Increasing the Size of the CCUS Prize: The Potential and Economic Viability of Storing CO_2 and Producing Oil from the ROZ of the Permian Basin Greatly Enhances the CCUS Option

Prepared for:
2nd Biennial CO_2 for EOR as CCUS Conference

Day 1: CO_2 for EOR with CO_2 Storage in Conventional Reservoirs

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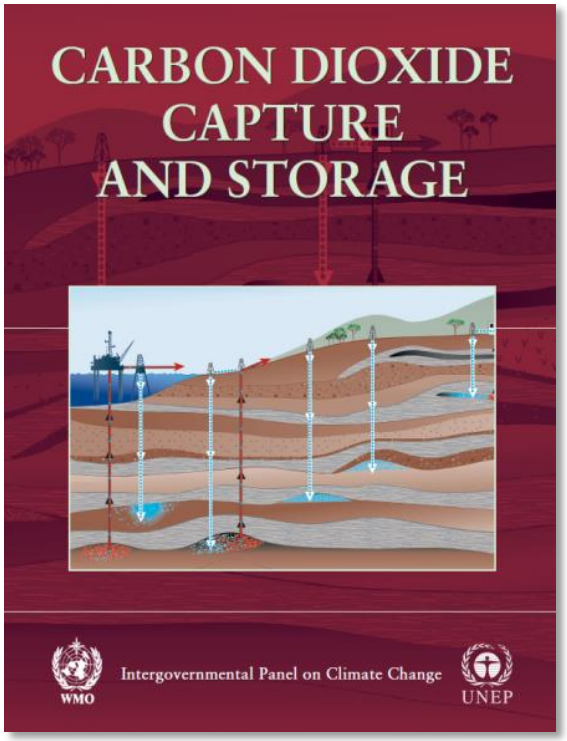
October 5, 2015
Rice University, Houston, Texas

Background



The first IPCC report set in-place a perspective that the CO_2 storage potential offered in mature oil fields by CO_2 enhanced oil recovery was a small, niche opportunity.

Given this perspective, major efforts were launched for assessing the viability of storing CO_2 in saline aquifers and other settings (i.e., coal seams, mineralization, etc.).

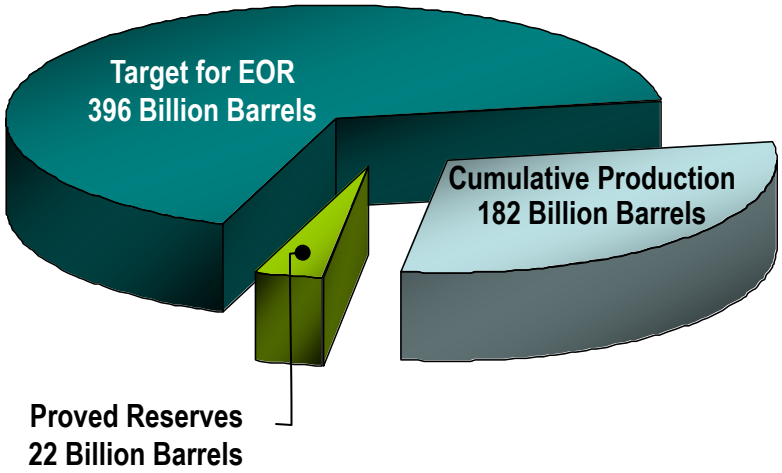
However, work in recent years has established that injection of CO_2 into oil fields for oil recovery and by-product storage of CO_2 have substantial potential, including revenues for captured CO_2 emissions.

Large Volumes of Oil Remain "Stranded" in Discovered U.S. Oil Fields

Nearly 400 Billion Barrels of Oil "Left Behind"

Original Oil In-Place: 600 B Barrels

"Stranded" Oil In-Place: 396 B Barrels



Source: Advanced Resources Int'l. (2011)

Traditional primary recovery and waterflooding have recovered only about a third of the oil in-place in discovered U.S. oil fields, leaving behind a target of nearly 400 billion barrels.

A variety of enhanced oil recovery technologies are being used to recover this "stranded" oil, including:

- Miscible/immiscible CO_2 injection
- Hydrocarbon miscible flooding
- Steam injection
- Chemical flooding

In the U.S., these methods currently provide 0.8 million barrels per day.

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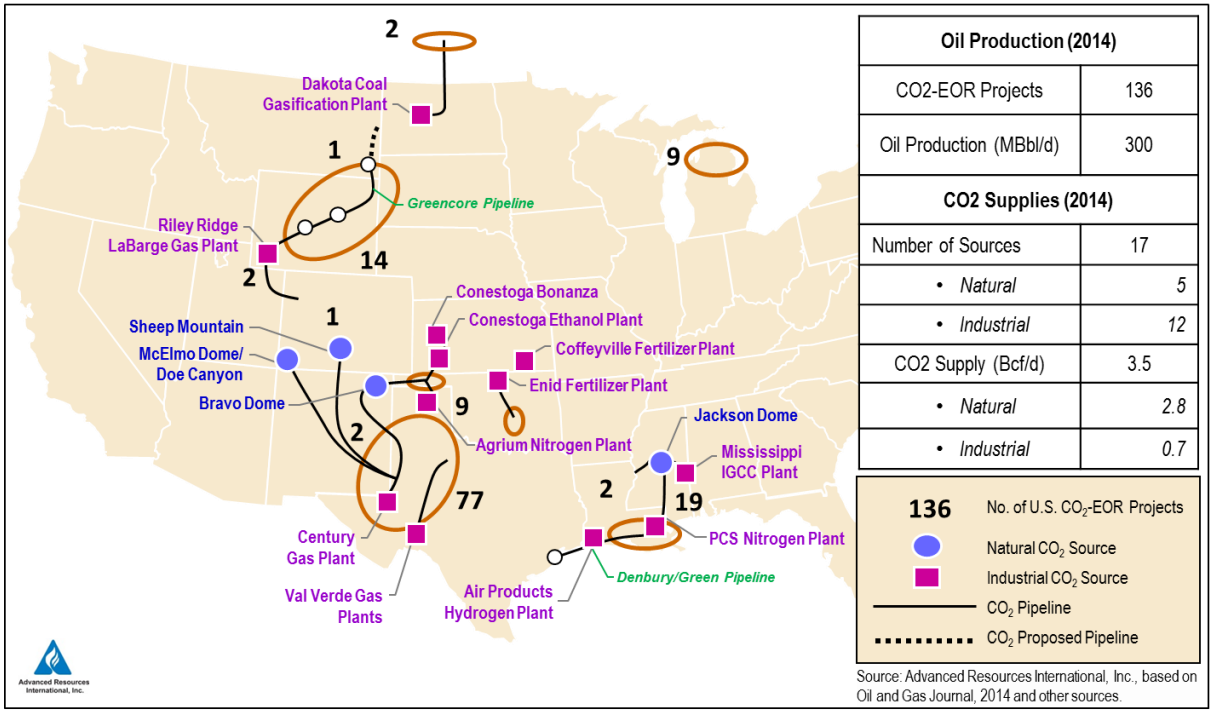
CO_2 Enhanced Oil Recovery: A Look at Today

The discovery of large natural sources of CO_2 in Colorado (McElmo Dome, Doe Canyon), in New Mexico (Bravo Dome) and in Mississippi (Jackson Dome) established the foundation for the CO_2-EOR industry.

Current CO_2-EOR Operations and CO_2 Sources (2014)



Oil Production (2014)	
CO2-EOR Projects	136
Oil Production (MBbl/d)	300
CO2 Supplies (2014)	
Number of Sources	17
• *Natural*	*5*
• *Industrial*	*12*
CO2 Supply (Bcf/d)	3.5
• *Natural*	*2.8*
• *Industrial*	*0.7*

136 No. of U.S. CO_2-EOR Projects
Natural CO_2 Source
Industrial CO_2 Source
CO_2 Pipeline
CO_2 Proposed Pipeline

Source: Advanced Resources International, Inc., based on Oil and Gas Journal, 2014 and other sources.

- The 136 significant CO_2-EOR projects currently produce 300,000 barrels per day from injecting 3.5 Bcfd of CO_2, with 0.7 Bcfd from industrial sources.
- Lack of reliable, affordable supplies of CO_2 is the major constraint to more intensive use of this technology.

Source: Advanced Resources International based on Oil & Gas Journal and other industry data, 2014.

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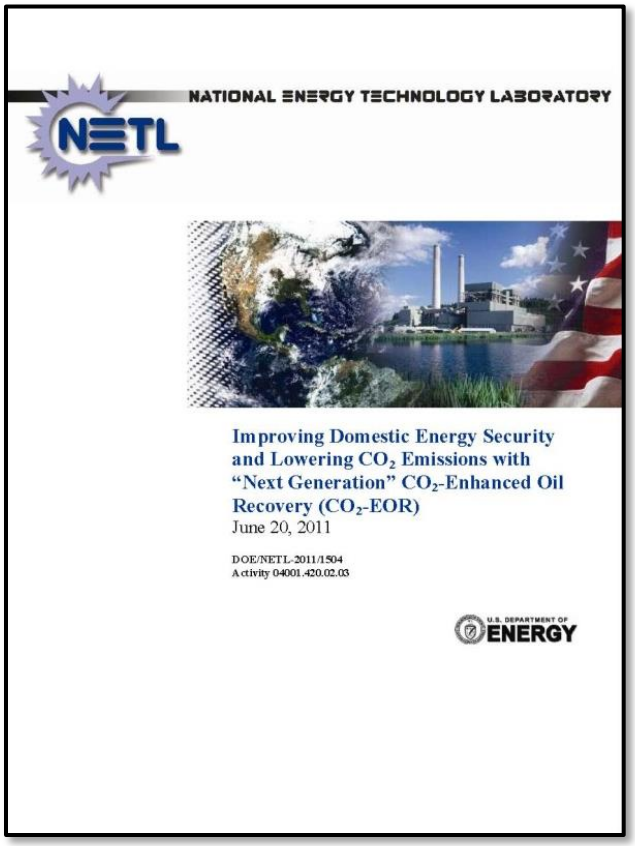
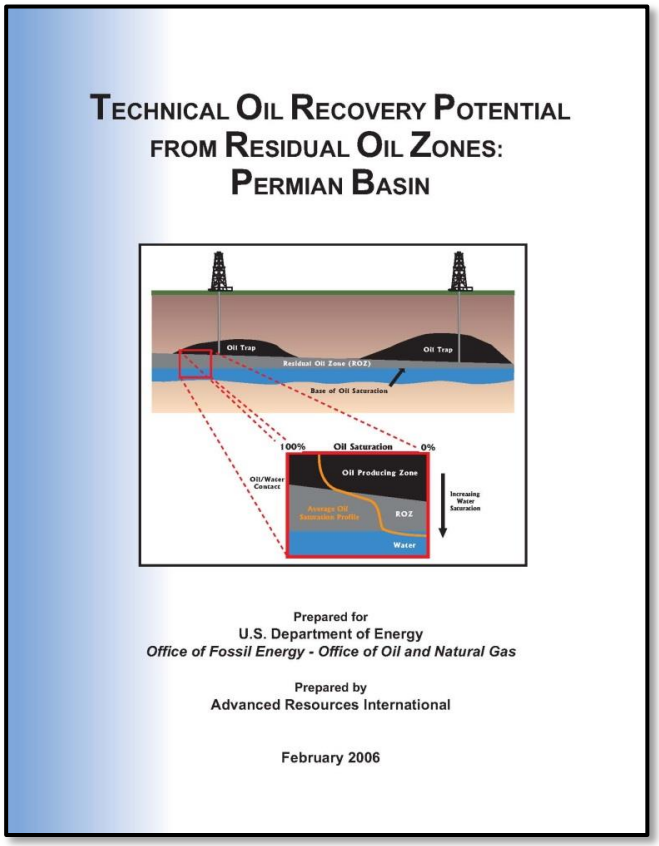
Oil Recovery and CO_2 Demand/Storage from CO_2-EOR

Two publically available reports, by Advanced Resources Int'l and Melzer Consulting for U.S. DOE/NETL, provided the initial analytical foundation for estimates of oil production and CO_2 demand by the CO_2-EOR industry.





The Size of the CCUS "Prize"

The assessment and inclusion of the ROZ "fairway" resource has significantly increased the size of the CCUS "prize."

- With "Current Technology," the economically viable* oil recovery and demand for CO_2 (lower-48) is:
  - 22 billion barrels of crude oil
  - 9 billion metric tons of CO_2
- "Next Generation" technologies and inclusion of the Residual Oil Zone "fairway" increases these values to:
  - 96 billion barrels of crude oil
  - 33 billion metric tons of CO_2

Oil Recovery and CO_2 Demand: Current and "Next Generation" EOR Technology

Resource Area	Economic Oil Recovery (BBbls)*		Demand for Purchased CO_2 (Billion Metric Tons)	
	Current Tech.	Next Gen. Tech.	Current Tech.	Next Gen. Tech.
Lower-48, Onshore	21	63	9	21
Lower-48, Offshore	1	15	**	5
ROZ "Fairways"*** (Four Counties Permian Basin)	-	18	-	7
Total	**22**	**96**	**9**	**33**

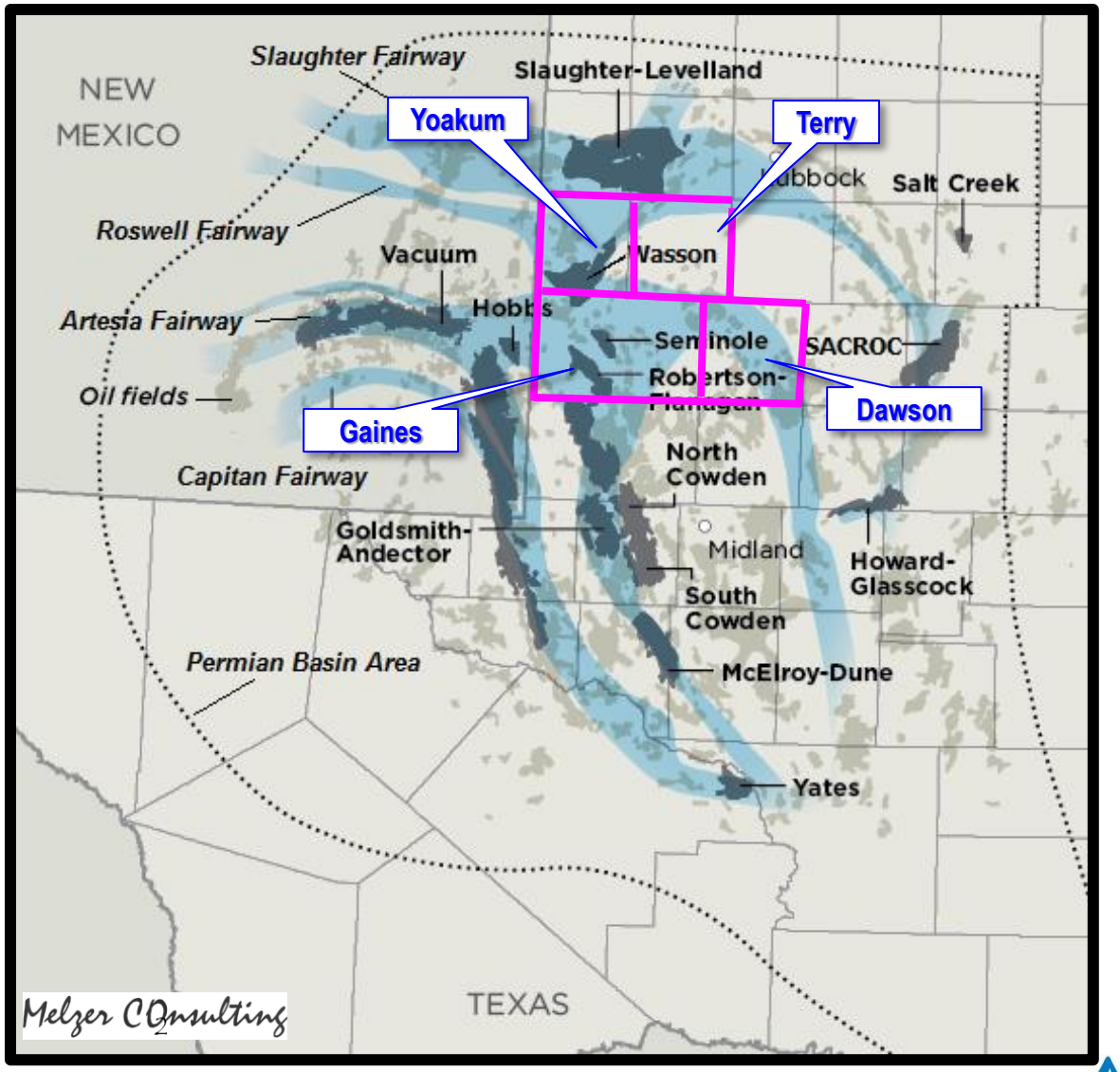
*At oil prices of $80 to $90/B, CO2 costs of $36 to $40/mt and 20% ROR (before tax).
**Less than 0.5 Bmt.
***Additional oil recovery and CO2 storage would be from ROZs below existing oil fields.

Today's presentation will discuss our most recent work involving the potential size and economic viability of the San Andres ROZ "fairway" resource in the Permian Basin of West Texas.

Residual Oil Zone "Fairways" of the Permian Basin

Our ROZ "fairway" resource assessment targeted the Slaughter and Roswell ROZ Fairways in the northern portion of the Permian Basin:

- These ROZ "fairways" were first defined by Melzer and Trentham (2010).
- Our initial study addressed the size, recoverability and economic viability of the San Andres ROZ "fairway" resource (beyond the structural boundary of existing oil fields) in four counties - - Gaines, Yoakum, Terry and Dawson.



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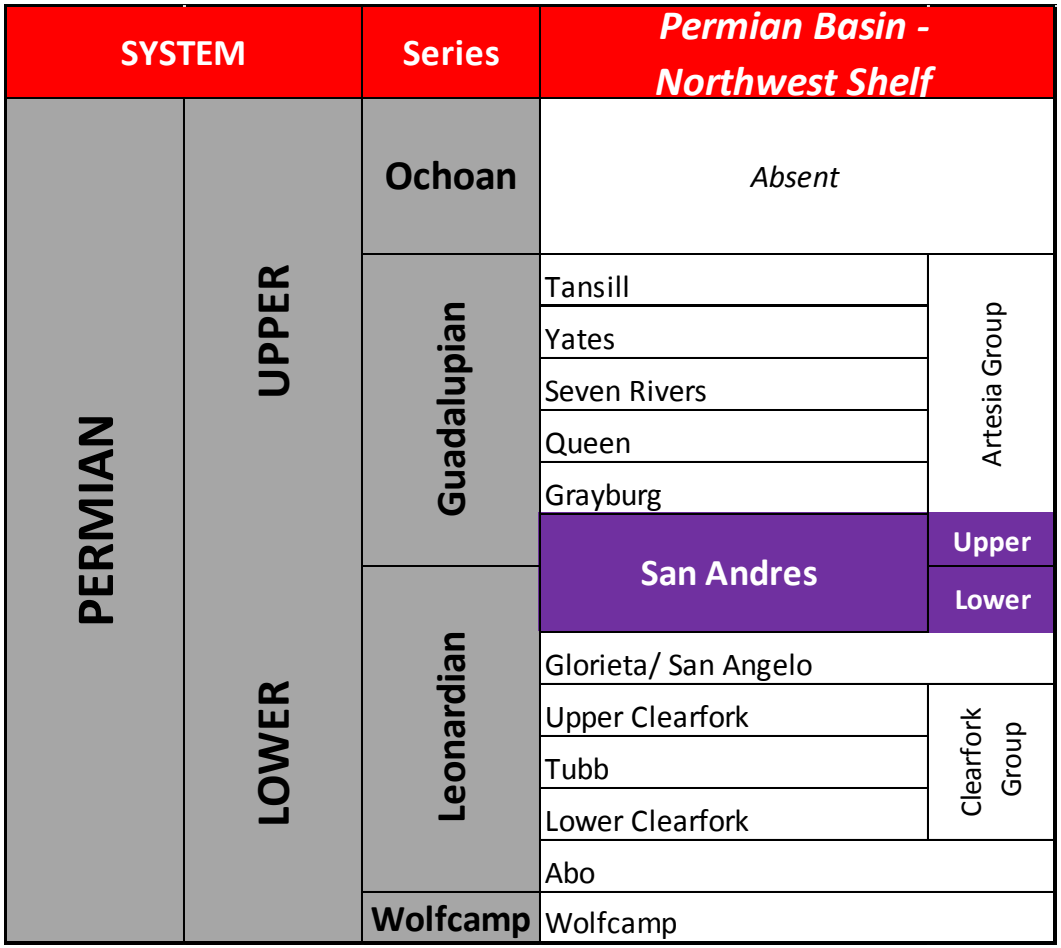
Stratigraphic Column: Permian Interval

The San Andres Formation in the four-county study area is 1,200 feet to 1,600 feet thick.

It is underlain by the Glorieta/ San Angelo Formation and overlain by the Grayburg and other formations of the Upper Permian Artesia Group.

Our initial work indicates that ROZ resources also exist in the Grayburg and Glorieta formations.



Source: Modified from Figure 3b, Stratigraphic nomenclature for the Permian section in the Permian Basin in: Dutton, S.P. and others, 2004, Play Analysis and Digital Portfolio of Major Oil Reservoirs in the Permian Basin: Application and Transfer of Advanced Geological and Engineering Technologies for Incremental Production Opportunities, Texas Bureau of Economic Geology, work performed under contract DE-FC26-02NT15131.

Overview of ROZ "Fairway" Study Methodology

The San Andres ROZ "fairway" resource assessment methodology involves three steps:

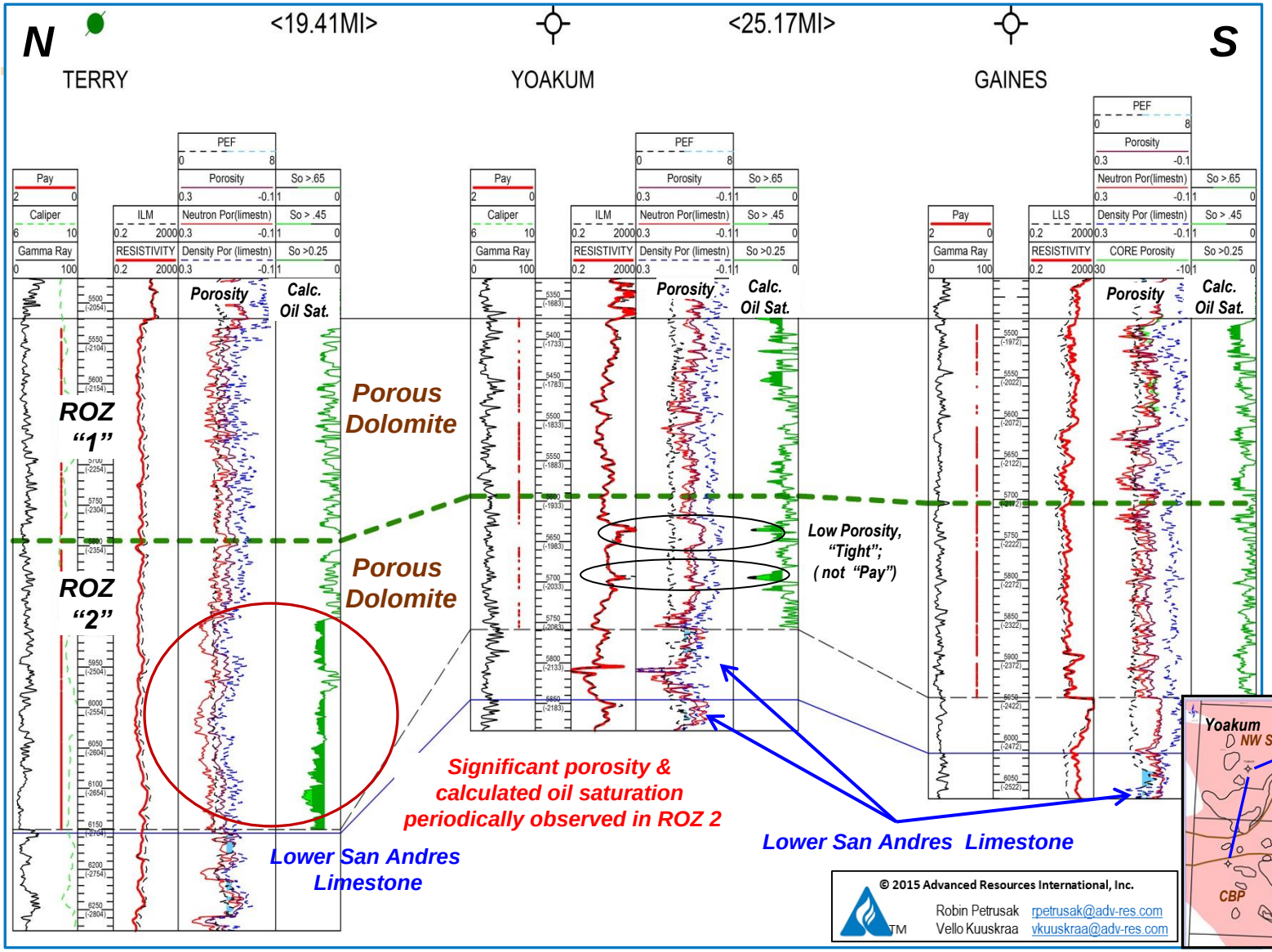
1. **Estimation of Oil In-Place.** The study utilized a data set of 123 digital logs,* calibrated to four sets of core data and to regional water salinity data, as well as regional cross-sections to establish the net thickness, porosity and oil saturation for the San Andres ROZ "fairway" interval in four counties of the Permian Basin.

2. **Modeling of Technically Recoverable Resources.** The study utilized the CO_2-PROPHET finite-difference stream-tube reservoir model to calculate fluid (oil, water, gas) recovery and fluid (CO_2 and water) injection. CO_2-PROPHET was calibrated to a full-scale compositional simulator, GEM.

3. **Calculation of Economically Recoverable Resources.** The study used ARI's CO_2-EOR Cost and Economics Model to determine what portion of the technically recoverable resource would be commercially (economically) viable.

*Thirty-three study logs, located within a San Andres oil field or with limited penetration through the ROZ, were excluded from the quantitative analysis of the ROZ "fairway" resource.

Three-Well ROZ Stratigraphic Cross Section



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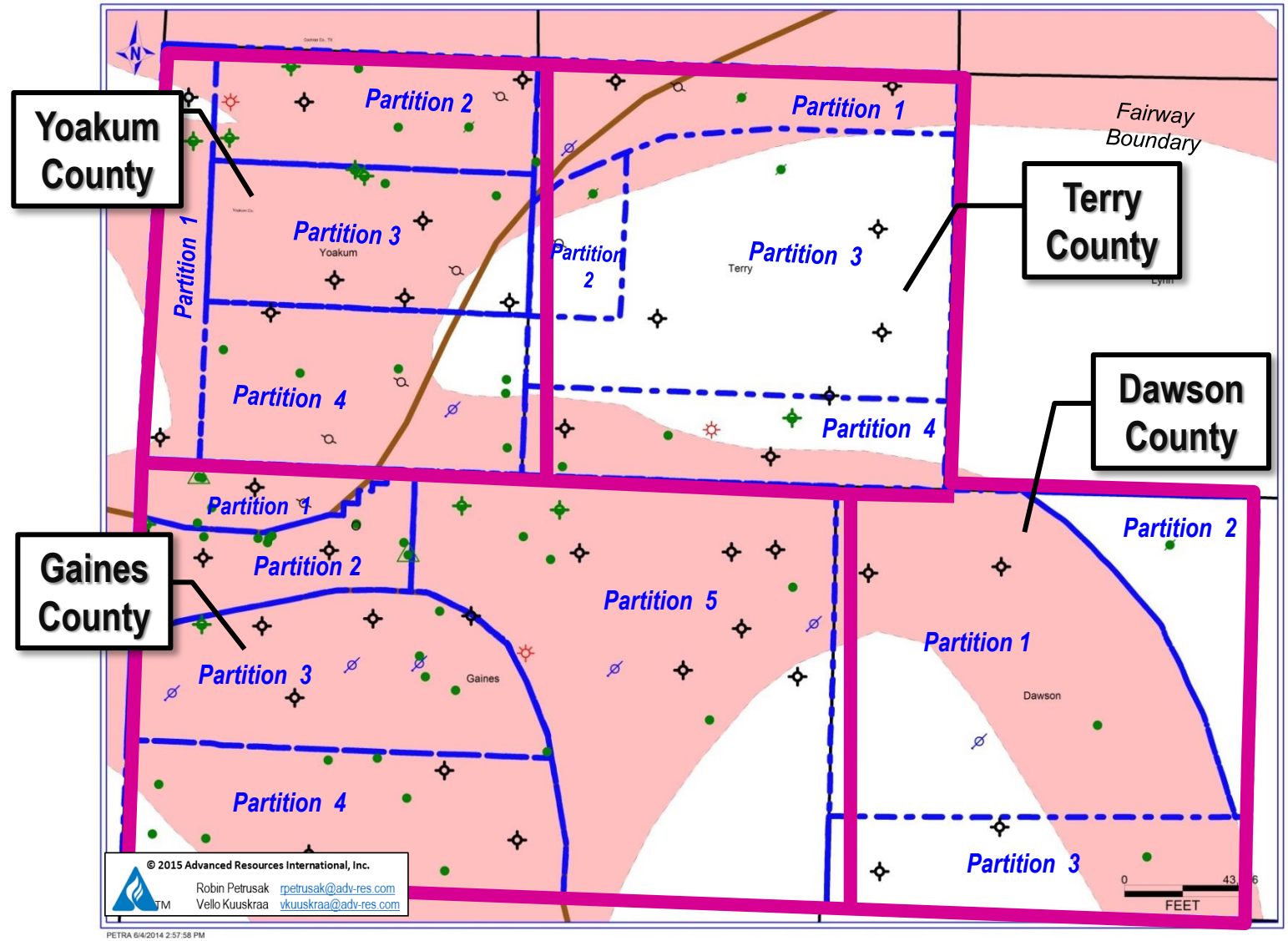
- ROZ "1" represents the upper part of the Lower San Andres porous dolomite.
- ROZ "2" represents the lower part of the Lower San Andres porous dolomite; it is often thinner- bedded and more shaley than ROZ "1".
- Base of ROZ "2" is defined by the underlying tight Lower San Andres limestone.

Four County Study Area, Permian Basin, West Texas

ROZ Study Wells, Fairways and Partitions



- For the resource assessment, each county was divided into several geologically established "partitions."
- Areas underlying existing oil fields (e.g., Seminole) are excluded from the ROZ "fairway" area and resource in-place.
- The ROZ "1" and ROZ "2" intervals of the Lower San Andres dolomite were separately assessed.

Fundamental Study Questions

The San Andres ROZ "fairway" resource assessment was undertaken to address four questions:

1. *What is the size, distribution and quality of the in-place San Andres ROZ "fairway" oil resource?*
2. *What portion of this in-place oil resource can be mobilized and produced using CO_2-EOR?*
3. *What volumes of CO_2 will be required to develop this resource using miscible CO_2-EOR? How much of the injected CO_2 will be securely stored?*
4. *What portion of the San Andres ROZ "fairway" resource is commercially viable for oil recovery with by-product storage of CO_2? How much is geologically viable for storing CO_2 with by-product recovery of oil?*

1. What Is the Size and Distribution of the In-Place San Andres ROZ "Fairway" Oil Resource?

Our assessment of the San Andres ROZ "fairway" resource in the four-county area of the Permian Basin identified 112 billion barrels of oil in-place.

Much of this in-place resource (77 billion barrels) is "higher quality", offering promise for commercially viable development with by-produce storage of CO_2.

In-Place San Andres ROZ "Fairway" Resource: Four-County Area of West Texas

County	In-Place Resource		
	Total	Higher Quality*	Lower Quality**
	(B Bbls)	(B Bbls)	(B Bbls)
Gaines	45.5	35.4	10.1
Yoakum	20.7	16.1	4.6
Terry	17.9	10.6	7.3
Dawson	27.8	14.6	13.2
Total	**111.9**	**76.7**	**35.2**

*Porosity greater than 8% and oil saturation greater than 25%.
**Porosity less than or equal to 8% and/or oil saturation less than or equal to 25%.

Source: Advanced Resources International, 2015.

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Comparison of Industry's Publically Available ROZ Data with This Study's ROZ Data

The study's assessments of the key volumetric San Andres ROZ "fairway" properties - - gross and net pay, porosity and oil saturation - - are consistent with industry published data for KinderMorgan's "Tall Cotton" ROZ "fairway" project (western Gaines County).

Comparison of Gaines County San Andres ROZ Reservoir Properties: "Tall Cotton" and This Study

Volumetric Reservoir Properties	"Tall Cotton" ROZ "Fairway"[1]	Gaines Co. ROZ "Fairway" Partition #3
Gross Pay (feet)	540	492
Net Pay (feet)	450	432
Porosity (%)	12%	10%
Oil Saturation (%)	35% to 50%	36%

The "Tall Cotton" ROZ project is located in Partition #3 of Gaines Count.

Source: Advanced Resources International, 2015., [1] Railroad Commission of Texas, 2014.

2. What Portion of This In-Place Oil Resource Can be Mobilized and Produced Using CO_2-EOR?

The application of miscible CO_2–EOR would enable 27 billion barrels, 24% of the San Andres ROZ "fairway" oil in-place in this Four County area, to become technically recoverable.

Because of its higher quality geologic setting, Gaines County accounts for nearly half of the technically recoverable San Andres ROZ "fairway" resource in this four-county study area.

In-Place and Technically Recoverable San Andres ROZ "Fairway" Resource: Four-County Area of West Texas

County	In-Place Resource	Technically Recoverable	
	(B Bbls)	(B Bbls)	(% OIP)
Gaines	45.5	12.4	27%
Yoakum	20.7	5.2	25%
Terry	17.9	3.6	20%
Dawson	27.8	5.9	21%
Total	**111.9**	**27.1**	**24%**

Source: Advanced Resources International, 2015.

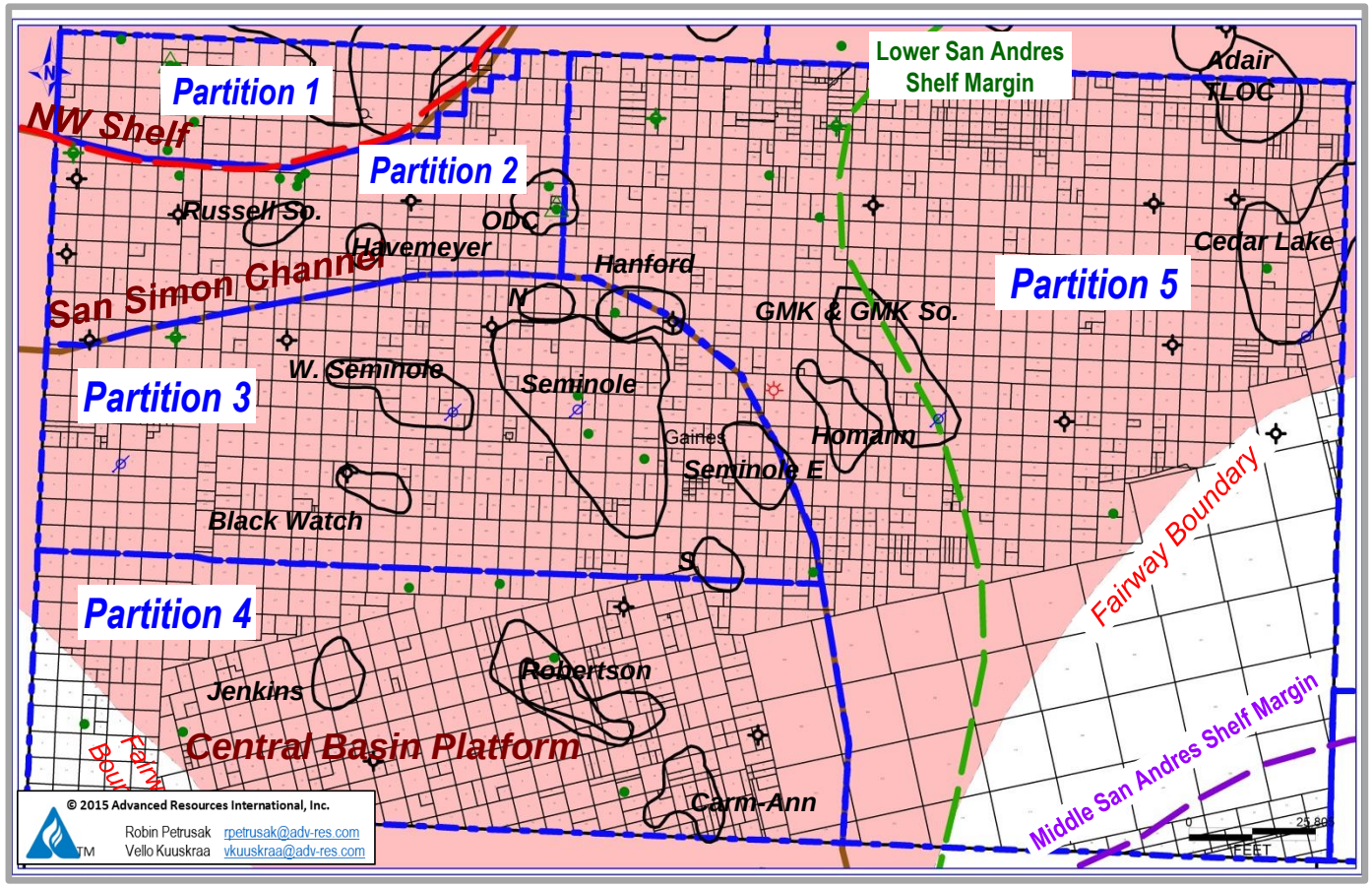
Recovering Residual (ROZ) Oil: A Gaines Country Case Study

The 45.5 billion barrels of oil in-place in the ROZ "fairway" of Gaines Co. has been placed into five partitions.

Partition #3, located in east-central Gaines Co. with 11.7 billion barrels of oil in-place, serves as the "case study".

Gaines Co., Partition #3, ROZ Oil In-Place

ROZ Unit	Higher Quality (Billion Barrels)	Lower Quality (Billion Barrels)
ROZ #1	5.46	0.39
ROZ #2	5.59	0.28
Total	**11.05**	**0.67**



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Recovering Residual (ROZ) Oil: A Gaines Country Case Study (Cont'd)

To provide confidence in the use of the CO_2-PROPHET finite-difference reservoir model, we calibrated it with an industry standard compositional, finite-difference reservoir simulator, GEM.

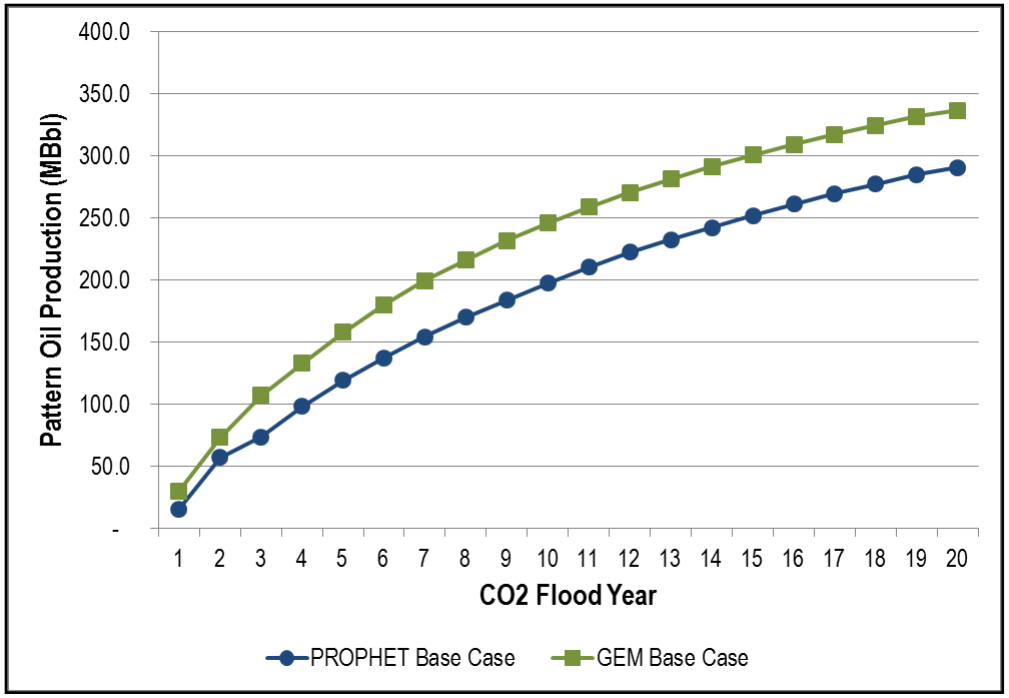
Gaines Co. ROZ "Fairway" Partition #3 ROZ 1 Higher Quality Reservoir Properties

Oil In Place	802,000 barrels
Area	20 acres
Net Pay	207.5 feet
Residual Oil Saturation	34%
Porosity	9.4%
Formation Volume Factor	1.28
Depth	5,340 feet
Permeability	6 md
Temperature	118˚ F
Operating Pressure	2,620 psi
Oil Gravity	35˚ API
Viscosity	1.0 cp
MMP (estimated)	1,385 psi
Dykstra-Parsons	0.83

Source: Advanced Resources International, 2015.

Cumulative Oil Production: CO_2-PROPHET and GEM

(Gaines Co. ROZ "Fairway"; Partition #3 ROZ 1 Higher Quality "Type Well")



Source: Advanced Resources International, 2015.

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Comparison of KinderMorgan's "Tall Cotton" ROZ Project and This ROZ Study

The study's estimates of oil recovery and CO_2 usage are also in-line with data reported for KinderMorgan's "Tall Cotton" miscible CO_2-EOR project for a geologically comparable San Andres ROZ "fairway" area of Gaines County.

Comparison of Performance : "Tall Cotton" ROZ "Fairway" Project and This Study's ROZ "Fairway" Project in Partition #3 of Gaines County*

Performance Measures	Tall Cotton "Type Patterns"		Representative "Type Pattern"
	Phase 1 (9 Patterns)	Phase 2 (194 Patterns)	Partition #3
Oil Recovery Efficiency			
% OOIP	13%	12%	12.6%
% OIP	32%	29%	28.9%
CO_2/Oil Ratio (Mcf/B)	n/a	6.9	7.4

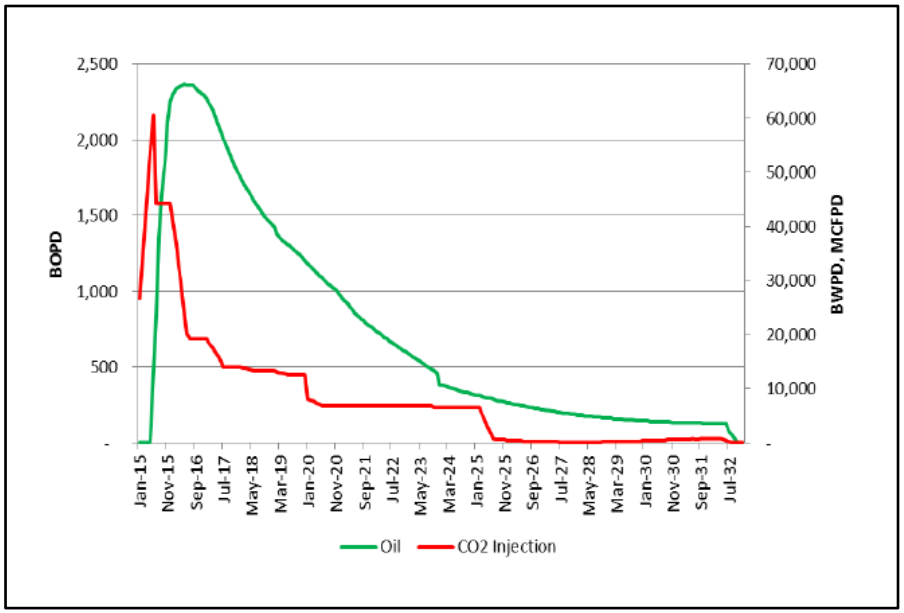
Source: Advanced Resources International, 2015

KinderMorgan's "Tall Cotton" CO_2-EOR ROZ Project

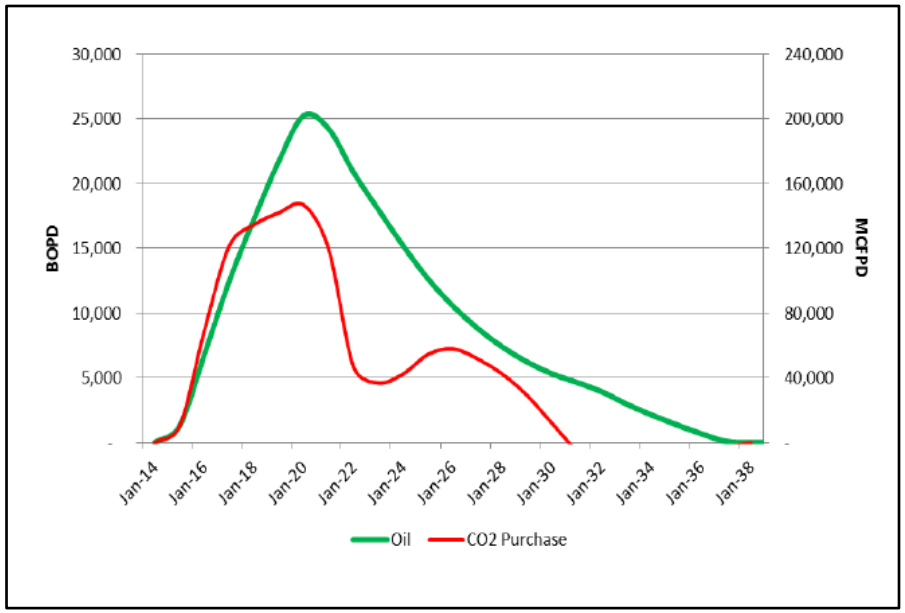
Phase 1 of KinderMorgan's nine pattern "Tall Cotton" ROZ "fairway" project involves a capital investment of $88 million and initial injection of 45 to 50 MMcfd of CO_2.

Phase 2 of KinderMorgan's "Tall Cotton" ROZ "fairway" project involves 194 patterns, purchase of 647 Bcf (34 million mt) of CO_2, and peak injection of about 150 MMcfd of CO_2.

KM ROZ Phase 1 Production Forecast



KM ROZ Phase 2 Production Forecast



Source: KinderMorgan Investor Presentation, 2015.

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3. What Volumes of CO_2 Will be Required to Develop This Resource Using Miscible CO_2-EOR? How Much of the Injected CO_2 Will be Securely Stored?

The study estimates the need for 18 billion metric tons (340 Tcf) of purchased CO_2 to develop the San Andres ROZ "fairway" resource in this four-county area of West Texas.

At the completion of the CO_2 flood, essentially all of the purchased CO_2 will be securely stored. During the operation of the CO_2 flood, the produced CO_2 is re-injected.

Volume of Purchased CO_2 Necessary for Developing the San Andres ROZ "Fairway" Resource: Four-County Area of West Texas

County	Purchased CO_2		Purchased CO_2/Oil Ratio	
	(Tcf)	(B mt)	(Mcf/Bbl)	(mt/Bbl)
Gaines	117	6.2	9.4	0.50
Yoakum	46	2.5	8.8	0.48
Terry	70	3.7	19.4	1.03
Dawson	107	5.6	18.1	0.95
Total	**340**	**18.0**	**12.5**	**0.66**

Source: Advanced Resources International, 2015

Storing CO_2 in the San Andres ROZ "Fairway"

Considerably more CO_2 is stored* - - an average of 0.66 metric tons per barrel of oil produced - - than the CO_2 in the oil recovered from the San Andres ROZ "fairway" resource.

The CO_2 content of one barrel of crude oil (when consumed) is about 0.4 metric tons, after exclusion of 7% for petrochemical and asphalt production.

In addition, each barrel of domestically produced ROZ "fairway" oil displaces a barrel of imported (or conventionally produced) oil that brings with it no offsetting storage of CO_2.

*This is a marginal, rather than a full life-cycle, analysis of CO_2 emissions associated with CO_2-EOR.

Source: Advanced Resources International, 2015

4A. What Portion of the San Andres ROZ "Fairway" Resource Is Commercially Viable for Oil Recovery With By-Product Storage of CO_2?

Over 17 billion barrels of the 27 billion barrels of technically recoverable San Andres "fairway" resource (in this four-county study area) is commercially viable* providing space for nearly 7 billion metric tons (129 Tcf) of by-product CO_2 storage.

The commercially viable ROZ "fairway" projects will use and store 7.4 Mcf (0.39 mt) of CO_2 per barrel of recovered oil.

Commercially Viable Oil Recovery with By-Product Storage of CO_2: San Andres ROZ "Fairway" Resource, Four-County Area of West Texas

County	Oil Recovery	By-Product CO_2 Storage		Purchased CO_2/ Oil Recovery Ratio	
	(B Bbls)	(Tcf)	(B mt)	(Mcf/Bbl)	(mt/Bbl)
Gaines	9.8	68	3.6	7.0	0.37
Yoakum	3.9	26	1.4	6.7	0.36
Terry	0.5	4.0	0.2	8.9	0.47
Dawson	3.3	31	1.6	9.3	0.49
Total	**17.5**	**129**	**6.8**	**7.4**	**0.39**

*At an oil price of $80 per barrel, a CO_2 cost of $36.30/mt ($1.92/Mcf), and a financial hurdle rate (ROR) of 20%, before tax.

Source: Advanced Resources International, 2015

ROZ Cost and Economics Models

The inputs and assumptions of ARI's CO_2-EOR Cost and Economics Model include the following:

- **Oil Price** - - $80 per barrel (West Texas Intermediate (WTI) oil price). The oil price selected for the analysis is consistent with the mid-term oil price in EIA's 2015 Annual Energy Outlook.
- **CO_2 Sales Price** - - 1.92 $/Mcf, equal to $36.29 per metric ton (delivered at pressure to the oil field). The CO_2 sales price used by the ROZ study is consistent with historical ratios relating the CO_2 sales price to the oil price.
- **Financial Hurdle Rate** - - 20% ROR (rate of return), before tax
- **Royalties** - - 20% of gross production
- **State Severance/Ad Valorem Taxes** - - Texas specific (the state severance tax used by the study did not incorporate any special incentives for operating a CO_2 flood or for storing CO_2.)

4B. How Much of the San Andres ROZ "Fairway" Resource Is Geologically Viable for Storing CO_2 With By-Product Recovery of Oil?

The geologically viable (but non-commercial) portion of the San Andres ROZ "fairway" (in this four-county study area) provides space for storing 11 billion metric tons (209 Tcf) with 9.6 billion barrels of by-product oil recovery.

The 9.6 billion barrels of by-product oil provides net revenues of $585 billion*, equal to $52/mt of CO_2 stored. The geologically viable ROZ "fairway" projects will use and store 21.7 Mcf (1.16 mt) of CO_2 per barrel of recovered oil.

Geologically Viable Storage of CO_2 with By-Product Recovery of Oil: San Andres ROZ "Fairway" Resource, Four-County Area of West Texas

County	CO_2 Storage		By-Product Oil Recovery	Purchased CO_2/ Oil Recovery Ratio		By-Product Net Revenues*
	(Tcf)	(B mt)	(B bbls)	(Mcf/Bbl)	(mt/Bbl)	($US, Billion)
Gaines	49	2.6	2.6	18.7	0.99	$158
Yoakum	20	1.1	1.3	15.7	0.83	$78
Terry	64	3.4	3.1	20.5	1.10	$192
Dawson	76	4.0	2.6	29.4	1.55	$157
Total	**209**	**11.1**	**9.6**	**21.7**	**1.16**	**$585**

*At an $80 per barrel oil price, after excluding a net revenue interest of 80% and a 5% state severance tax.

Source: Advanced Resources International, 2015

Acknowledgements

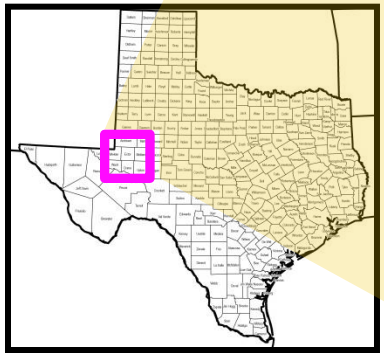
This study, entitled **"Defining an Overlooked Domestic Oil Resource: A Four-County Appraisal of the San Andres Residual Oil Zone (ROZ) "Fairway" of the Permian Basin",** draws on the extensive geological and log analyses performed by Advanced Resources International, in partnership with the University of Texas of the Permian Basin (Dr. Robert Trentham) and Melzer Consulting (Mr. Steve Melzer), sponsored by the Research Partnership to Secure Energy for America (RPSEA).

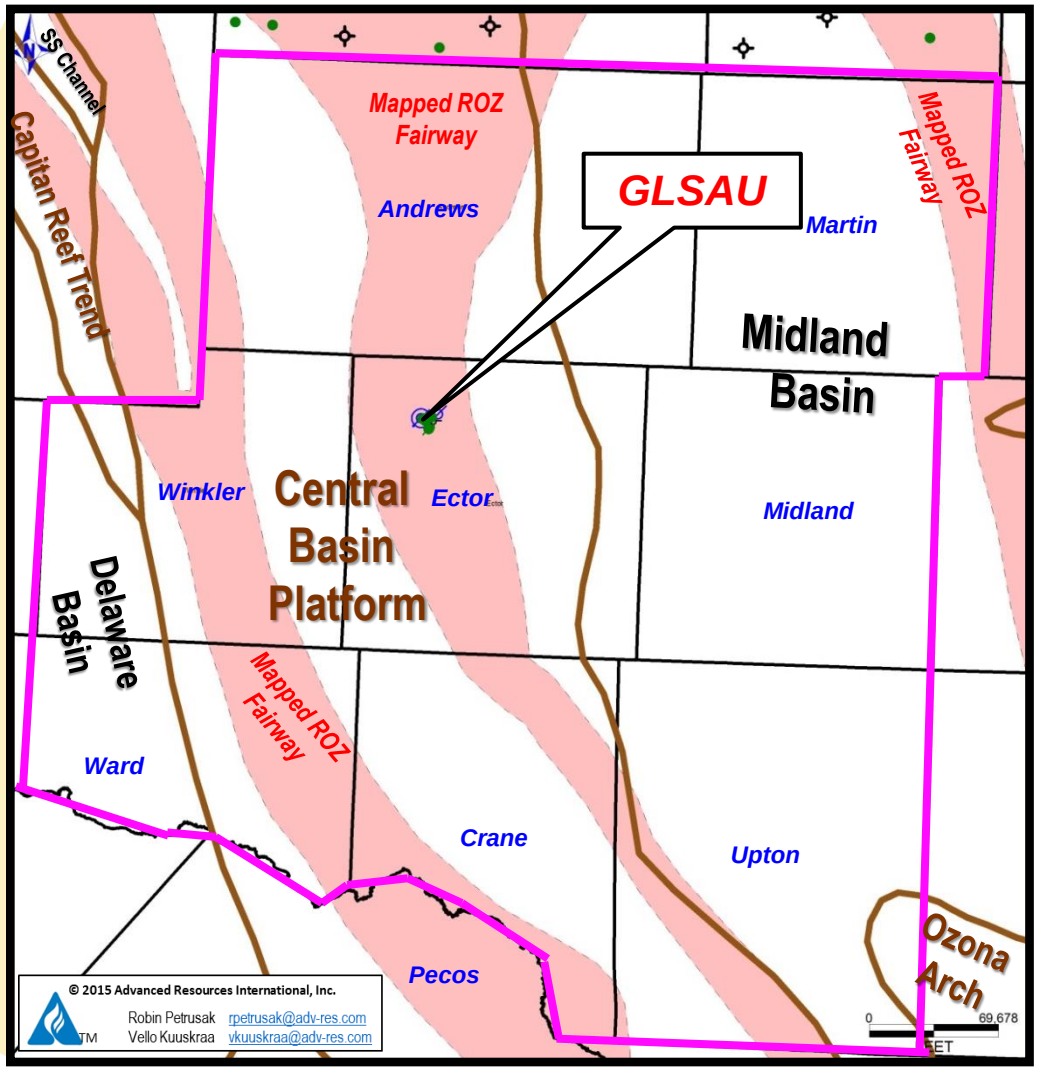
The geological work for the four-county ROZ "fairway" study area, sponsored by RPSEA, has been combined with the reservoir engineering and economics analyses work for the study area performed by Advanced Resources International, sponsored by the U.S. DOE National Energy Technology Laboratory.

Eight County Study Area of Permian Basin ROZ "Fairway"

We recently extended the San Andres ROZ "fairway" resource assessment to eight additional Permian Basin counties - - Andrews, Martin, Winkler, Ector, Midland, Ward, Crane and Upton.

- The study used an extensive set of log- and core-based reservoir data to estimate the size of the ROZ oil in-place.
- Data were assembled for wells both inside and outside the currently mapped ROZ "fairway" boundaries.
- The Goldsmith-Landreth San Andres Unit (GLSAU) provided valuable core data for calibrating the log-based San Andres ROZ resource assessment.





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Results of Eight County ROZ "Fairway" Resource Assessment

Our detailed analysis of 155 study area logs (with 121 log-based data points used in the quantitative portion of the resource assessment) identifies 79 billion barrels of San Andres ROZ oil in-place in this expanded eight county area:

- Nearly three-quarters of this San Andres ROZ resource, 58 billion barrels, is higher quality, with porosity greater than 8% and oil saturation greater than 25%.
- The remainder of the San Andres ROZ resource, 21 billion barrels, is lower quality, with porosity less than 8% and oil saturation less than 25%.
- Significant portions of the eight county area, including much of the Midland County, contain Grayburg Formation ROZ "fairway" resources.

Summary of San Andres ROZ "Fairway" Resources: Eight Counties of the Permian Basin

County	Total ROZ Resources (Billion Bbls)	Higher Quality ROZ Resources (Billion Bbls)	Lower Quality ROZ Resources (Billion Bbls)
Andrews	37.13	31.23	5.90
Martin*	6.74	4.80	1.94
Winkler	9.47	7.98	1.49
Ector*	6.95	5.55	1.40
Three Southern Tier*	19.18	8.67	10.51
Midland (Grayburg ROZ)	0.00		
Total (San Andres ROZ)	**79.47**	**58.23**	**21.24**

Counties with potential Grayburg Fm ROZ "fairways".

JAF2015_037.XLS

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Concluding Thoughts

Utilization of CO_2 for enhanced oil recovery, the "U" in CCUS, is a key component of the major CO_2 capture and storage projects:

- Southern Company's Kemper County IGCC project
- Summit Power's Texas Clean Energy IGCC project
- Petra Nova's (NRG & JX Nippon) WA Parish Post-Combustion project
- Saskpower's Boundary Dam Post Combustion project

With the addition of ROZ resource, the CO_2-EOR market is sufficiently large to serve as the primary storage option for captured CO_2 emissions.

The revenues from the sale of CO_2 combined with potential incentives (tax credits) of $30 to $40/mt ("son of 45Q") would enable a large number of additional coal-fired electric power plants to undertake CO_2 capture, helping keep coal- and natural gas-fired power generation part of the energy mix while revitalizing the CO_2-EOR industry.

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