"*Residual Oil Zone's (ROZ's) as an Unconventional Target*
Enhanced Oil Recovery and Carbon Capture Utilization and Storage(CCUS):

CO2 for EOR as CCUS

Robert Trentham[i], L. Stephen Melzer[ii], and David Vance[iii]

[i] CEED/UTPB-MC, [ii] Melzer Consulting, [iii] Arcadis U. S.

- Regional Understanding
- Model of “Mother Nature’s Waterflood”
- The Gold Standard – Seminole Field
- Goldsmith – Independent’s view of CO2 in ROZ’s
- Greenfields
- What Does an ROZ look like?
- Size of the Prize

Our Final Report on the Modeling Project has been submitted and accepted by the Research Partnership to Secure Energy for America (RPSEA).

RPSEA
Research Partnership to Secure Energy for America

Commercial Exploitation and the Origin of Residual Oil Zones: Developing a Case History in the Permian Basin of New Mexico and West Texas

Document Number

Contract 81.089 08123-19-RPSEA

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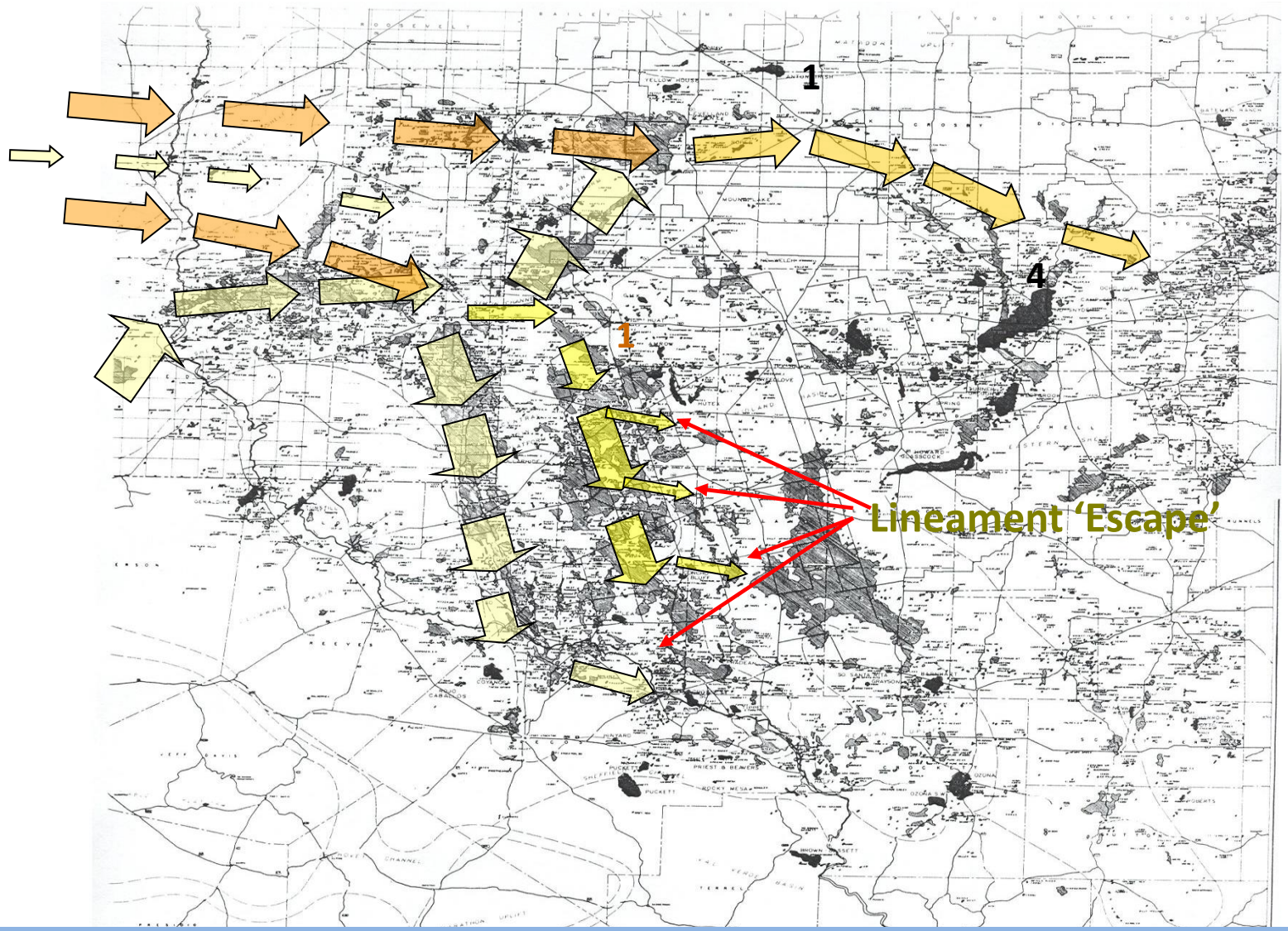
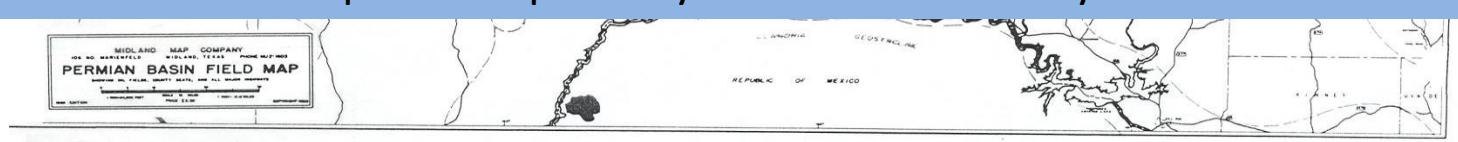
Key Findings

- The meteoric derived sweep of oil from the ROZ portion of San Andres reservoirs was probable.
- Modeled pore volume flushing in the Artesia Fairway ranges from 20 to 50 pore volumes over 15 million years (Late Oligocene through Middle Miocene), with flow rates of 10 to 25 cm/year.
- This hydrodynamic origin can also explain the Oil/Water contact tilts seen in many of the San Andres reservoirs at the time of discovery.

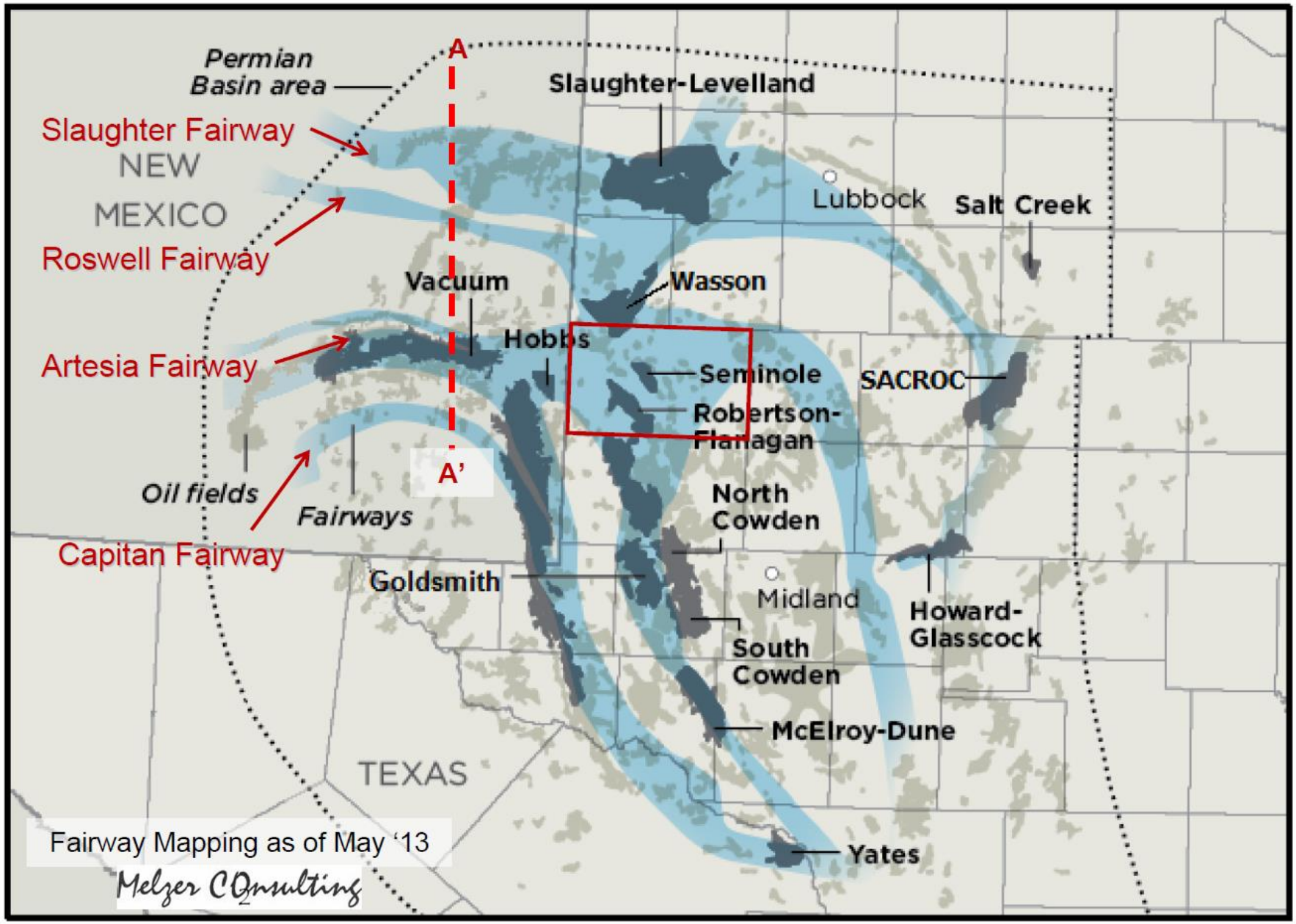
THEORIZED (U. PERMIAN) HYDRODYNAMIC FAIRWAYS



There are a number of probable pathways that will eventually documented

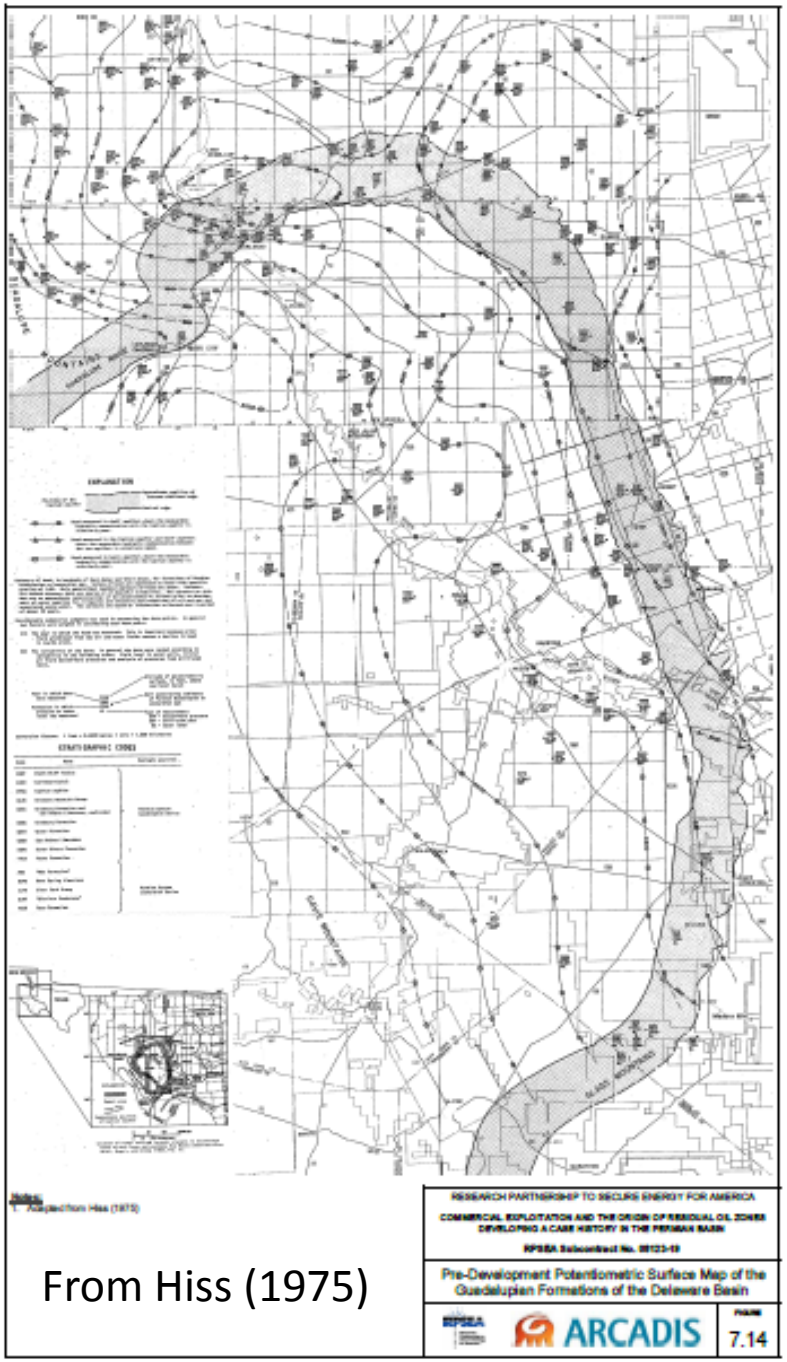


The Permian Basin Region of the Southwestern U.S.
Major Carbonate Fields and Residual Oil Zone Fairways

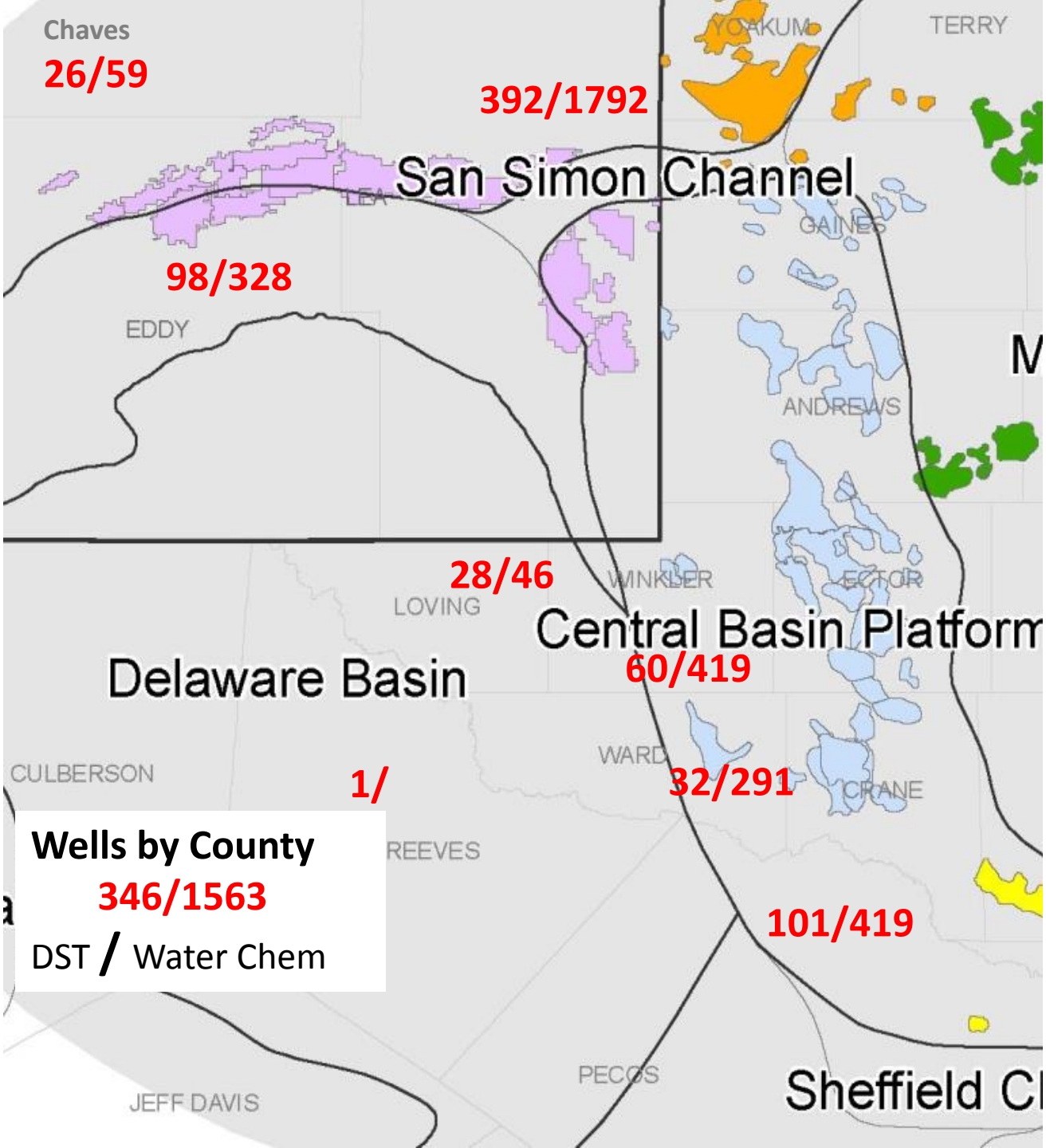


The Modeling Effort

- Used Groundwater Modeling package.
- Input Core, DST, Produced Water, Ground Water, Log Tops.
- Included pre-existing data sets
- Developed a three layer model with variable permeability.



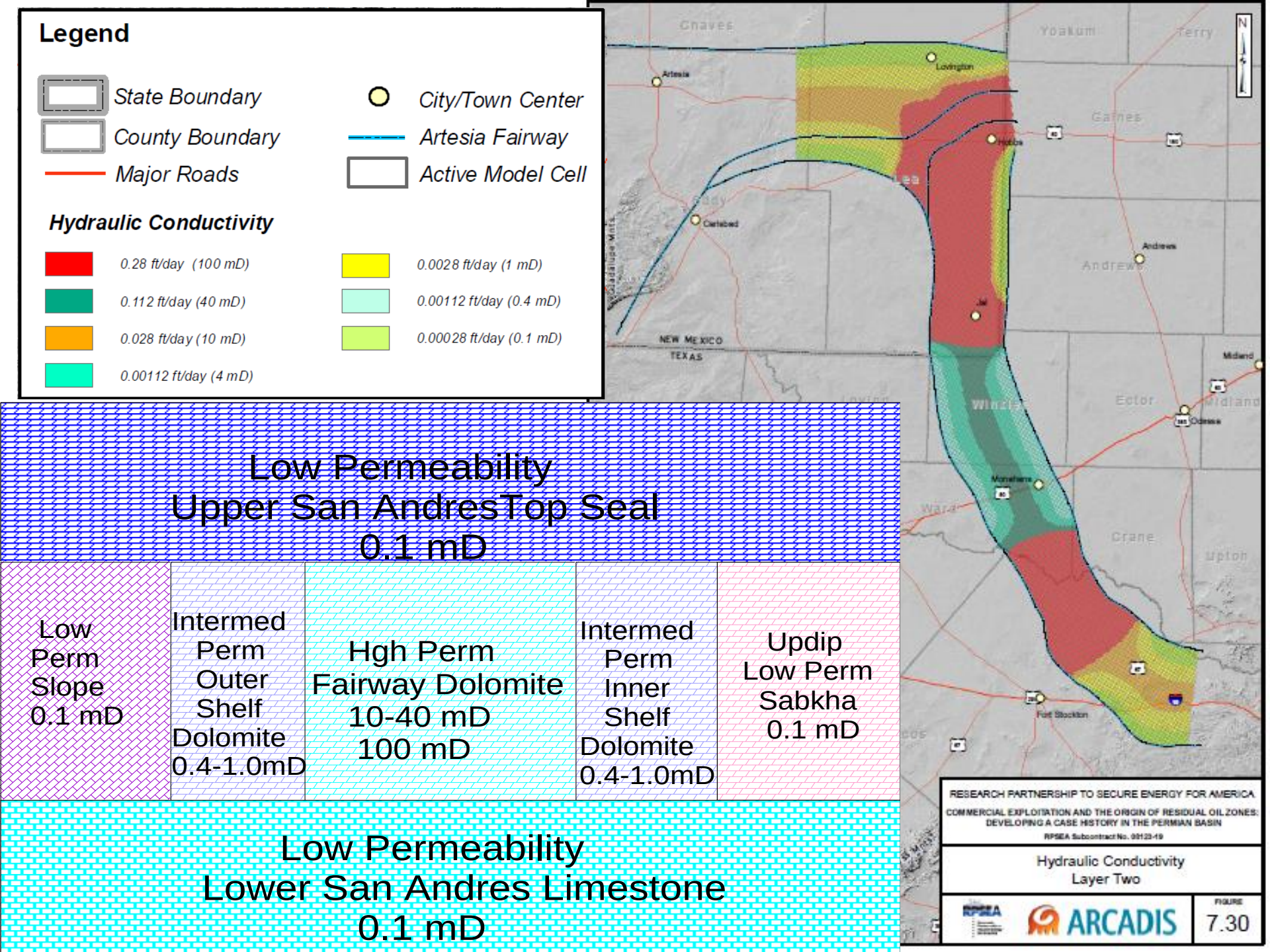
From Hiss (1975)

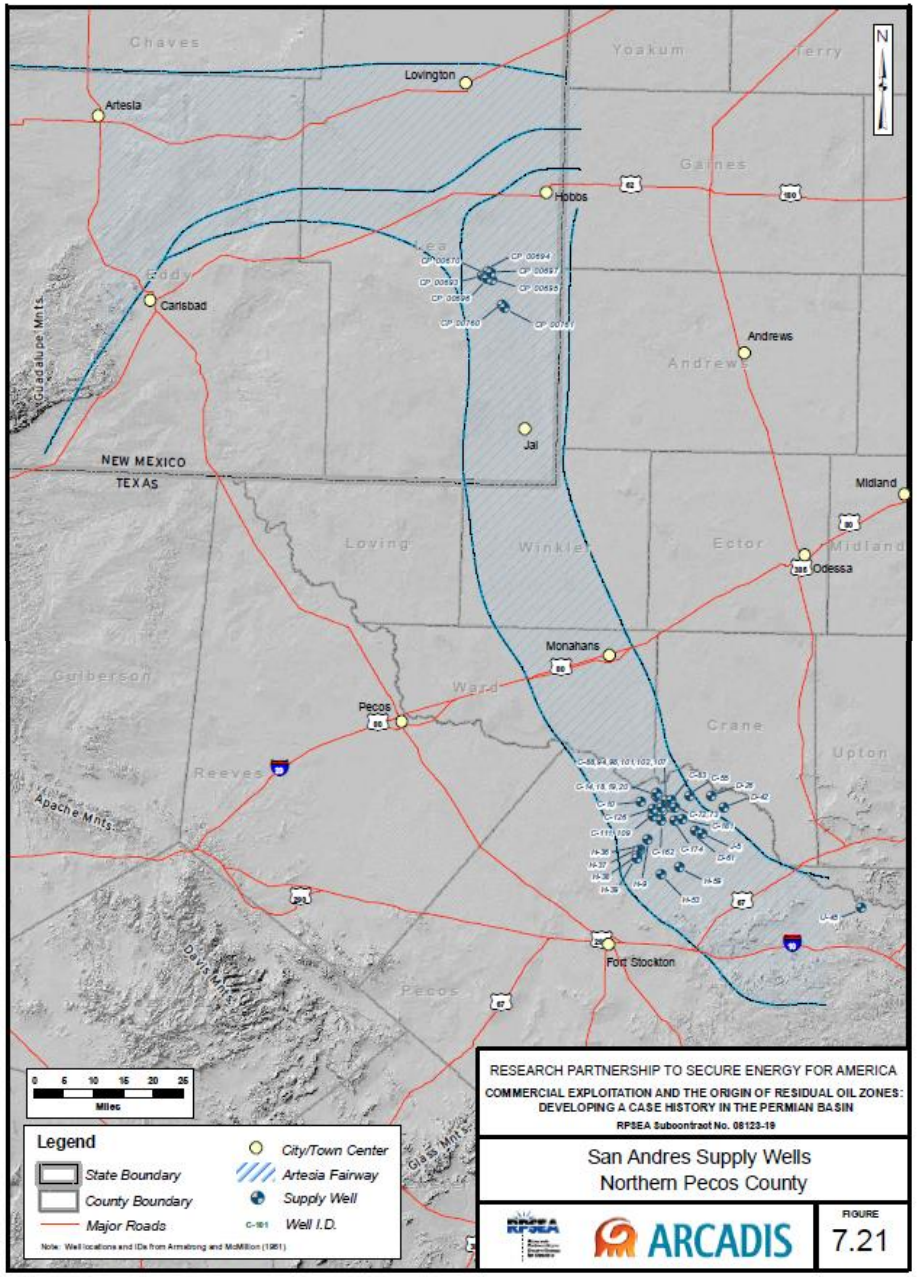


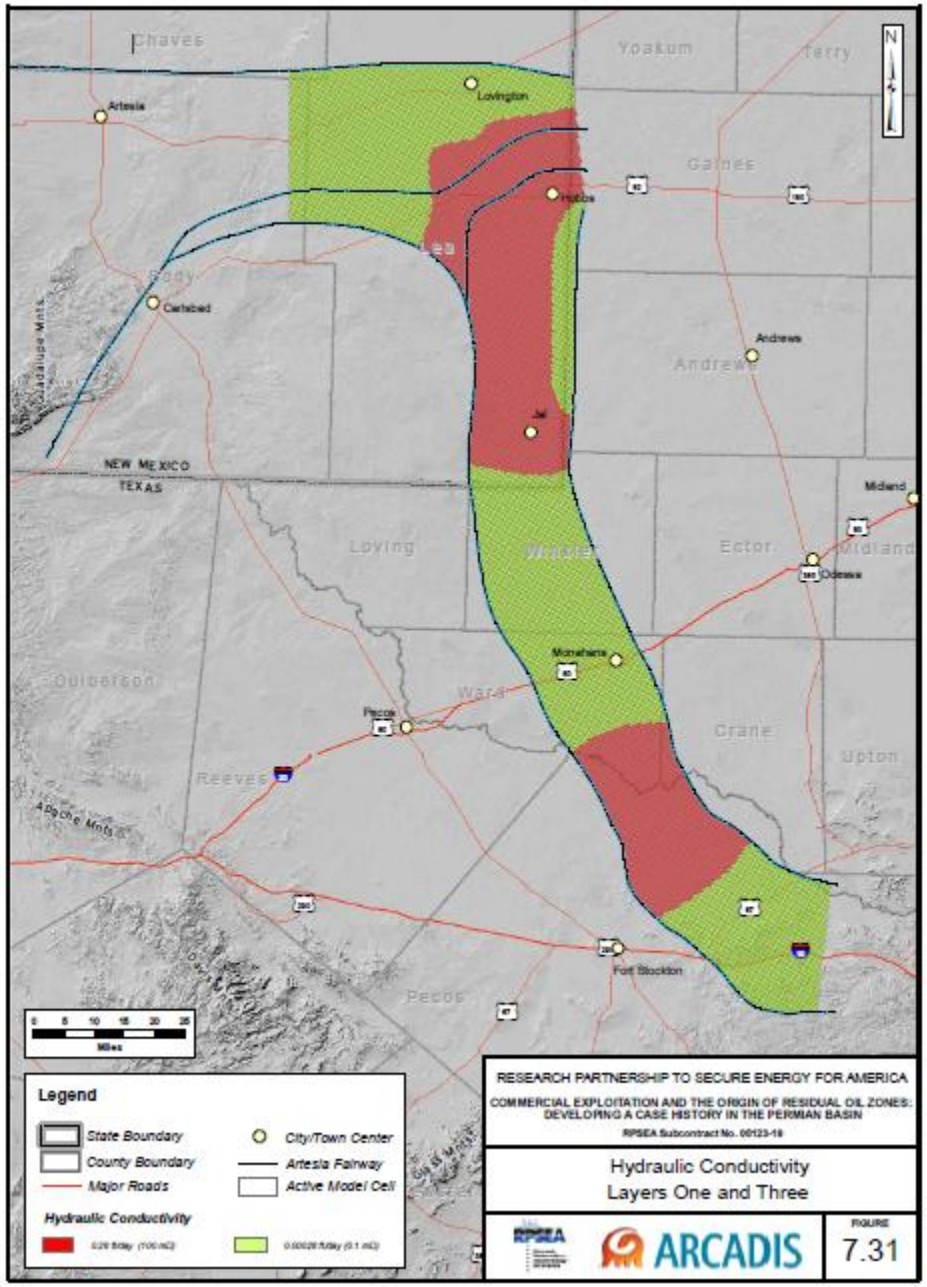
Wells by County

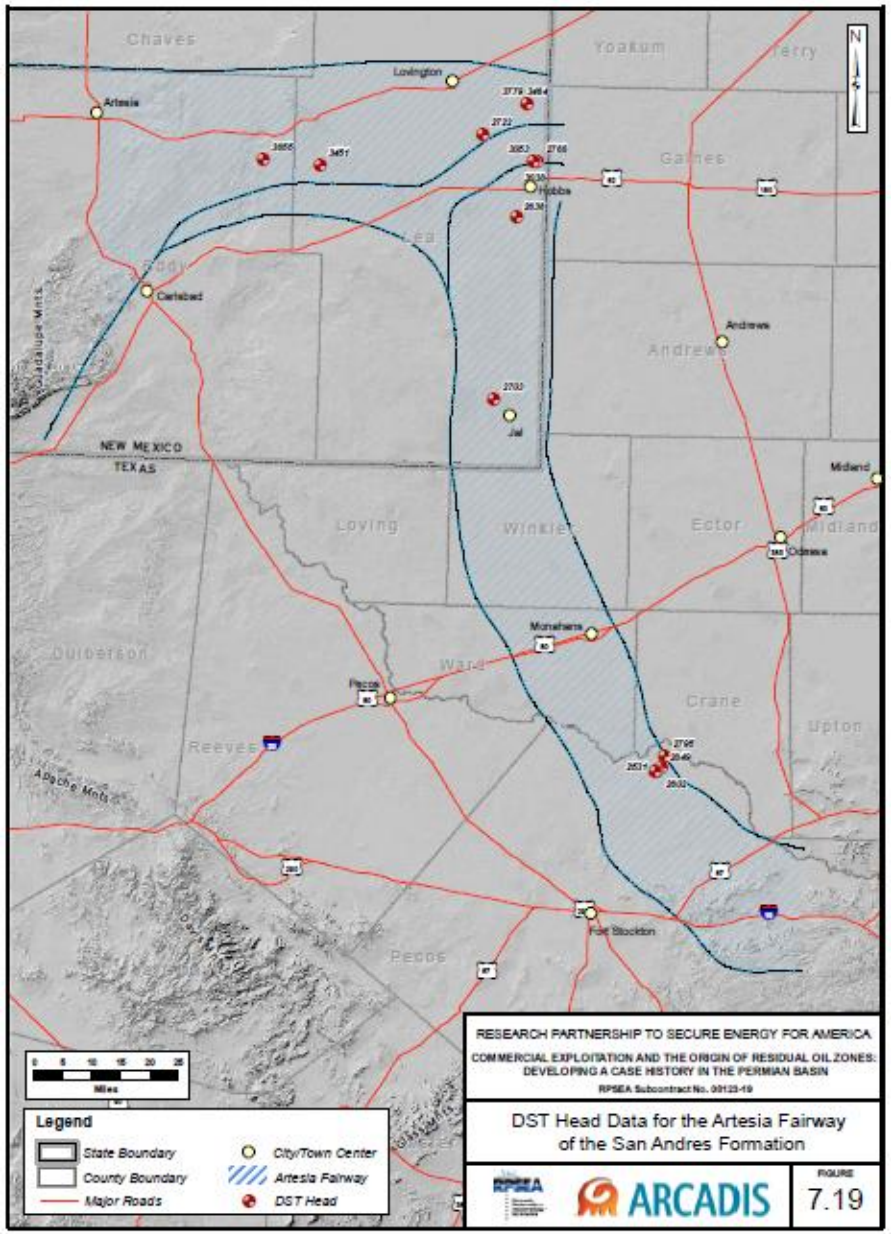
346/1563

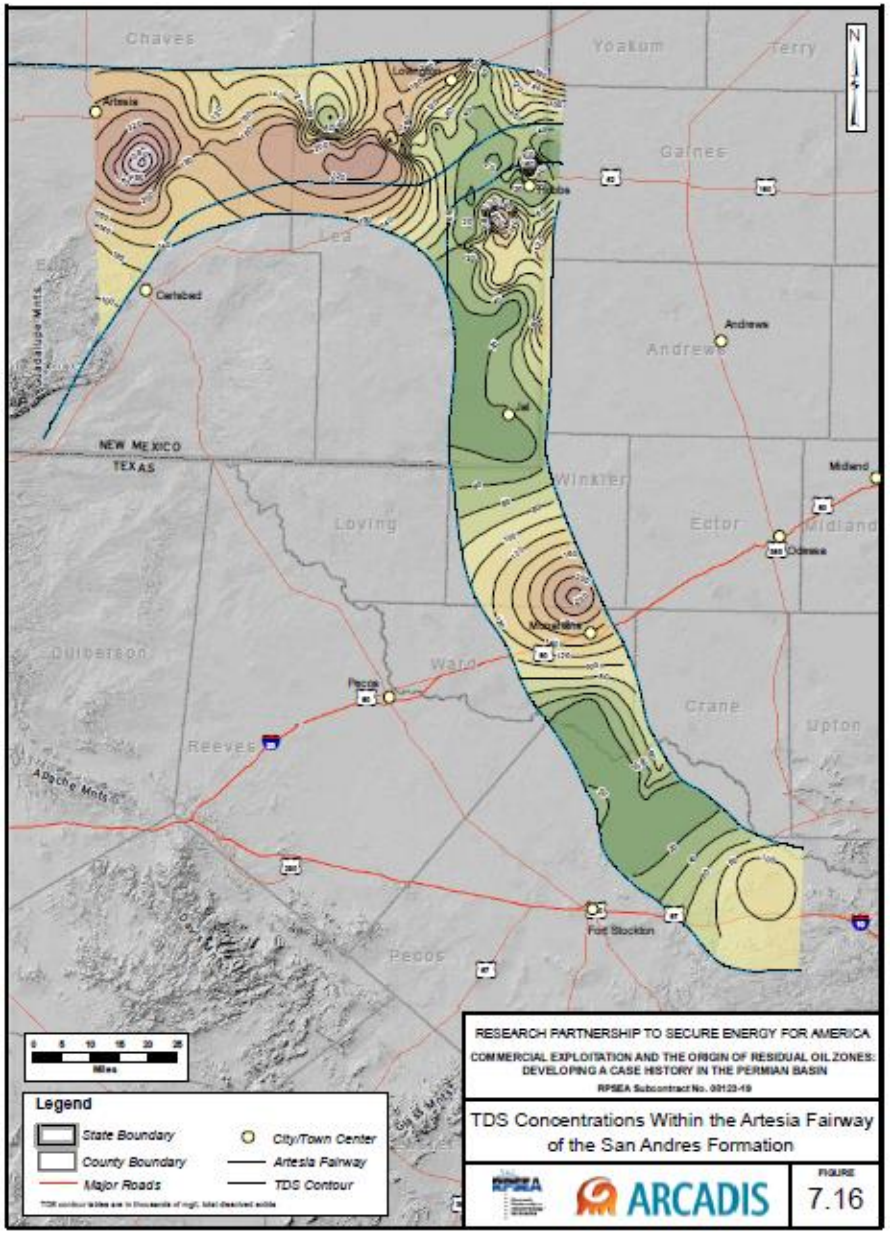
DST / Water Chem


Legend
State Boundary
County Boundary
Major Roads
City/Town Center
Artesia Fairway
Active Model Cell
Hydraulic Conductivity
0.28 ft/day (100 mD)
0.112 ft/day (40 mD)
0.028 ft/day (10 mD)
0.00112 ft/day (4 mD)
0.0028 ft/day (1 mD)
0.00112 ft/day (0.4 mD)
0.00028 ft/day (0.1 mD)
Low Permeability
Upper San Andres Top Seal
0.1 mD
Low Perm Slope 0.1 mD
Intermed Perm Outer Shelf Dolomite 0.4-1.0mD
Hgh Perm Fairway Dolomite 10-40 mD 100 mD
Intermed Perm Inner Shelf Dolomite 0.4-1.0mD
Updip Low Perm Sabkha 0.1 mD
Low Permeability
Lower San Andres Limestone
0.1 mD
Chaves
Yoakum
Terry
Artesia
Lovington
Gaines
Hobbs
Lea
Carlsbad
Andrews
Andrews
NEW MEXICO
TEXAS
Midland
Ector
Midland
Odessa
Winkler
Monahans
Ward
Crane
Upton
Fort Stockton
RESEARCH PARTNERSHIP TO SECURE ENERGY FOR AMERICA
COMMERCIAL EXPLOITATION AND THE ORIGIN OF RESIDUAL OIL ZONES: DEVELOPING A CASE HISTORY IN THE PERMIAN BASIN
RPSEA Subcontract No. 08123-19
Hydraulic Conductivity
Layer Two
RPSEA
ARCADIS
FIGURE
7.30


Chaves
Yoakum
Terry
Lovington
Artesia
Gaines
Hobbs
Eddy
Carlsbad
Guadalupe Mnts.
Andrews
Jal
NEW MEXICO
TEXAS
Midland
Loving
Winkler
Ector
Odessa
Monahans
Ward
Pecos
Crane
Upton
Reeves
Apache Mnts.
Davis Mnts.
Pecos
Fort Stockton
Glass Mnts.
0 5 10 15 20 25
Miles
Legend
State Boundary
County Boundary
Major Roads
City/Town Center
Artesia Fairway
Supply Well
Well I.D.
Note: Well locations and IDs from Armstrong and McMillion (1981)
RESEARCH PARTNERSHIP TO SECURE ENERGY FOR AMERICA
COMMERCIAL EXPLOITATION AND THE ORIGIN OF RESIDUAL OIL ZONES: DEVELOPING A CASE HISTORY IN THE PERMIAN BASIN
RPSEA Subcontract No. 08123-19
San Andres Supply Wells
Northern Pecos County
RPSEA
ARCADIS
FIGURE
7.21


Chaves
Yoakum
Terry
Lovington
Artesia
Gaines
Hobbs
Eddy
Carlsbad
Guadalupe Mnts.
Andrews
Jal
NEW MEXICO
TEXAS
Midland
Loving
Winkler
Ector
Odessa
Monahans
Ward
Pecos
Crane
Upton
Reeves
Apache Mnts.
Davis Mnts.
Pecos
Fort Stockton
Glass Mnts.
0 5 10 15 20 25
Miles
Legend
State Boundary
County Boundary
Major Roads
City/Town Center
Artesia Fairway
Active Model Cell
Hydraulic Conductivity
RESEARCH PARTNERSHIP TO SECURE ENERGY FOR AMERICA
COMMERCIAL EXPLOITATION AND THE ORIGIN OF RESIDUAL OIL ZONES: DEVELOPING A CASE HISTORY IN THE PERMIAN BASIN
RPSEA Subcontract No. 08123-19
Hydraulic Conductivity
Layers One and Three
RPSEA
ARCADIS
FIGURE
7.31


Chaves
Yoakum
Terry
Lovington
Artesia
Gaines
Hobbs
Lea
Eddy
Carlsbad
Andrews
Jal
NEW MEXICO
TEXAS
Midland
Loving
Winkler
Ector
Odessa
Monahans
Ward
Pecos
Crane
Upton
Reeves
Apache Mnts
Fort Stockton
Pecos
Legend
State Boundary
County Boundary
Major Roads
City/Town Center
Artesia Fairway
DST Head
Miles
RESEARCH PARTNERSHIP TO SECURE ENERGY FOR AMERICA
COMMERCIAL EXPLOITATION AND THE ORIGIN OF RESIDUAL OIL ZONES: DEVELOPING A CASE HISTORY IN THE PERMIAN BASIN
RPSEA Subcontract No. 00123-19
DST Head Data for the Artesia Fairway of the San Andres Formation
ARCADIS
FIGURE
7.19


Chaves
Yoakum
Terry
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Artesia
Gaines
Hobbs
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Eddy
Carlsbad
Andrews
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NEW MEXICO
TEXAS
Midland
Loving
Winkler
Ector
Odessa
Monahans
Ward
Pecos
Crane
Upton
Reeves
Apache Mnts
Fort Stockton
Pecos
Legend
State Boundary
County Boundary
Major Roads
City/Town Center
Artesia Fairway
TDS Contour
Miles
RESEARCH PARTNERSHIP TO SECURE ENERGY FOR AMERICA
COMMERCIAL EXPLOITATION AND THE ORIGIN OF RESIDUAL OIL ZONES: DEVELOPING A CASE HISTORY IN THE PERMIAN BASIN
RPSEA Subcontract No. 00123-19
TDS Concentrations Within the Artesia Fairway of the San Andres Formation
ARCADIS
FIGURE
7.16

Horizontal Fluid Movement per 1000 years

Conductivity Zone	Velocity (ft/1,000 years)	Velocity (ft/1,000 years)	Velocity (ft/1,000 years)
Layer One	1.9	1.1	0.7
Layer Two – Center Zone	**738**	**446**	**278**
Layer Two – Intermediate Zone	72	44	27
Layer Two – Edge Zone	7.2	4.3	2.7
Layer Three	1.9	1.1	0.7

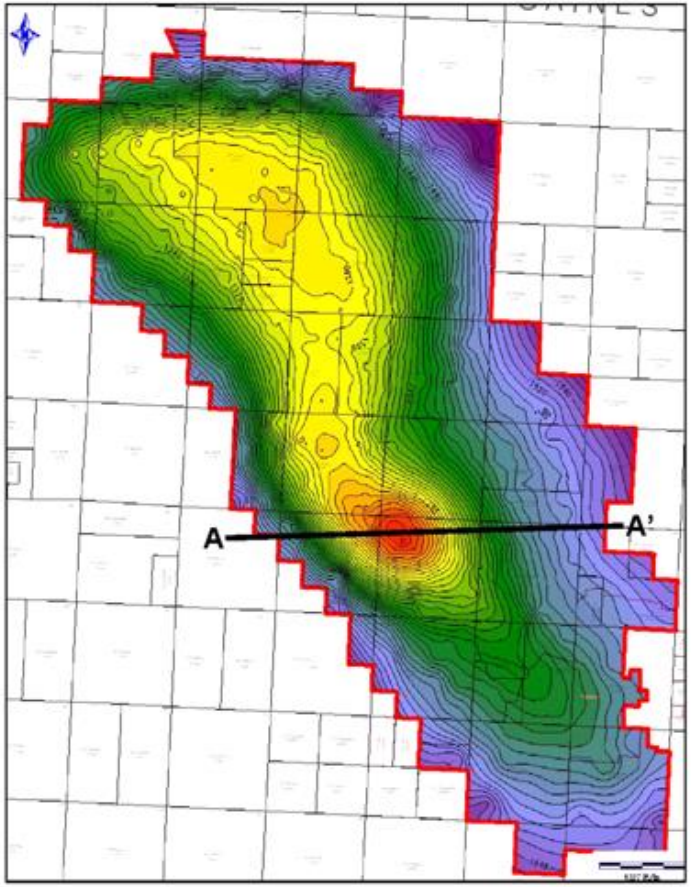
Time Period and Pore Volumes

I	n = 6%	n = 10%	n = 16%
Total Pore Volume (ft^3)	1.22×10^{11}	2.04×10^{11}	3.26×10^{11}
Flow Rate (ft^3/day)	1,030		
Time Period (Million Years)	15		
Total Flow (cubic feet)	5.64×10^{12}		
Number of Pore Flushes	46.0	27.7	17.3

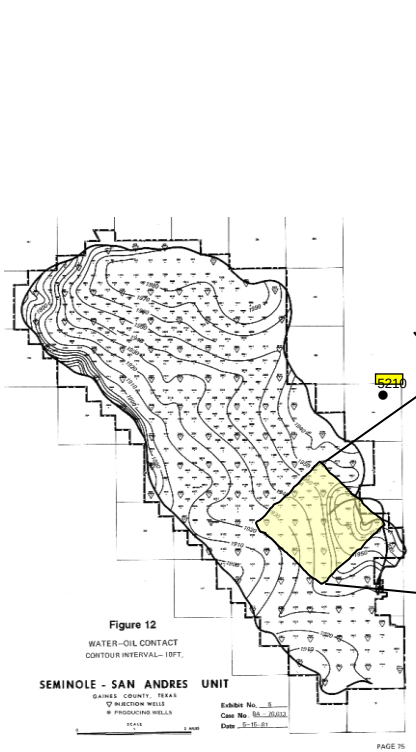
Modeling of the system that created "Mother Natures Waterflood" will be completed as part of this study.

- The large sulfur deposits in northern Pecos County are believed to represent one exit point on the Central Basin Platform for the flushed oil and meteoric waters.
- These deposits are the result of the mutual occurrence of Water, Oil and a Source of Sulfur
  - Water – from the meteoric system
  - Flushed Oil (Replenishing the Food for the Anaerobes)
  - Sulfur – from dissolution of evaporites
    - As the Source of H_2S (and Sour Oil)
- The Sulfur Deposits (product-of-reaction, residue)
    - Are Proof of Oil 'Passing By'
    - Fairways of Oil Movement
    - As Proof of Oil 'Consumption'

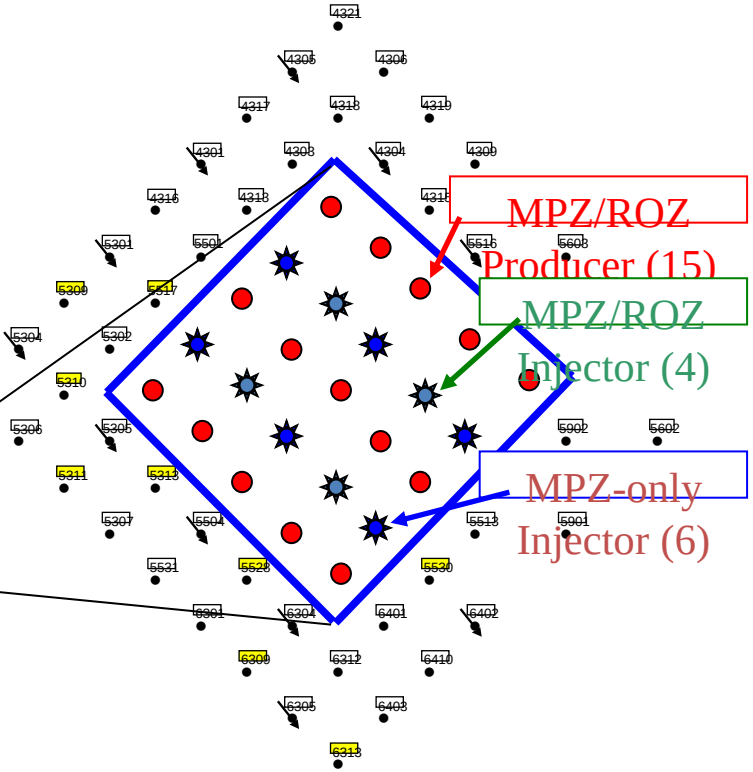
Seminole Field – The Gold Standard for Brownfield ROZ's



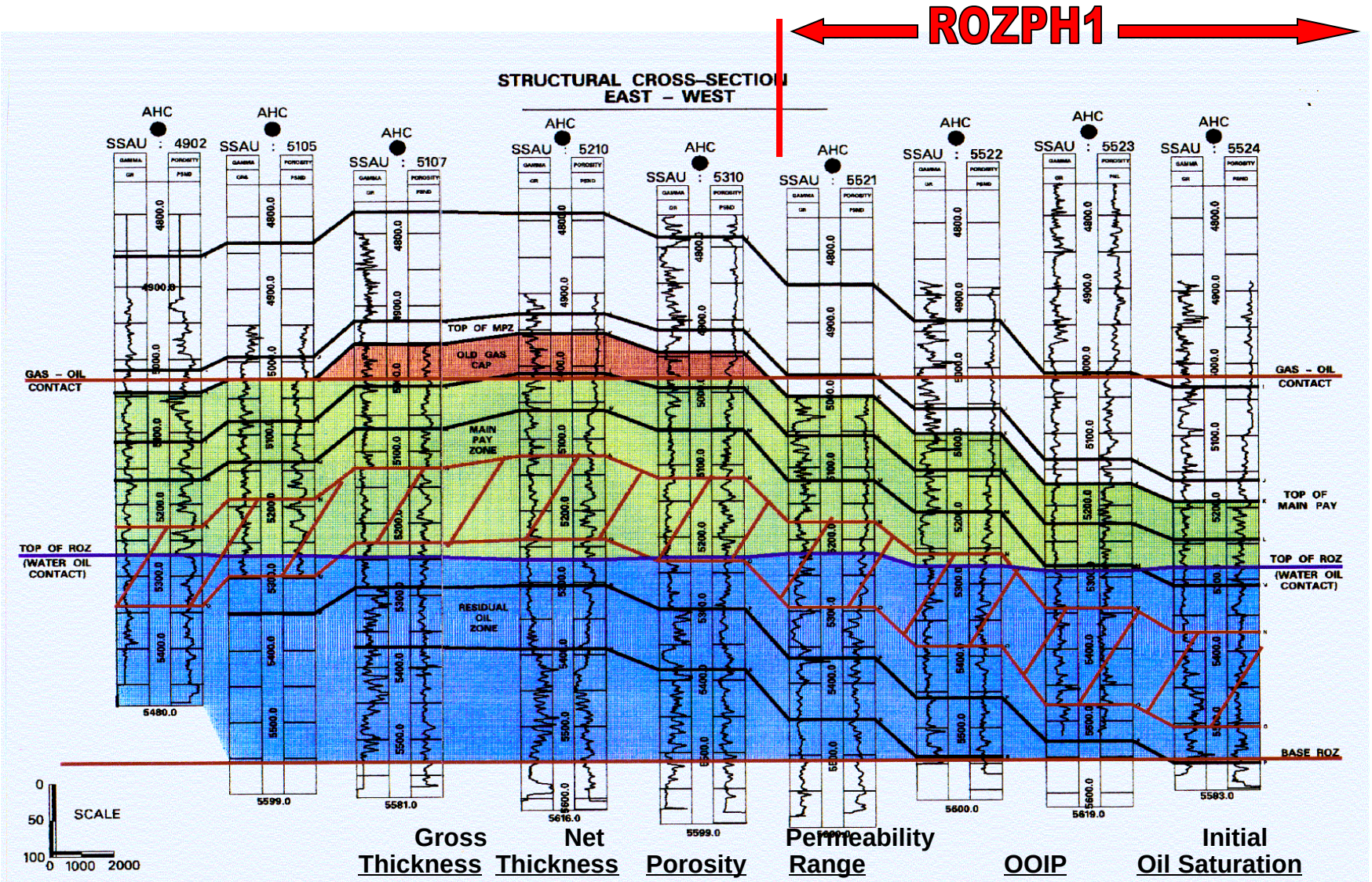
Pilot Area for the SSAU ROZ Phase I Pilot



Reference 2a



SSAU MPZ & ROZ Crossection and Zonal Attributes

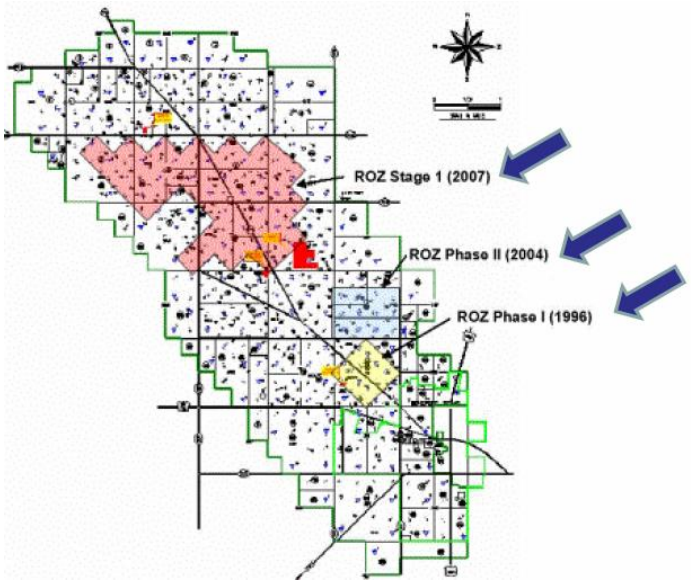


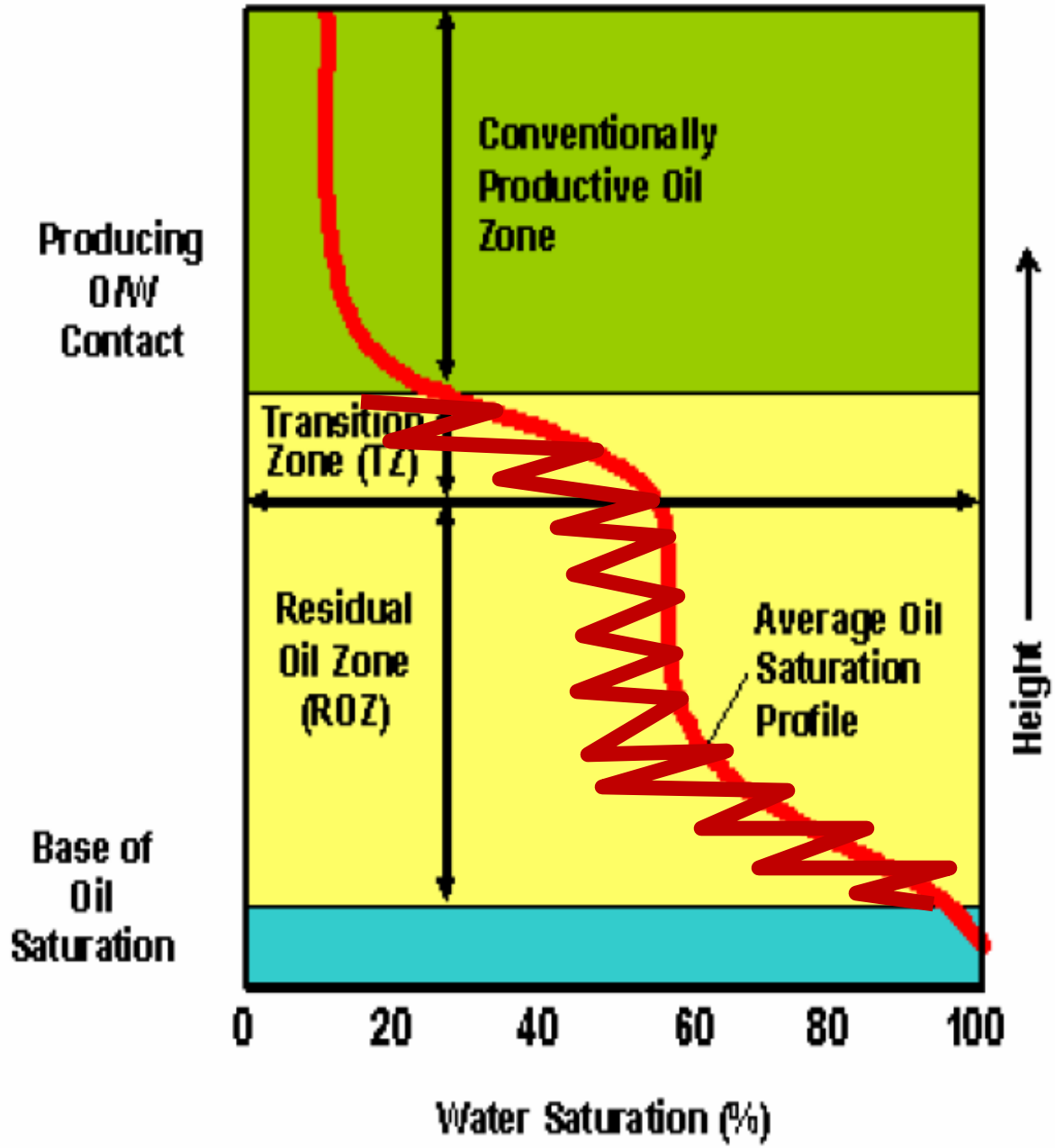
	Gross Thickness	Net Thickness	Porosity	Permeability Range	OOIP	Initial Oil Saturation
Main Pay Zone (MPZ):	160’	126’	12%	0.8-120 md	1 billion stbo	0.84
Residual Oil Zone (ROZ):	246’	197’	12.6%	0.5-270 md	0.4-1.1 billion stbo	0.32

Reference 2a

Seminole Water Saturation Profile.

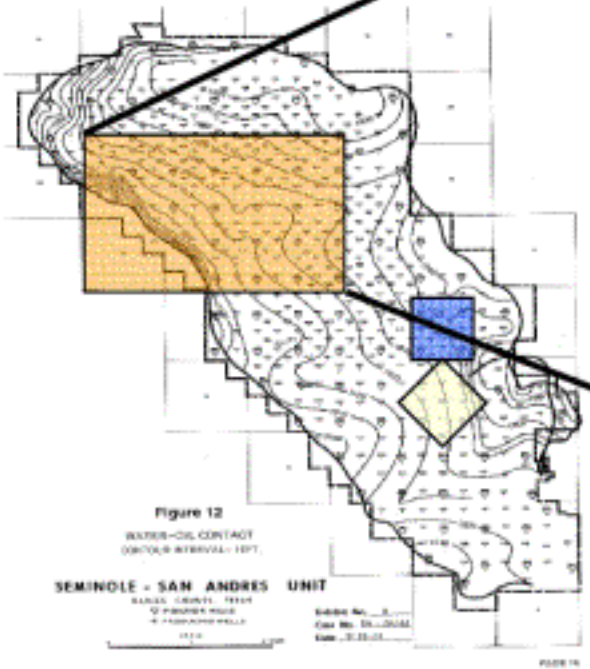
Reservoir Description	Limestone and dolomite deposited in a shallow carbonate ramp environment
Fluid Type	Saturated black oil
Drive Mechanism	Gas in solution and gas cap during primary. External energy from water and CO_2 injection during secondary and tertiary recovery.
Develop. History	1936 Discovery 1936 First Production 1969 Unitized/Waterflood 1983 MPZ CO_2 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 CO_2+HC 25,500 MBOEPD (Oil+NGL+Gas)

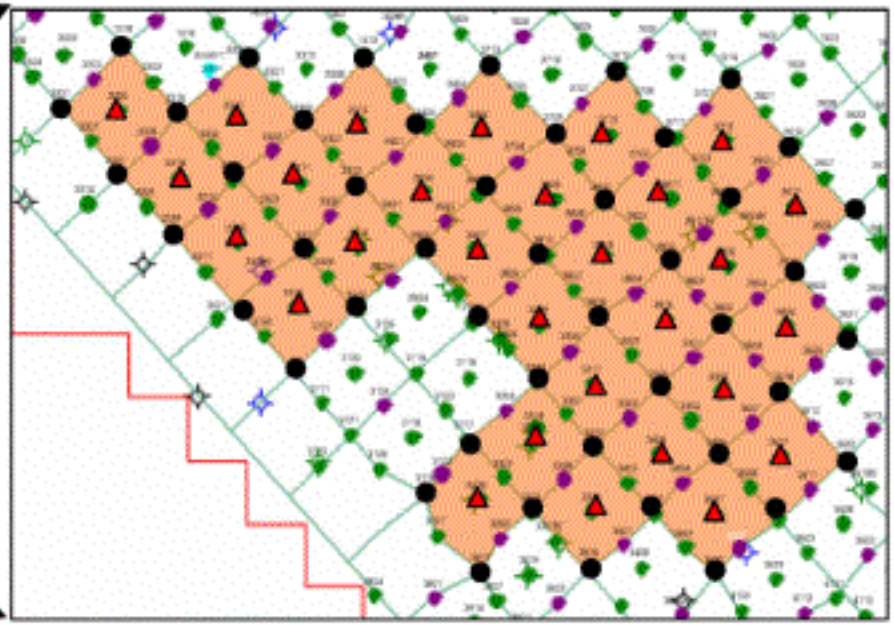




Stage 1 Project Area

- **Objective: Begin full field development of the Residual Oil Zone**
- **Twenty-nine 80 acre patterns with inverted five-spots**
- **Injection commenced October 31, 2007**
- **Plant Expansion of 70 MMSCFD (Complete Q2 2009)**
- **Gross capital cost of $ 132 MM field, $ 148 MM plant**





47 - MPZ/ROZ Producers

29 - ROZ Only Injectors

Summer 2013 Update

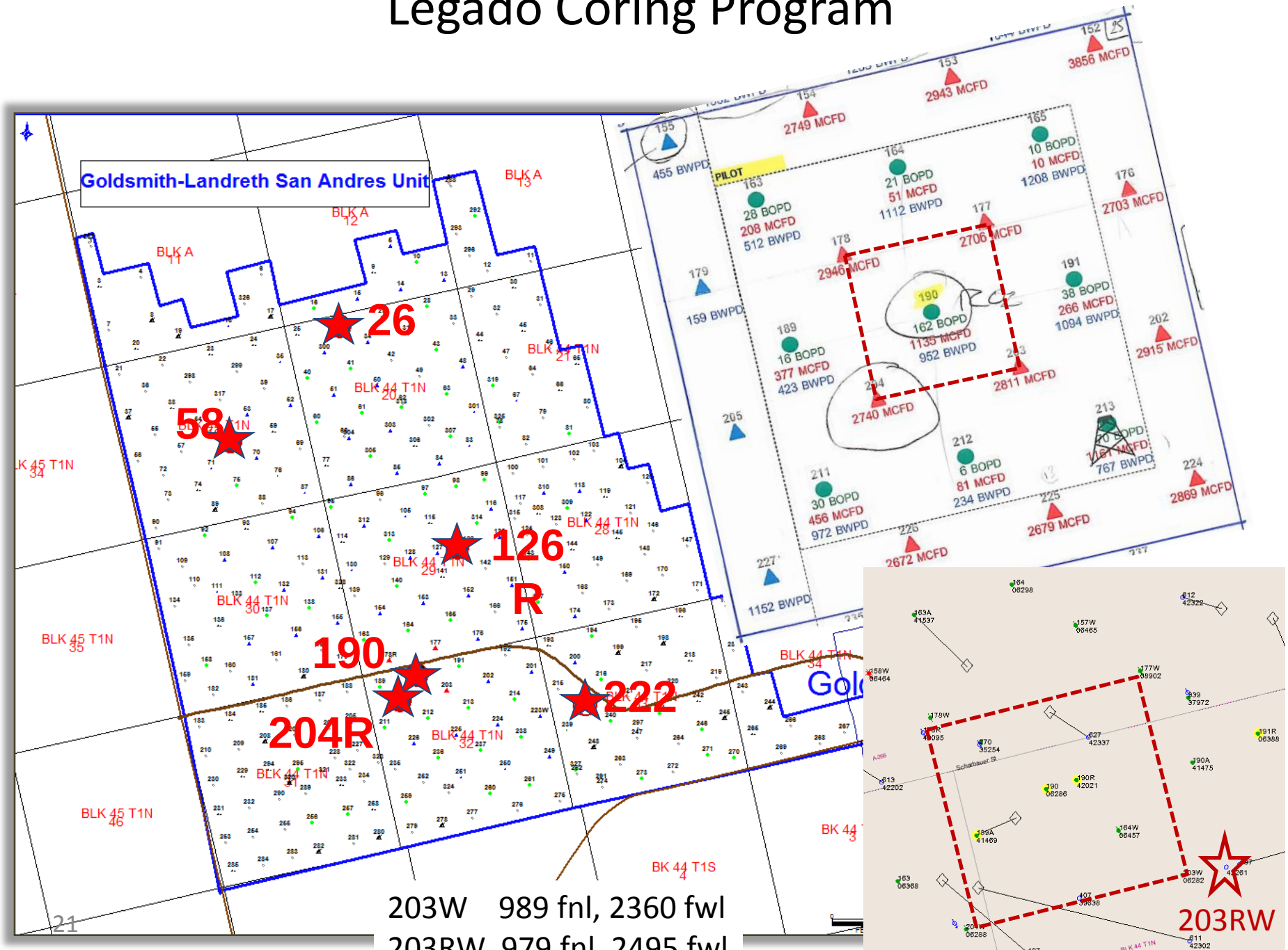
- The Two Pilots Plus Stages 1 & 2 now Making >8,000 BOPD
- Now in Stage 3 and Work Underway for implementing Stage 4
- All ROZ Projects in the Permian Basin are Making in Excess of 12,000 BOPD
- With a utilization factor of 10 MCF CO2/barrel of oil, 120 MMCF CO2 are “utilized” a day in the ROZ’s portions of floods alone.

GLSAU 203R –
A CO2 Flood Front Caught in the Act

Core Saturations

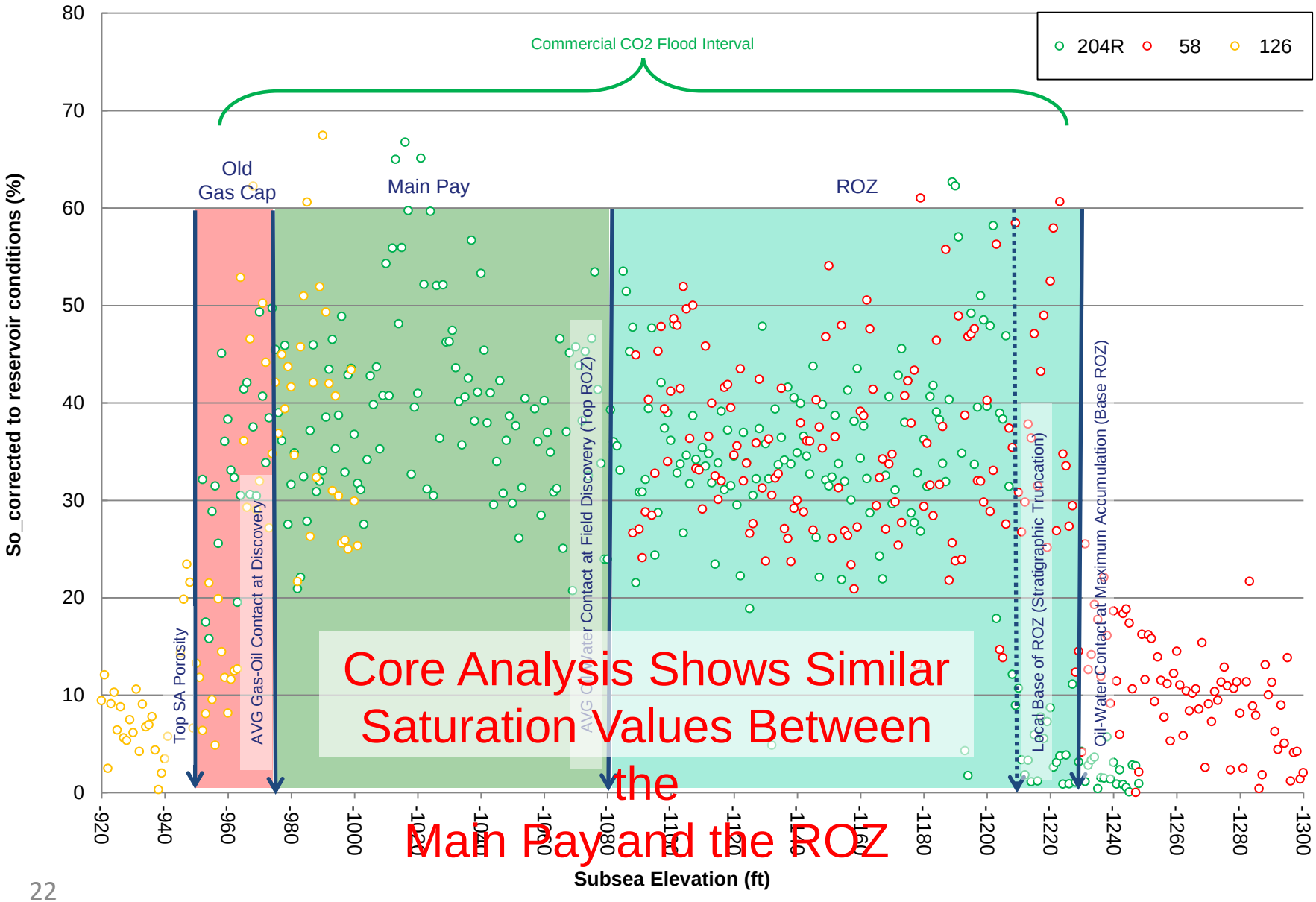
Apr-2013

Legado Coring Program



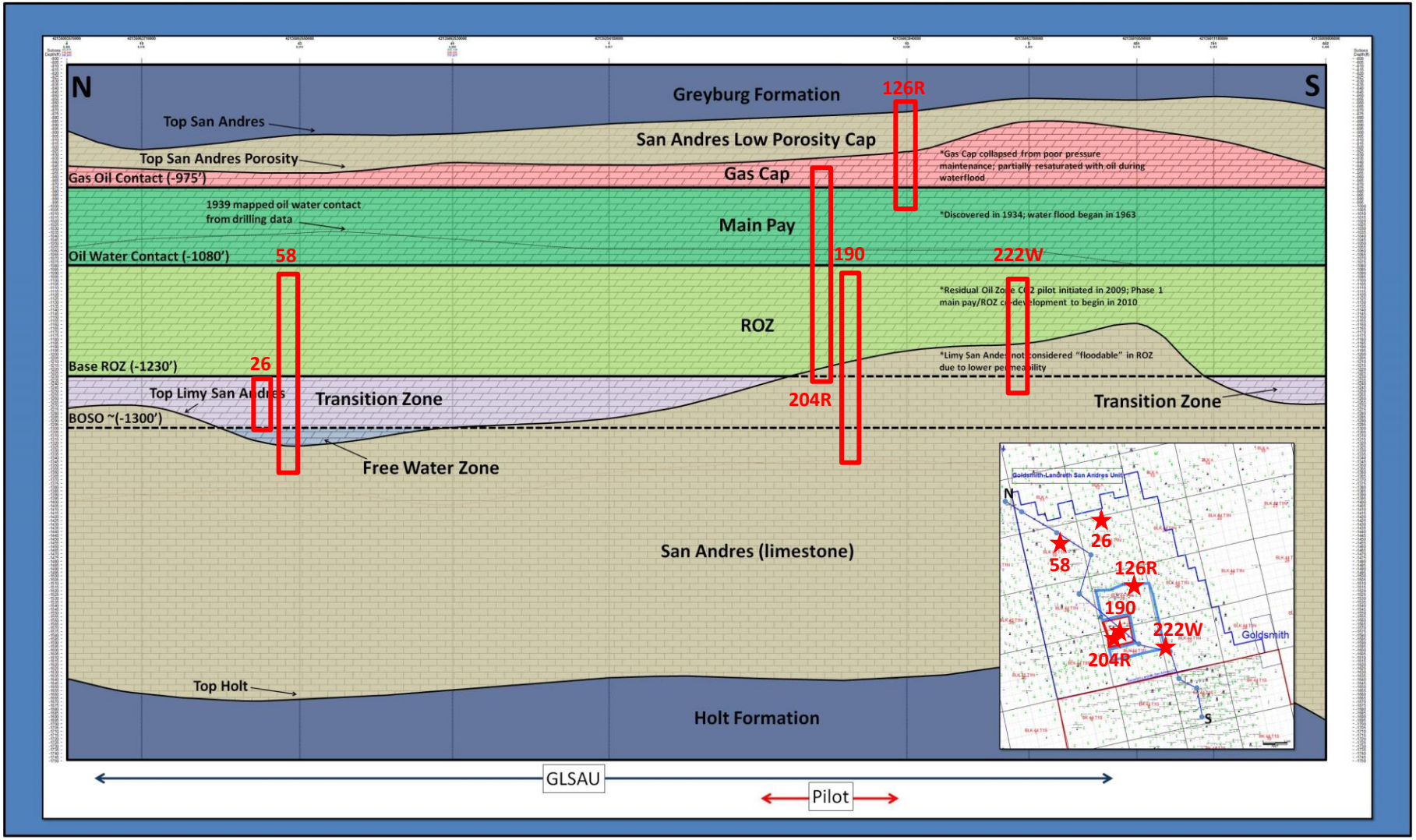
203W 989 fnl, 2360 fwl
203RW 979 fnl, 2495 fwl

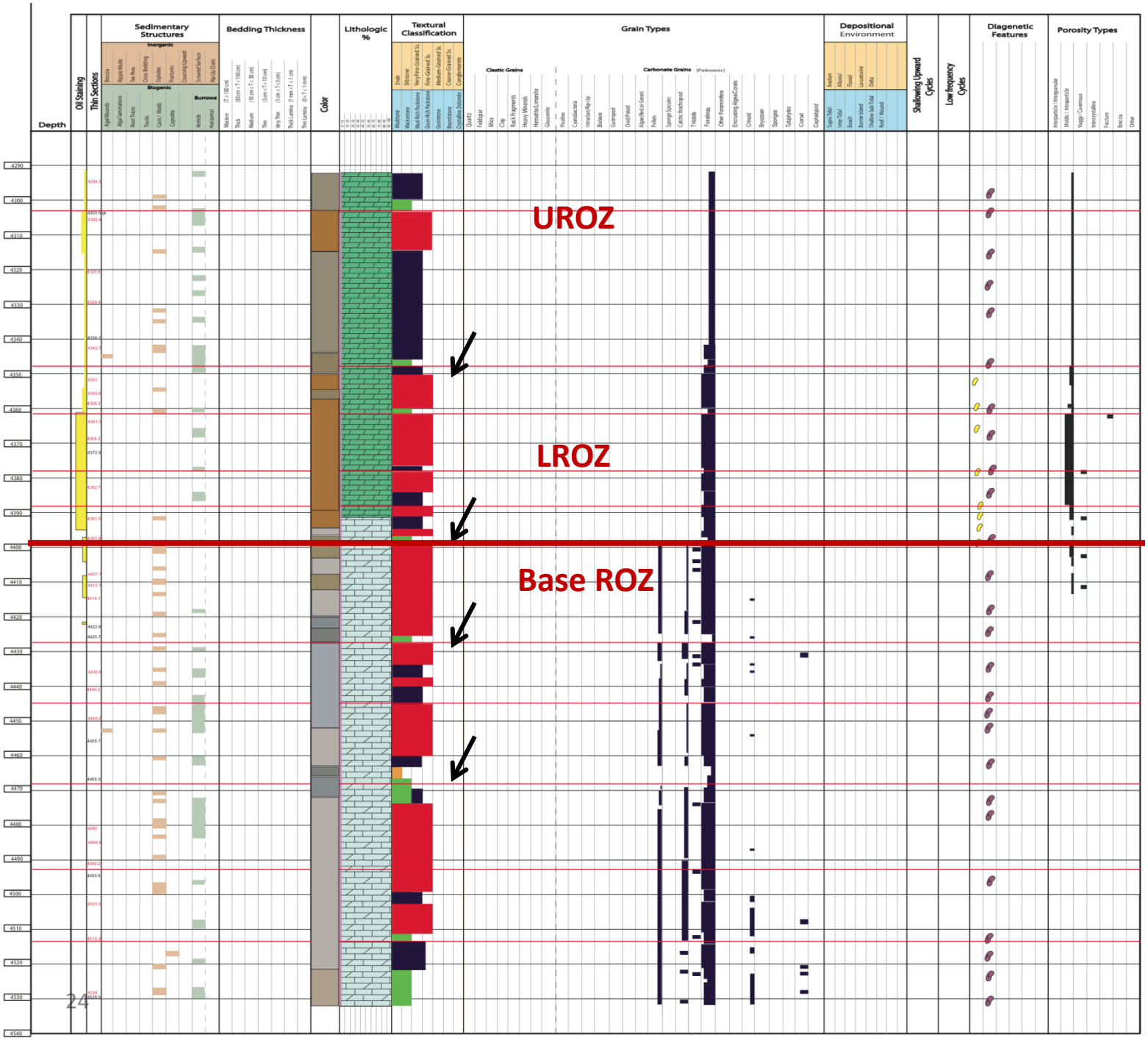
Core Saturation



Core Analysis Shows Similar Saturation Values Between the Main Pay and the ROZ

GLSAU Geologic Model





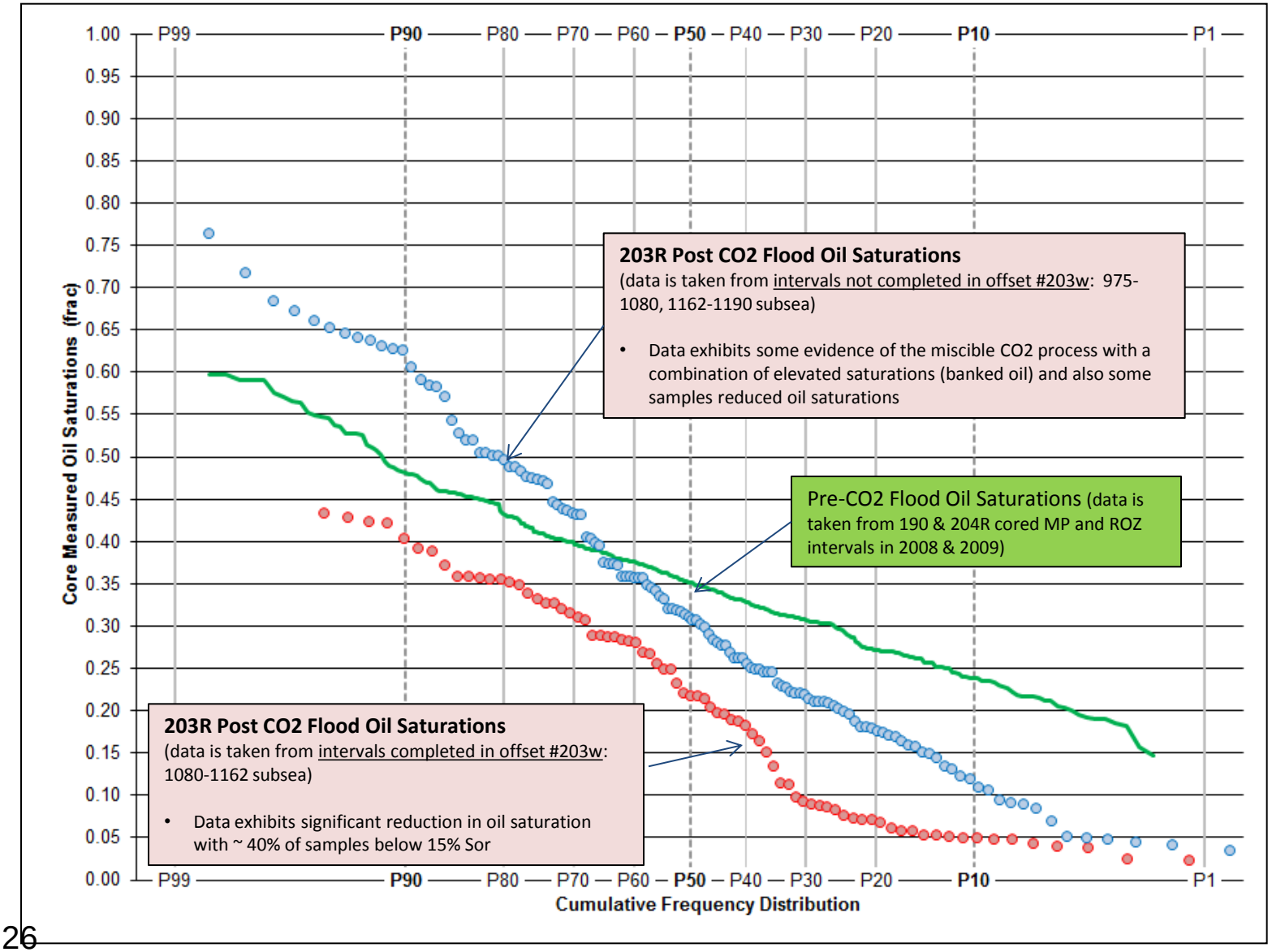
Detailed Core Description of the GLSAU #190 Well, Goldsmith Landreth Unit, Ector County, Texas. NOTE WELL DEVELOPED MAXIMUM FLOODING SURFACES MARKED WITH BLACK ARROWS

GLSAU #203R – Background

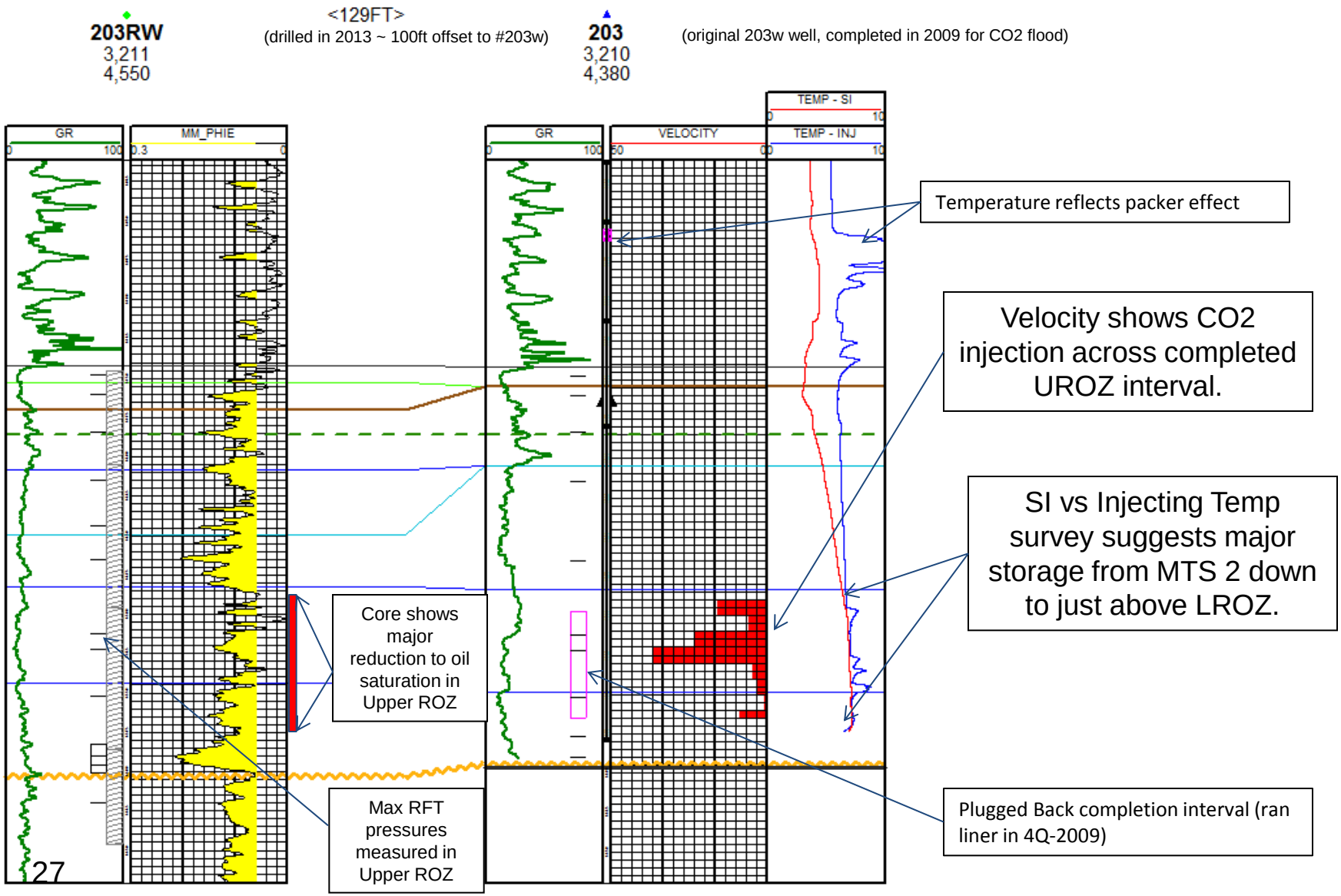
1. Observed major CO_2 injection into LROZ zone in 203w initial profile (MP+ROZ) from 2009.
2. Observed oil and gas response from #190 in 2009 prior to having compression in place.
3. **Plugged back LROZ** and MP in #203 injector (10/2009) - completed as Upper ROZ only injector.
4. Subsequent 203 profiles showed major injection into Upper ROZ.
5. Drilled 203 replacement in 2013 for improved wellbore and to re-establish injection into Lower ROZ.
6. RFT data from 203 replacement well showed elevated pressures in all zones (confirming general injection support in MP and ROZ for the area), with maximum local pressures occurring in the completed Upper ROZ zone (suggests CO_2 injection remained concentrated in Upper ROZ).
7. Obtained core from the 203 replacement well in 2013 and ran routine analysis using Core Labs.
   - Confirmed significant reduction to oil saturations in the equivalent 203W completed UROZ interval (4285-4370) with nearly 40% of the samples being reduced below 15% Sor (versus <2% of pre-CO_2 flood samples measuring below 15%)
   - Saturations in the UROZ completed interval were much lower than both the pre-CO2 flood oil saturations and the post-CO_2 flood oil saturations in the non-completed LROZ & MP intervals.
   - Results suggest the 203W workover to plug back the LROZ in 2009 was successful at isolating CO_2 injection from that zone.
8. **Completed the Lower ROZ in 203 RW and tested on 4/22/2013. Flowed ~25 BPH at 5% oil cut with very little gas (FTP 100 psi), confirming isolation from #203W and banked ROZ oil from miscible CO_2 flood process** (typical oil cut prior to CO_2 is <1%).

Core oil saturations in the 203R demonstrate varying degrees of miscible displacement maturity throughout the Main Pay & ROZ, corresponding to the offset completed CO_2 injection intervals.

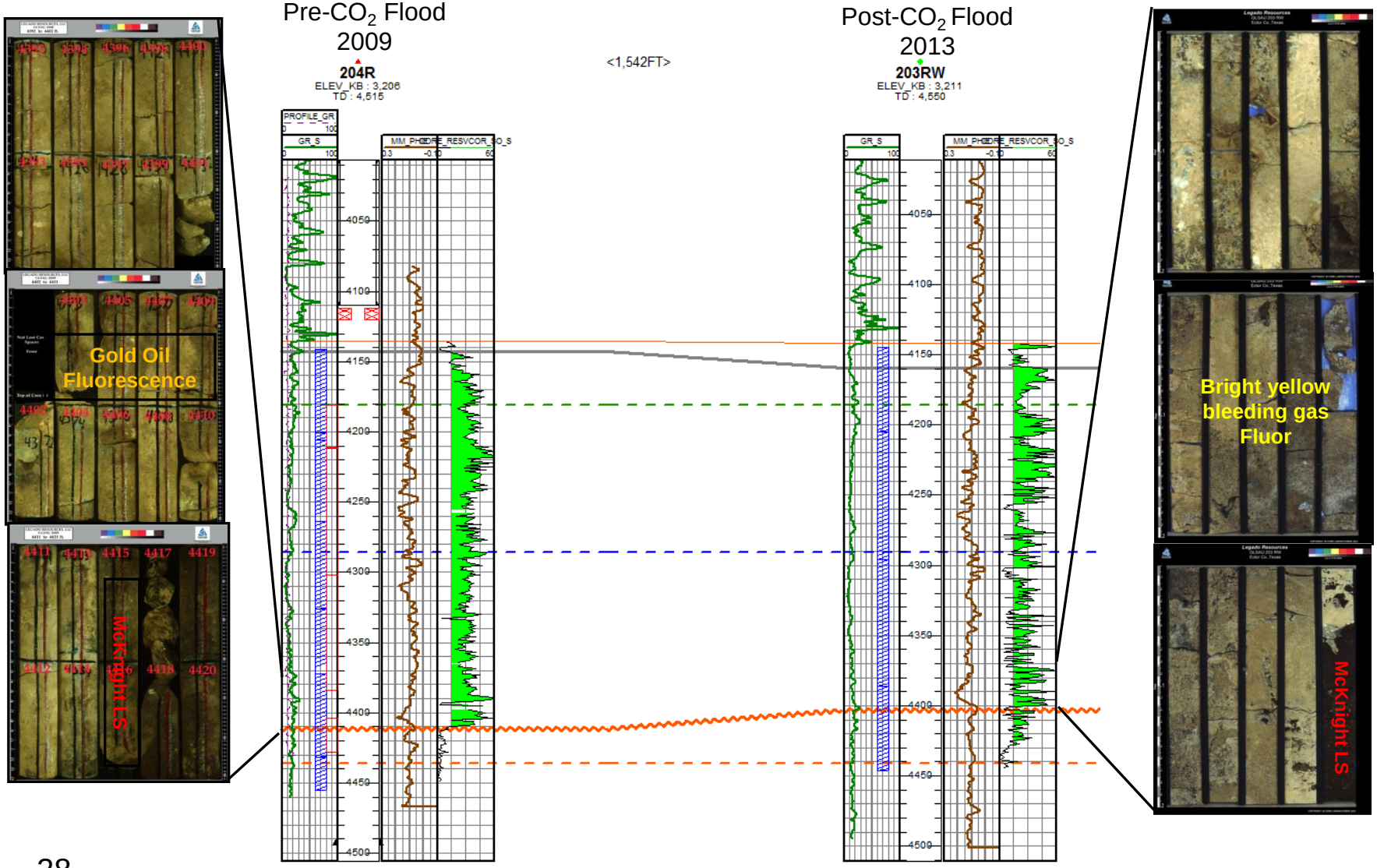
GLSAU #203R – Post CO_2 Flood S_{or} vs Offset Pre-CO_2 Flood S_{or}



GLSAU #203R & 203w – Completion Intervals & Inj Profile Results

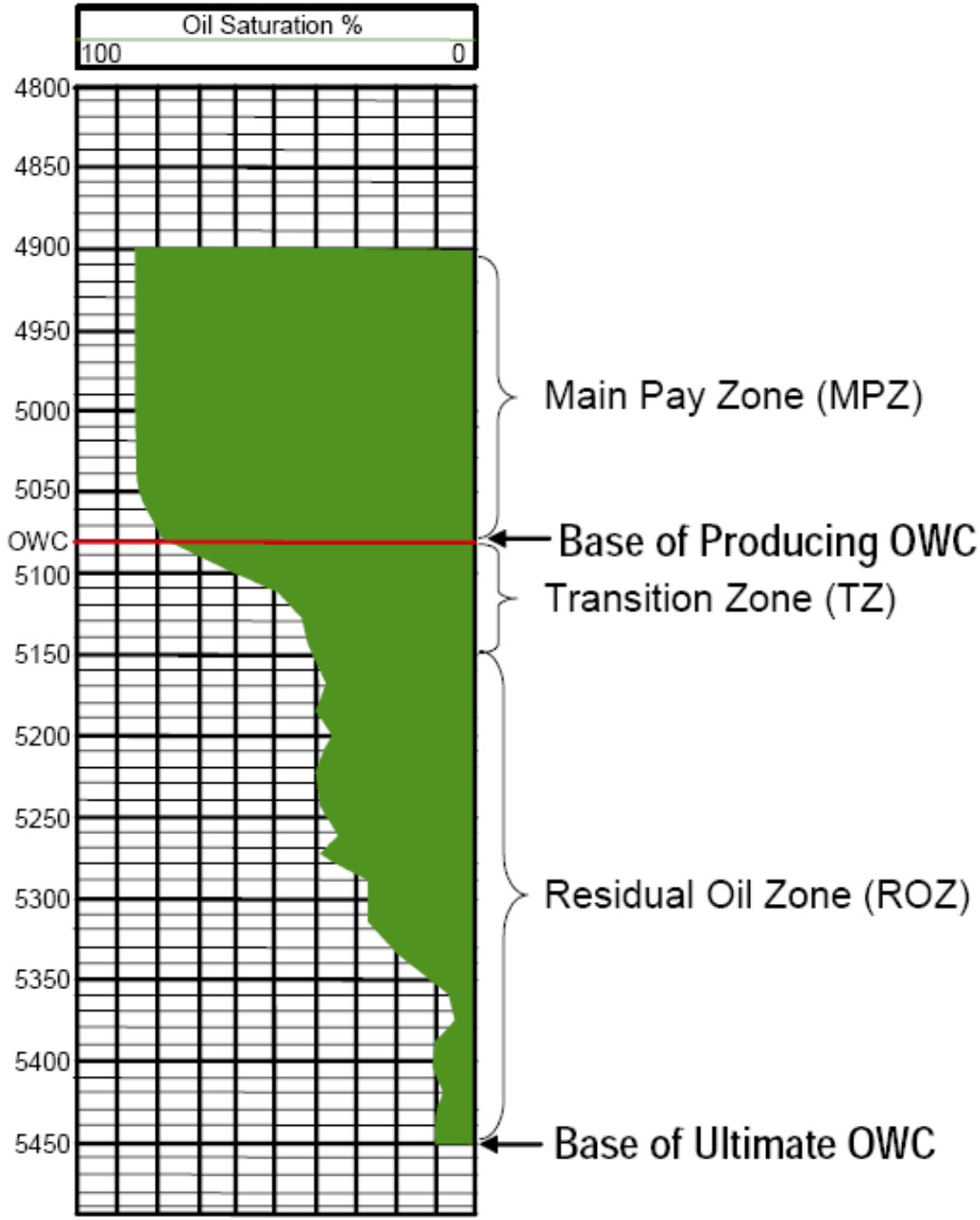


GLSAU 204R and 203RW Saturation Comparisons



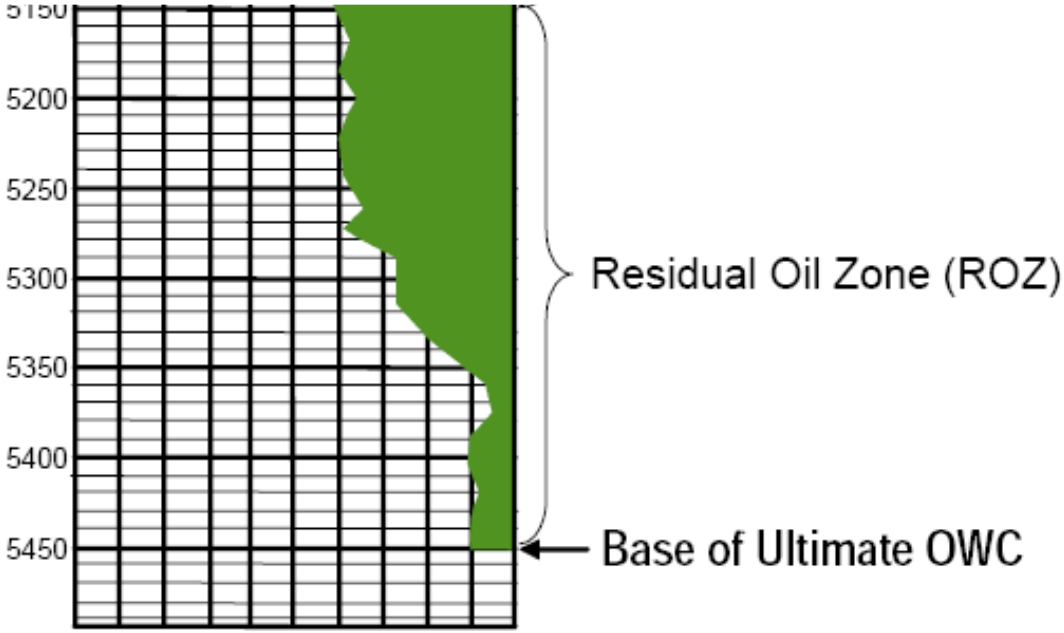
Green > 15% Reservoir –corrected Sor

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



GREENFIELDS

Your left with a tertiary recovery target.

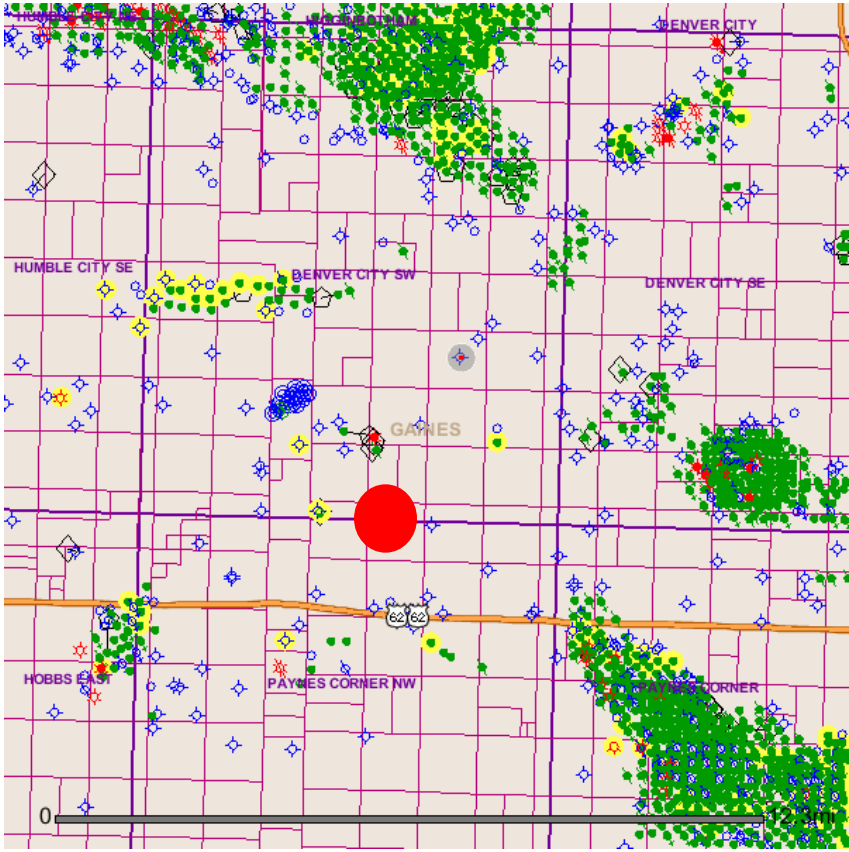


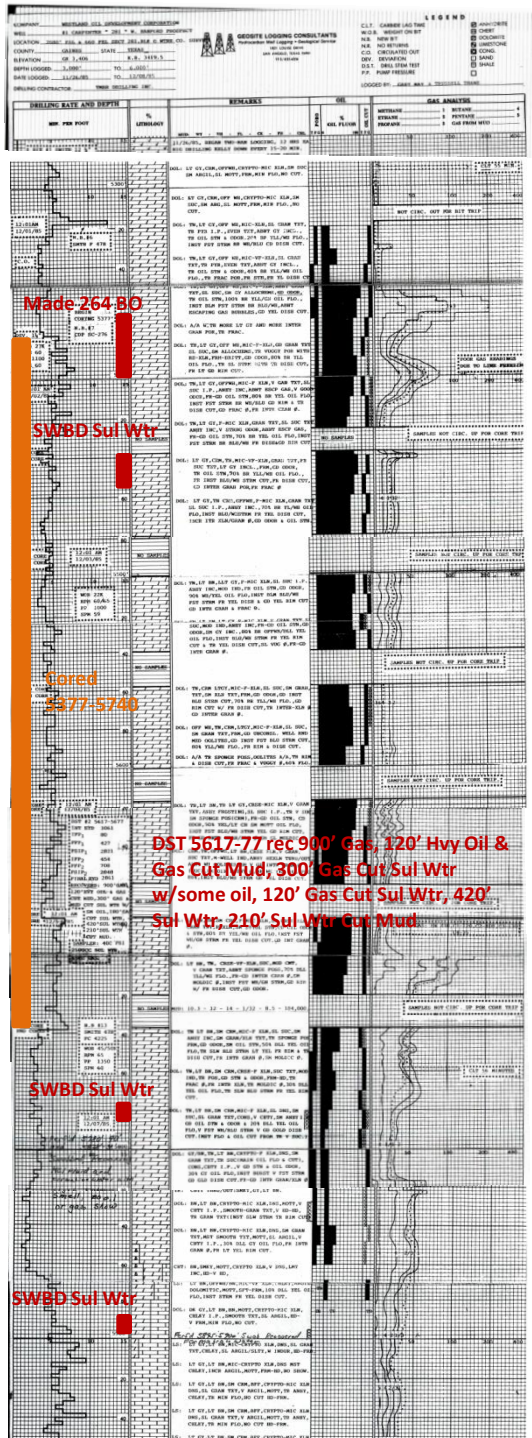
Anecdotal Evidence

- The anecdotal evidence from a growing number of exploration wells documents examples of what can be interpreted as ROZ's where the tests were unsuccessful as there was no associated primary production. From discussions with a number of explorationists and review and reinterpretation of research articles on Permian Basin fields, a set of common ROZ characteristics is developing:
  - The presence of sulfur crystals associated with gypsum in the swept carbonates,
  - Evaporites may be dissolved or altered in the lower part of the main pay.
  - Enhanced porosity and permeability developed as the result of meteoric dissolution of sulfates in the ROZ
  - Sample shows of oil and/or gas,
  - Sulfur water produced on DST's or attempted production tests not salt water,
  - Core with 10-40% oil saturation,
  - Log calculations that suggest producible hydrocarbons.
  - Porosities and Permeabilities can be higher in the ROZ than in the main pay zone as a result of the meteoric dissolution.
  - Pervasive "late" dolomitization may indicate meteoric sweep.

Gaines, Future Targets or goat pasture?

- **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.





Westland #1 Carpenter "281"

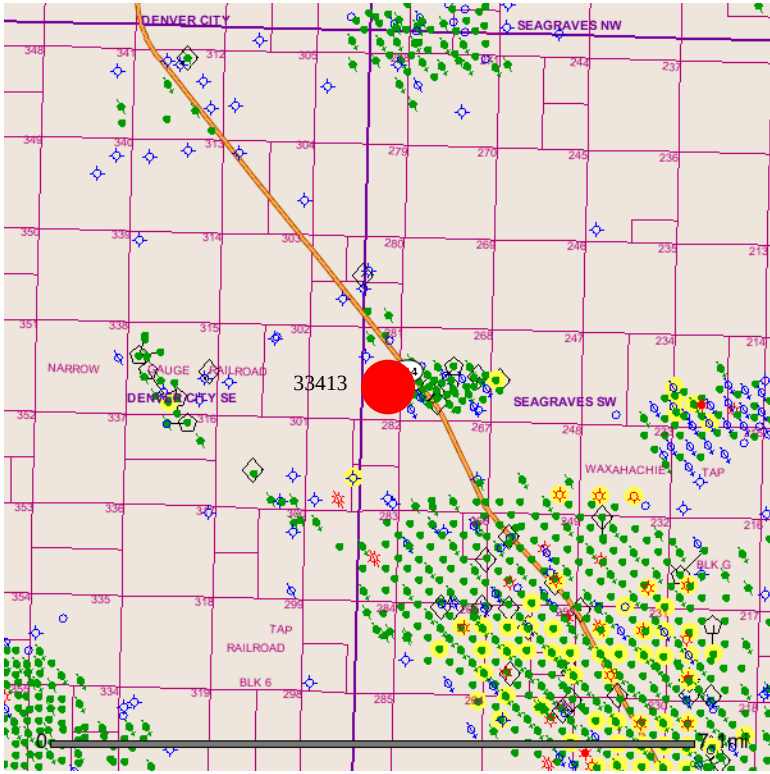
Drilled on the west edge of Seminole N. E.

Core with oil,

DST with Oil, Gas, and Sulfur Water.

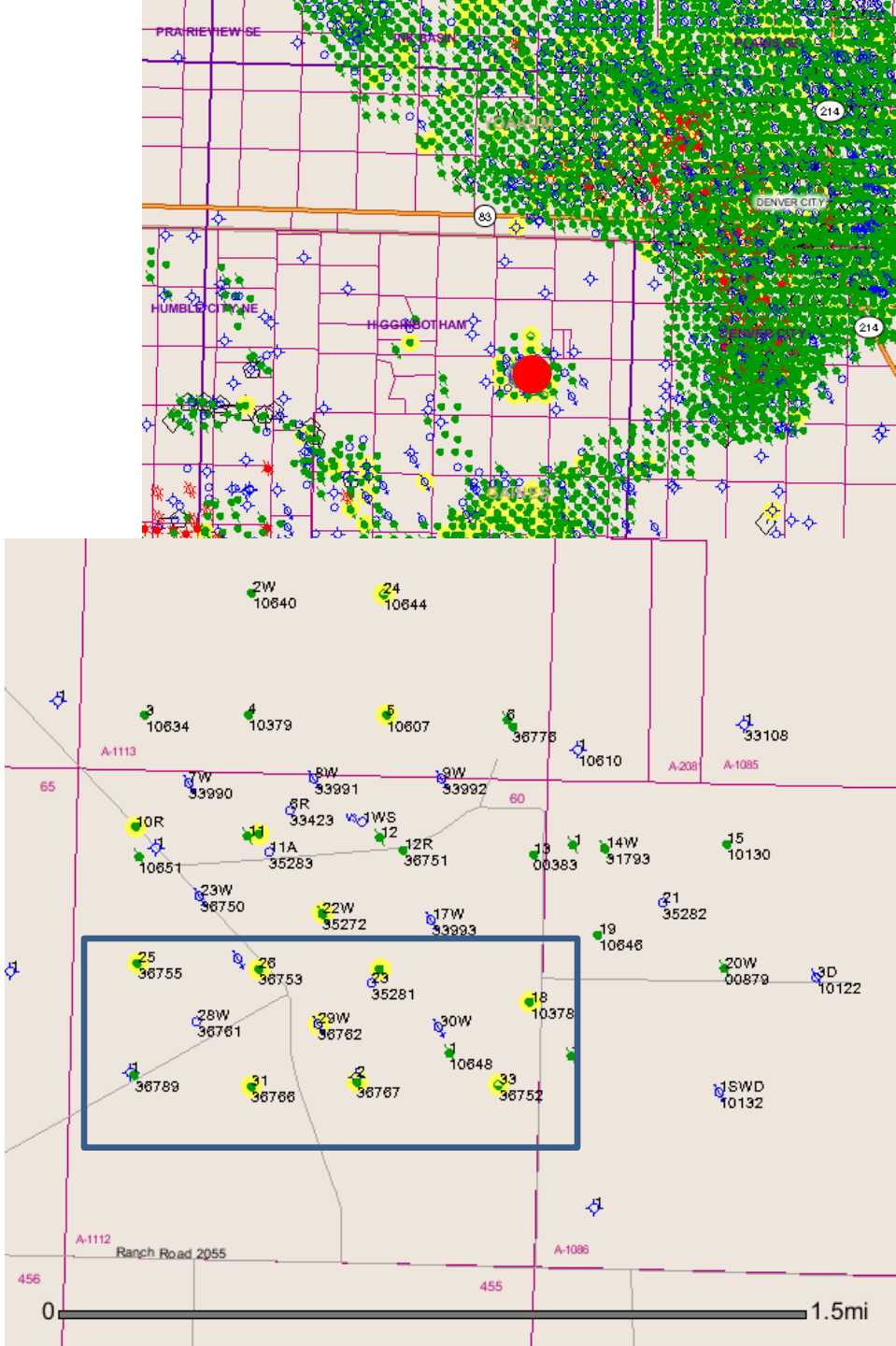
Produced 264 BO from upper perfs.

Over 400' of possible ROZ based on shows and gas on sample logs.



George Allen Field. Peripheral ROZ Flood.

The George Allen Field, discovered in 1956, has recently been the site of the development of 2 “rings” of wells (Blue Box) of CO2 producers and injectors OUTSIDE the original boundaries of the field .

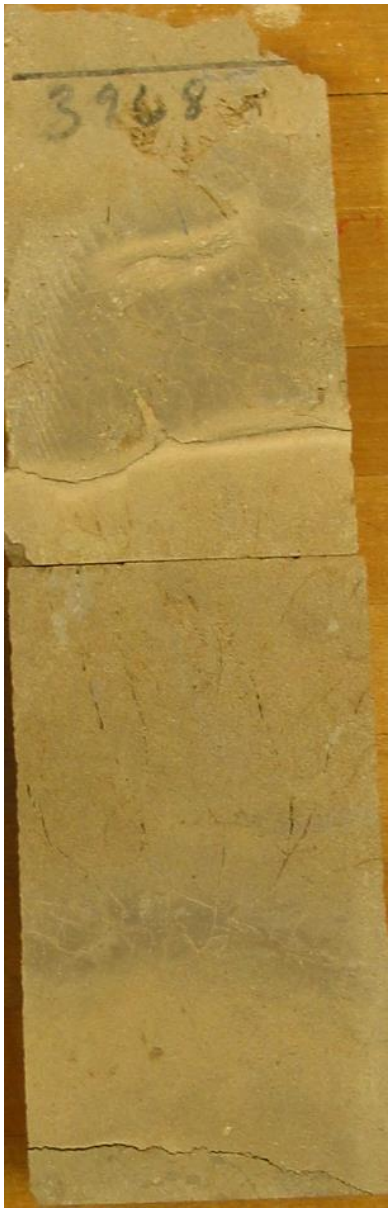


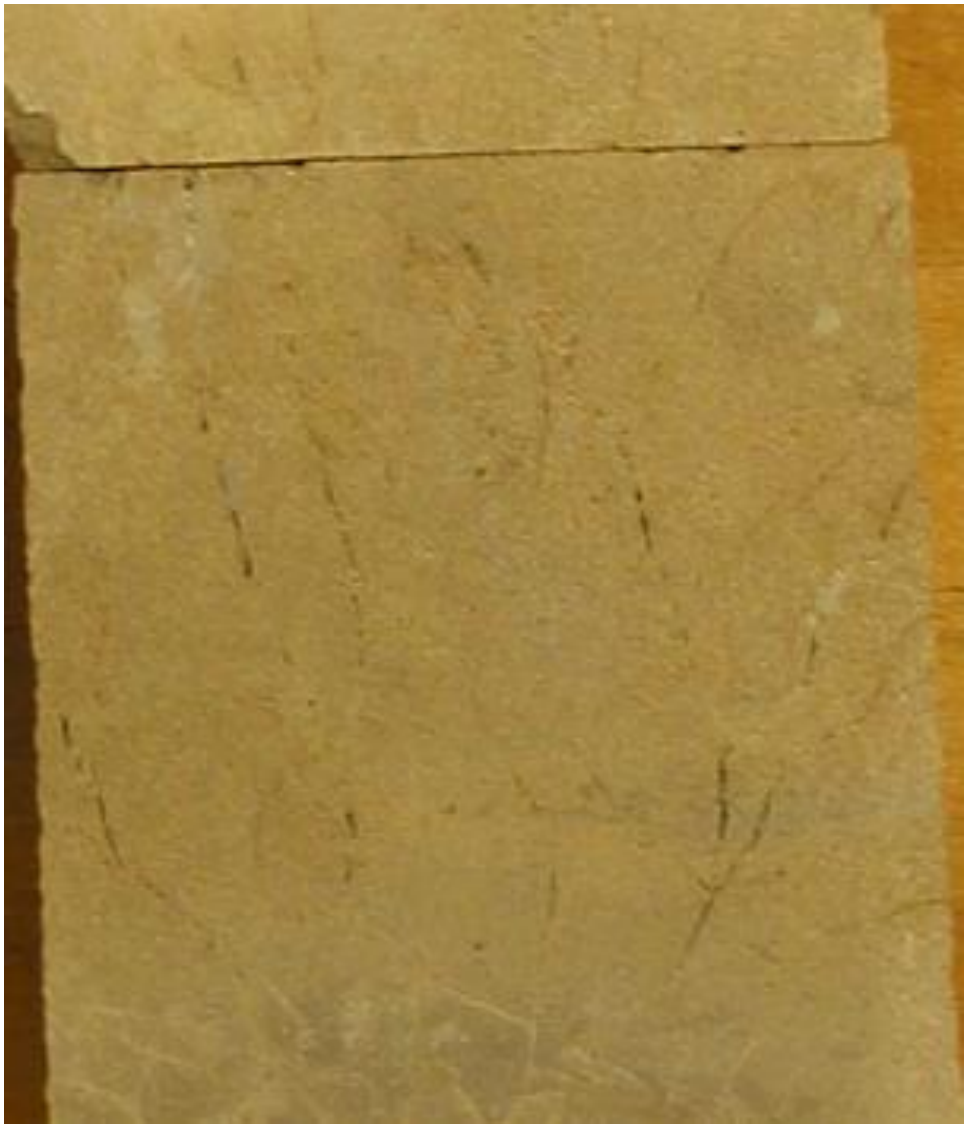
When does a “One Of a Kind” become a Trend?

- There appears to be a number of attributes of the BOSO at or near the base of the ROZ:
  - Large vugs (removed Anhydrite Nodules) filled or partially filled with SULFUR
  - “Spotty” oil stain/SHR/Dead Oil in the tight portions of more porous intervals
  - Transition from dolomite above to limestone below
  - The presence of a baffle or barrier to vertical flow (Sequence or Cycle Set Boundary)
  - Solution enhanced fractures

Gypsum with Sulfur

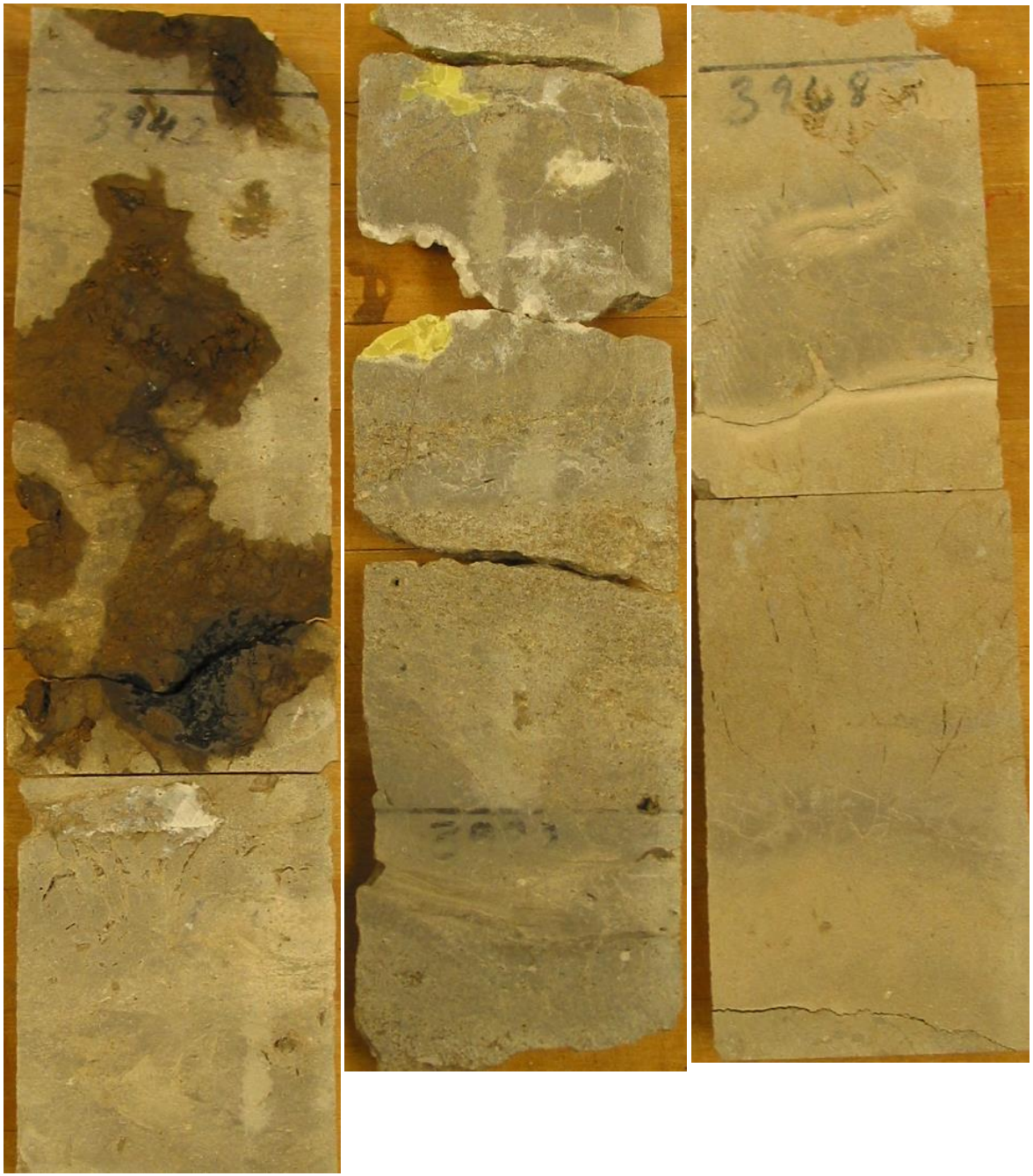
Calcite with Sulfur





Late solution enhanced features with no SHR on faces

“Spotty” high oil saturation near BOSO

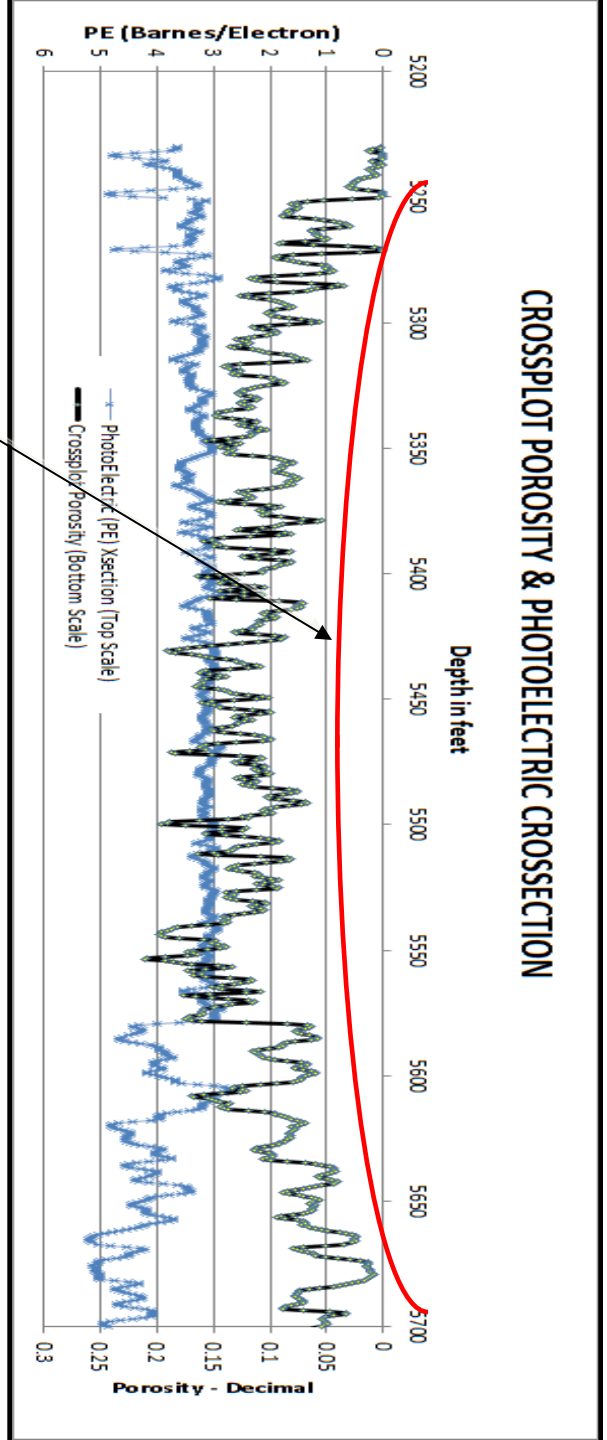


These late features can be found at or near the base of an ROZ regardless of the formation

“Bow” Shaped Character of Porosity Curve

Porosity and PhotoElectric Cross section Log

A characteristic “bow” shape on logs is generally present in the ROZs with decreasing resistivity and increasing porosity below the oil/water contacts



Size of the Prize

Advanced Resources International, Inc.

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

Summary

- Our ROZ Team has only just begun their Studies
- ROZ's are real and a major tertiary recovery target for today and long into the future.
- Modeling using regional scale groundwater modeling package has demonstrated slow hydrodynamic flushing and results consistent with the observed tilted OWCs.
- Documentation of areas/fields with large potential is underway.
- Phase 2 study will give the estimates of ROZ oil in place.