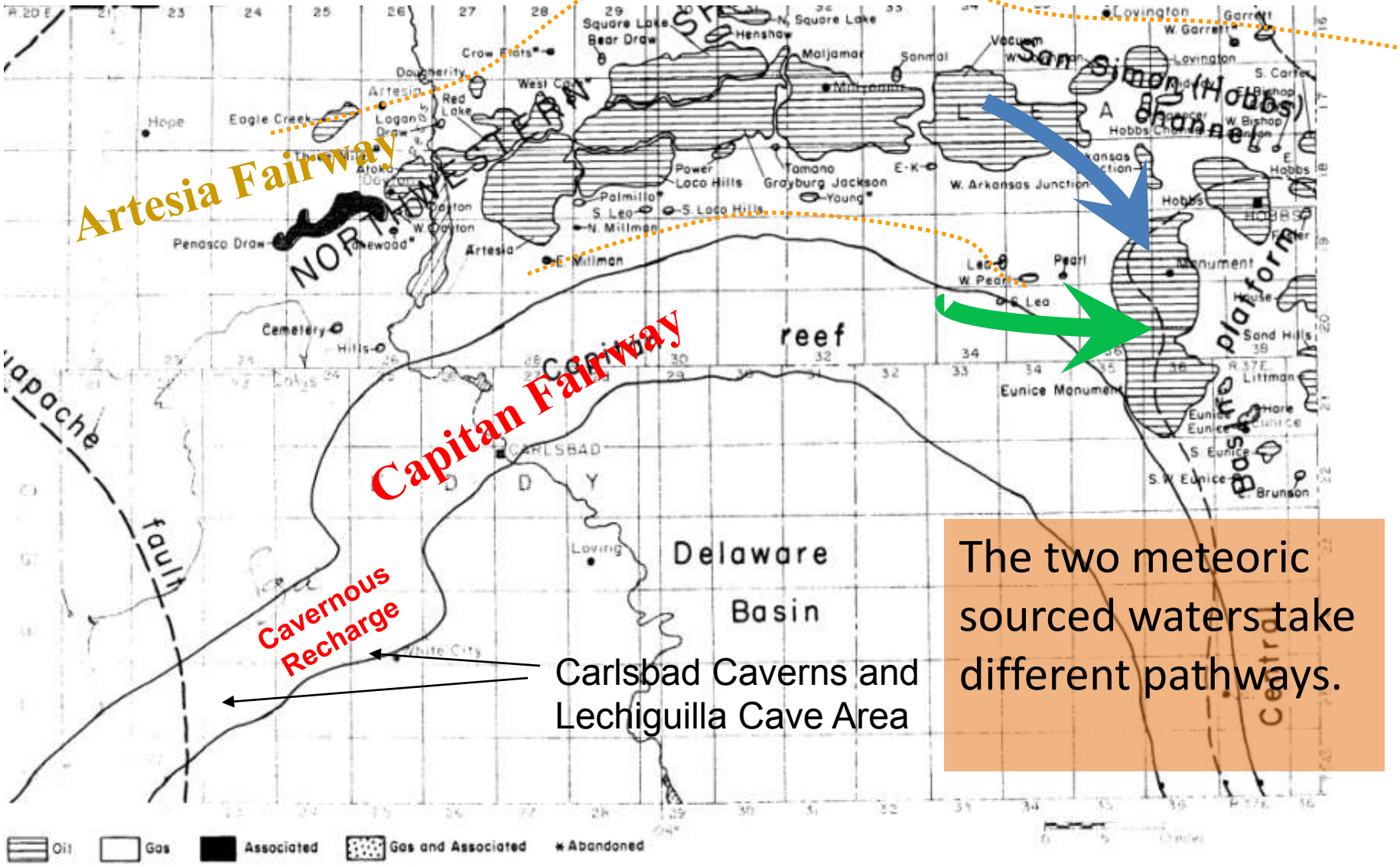
- Eunice Monument
- -150 G/O, -400' O/W (150' below top SADR).
- Na 2000ppm, Cl 2950ppm, TDS 7800PPM (similar to Capitan Reef in Winkler Co.)





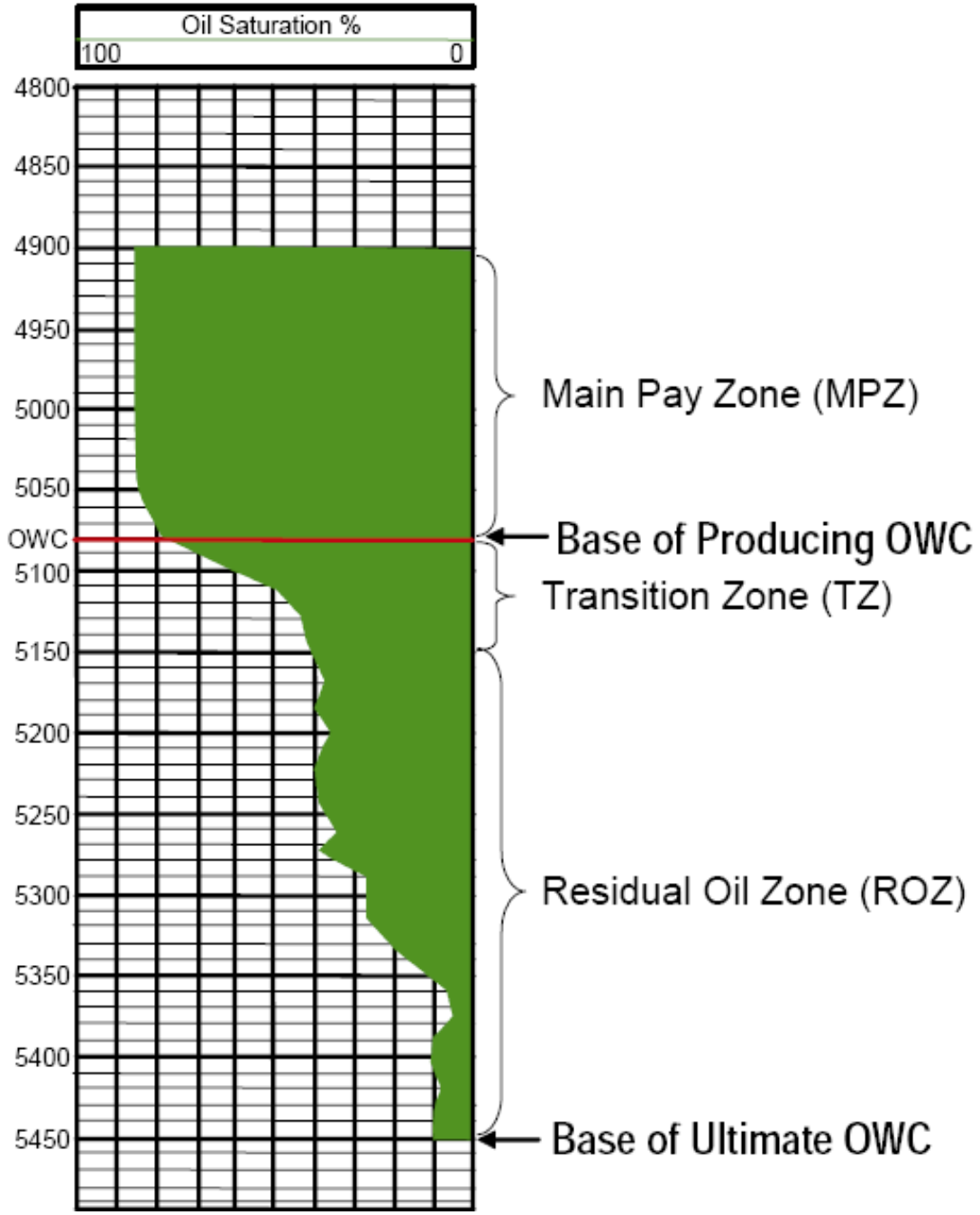
Lindsay (2000)

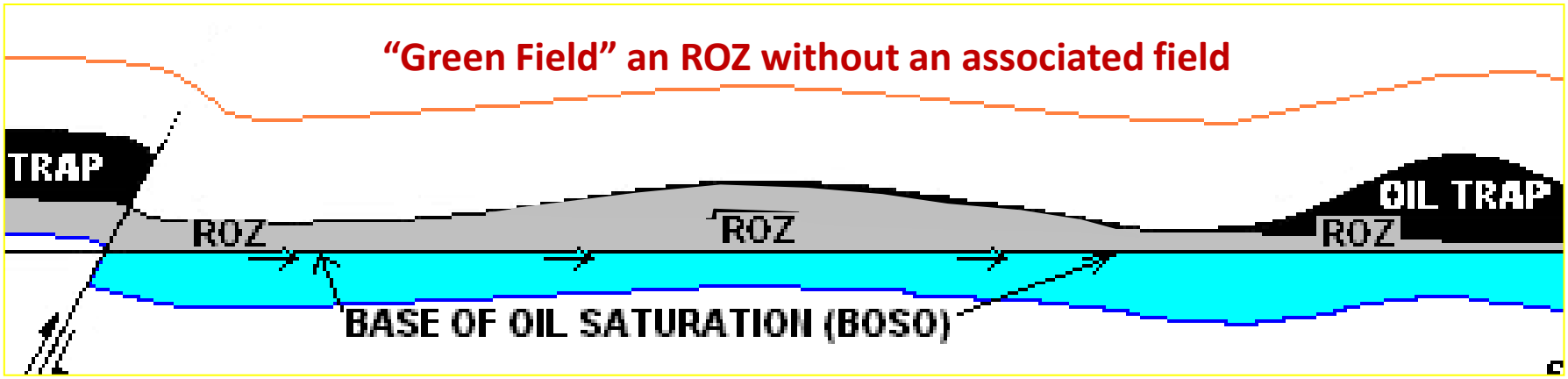
SE NM Grayburg & Upper San Andres Dolomitization Trend



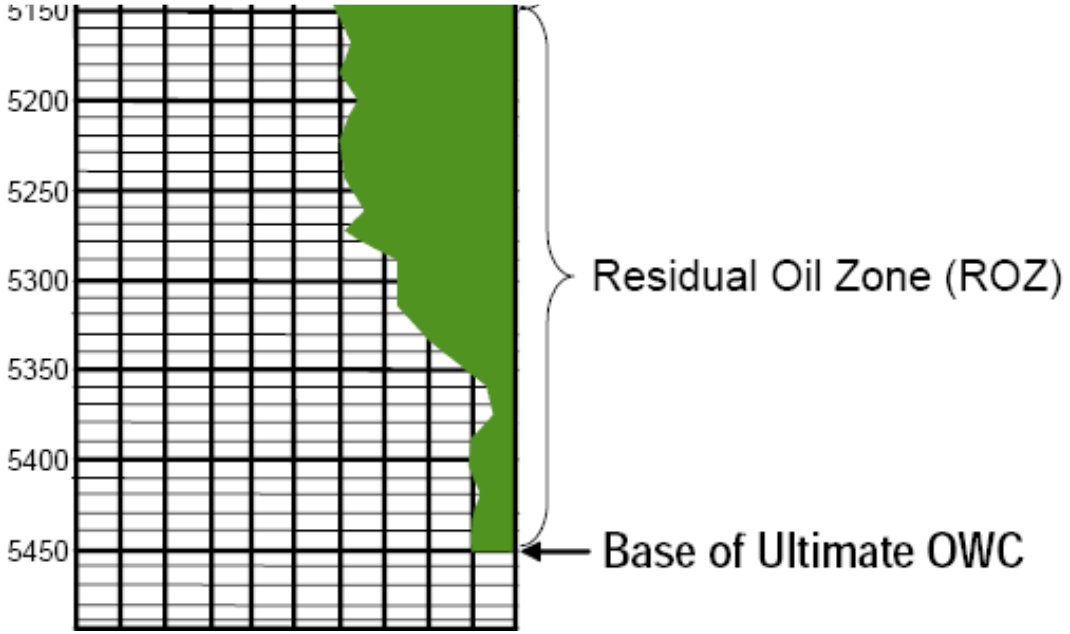
Ref: Future Petroleum Provinces in New Mexico – Discovering New Reserves, Philip R. Grant, Jr. and Roy W. Foster, NM Bur of Mining & Mineral Resources, 1989

What happens when the entire oil column is swept by Mother Nature?

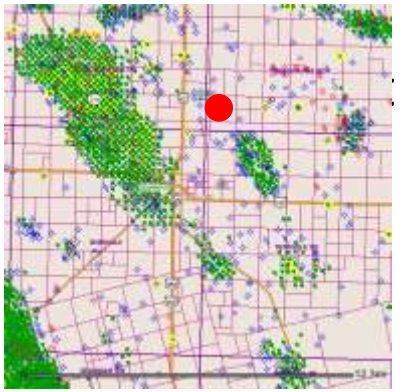




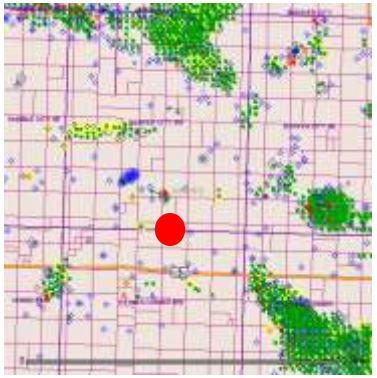
Your left with a tertiary recovery target.



Gaines, Future Targets or goat pasture?



- A Clearfork test, the **IP #1 Campbell Heirs "158"** pipe on "WET" San Andres test just south of Seminole.
- All wireline logs, drill time, gas curves and sample shows said "slam dunk" oil production. Atlas log analyst said it should be a producer.
- 100% water test with barely a sniff of live oil. ROZ?
- **Anschutz #1 Patrick Keating** "447", drilled for San Andres west of Seminole, had good shows but made only water for a few months before P & A (3600 BW, 3 BO). Water analyses show progressive drop in TDS over the two months of production.



- The 2 CORED intervals, from 5464 – 5602, had oil saturations ranging from 15 to 35%, 3 - 12% porosity, & 50-100% fluorescence.
- These are what we term "GREENFIELDS"
- TZ/ROZ's are "BROWNFIELDS".

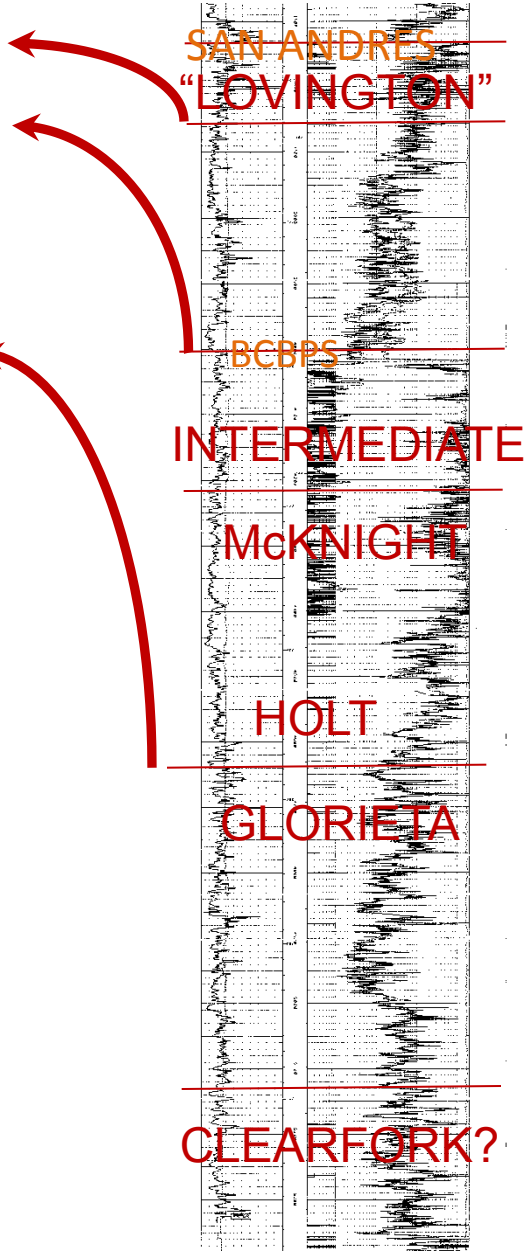
ROZ Regional Context

- Establish regional flow paths through and between reservoirs along the “reservoir trend”.
- Modeling to establish inflow and outflow pathways.
- Determine timing of oil emplacement(s) relative to potential regional sweep events.
- Develop a regional understanding and time line for the relationships among major post depositional/oil emplacement tectonic events and the meteoric associated flushing that create the ROZ’s.
- Understand the impact of tectonic events on the fluid/rock properties along the reservoir trend.
- Characterize the difference and similarities between “classic” reservoir and Residual Oil Zone (ROZ) Reservoir.

Regional San Andres

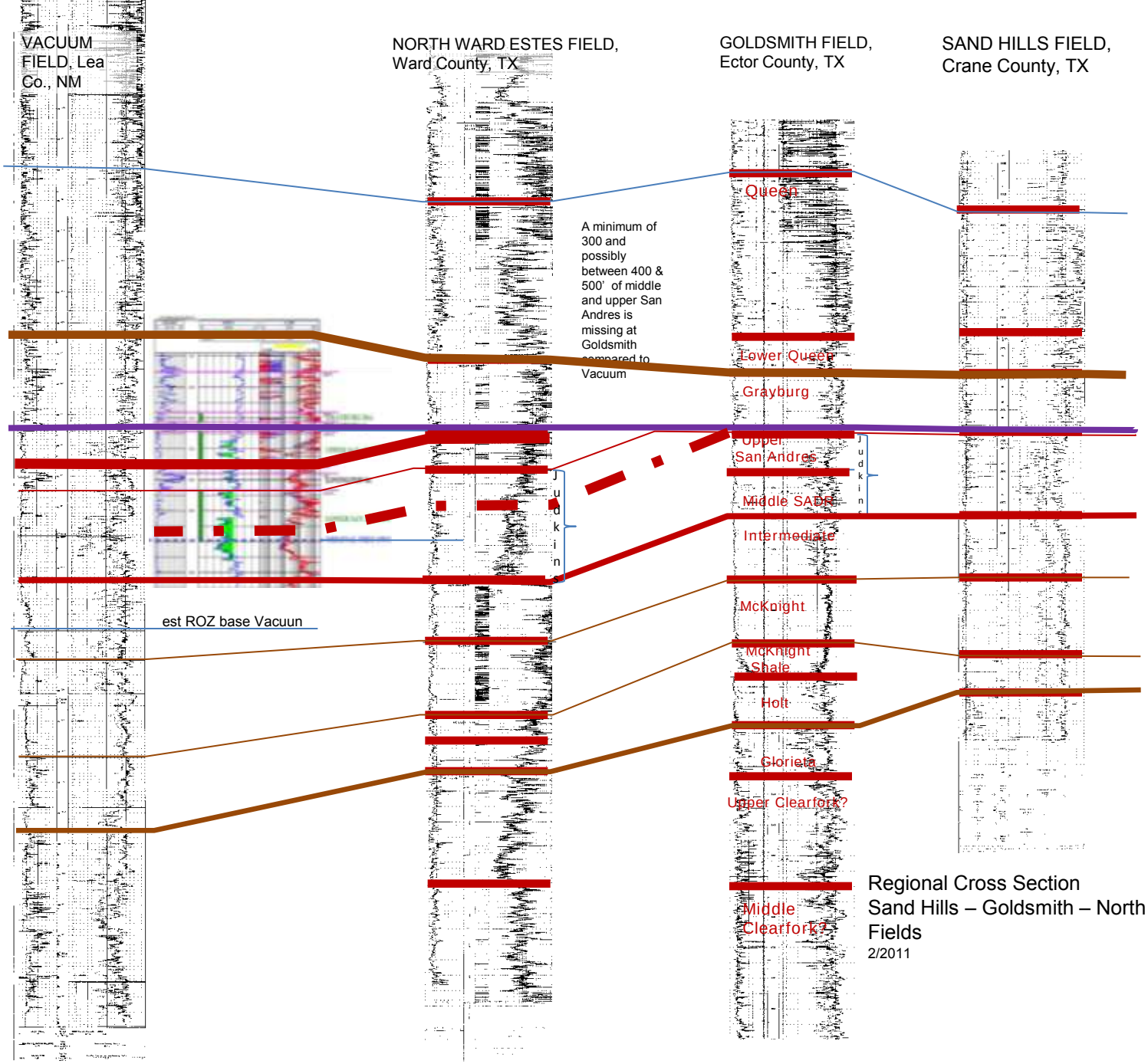
- Placing the San Andres in a regional context is important in understanding the development of the ROZ's.
- The San Andres can be divided into three intervals:
  - A lower San Andres composed of L7 & L8 (Holt) and G1 & G2 (McKnight),
  - a middle San Andres composed of G3-G4 (Intermediate), and
  - an upper San Andres composed of G8-G9 (Pre- and Post-Lovington Sand).
- In addition, the southern end of the Central Basin Platform has had a different tectonic history then the northern end of the platform, the Northwest Shelf and the Guadalupe Mountains.

The major San Andres Sequence Stratigraphic boundaries may act as the boundaries for the original O/W (base of ROZ) and between the present day Main Pay and TZ/ROZ.



G 9	Lovington Sand / Lime
G 8	Pre- Lovington / Judkins
G 5 – 7	Brushy Canyon BPS
G 3 – 4	Intermediate
G 1 – 2	McKnight
L 7 – 8	Holt
L 5 – 6	Glorieta

Nomenclature, based on Gulf Oil's Central Basin Platform "Formations"

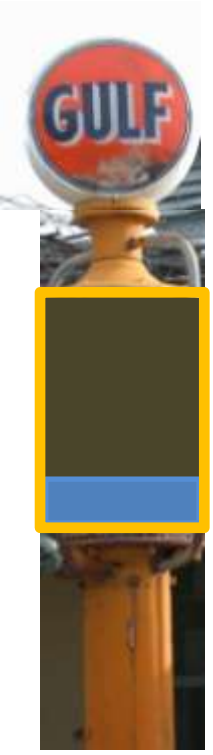


The "top" of the San Andres can be anywhere. As a result of PERMIAN tectonism, the San Andres can range from 650 to 1650' thick.

Regional Cross Section
Sand Hills – Goldsmith – North Ward Estes – Vacuum Fields
2/2011

WD3:Goldsmith:E-W X sec

“Early” Reservoir Parameters

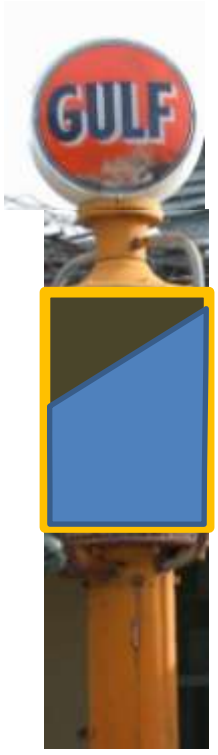


Main Pay

- >80% So
- Salt Water – higher TDS
- Will respond to Waterflood
- CO2 EOR Potential
- Dolomite Reservoir
- Infill potential
- More Karst
- No Sulfur in cuttings and core
- Lower Porosity and Permeability
- Mixed wet
- No Greenfield Potential
- Oil Gravity
- Man made flowpaths /fractures

Residual Oil Zone

- 20 to 40% So
- Sulfur Water – lower TDS
- NO waterflood potential
- CO2 EOR Potential
- Dolomite Reservoir
- Deepening potential
- Less Karst
- Sulfur in cuttings and core
- Higher Porosity and Permeability
- Wettability issues
- Greenfield Potential
- Oil Gravity
- “Virgin” Reservoir Conditions



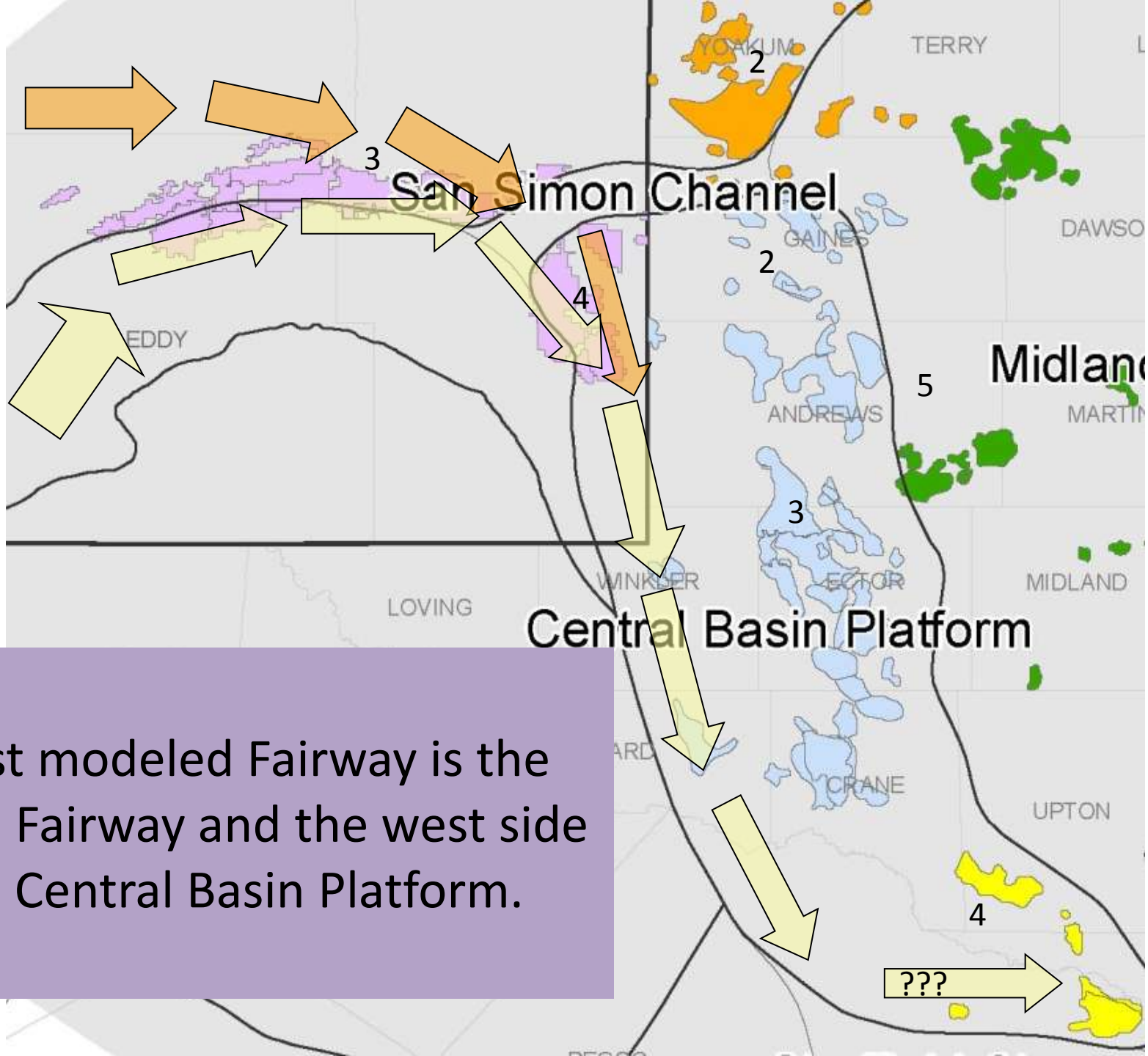
“Late” Reservoir Parameters

Waterflooded Main Pay

- 20 to 40% So
- Salt Water – ???? TDS
- No remaining Waterflood Potential
- CO2 EOR Potential
- Well known reservoir parameters
- Enhanced high perm streaks
- Mixed wetability
- Man made flowpaths /fractures

Residual Oil Zone

- 20 to 40% So
- Sulfur Water – lower TDS
- NO waterflood potential
- CO2 EOR Potential
- Estimated reservoir parameters
- Potentially more homogeneous
- Wettability questions
- Untouched



The first modeled Fairway is the “Artesia” Fairway and the west side of the Central Basin Platform.

Some other questions to consider:

- The total thickness of the San Andres at major producing field ranges from 650-750' [Yates and Goldsmith] to 1400 to 1600' [Seminole to Vacuum], yet,
  - The ratio of ROZ to main pay thickness in many of those large field may remain close to 1:1.
  - In other fields the thickness of the ROZ can equal or exceed the thickness of the main pay AND the ROZ elsewhere, and
  - Where there is no main pay, "Greenfields", the ROZ can be 50 – 300' thick or more. WHY?
- Why is there no major San Andres, Grayburg or Clearfork production south of the Texas/New Mexico border on the west side of the Central Basin Platform?
- How many pore volumes of water passed through the ROZR during Mother Nature's Waterflood (MNW)?
- How does that relate to the volumes of water that passed through our Main Pays during modern Waterfloods.
- Consider the time frame in which these two "sweeps" occur, would you expect to see the same results?
- Significant ROZ's appear to be present in the Leonard (Glorieta and upper and lower Clearfork) which are below the San Andres (Guadalupian) path across the San Simon channel.

Camels passing through the eye of a needle

- Dolomitizing pathways.
- Basin dewatering is often invoked for late dolomitization of reservoirs
- How many pore volumes can you pass through a reservoir when the updip traps are sabkha's?
- What is the pathway down dip to up dip then parallel to the margin?

Working backward from what we see. Characteristics of the ROZ vs. the Main Pay.

- Sulfur crystals associated with anhydrite and calcite in vuggy porosity at the Base of ROZR.
- Patchy high oil saturation above/at/below the Base of Saturation of Oil (BOSO) in low permeability intervals.
- Late stage solution enhanced fractures
- Solid Hydrocarbon Residue
- Oil Chemistry differences
- Oil Gravity differences
- Transition from limestone below the ROZ reservoir, to dolomite within the ROZ reservoir.
- Relationship of Limestone to dolomite transition to Sequence Stratigraphic Boundaries
- Enhanced Porosity due to the limestone-to-dolomite conversion
- Enhanced Porosity due to the dissolution of evaporites
- Enhanced Permeability due to limestone to dolomite conversion and secondary dolomitization
- Changes in wettability
- Vertical ROZ salinity variations
- Lateral/Trend salinity variations
- Chloride to sulfate water transition
- Bow Shaped, Pervasively Dolomitized Intervals (PDI)
- Relationship between ROZ and MP thickness.
- 90 degree turn for fluids
- Relationship of MP/ROZ/100% water transitions to Sequence Stratigraphic boundaries.

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Chevron & Legado our industry partners
George Koperna, Advanced Resources International
All those who have battled with ROZ's in the past.

Summary

- We've only just begun.
- ROZ's are real and a major tertiary recovery target for today and long into the future.
- Modeling using regional scale groundwater modeling package is underway.
- Documentation of areas/fields with potential is underway.
- Phase 2 – testing models in the field has begun.
- A number of presentations have been/or will be made and can be found on our RPSEA supported website: **Residualoilzones.com**.