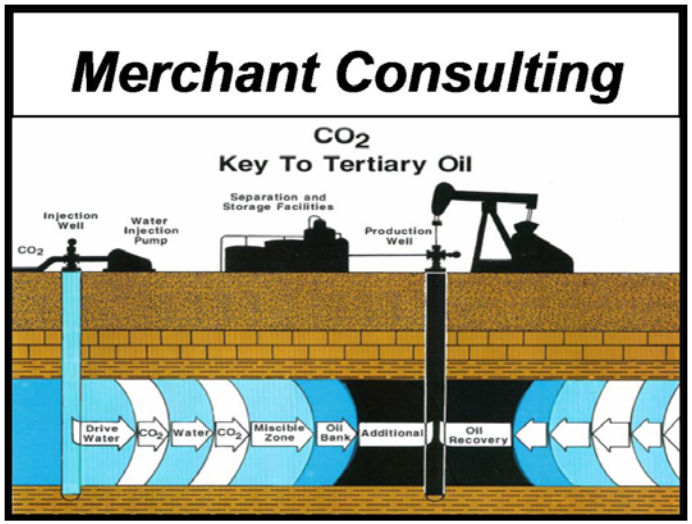
"The Energy Gap – How CO_2 Tertiary Recovery will mark its place in the 21st Century"

David H. Merchant



CO_2 Storage Solutions

WEB Site: www.CO2StorageSolutions.com

Merchant Consulting

Email: merchantconsulting@comcast.net

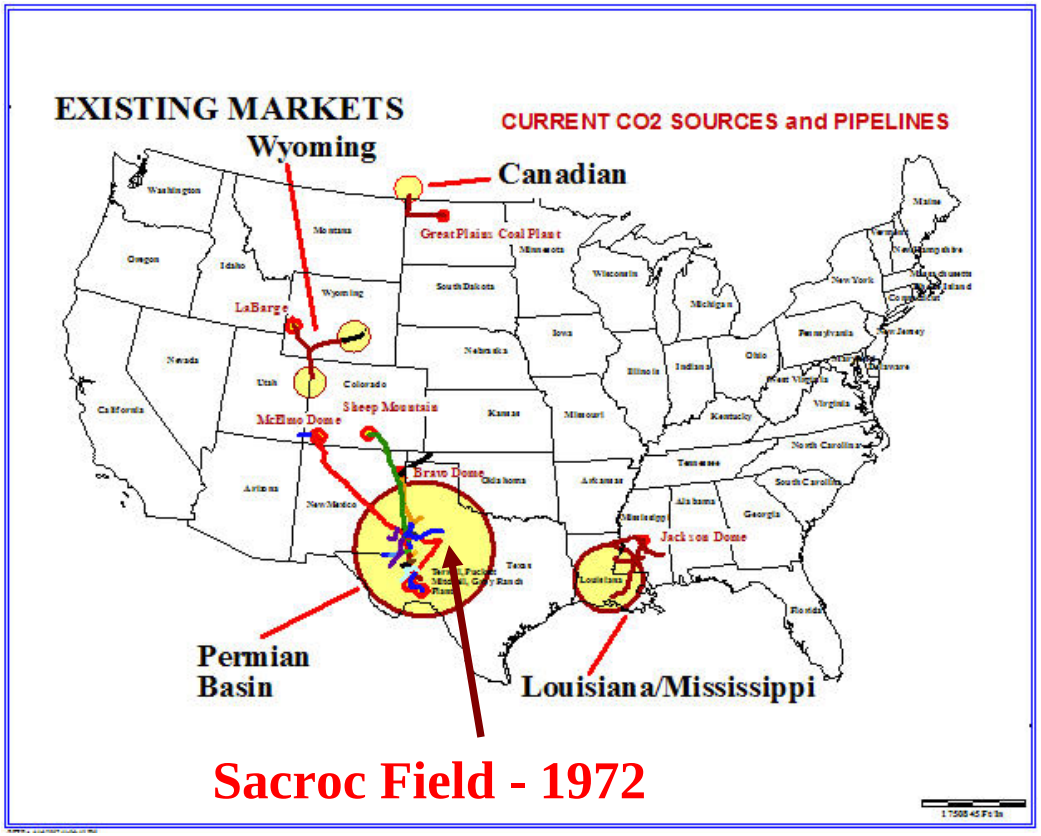
Presented to Midland CO_2 Conference

December 6, 2012

Midland, Texas

Tertiary CO_2 Flooding

"CO_2 Flood History since 1972"



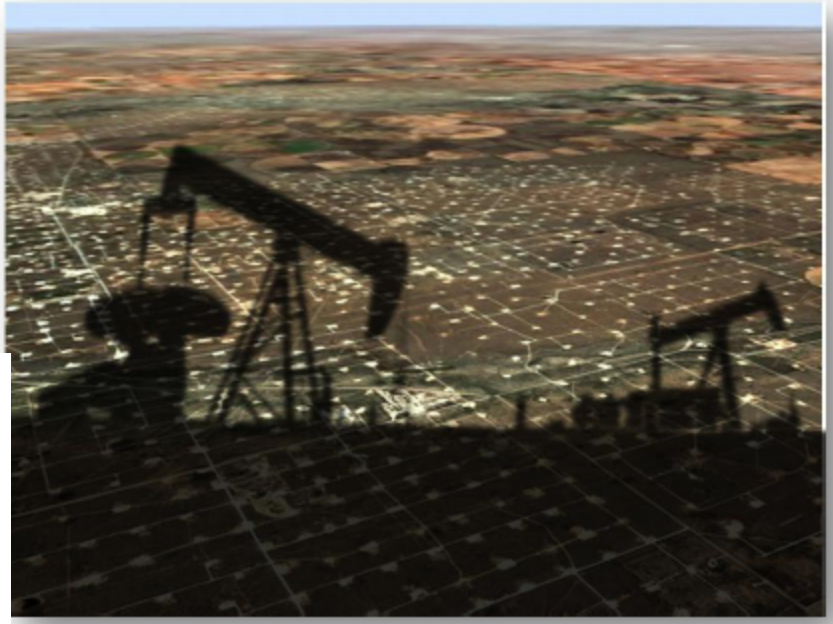
Since 1972 over 120+ CO_2 Tertiary Projects have been implemented in the United States.

Today, over 237,000 BOPD of Tertiary Oil is produced with CO_2 Injection with over 3,100 miles of CO_2 pipeline.

Permian Basin Statistics

Permian Basin – Central Basin Platform

- Has produced oil for over 80 years
- Is the 3rd largest petroleum producing area in the U.S. after the Gulf of Mexico and Alaska
- 29 billion barrels produced from the Permian Basin
- 1.2 billion barrels of tertiary oil have been recovered due to CO_2 Injection



CO_2 Well Operations

10,000 Production Wells

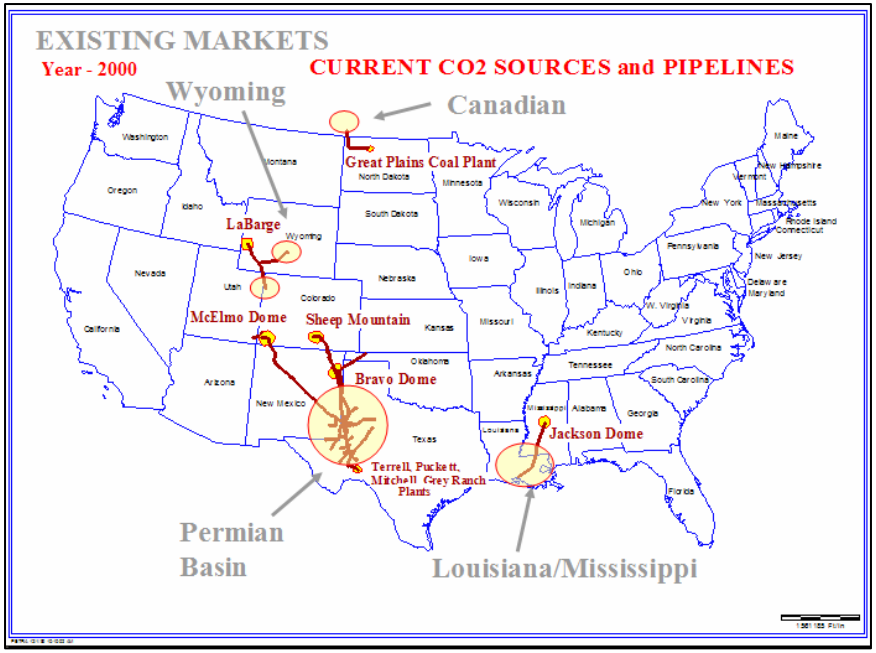
8,000 CO_2 Injection Wells

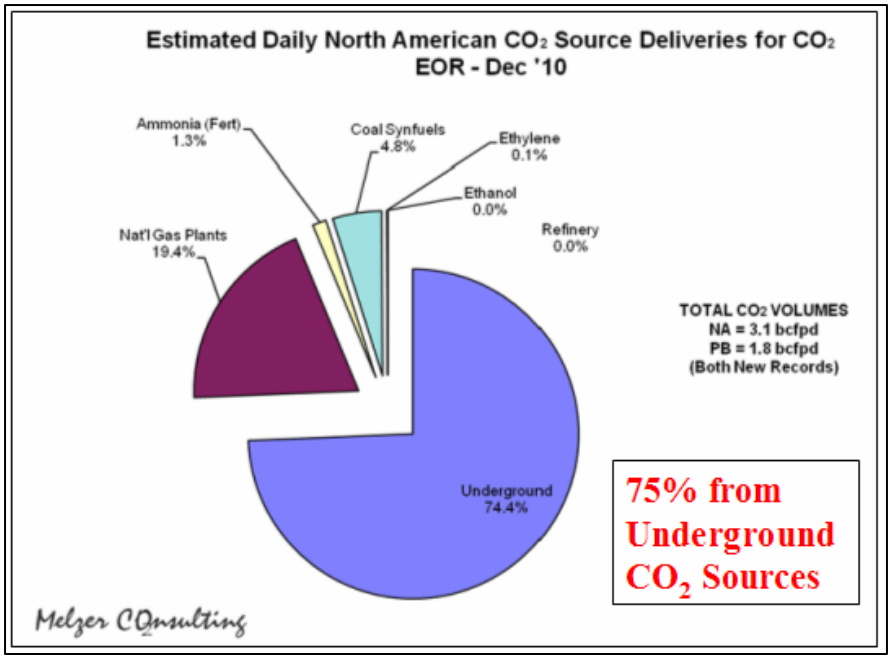
Note: Since 1972, the oil and gas industry has:

<u>Excellent Safety Record</u>.

Note: Corrosion is not an issue - Casing, Tubulars, Field Piping, etc. are 95+% Carbon Steel

United States CO_2 Supply (Natural Sources)





Approximately 75% of the CO_2 today is supplied by Natural CO_2 Source Fields

1. **Permian Basin - McElmo Dome, Sheep Mountain, Bravo Dome**
2. **Mississippi – Jackson Dome**
3. **Wyoming – LaBarge**

Conventional CO_2 Pipeline Operations

Pipeline Transport is "Best Overall"

Note: Since 1972, the oil and gas industry has:

1. Produced and injected more than 10.8 TCF of CO_2 from 7 sources. 1.2 TCF of which came from sources otherwise would have been vented.
2. Constructed over 3,100 miles (4,960 kilometers) of CO_2 mainline pipeline systems.
3. In 2010, Producing at Maximum Capacity of over 3.1 BCF/day.

Conventional CO_2 Pipeline Operations

Pipeline Transport is "Best Overall"

Note: Since 1972, the oil and gas industry has:

Excellent Safety Record.

The CO_2 is dehydrated (water removed), pumped, and transported as a super-critical fluid. Very little corrosion problems have been reported to date.

Conventional CO_2 Operations

Oil Production Facilities and Gas Separation Facilities

Note: Corrosion is not an issue

Vessels, piping, etc. is 95+% Carbon Steel

What are they doing?

CO_2 Tertiary Flood Management

Pattern Review In Progress: Control Central

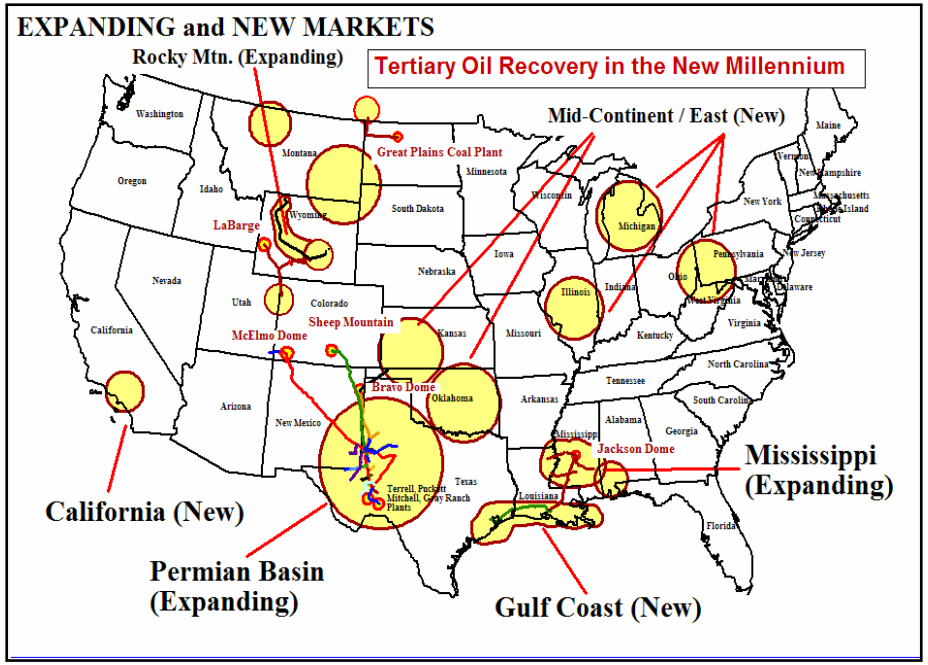
1. **Evaluating Individual Well Performance**
2. **Evaluating Individual Pattern Performance**
3. **Making WAG Adjustments based on Pattern Performance**

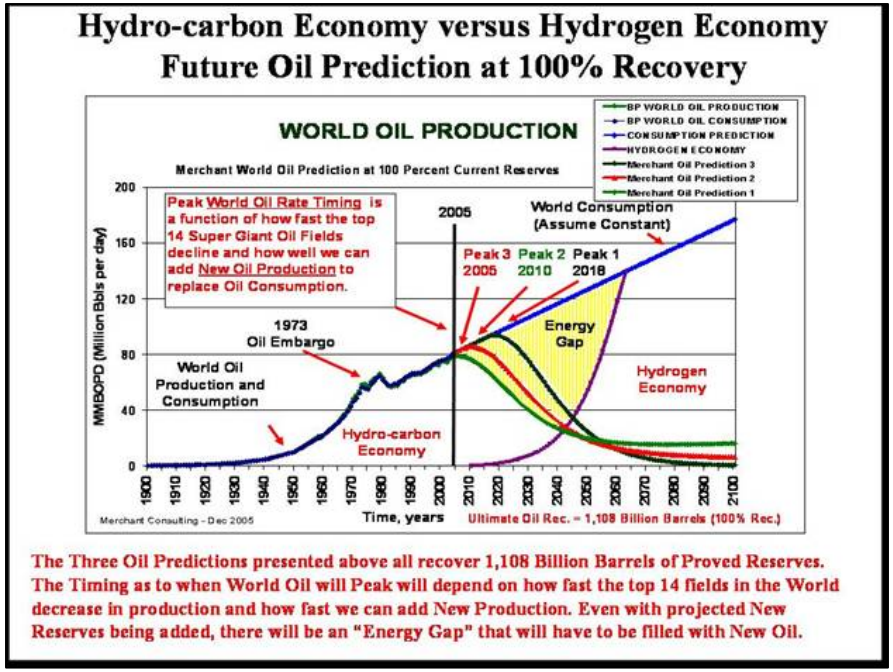
Tertiary CO_2 Flooding

"The Energy Gap"
21st Century

Tertiary CO_2 Flooding

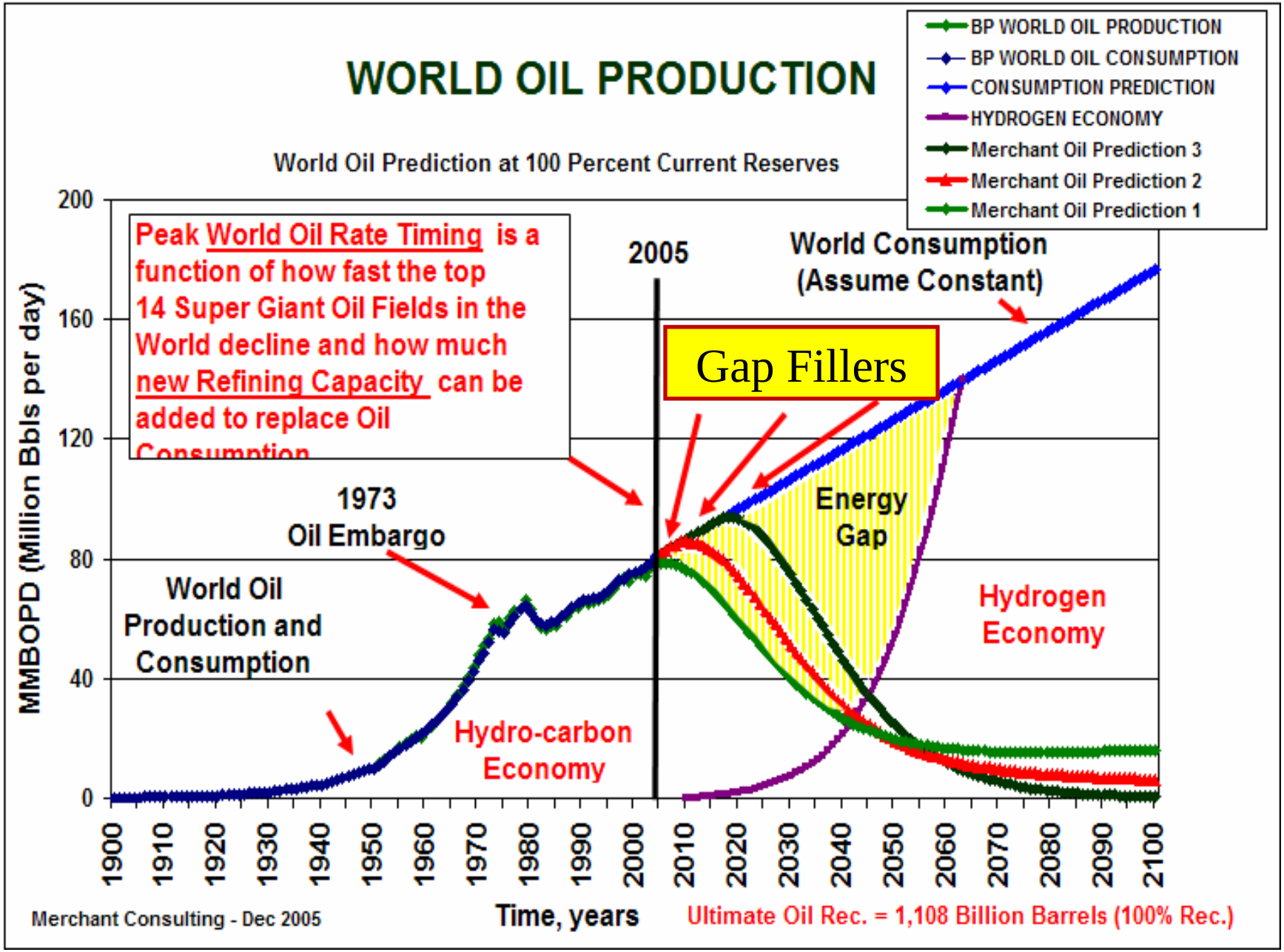
"CO_2 Sequestration Future"





The Three Oil Predictions presented above all recover 1,108 Billion Barrels of Proved Reserves. The Timing as to when World Oil will Peak will depend on how fast the top 14 fields in the World decrease in production and how fast we can add New Production. Even with projected New Reserves being added, there will be an "Energy Gap" that will have to be filled with New Oil.

In the 21st Century, CO_2 Sequestration will provide CO_2 from IGCC Natural Gas and Coal Fired Power Plants, Refineries, and other large scale Anthropogenic CO_2 Sources to fill the <u>Energy Gap</u> that exists between "Peak Oil" and the future "Hydrogen Energy Economy".


WORLD OIL PRODUCTION
World Oil Prediction at 100 Percent Current Reserves
BP WORLD OIL PRODUCTION
BP WORLD OIL CONSUMPTION
CONSUMPTION PREDICTION
HYDROGEN ECONOMY
Merchant Oil Prediction 3
Merchant Oil Prediction 2
Merchant Oil Prediction 1
Peak World Oil Rate Timing is a function of how fast the top 14 Super Giant Oil Fields in the World decline and how much new Refining Capacity can be added to replace Oil Consumption
2005
World Consumption (Assume Constant)
Gap Fillers
1973 Oil Embargo
Energy Gap
World Oil Production and Consumption
Hydrogen Economy
Hydro-carbon Economy
MMBOPD (Million Bbls per day)
200
160
120
80
40
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Merchant Consulting - Dec 2005
Time, years
Ultimate Oil Rec. = 1,108 Billion Barrels (100% Rec.)

Gap Fillers

1. Primary Oil Recovery
2. Secondary Oil Recovery
3. Tertiary CO_2 - Conventional Tertiary Oil Recovery
4. Tertiary CO_2 - Residual Oil Zone (ROZ)
5. Tertiary CO_2 – Heavy Oil (14+ API)
6. Offshore – Shallow and Deep Water
7. Natural Gas (Conventional Reservoirs)
8. Liquefied Natural Gas (LNG)
9. Shale Oil (Bakken, Others)
10. Shale Gas (Marcellus, Barnett, Eagle Ford)
11. Coal to Gas, Coal to Liquids
12. Steam, Thermal, and MEOR (Bacteria)

Hydrogen Economy –"Clean Air Environment"

1. Wind Power
2. Solar Power
3. Nuclear (Fission)
4. Nuclear (Fusion)
5. Hydrogen Power (Hydrogen Cars and Hydrogen Fuel Cells)
6. Tertiary CO_2 – EOR and CO_2 Sequestration
7. Mass Transportation (Automobiles poor means to move people)
8. Clean Coal Gasification (Pre-Post Combustion, Oxy-fuel)
9. Clean Natural Gas – (Conventional and Un-Conventional)
10. Biomass – Balance with Mother Nature
11. Nano Tech
12. Algae (Clean Fuels)

CO_2 Flood Basics – What makes CO_2 work?

Oil Field Basics

Oil Field Life Cycle – (All Fields Worldwide)

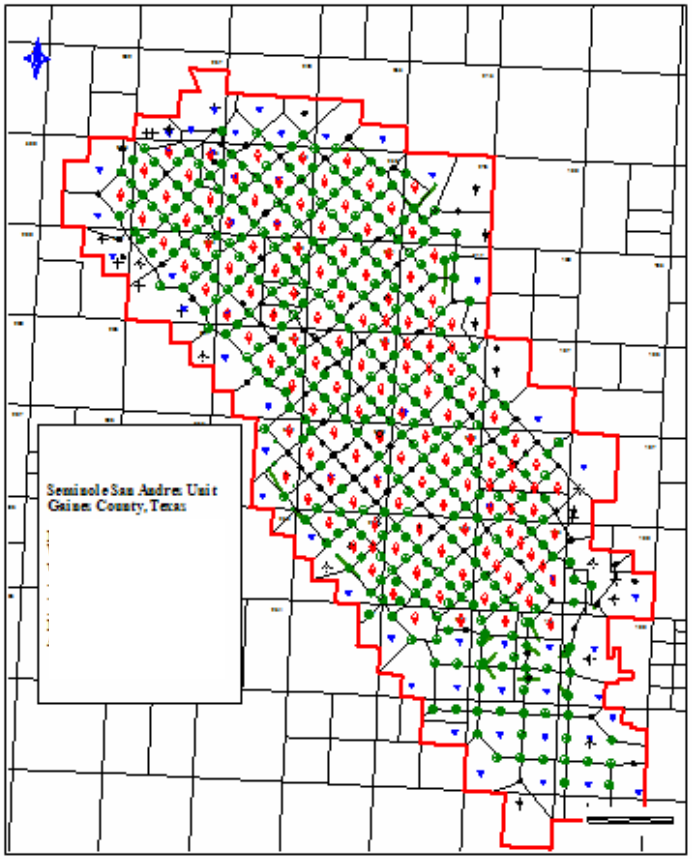
Recovery Mechanisms

Primary Oil Recovery

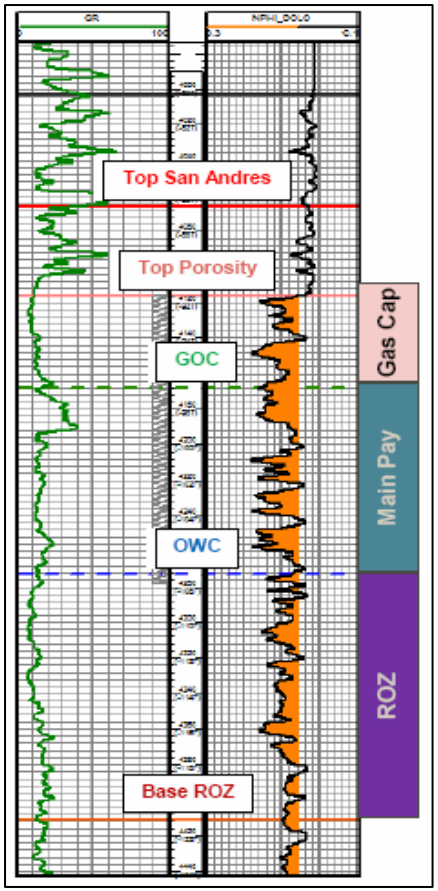
Secondary Recovery

Tertiary Oil Recovery

Seminole San Andres Unit /with Pattern Grid Overlay

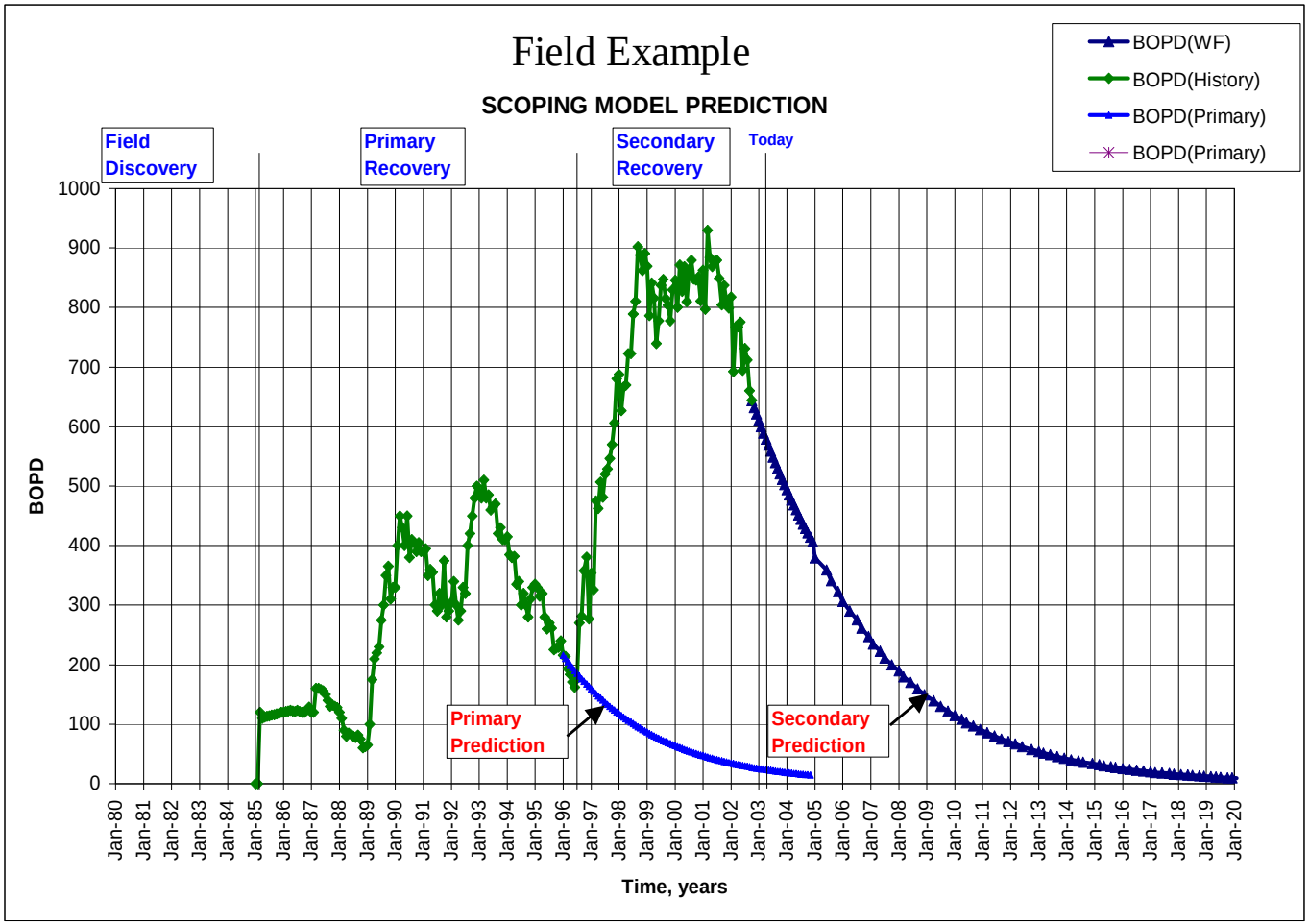


Well Log



Primary and Secondary Oil Recovery

Historical Unit Oil Production Performance

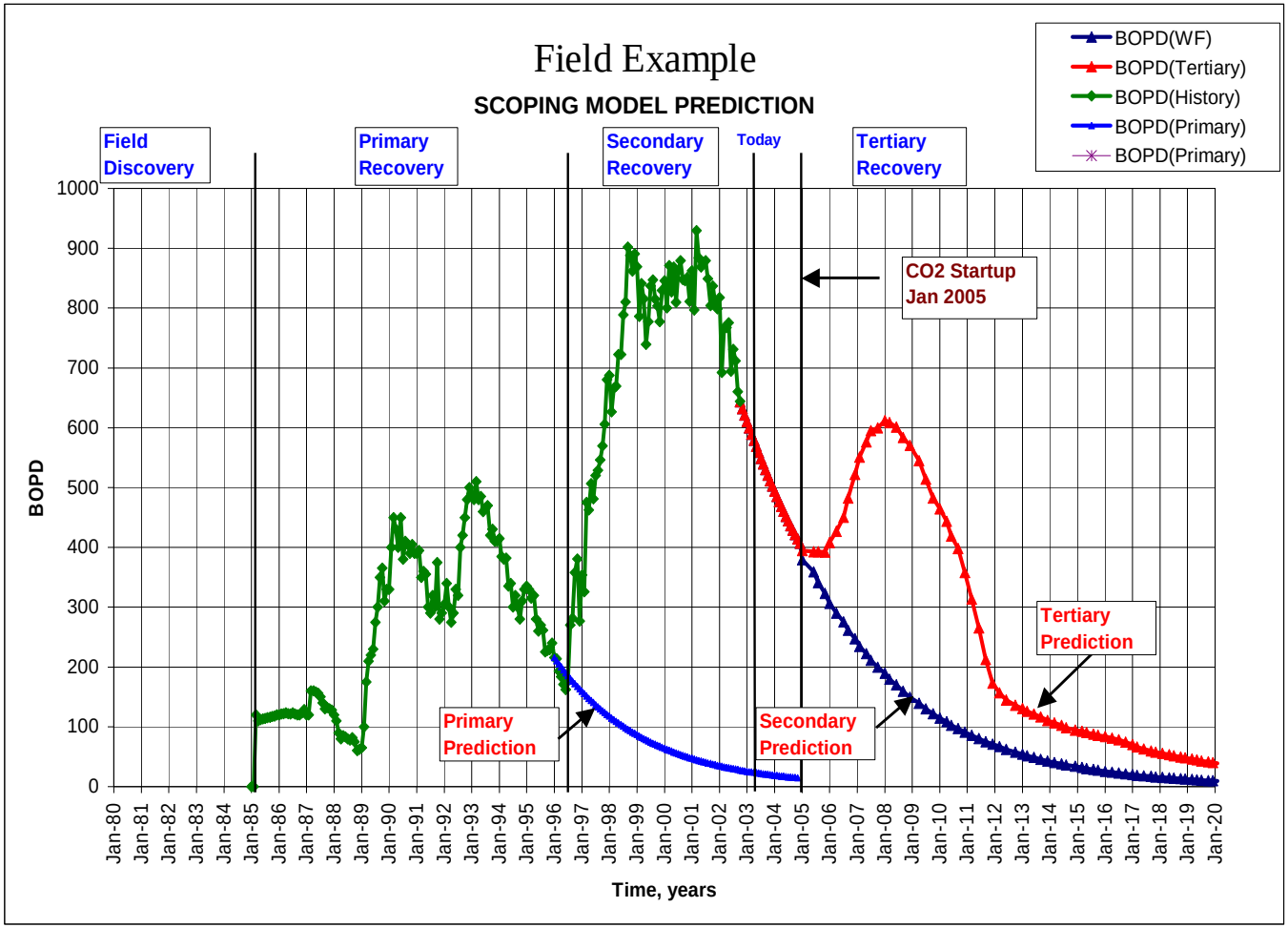


(World Perception - Two Stages of Oil Recovery)

Primary, Secondary, and Tertiary Oil Recovery

CO_2 Tertiary Flooding

Primary, Secondary, and Tertiary Prediction

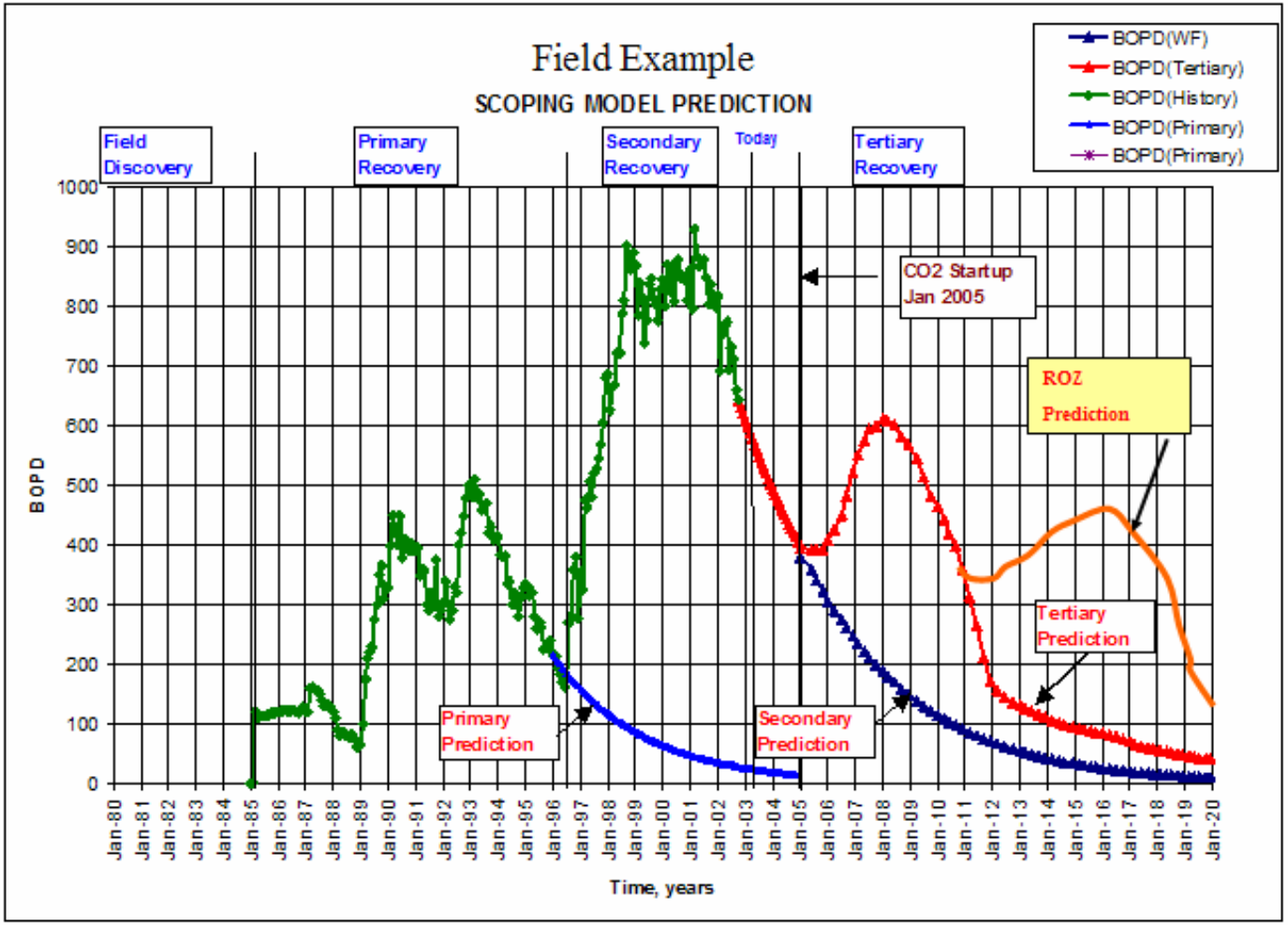


(Three Stages of Oil Recovery)

Primary, Secondary, and Tertiary Oil Recovery (Main Pay + ROZ)

Primary, Secondary, and Tertiary Prediction

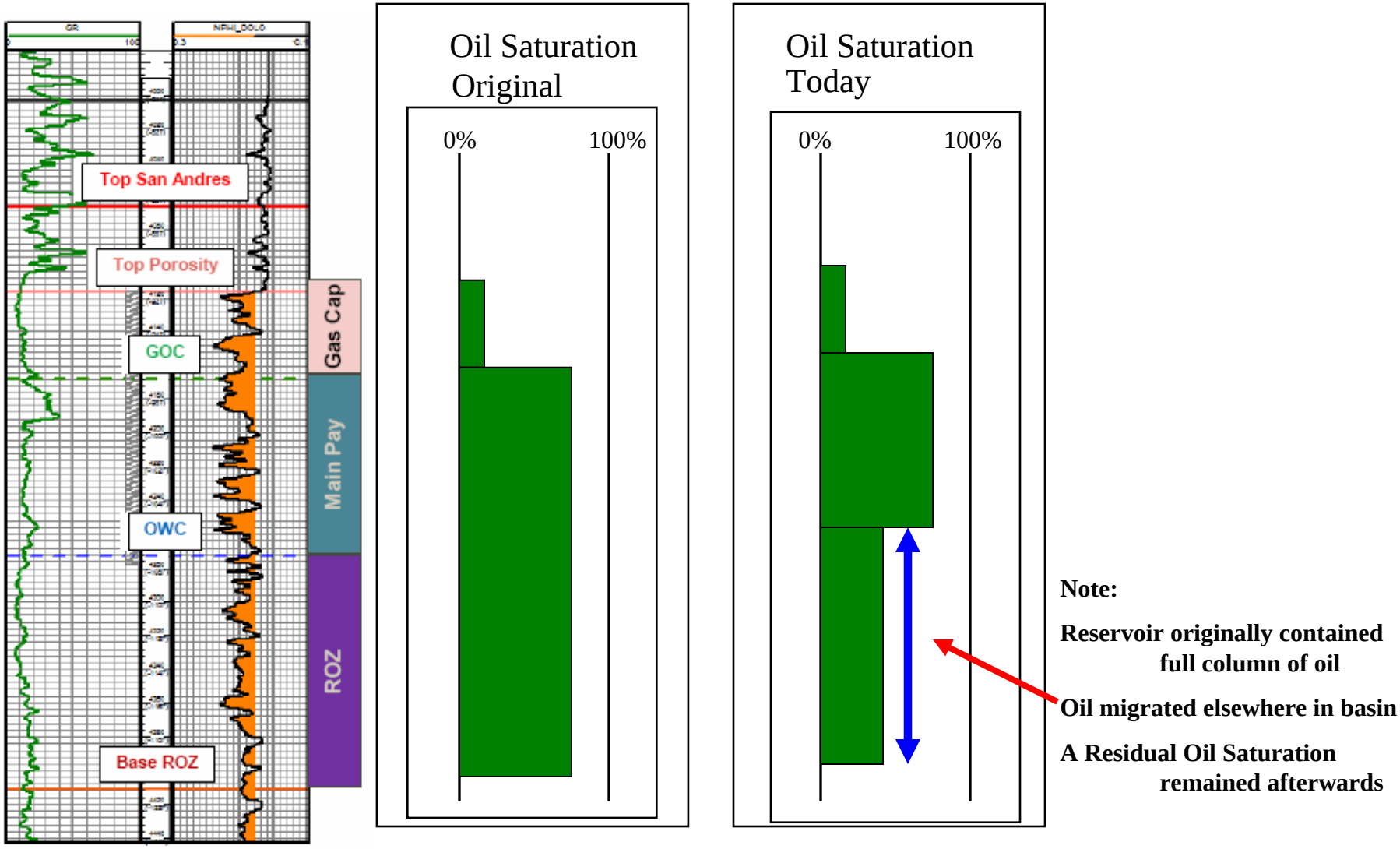
ROZ CO_2 Flooding



(Four Stages of Oil Recovery - ROZ)

Permian Basin (Residual Oil Zone - ROZ)

ROZ - Oil Saturation Profile



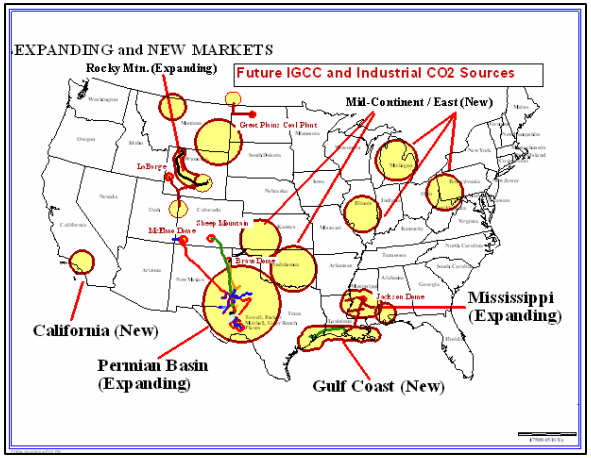
Note: ROZ Pay Zones do not exist in all Basins

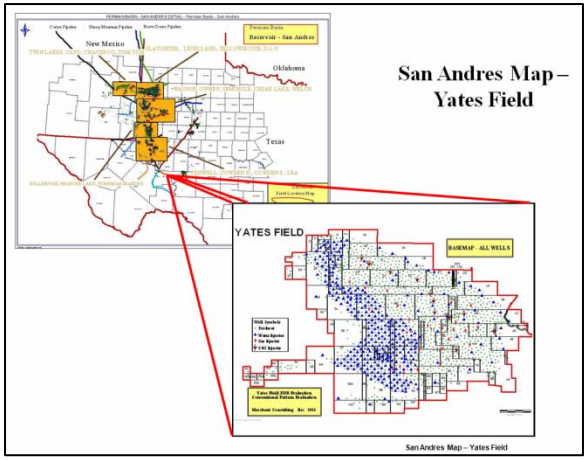
CO_2 Flooding Techniques

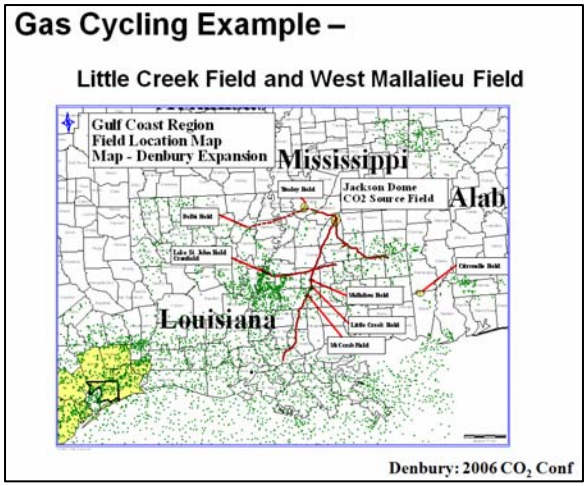
Tertiary CO_2 Flooding

<u>Eight</u> CO_2 Recovery Methods used for Tertiary Oil Recovery in the United States

1. Conventional WAG Recovery (90%+)
2. Residual Oil Zone (ROZ) (Seminole)
3. Gravity Drainage (Yates Field)
4. Double Displacement (Yates Field)
5. Gas Cycling (Denbury, Mississippi).
6. Huff-and-Puff (100+ Projects)
7. Heavy Oil - Calif. (14+ API Gravity)
8. Shale Oil (Bakken) (Under Investigation)







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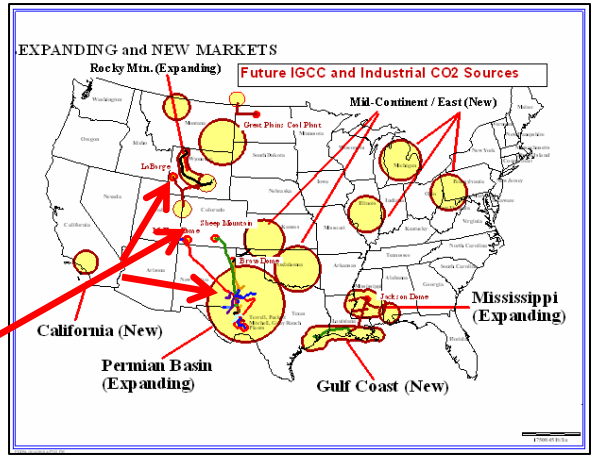
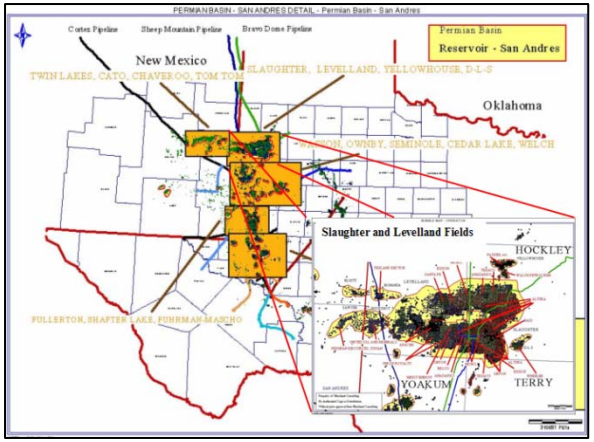
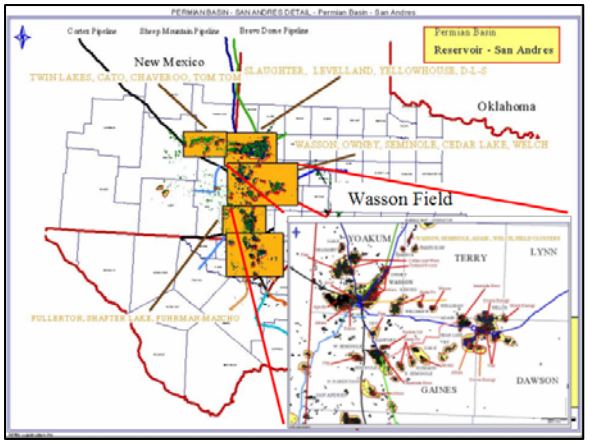
SPE Paper 139516 – "Life Beyond 80 – A look at Conventional WAG Recovery beyond 80% HCPV Injection in CO_2 Tertiary Floods"

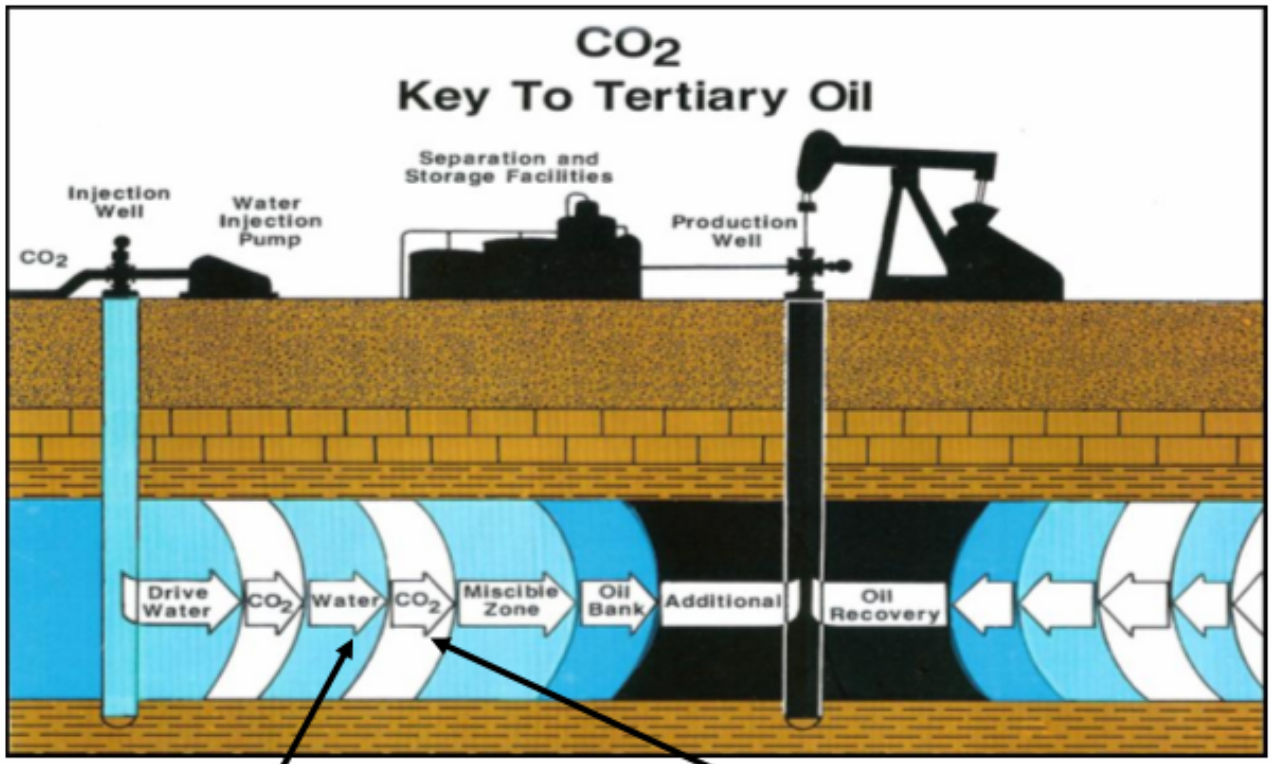






What is Conventional WAG Management?

Conventional WAG Injection Techniques



Water (% HCPV Inj.) CO_2 (% HCPV Inj.)

DIFFERENT OPERATORS

DIFFERENT PHILOSOPHIES (Reservoir Driven)

- Continuous CO_2 - Continuously inject CO_2 (No water)
- Constant WAG - example - 1:1 WAG with (1.0 % CO_2 , 1.0% H_20)
  Note: No change in WAG Ratio with time
- Simultaneous WAG – Hourly WAG Changes
- Tapered WAG - Combination of both continuous and WAG
  example - Continuous injection for 20% HCPV
  WAG (1.0 % CO_2 , 0.10 % H_2O) for 5% HCPV
  WAG (1.0 % CO_2 , 0.50 % H_2O) for 10% HCPV
  WAG (1.0 % CO_2 , 1.00 % H_2O) for 20% HCPV
  WAG (1.0 % CO_2 , 2.00 % H_2O) for 30% HCPV
  Chase Water Injection

"Wetting the WAG"

Note: Total Slug Size = 85% HCPV Inj. Of CO_2

Tertiary CO_2 Flooding

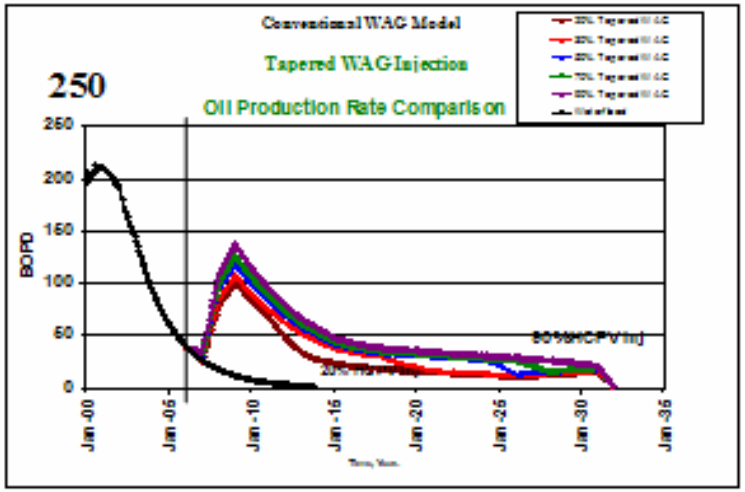
"The Previous Millennium"

20th Century

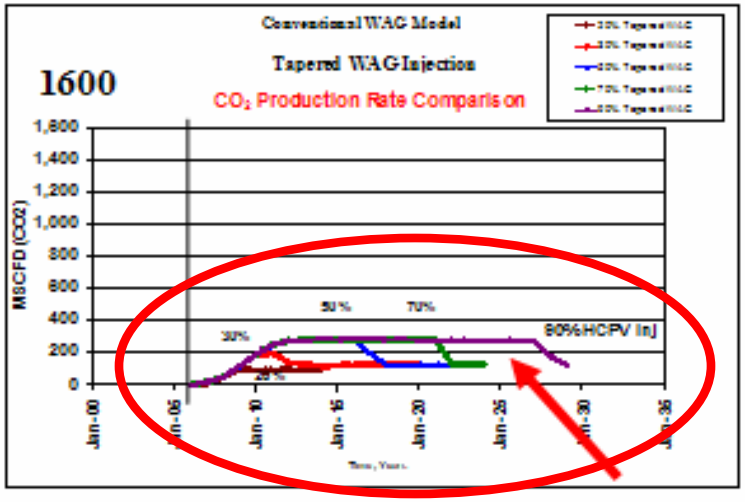
"Life to 80% HCPV Injected"

Tapered WAG Injection

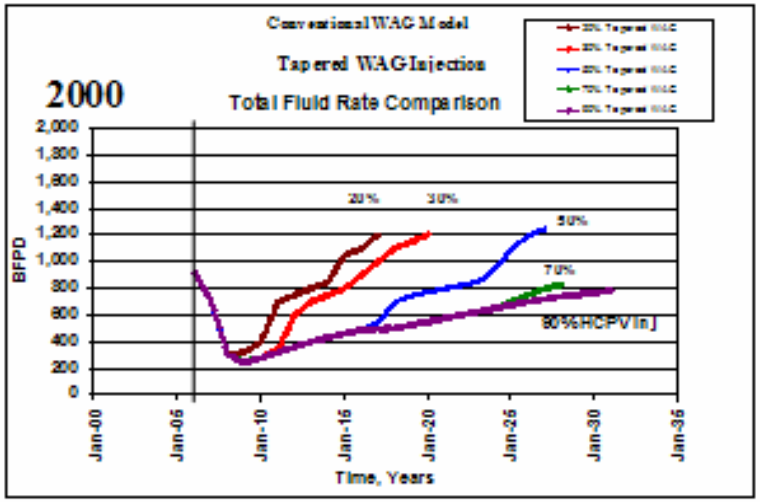
1980's



BOPD (20,30,50,70,90 - %HCPV (Inj)



LEVEL LOAD



BFPD (Total) (20,30,50,70,90 - %HCPV (Inj)

Tapered WAG Ratio Injection

- Advantages
  1. Controls Mobility (Reduces Gas Processing)
  2. Improves Operations (less gas cycling)
  3. Extends flood life beyond 50% HCPV Inj.
  4. Can control the flood to Plant and Pipeline Capacities
  5. Can accelerate or retard Flood Response
- Disadvantages
  1. None to date

CO_2 Flooding in the United States
40 Years of CO_2 Flood History

1980's – 1990's

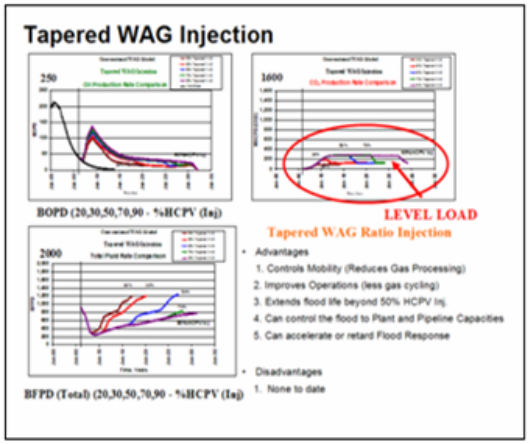
SPE 18977 (1989), Table 1

Field	State	Reservoir	Lithology	%HCPV Injected	Rec Eff, % OOIP	Gross Utilization, Mcf/Bbl	Net Utilization, Mcf/Bbl
Field Scale							
Dollarhide	Texas	Devonian	Trip Chert	30	14		2.4
East Vacuum	Texas	San Andres	Oolitic Dolomite	30	8	11.1	6.3
Ford Geraldine	Texas	Delaware	Sandstone	30	17	9	5
Means	Texas	San Andres	Dolomite	55	7.1	15.2	11
North Cross	Texas	Devonian	Trip Chert	40	22	18	7.8
Northeast Purdy	Oklahoma	Springer	Sandstone	30	7.5	6.5	4.6
Rangely	Colorado	Weber	Sandstone	30	7.5	9.2	5
Sacroc (17 Pattern)	Texas	Canyon Reef	Carbonate	30	7.5	9.7	6.5
Sacroc (4 Pattern)	Texas	Canyon Reef	Carbonate	30	9.8	9.5	3.2
South Welch	Texas	San Andres	Dolomite	25	7.6		
Two Freds	Texas	Delaware	Sandstone	40	15.6	15.6	8
Wertz	Wyoming	Tensleep	Sandstone	60	10	13	10

SPE 18977 Brock and Bryon 1989

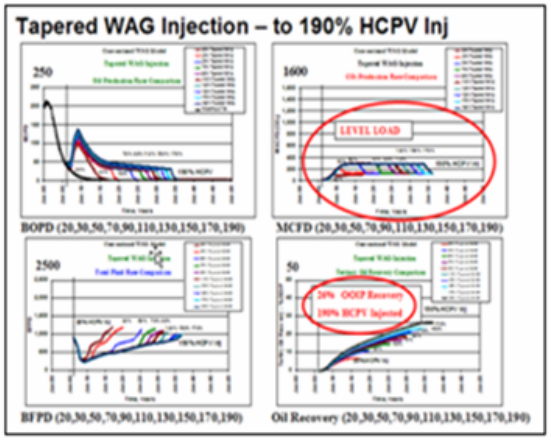
7% to 12% OOIP Rec
30% to 40% HCPV Inj

2000's



18% OOIP Rec
80% HCPV Inj

2010's



20% to 26% OOIP Rec
140% to 190% HCPV Inj

Note: Not all fields will achieve this

Tertiary CO_2 Flooding

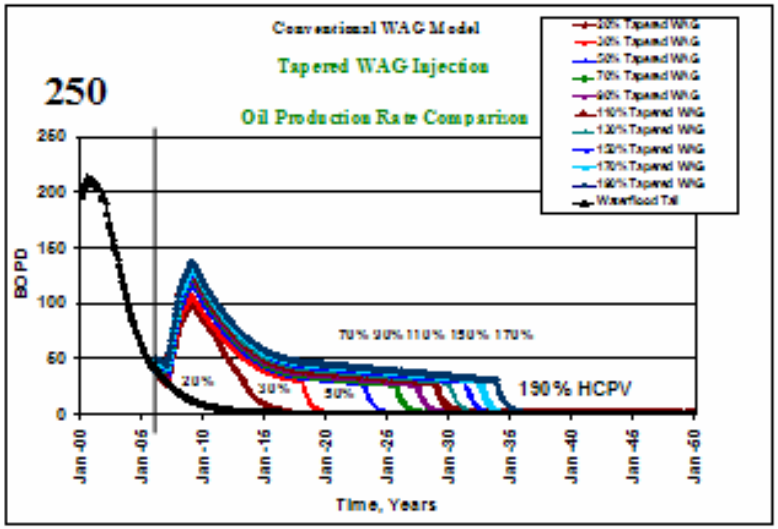
"The New Millennium"

21st Century

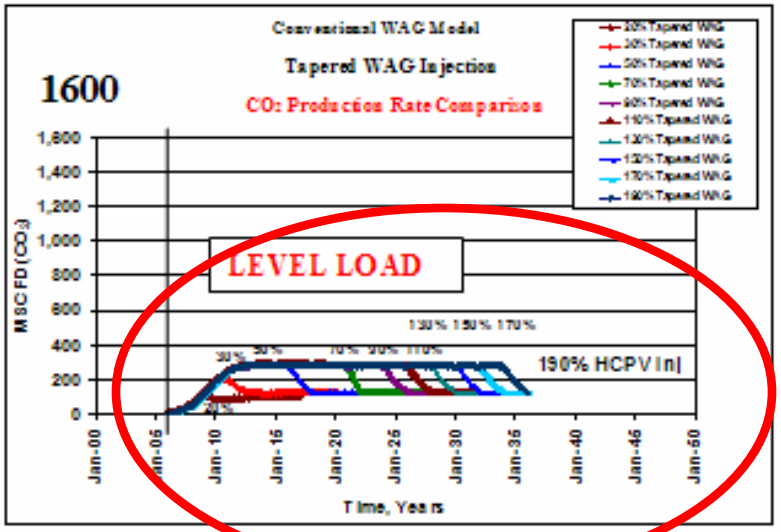
"Life beyond 80% HCPV Injected"

Tapered WAG Injection – to 190% HCPV Inj

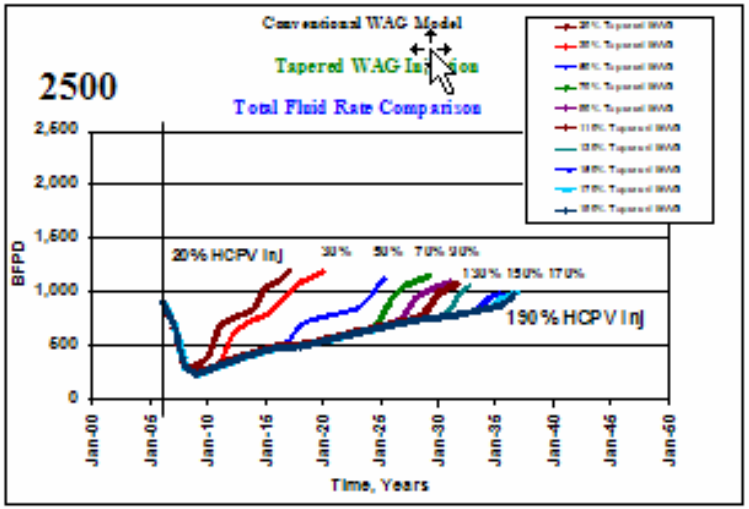
2010's



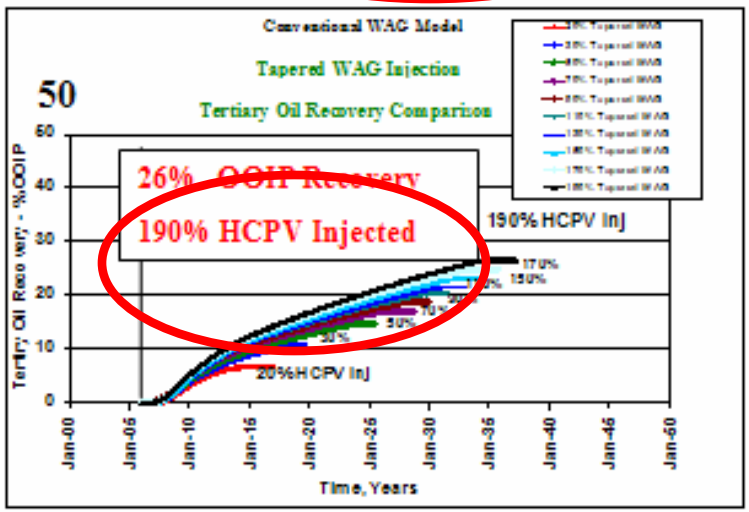
BOPD (20,30,50,70,90,110,130,150,170,190)



MCFD (20,30,50,70,90,110,130,150,170,190)



BFPD (20,30,50,70,90,110,130,150,170,190)

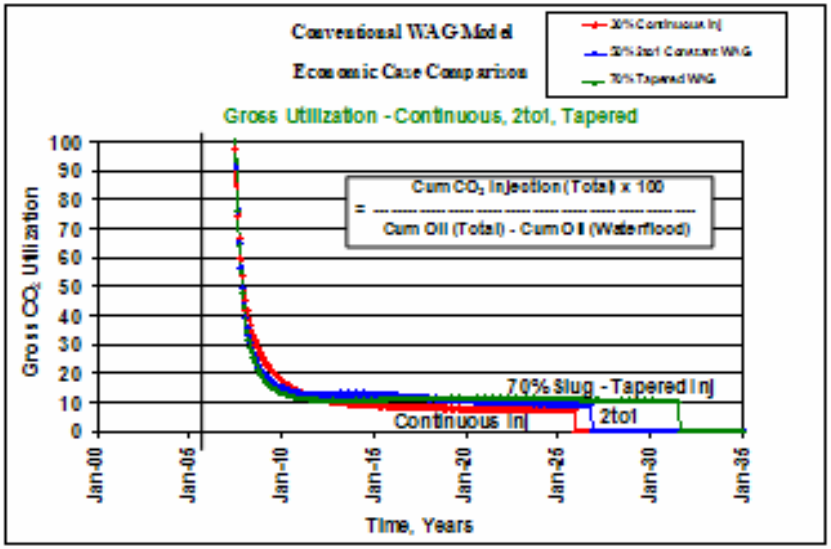


Oil Recovery (20,30,50,70,90,110,130,150,170,190)

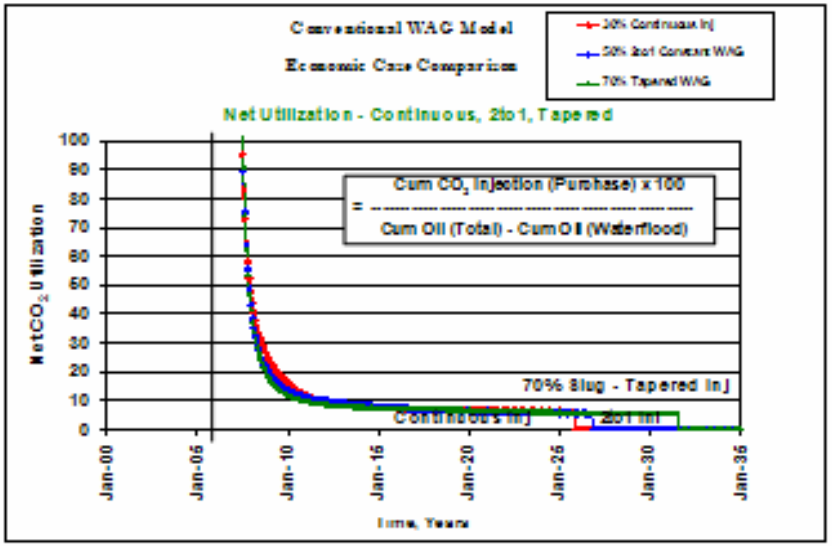
SPE Paper 139516 – "Life Beyond 80 – A look at Conventional WAG Recovery beyond 80% HCPV Injection in CO_2 Tertiary Floods"

Economic Case Comparisons – Continuous 30, Constant WAG 50, Tapered 70)

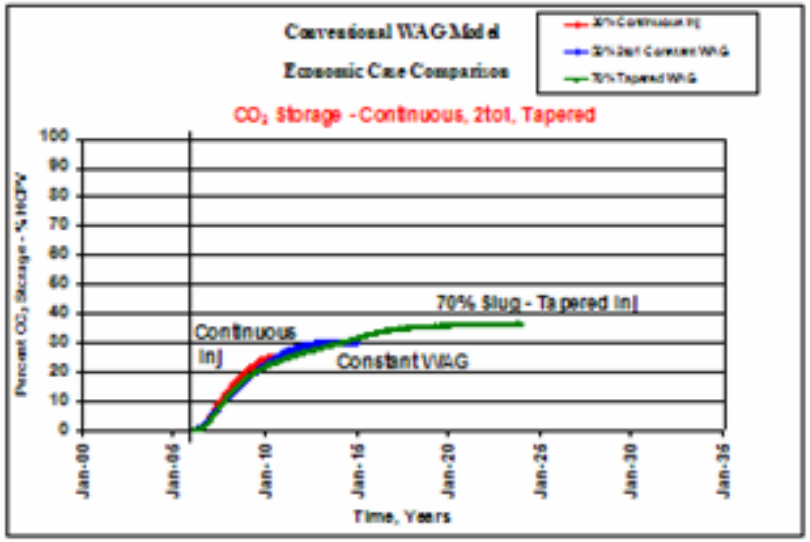
Gross – CO_2 Utilization



Net – CO_2 Utilization



CO_2 Storage - % HCPV



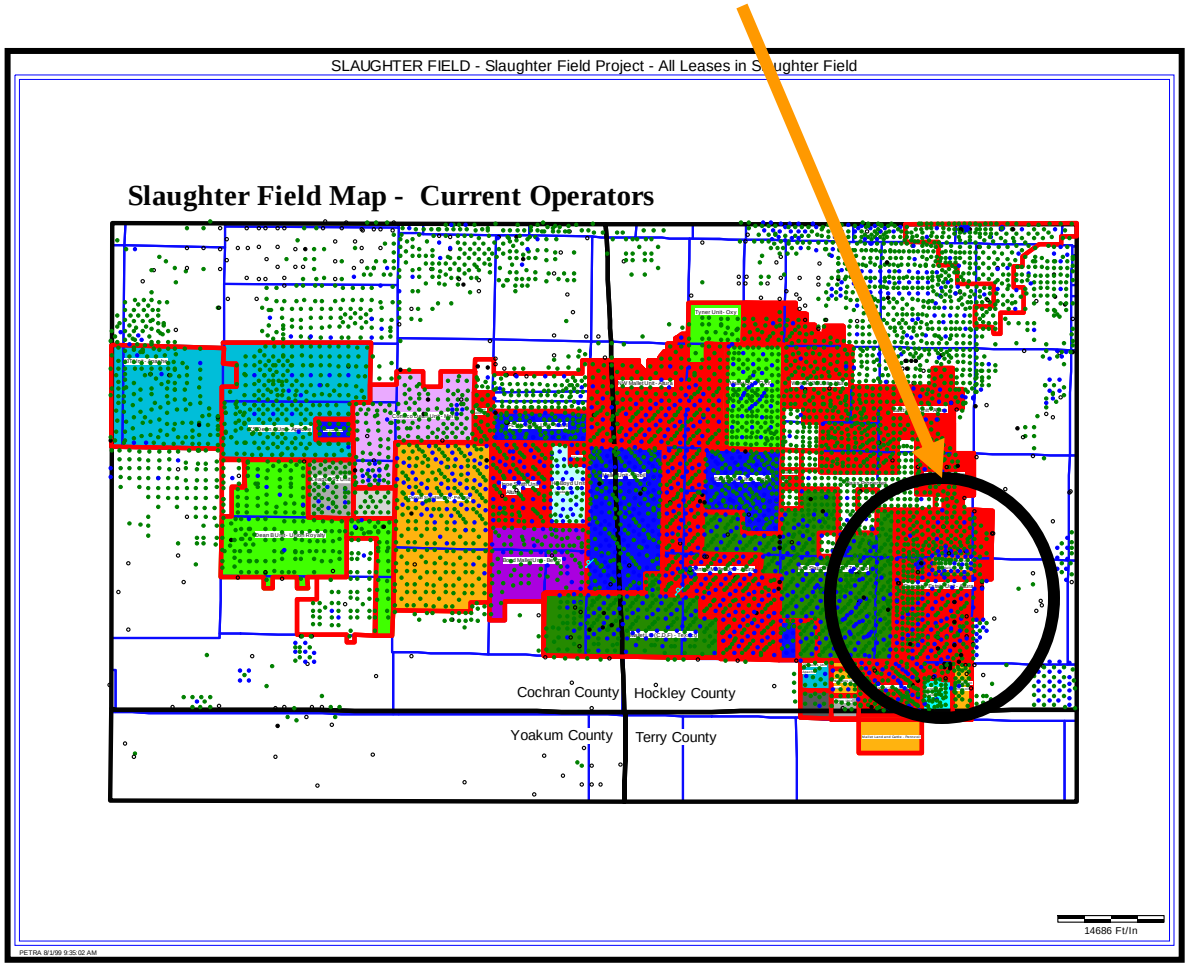
CO_2 Utilization and CO_2 Retention

CO_2 Gross Utilization is a measure of the **Efficiency** of the CO_2 Process (Amount of Total CO_2 Injected per Bbl Tertiary Recovered)

CO_2 Net Utilization is a measure of the **Efficiency** of the CO_2 Process (Amount of Purchased CO_2 Injected per Bbl Tertiary Recovered)

Example -WAG BENEFITS
(Control CO_2 Process)

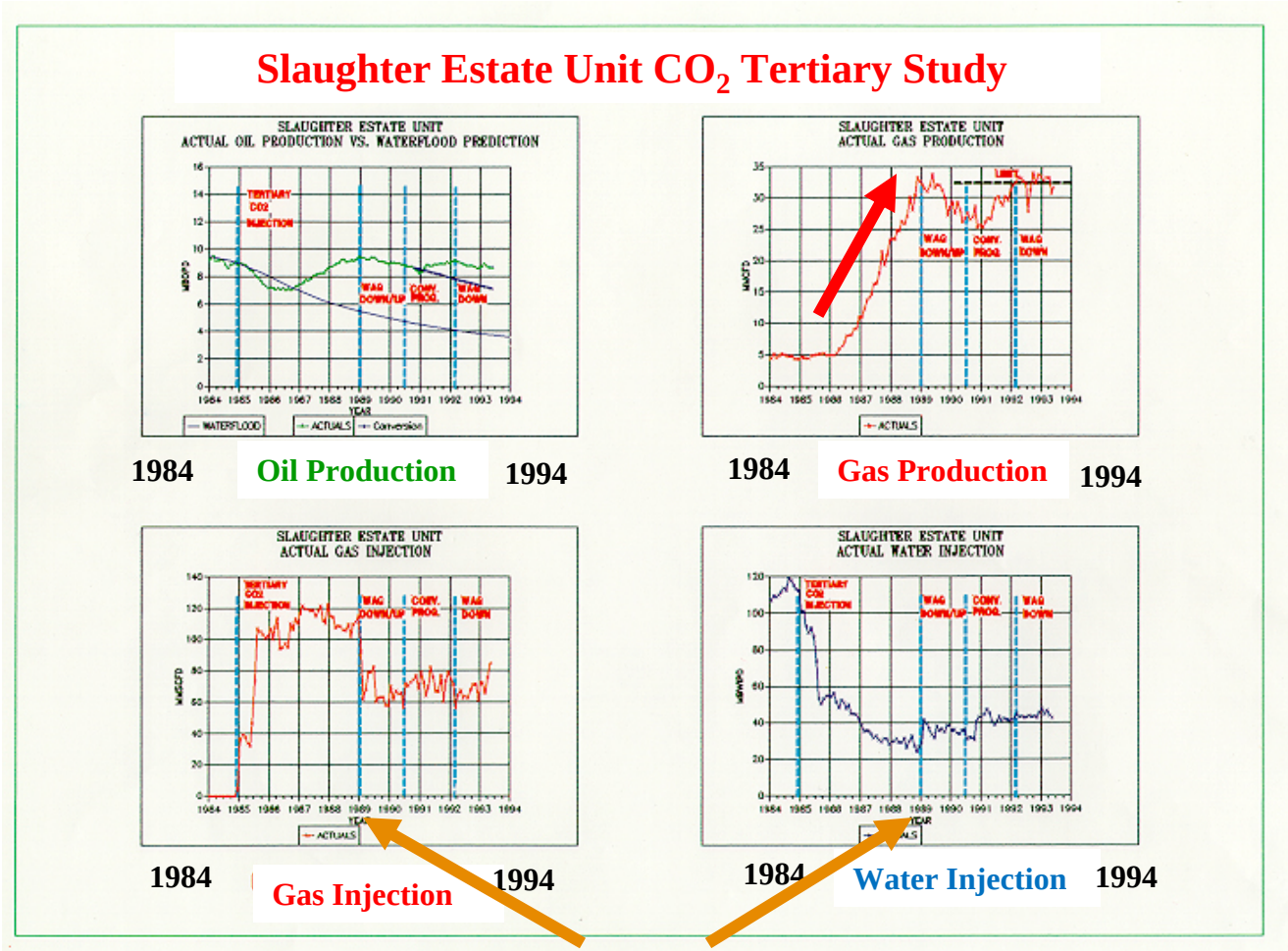
Slaughter Estate Unit in Slaughter Field



SPE Paper 26624 – "Reservoir Management in Tertiary CO_2 Floods"

Example - WAG BENEFITS
(Control CO_2 Process)

Slaughter Estate Unit in Slaughter Field Production and Injection (1984 – 1994)



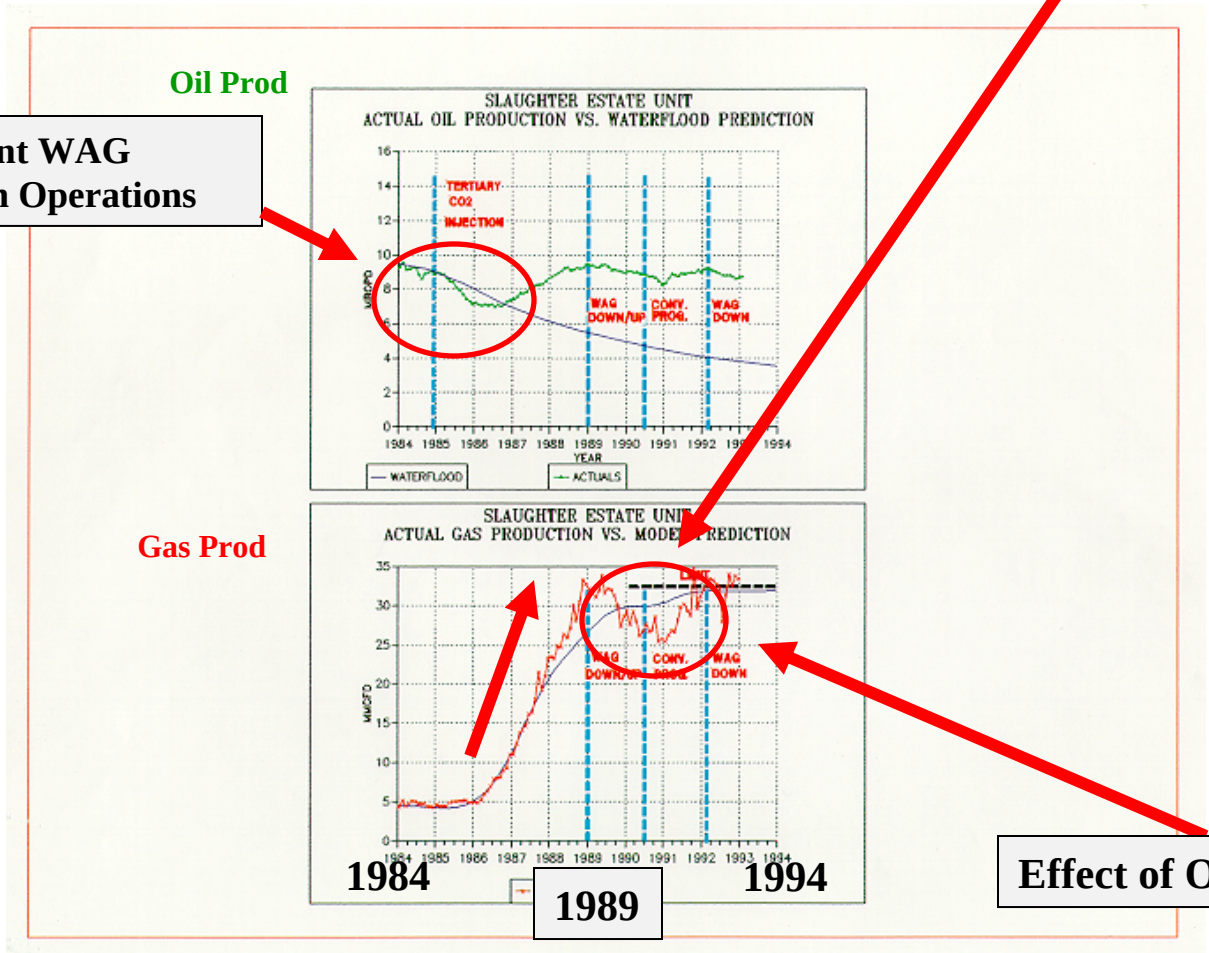
SPE Paper No. 26624

Example - WAG BENEFITS

(Control CO_2 Process)

Level Load Gas Production WAG Change - 1989

Effect of Constant WAG Injection Operations



Effect of Over-WAG Ops.

Tertiary CO_2 Flooding

<u>Eight</u> CO_2 Recovery Methods used for Tertiary Oil Recovery in the United States

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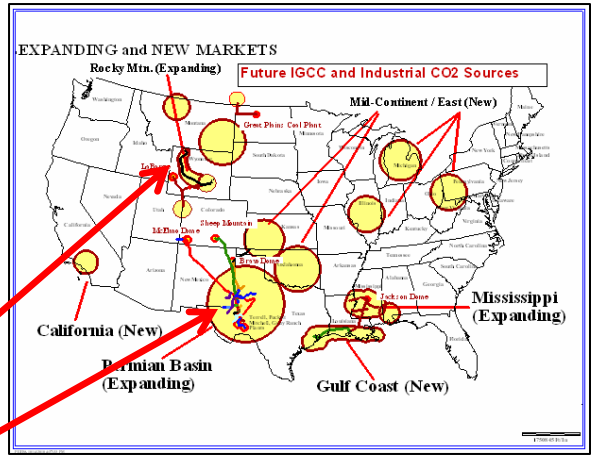
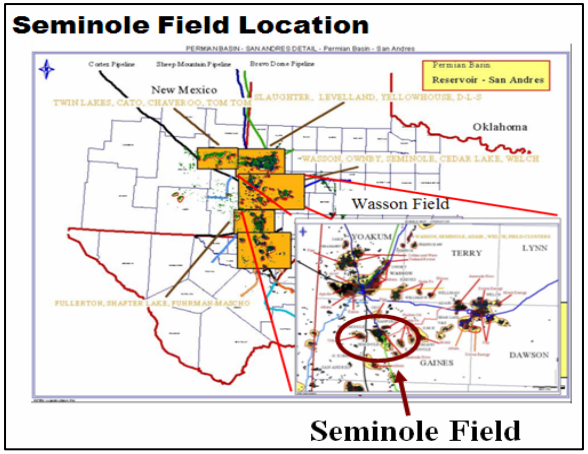
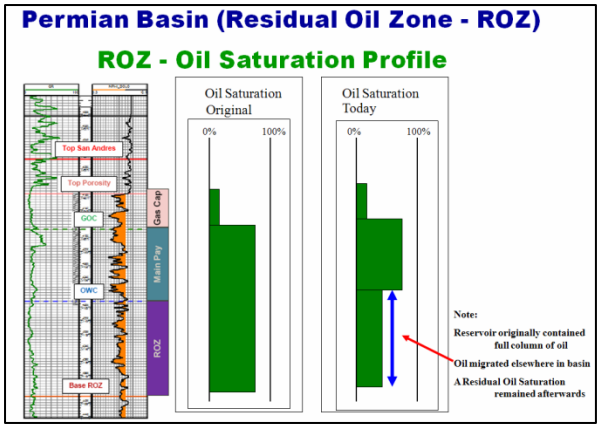


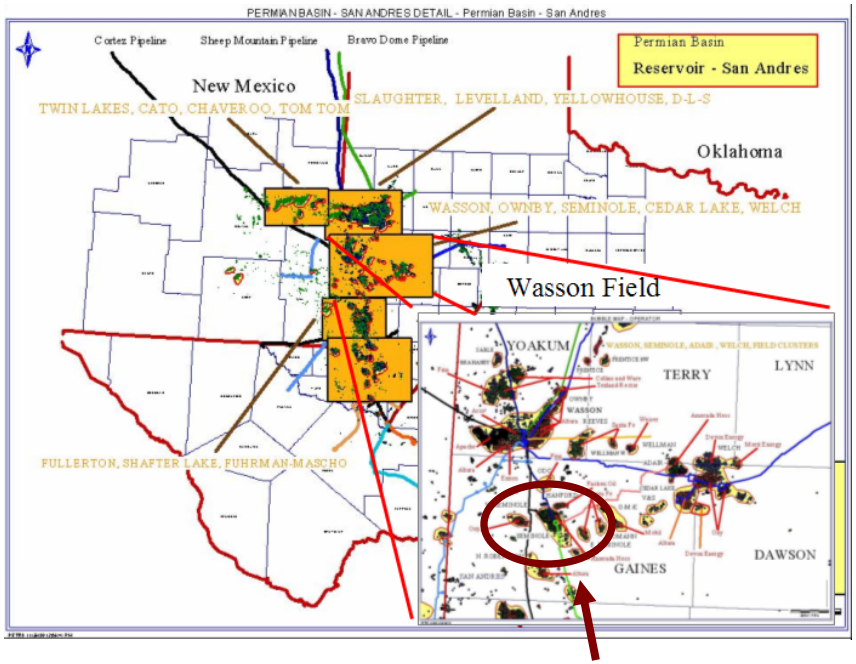




Tertiary CO_2 Flooding

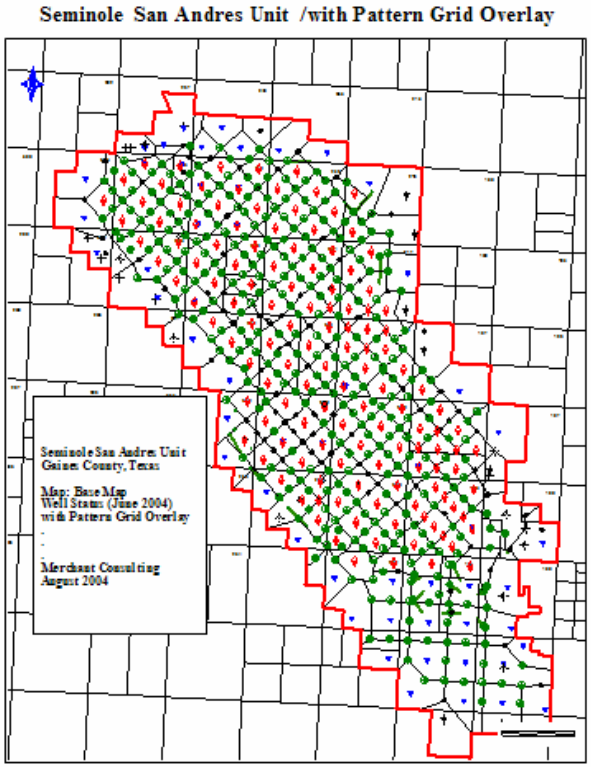
Permian Basin (Seminole Field)

Seminole Field Location



Seminole Field

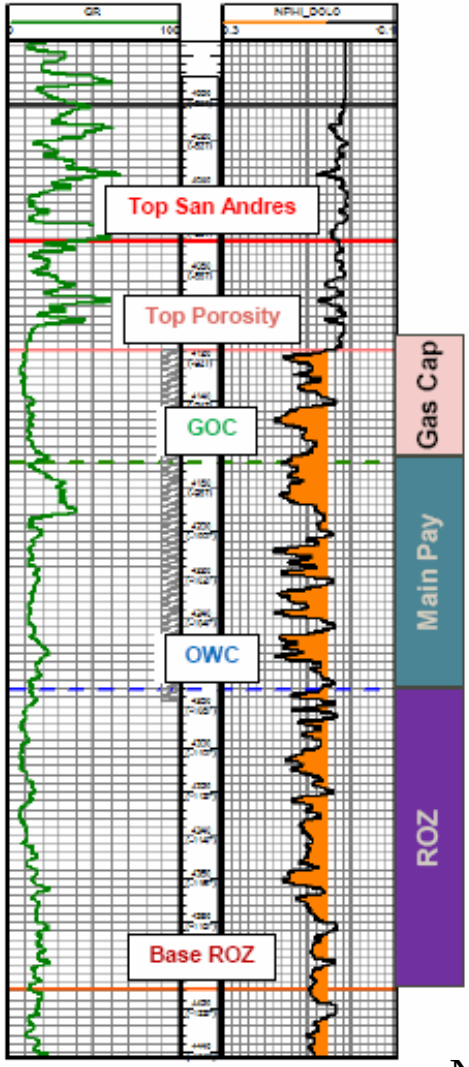
Seminole Field

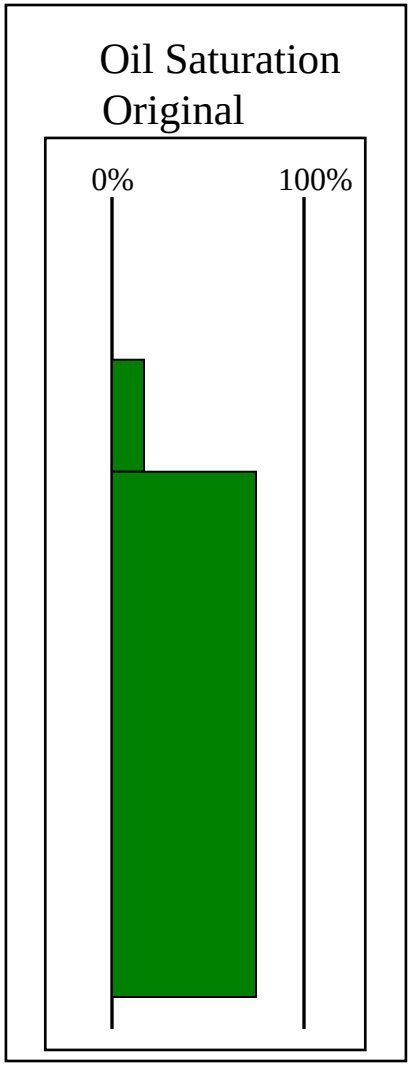


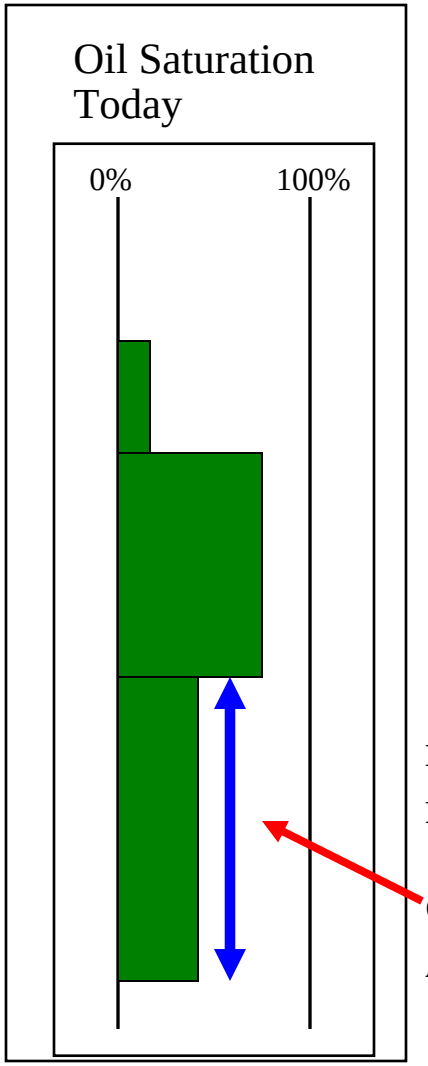
The Seminole field recovers Tertiary Oil from the San Andres Formation about 5,500 ft. deep which also includes a large Residual Oil Zone (ROZ). The Field is developed on 9-spot pattern spacing.

Permian Basin (Residual Oil Zone - ROZ)

ROZ - Oil Saturation Profile







Note:

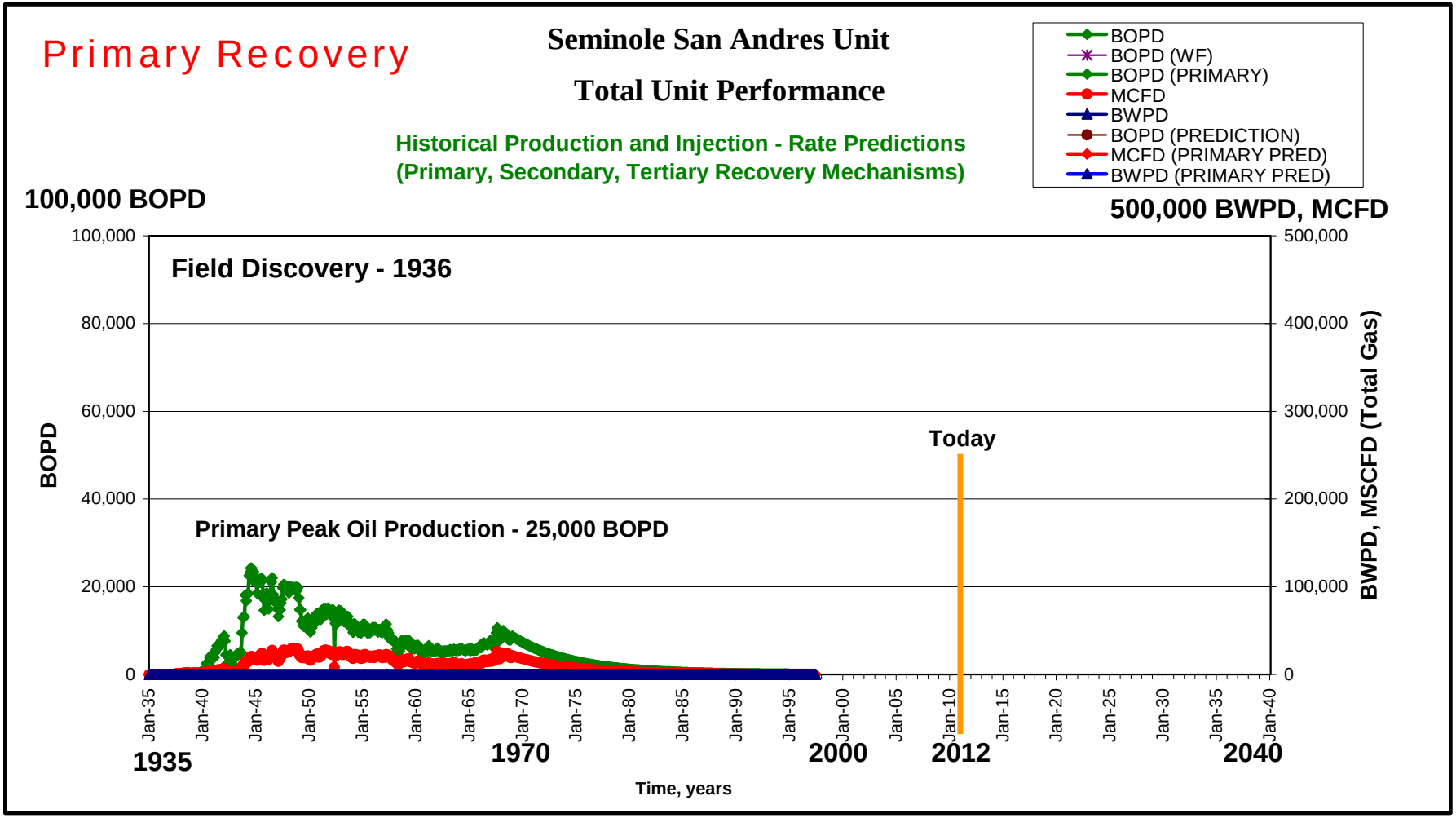
Reservoir originally contained full column of oil

Oil migrated elsewhere in basin

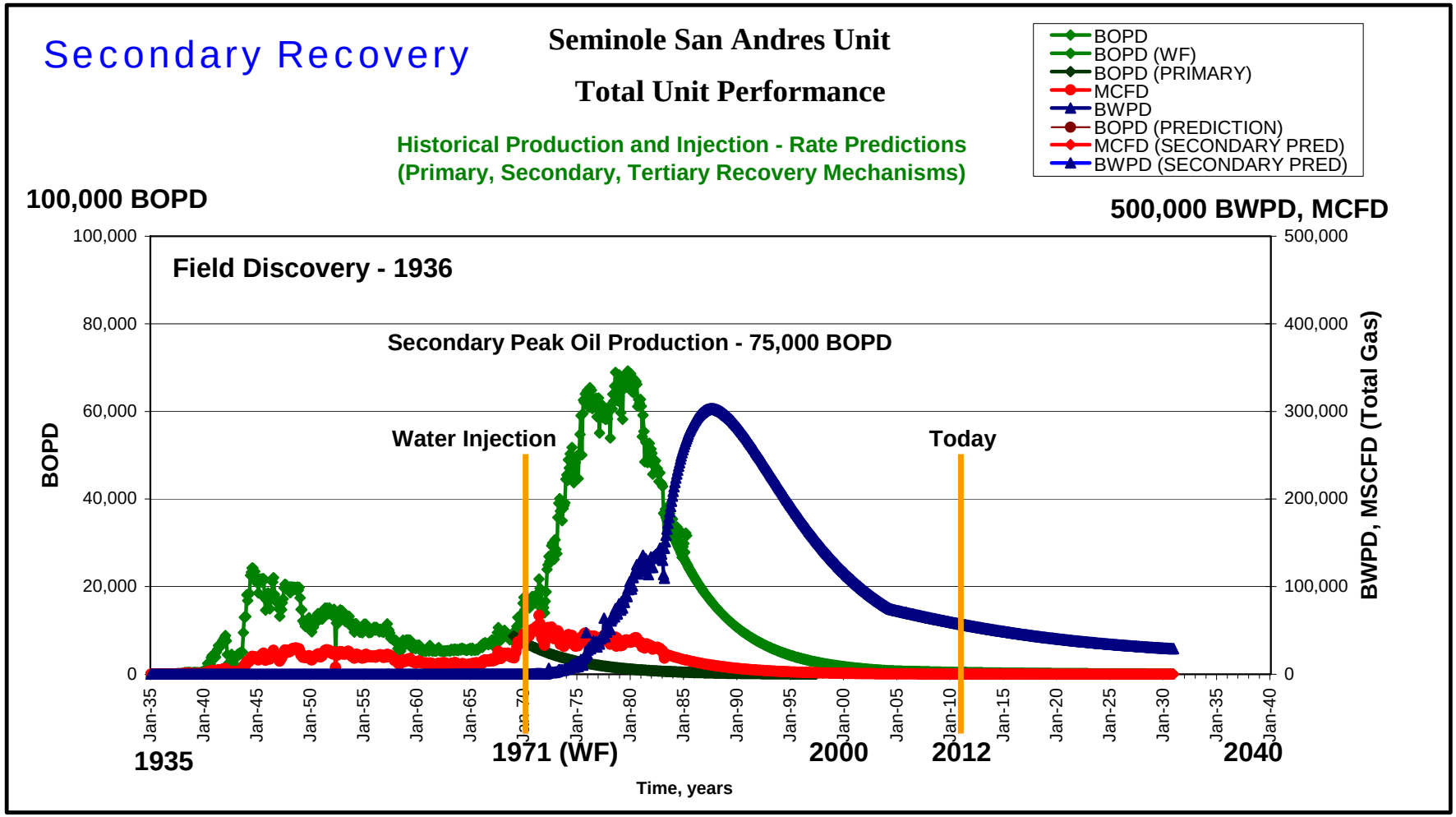
A Residual Oil Saturation remained afterwards

Note: ROZ Pay Zones do not exist in all Basins

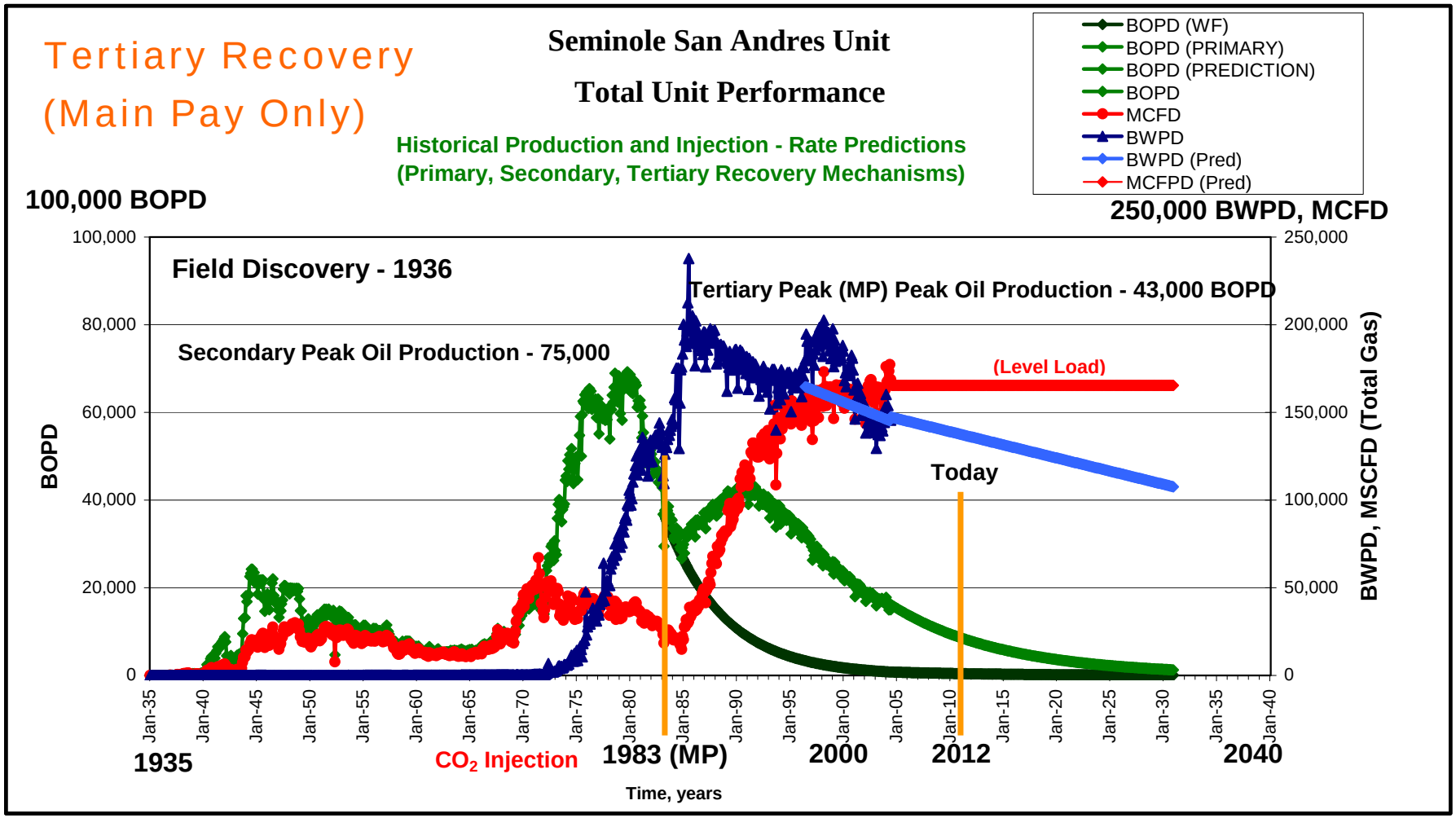
Seminole San Andres Unit



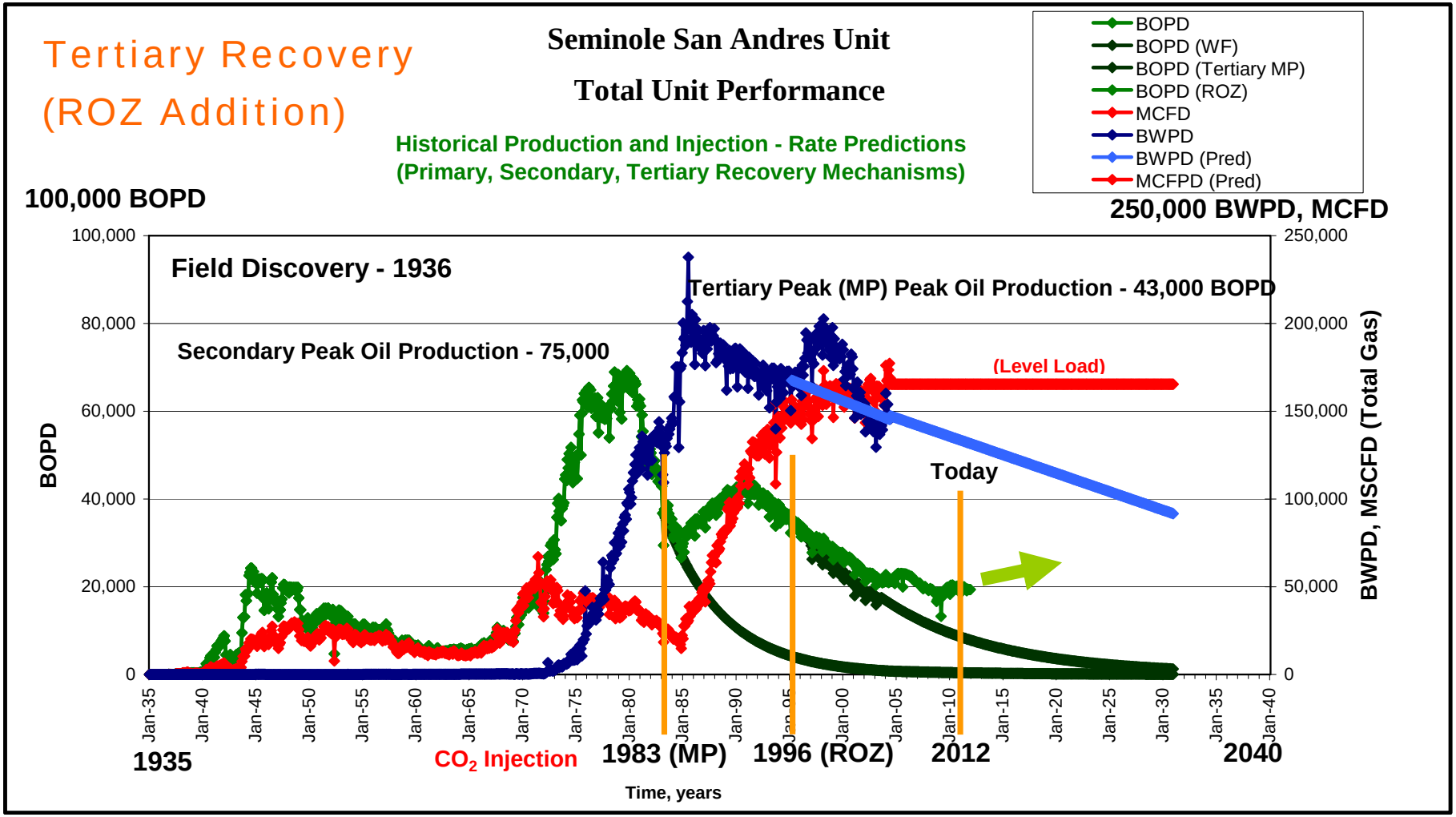
Seminole San Andres Unit



Seminole San Andres Unit



Seminole San Andres Unit



Tertiary CO_2 Flooding

"Size of the Prize - Permian Basin ROZ"

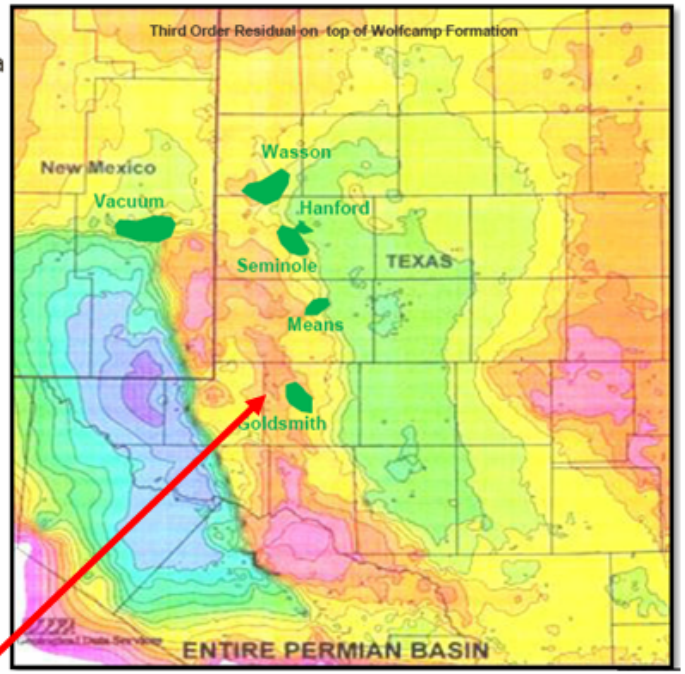
ARI estimates 30 BBOOIP are sitting in ROZ zones in the Permian Basin alone.

- Large opportunity for EOR
- Big impact on West Texas Oil Industry
- Huge Potential Energy Resource for America

Active ROZ Projects

Seminole - Hess
Wasson - Oxy
Hanford - Fasken
Vacuum – Chevron
Means – Exxon
East Seminole – Tabula Rasa
Goldsmith – Legado

Fields with Active ROZ EOR Projects



Ref: ARI ROZ Report

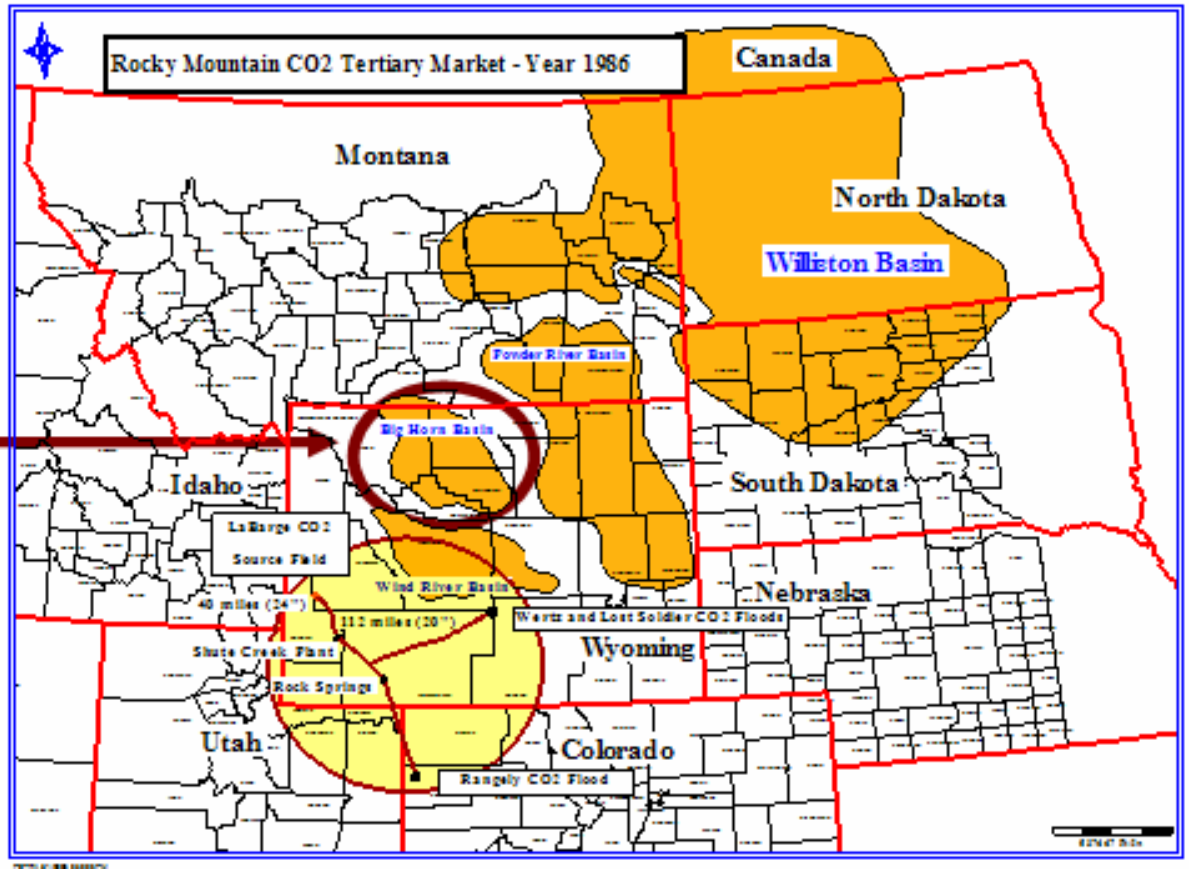
Advanced Resources International (ARI) Estimates – 30 Billion Barrel OOIP Target in ROZ

Tertiary CO_2 Flooding

"Residual Oil Zone Target"

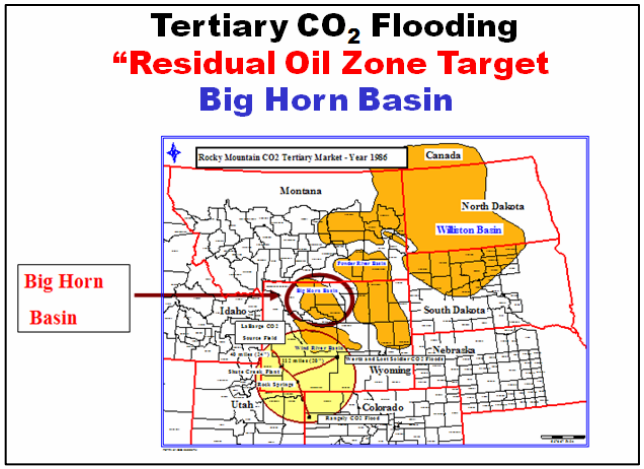
Big Horn Basin

Big Horn Basin



Tertiary CO_2 Flooding

"Wyoming - Big Horn Basin"



1. **Main Pay** — **500 to 800 Million barrels over 40 years**
2. **ROZ** — **800 to 1,200 million barrels over the next 40 years**
3. **Existing Wells** — **Implementation will utilize a majority of the estimated 2,000 existing wells drilled**
4. **Facilities** — **New Facilities will be required for implementation**
5. **Sequestration** — **EORI estimates between 12 and 19 TCF can be sequestered in petroleum reservoirs**

Ref: Enhanced Oil Recovery Institute

Tertiary CO_2 Flooding

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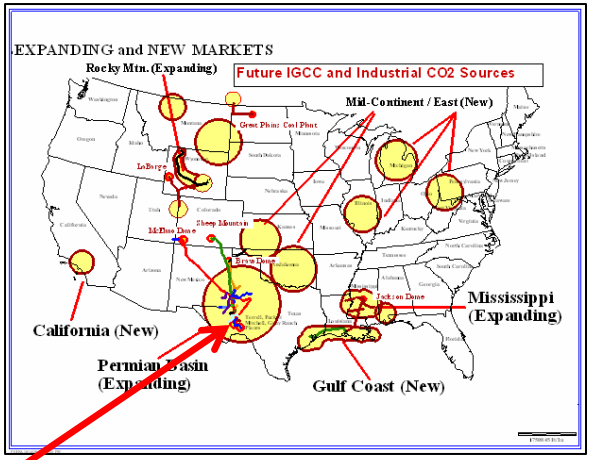
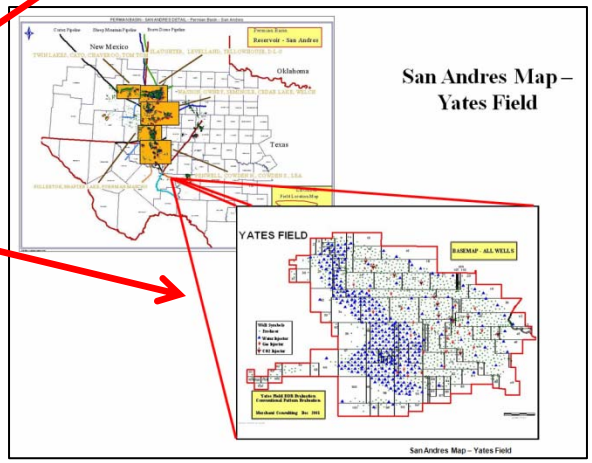
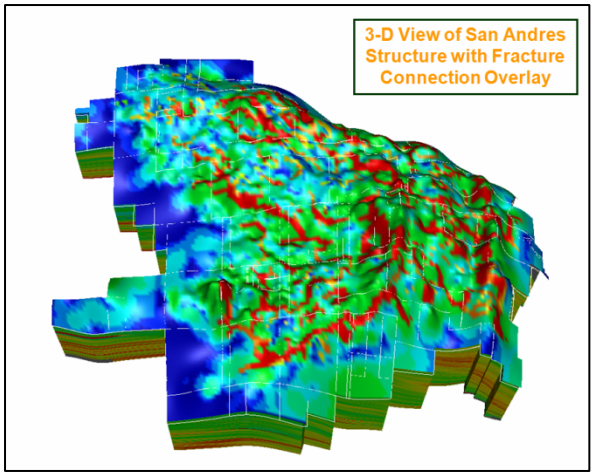






CO_2 Sequestration, Gas Storage and Gravity Drainage Projects

Low Dip Reservoir

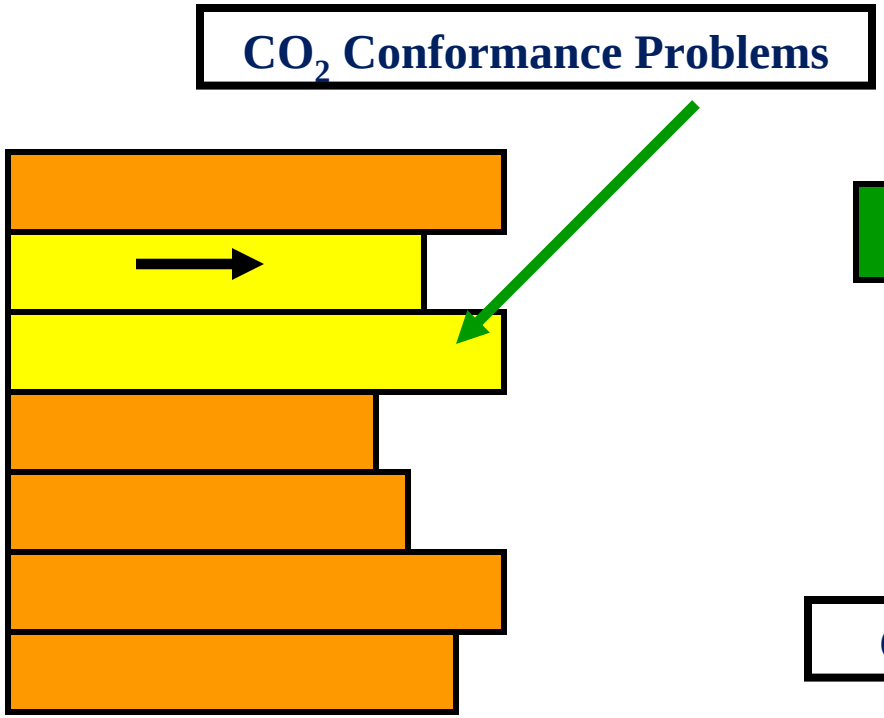
(Conformance can be detrimental)

Gas Cycling is a big problem

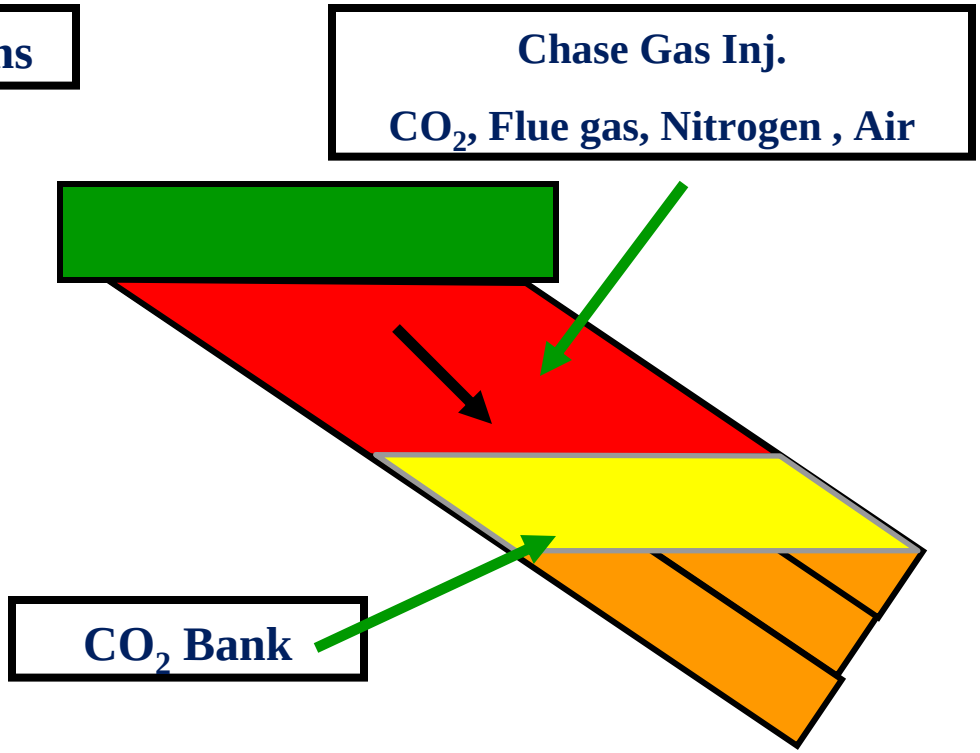
Moderately Low or High Dip Res.

(Can run Miscible or Immiscible)

Conduct a gravity Stabilized CO_2 flood with chase gas

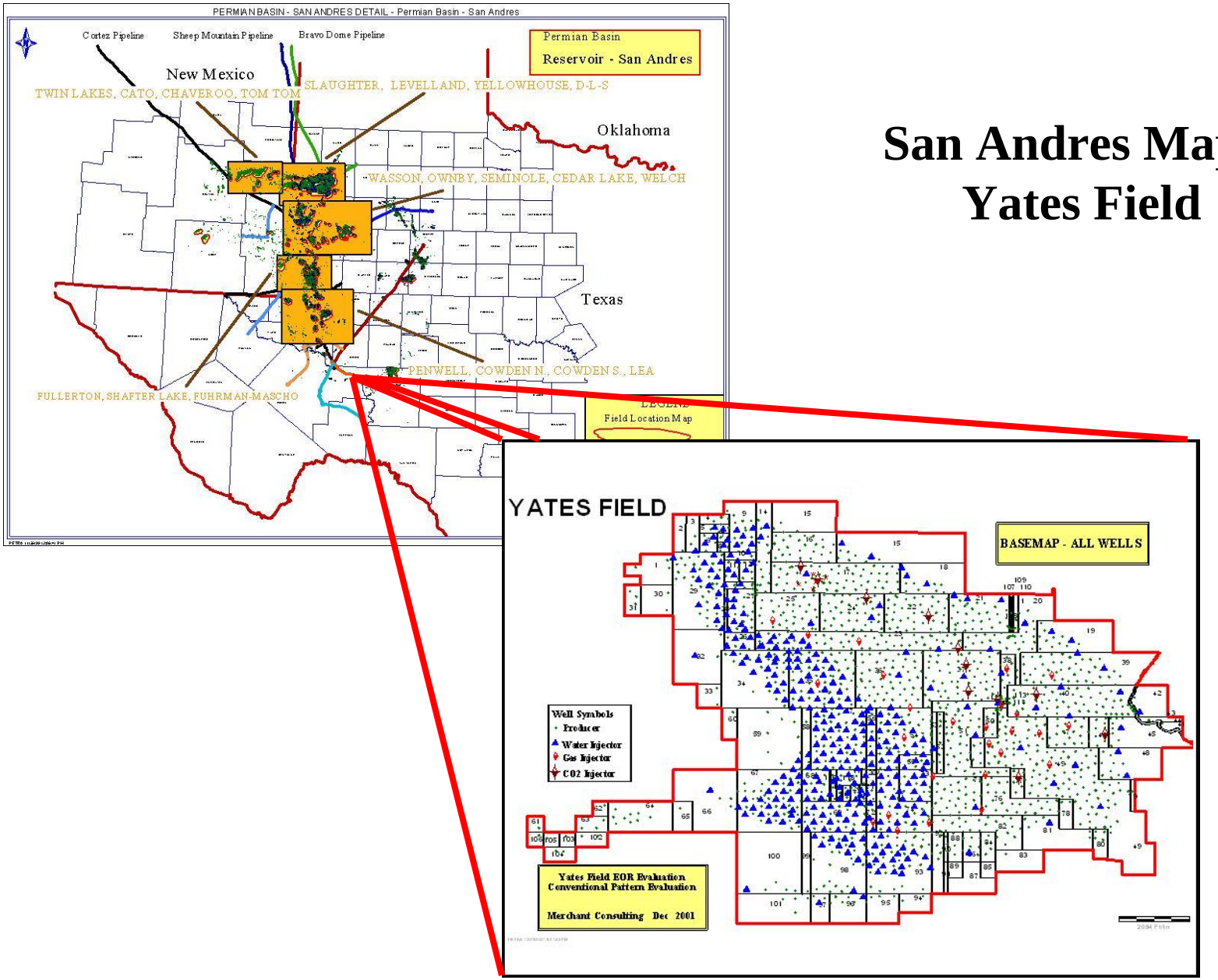


Displacement Process



Replacement Process

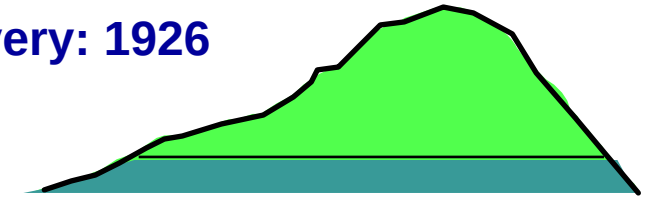
San Andres Map – Yates Field



San Andres Map – Yates Field

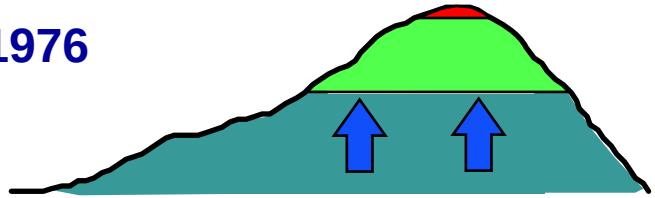
Yates Reservoir History

Discovery: 1926



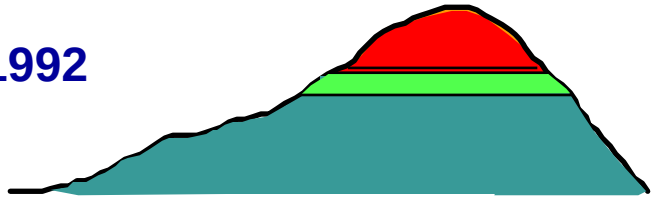
Discovered in 1926
550' of Oil Column at Structure Top

1926 - 1976



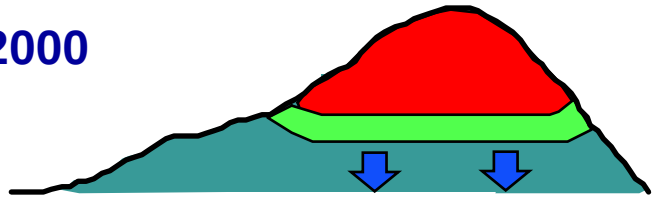
Produced By Individual Operators
Unitized in 1976 to Prevent Aquifer Influx

1976 - 1992



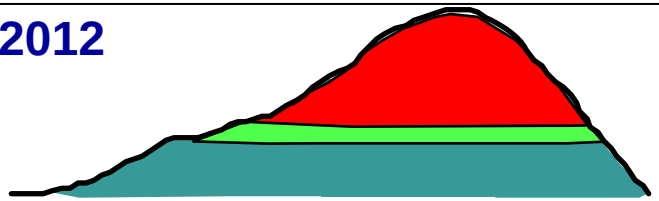
Gas Re-injected,Water Re-injected
Oil Column Thinned

1992 - 2000



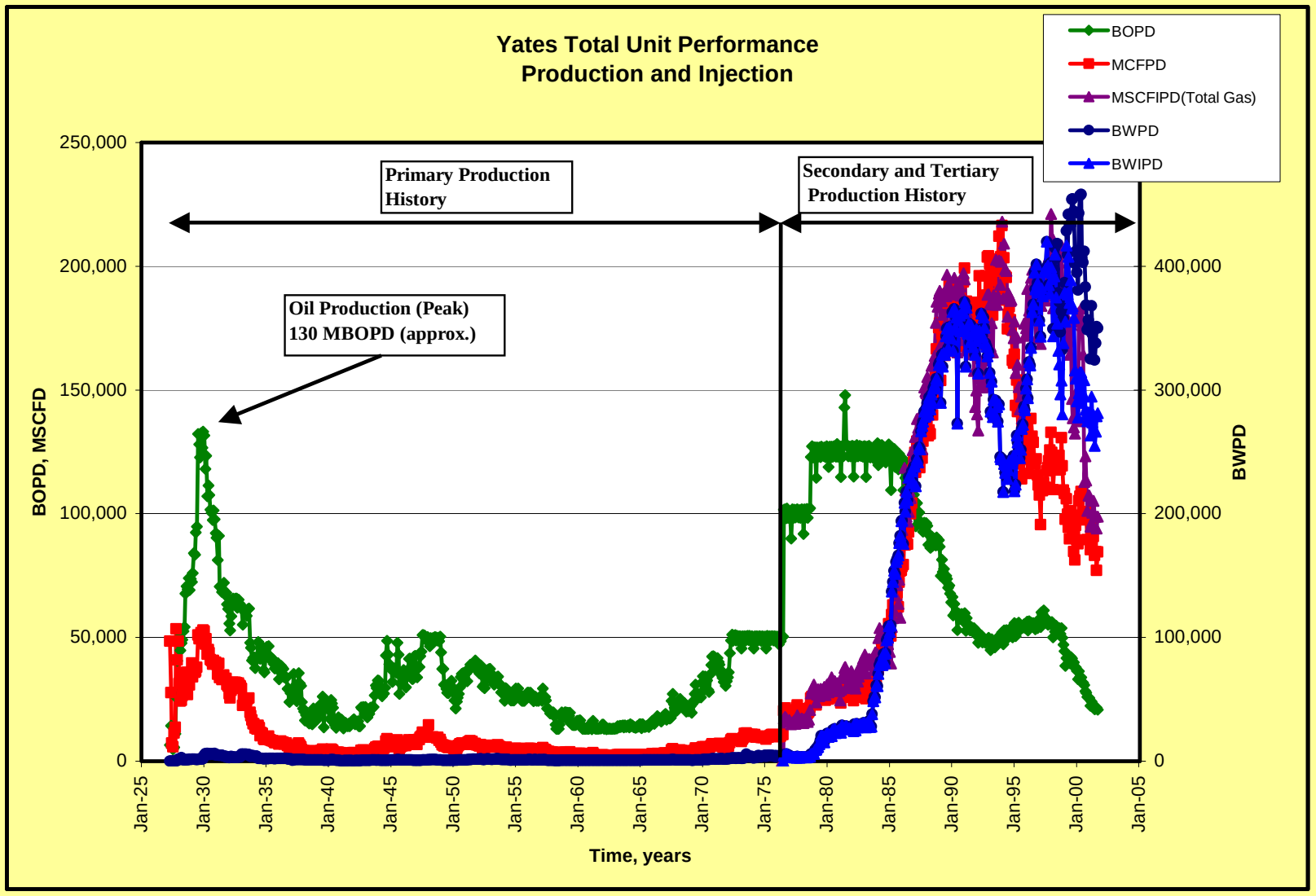
Double Displacement
Reservoir Dewatering
Contact Lowering

2000 - 2012



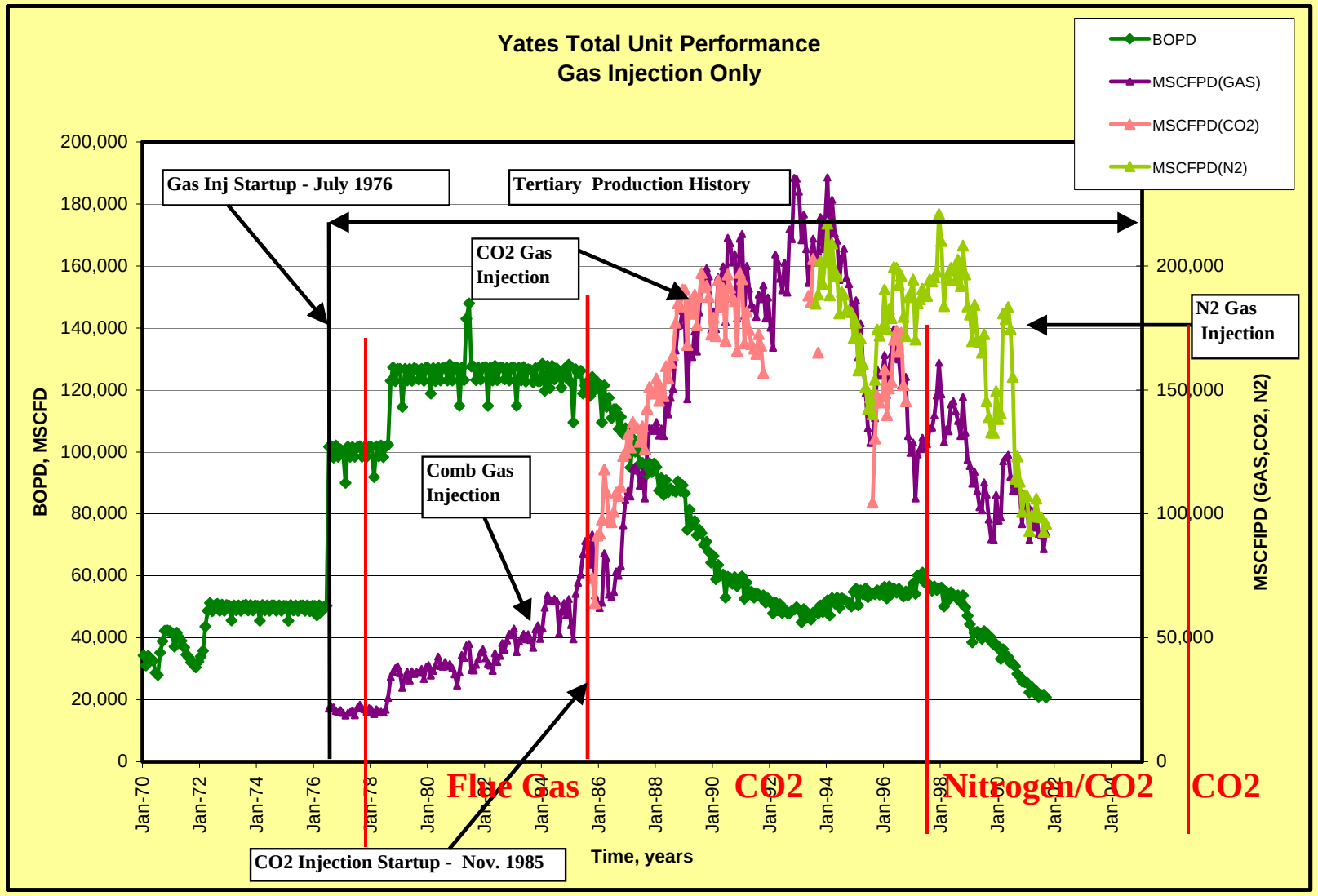
Contact Stabilization (30 ft oil column)
Gas Cap Injection
Aquifer "Maintenance" By Offsite Disposal

Yates Unit Historical Performance



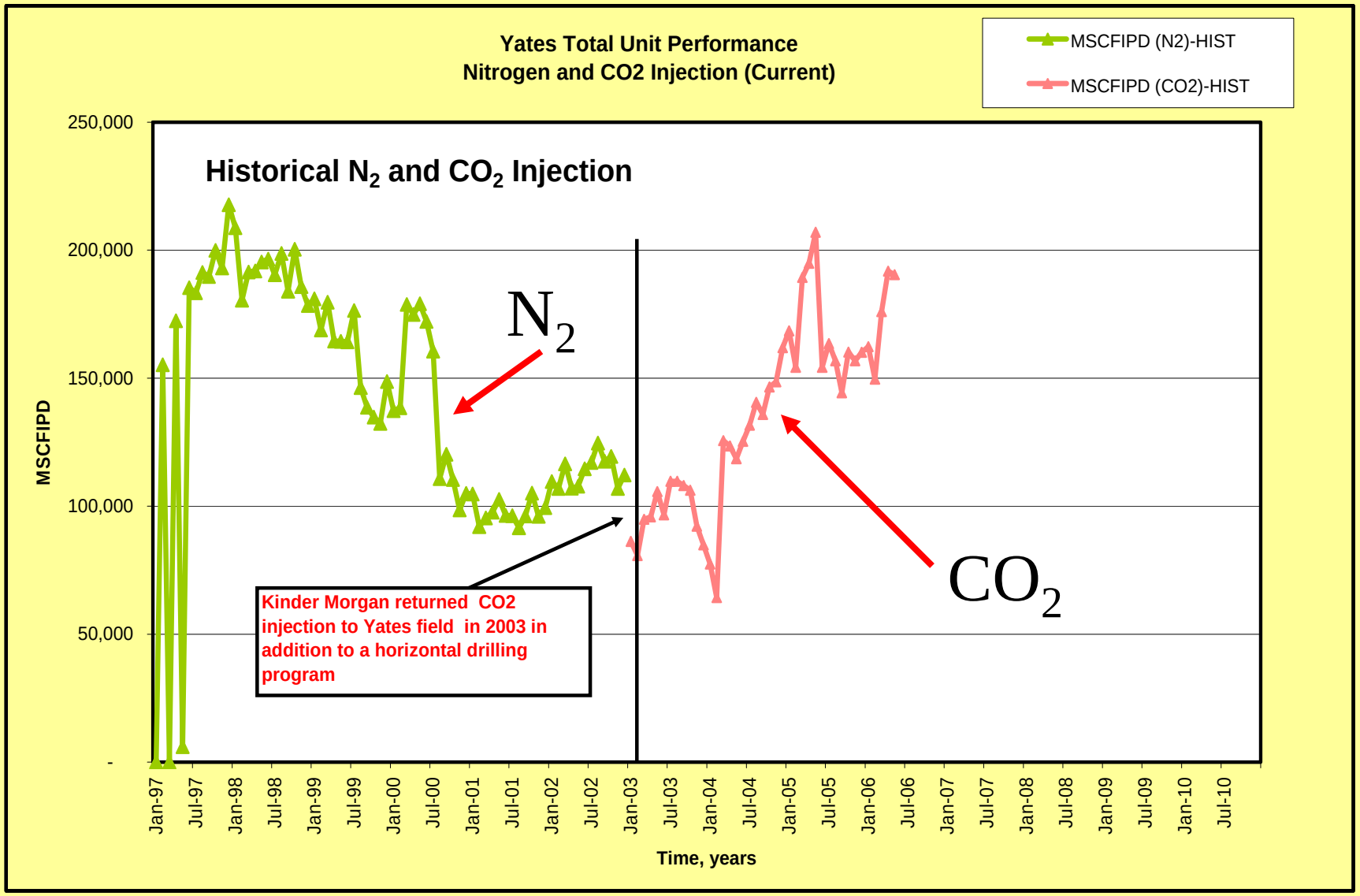
Field Production and Injection

Yates Unit Historical Performance



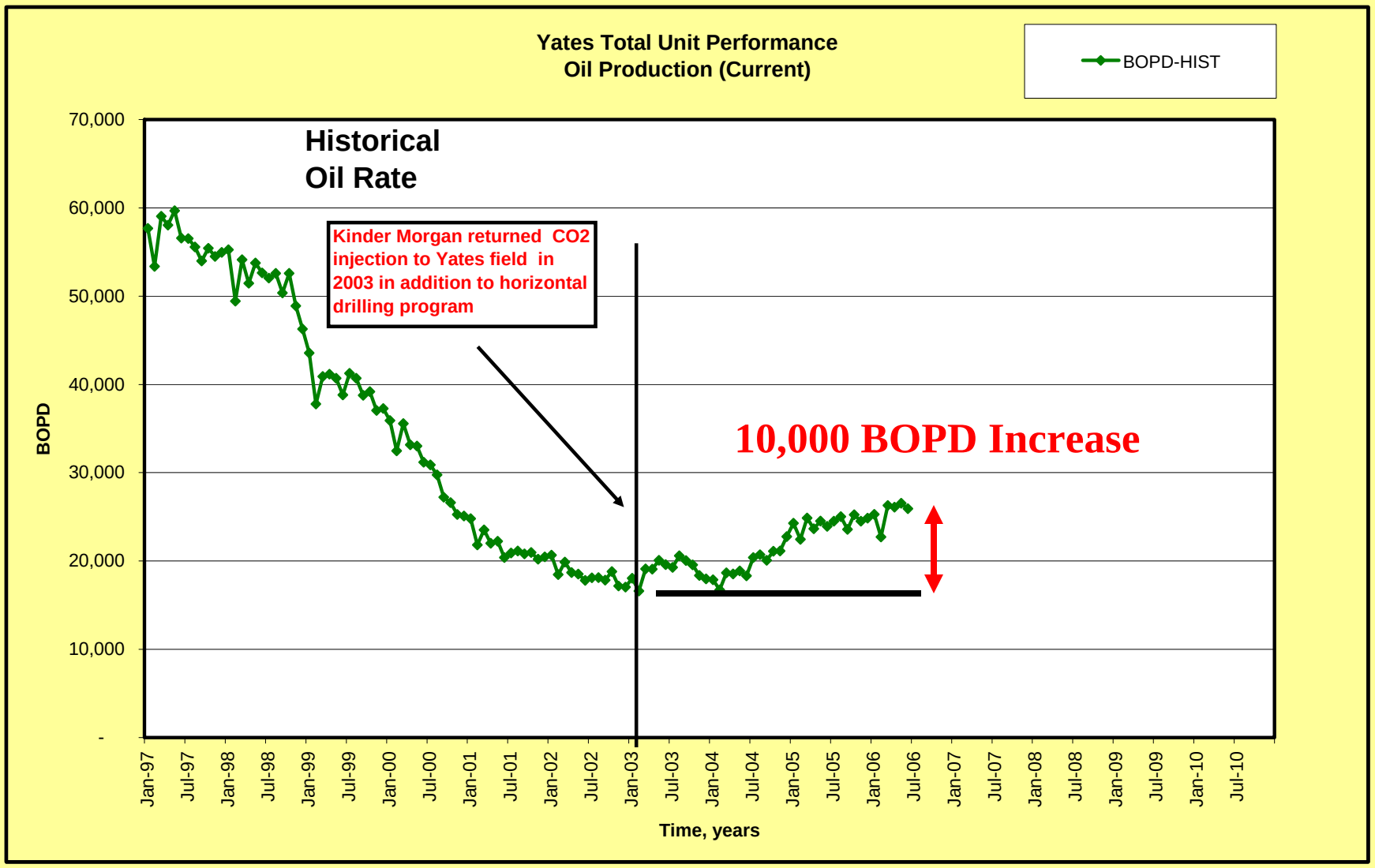
Field Gas Injection Breakout

Yates Unit Historical Performance



Field Injection (Current)

Yates Unit Historical Performance



Field Production (Current)

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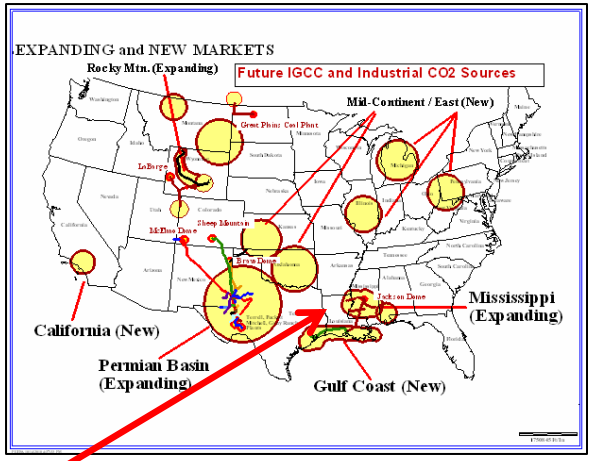
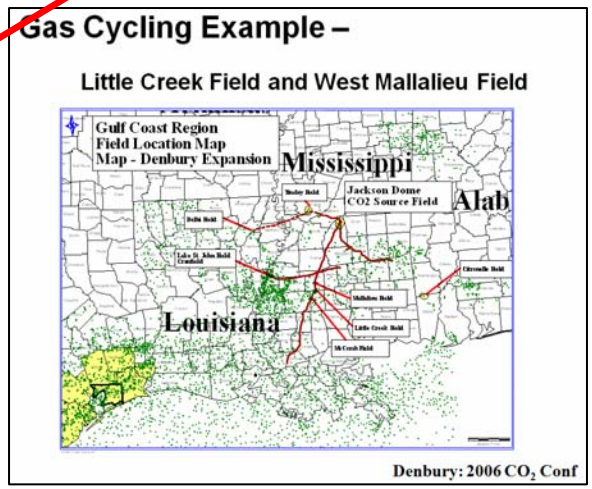
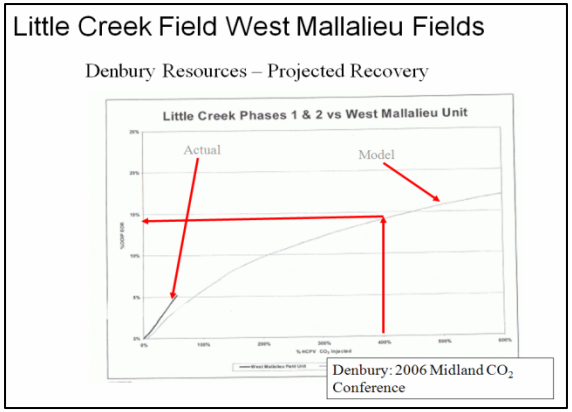
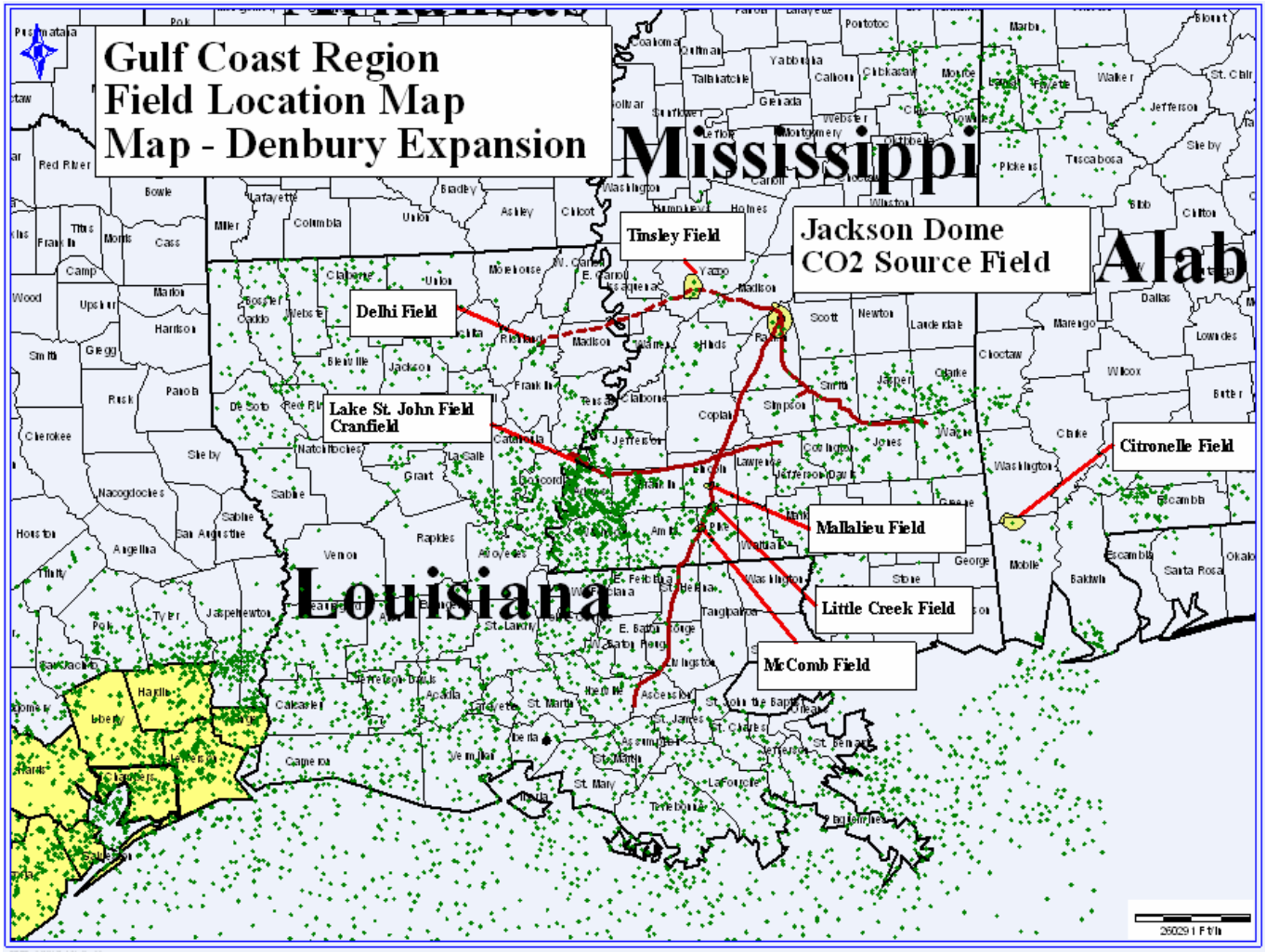






Gas Cycling Example – Denbury

Little Creek Field and West Mallalieu Field



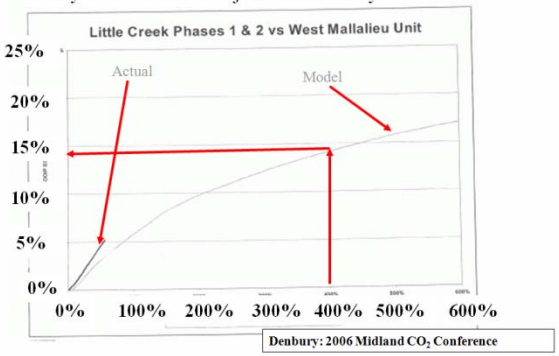
Gas Cycling Example – Denbury

Little Creek Field and West Mallalieu Field

Example –Little Creek Field
West Mallalieu Field

Example –Little Creek Field West Mallalieu Fields

Denbury Resources – Projected Recovery



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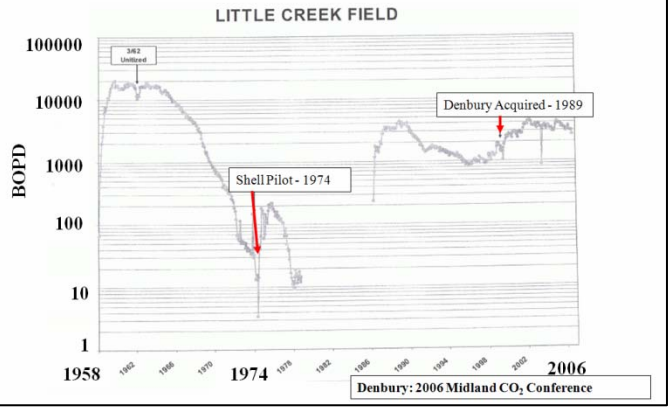
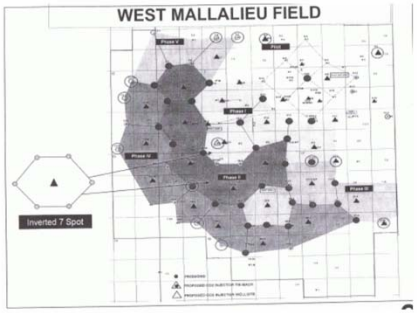


Example –West Mallalieu Field

Denbury Resources – Base Map



Note: Good for fields with limited No. of Wells or Patterns

Denbury: 2006 CO_2 Conf

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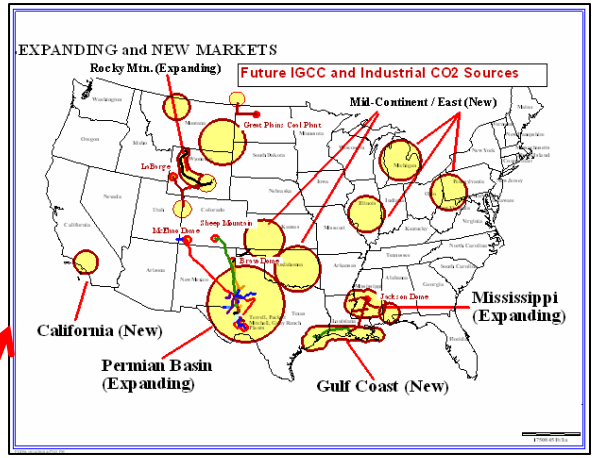

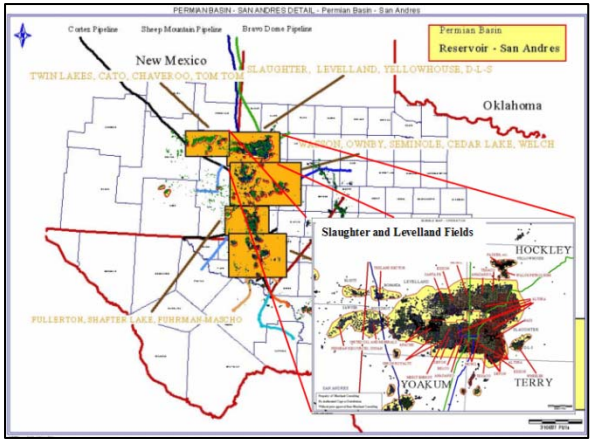

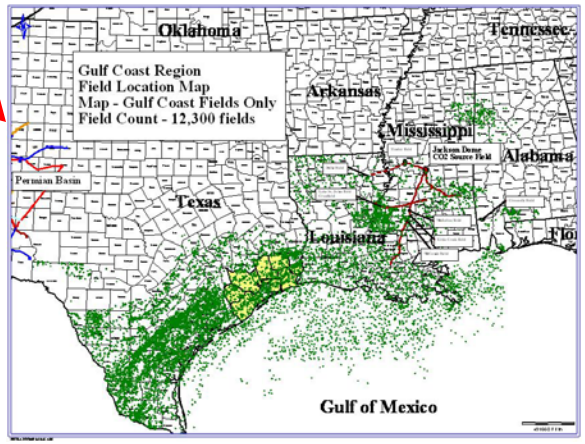

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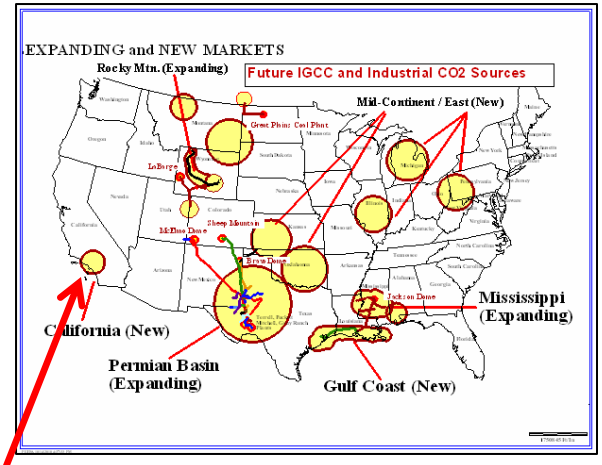
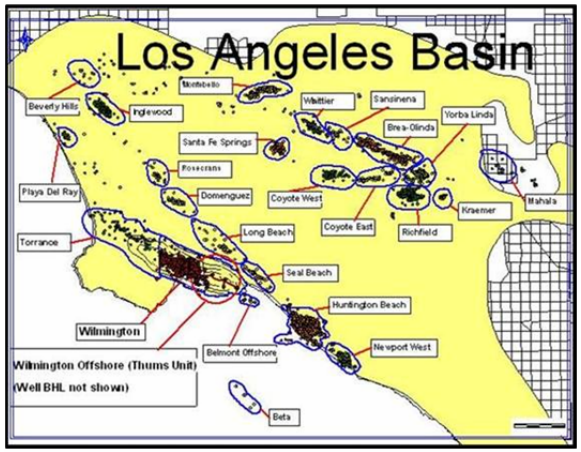
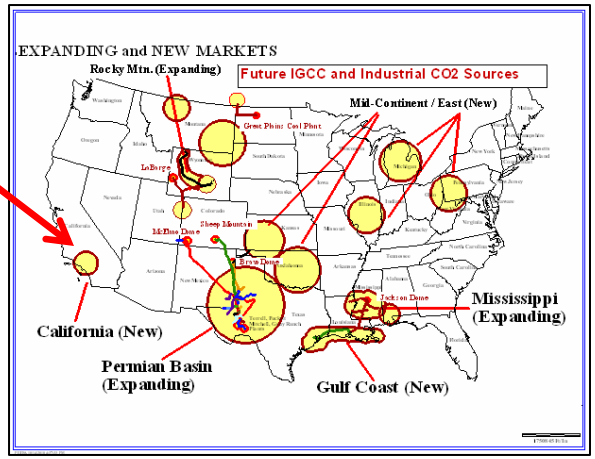
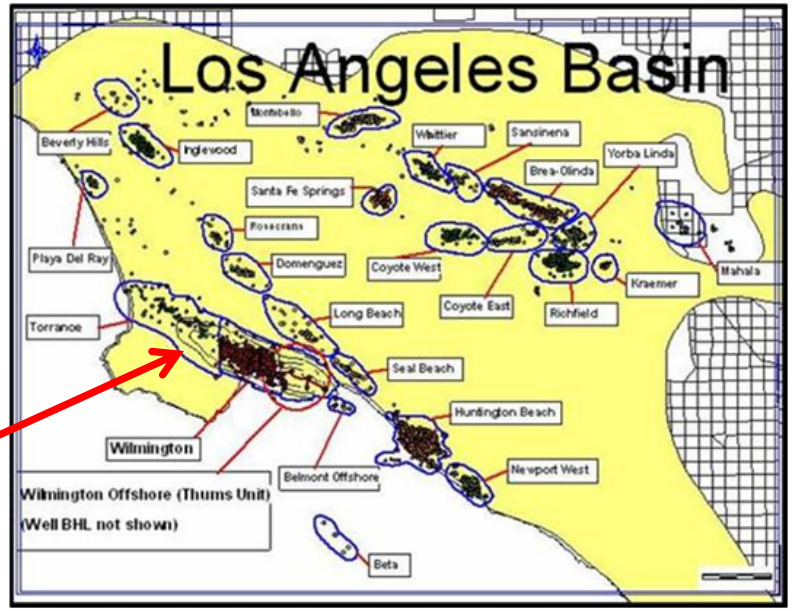






Heavy Oil Example – 14+ API Gravity

Wilmington Field – Los Angeles (3 CO_2 Pilots)



Wilmington Field

Wilmington CO_2 Pilot Results

1. Pilots were Demonstration Projects (Not Oil in the Tank Pilots)
2. Wilmington Oil – 10 fold decrease in Viscosity (300 cp to 30 cp)
3. Wilmington Oil – 1.15 fold increase in Oil Swelling
4. Wilmington Oil – Immiscible with 85% CO_2 and 15% N_2
5. Wilmington Oil Response – Single Well Response 30 BOPD to 300 BOPD

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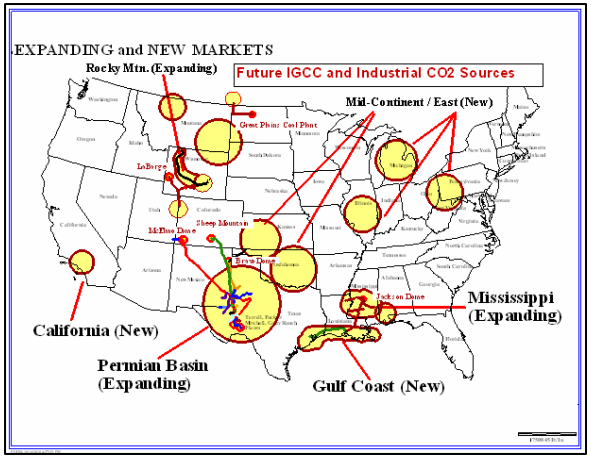
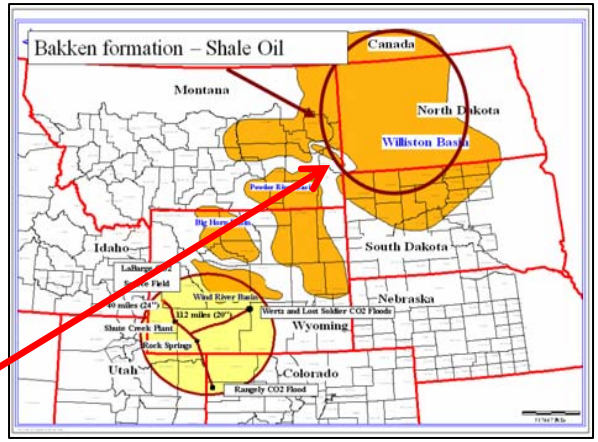
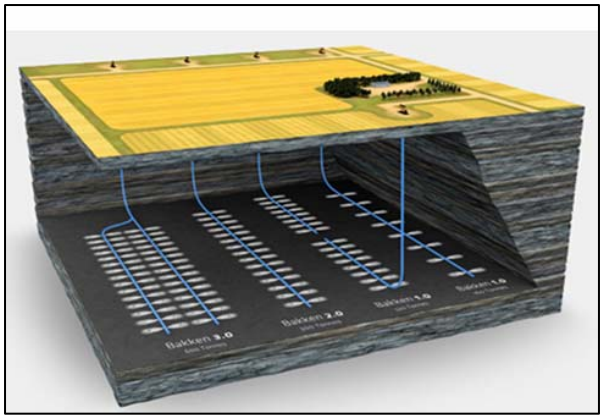
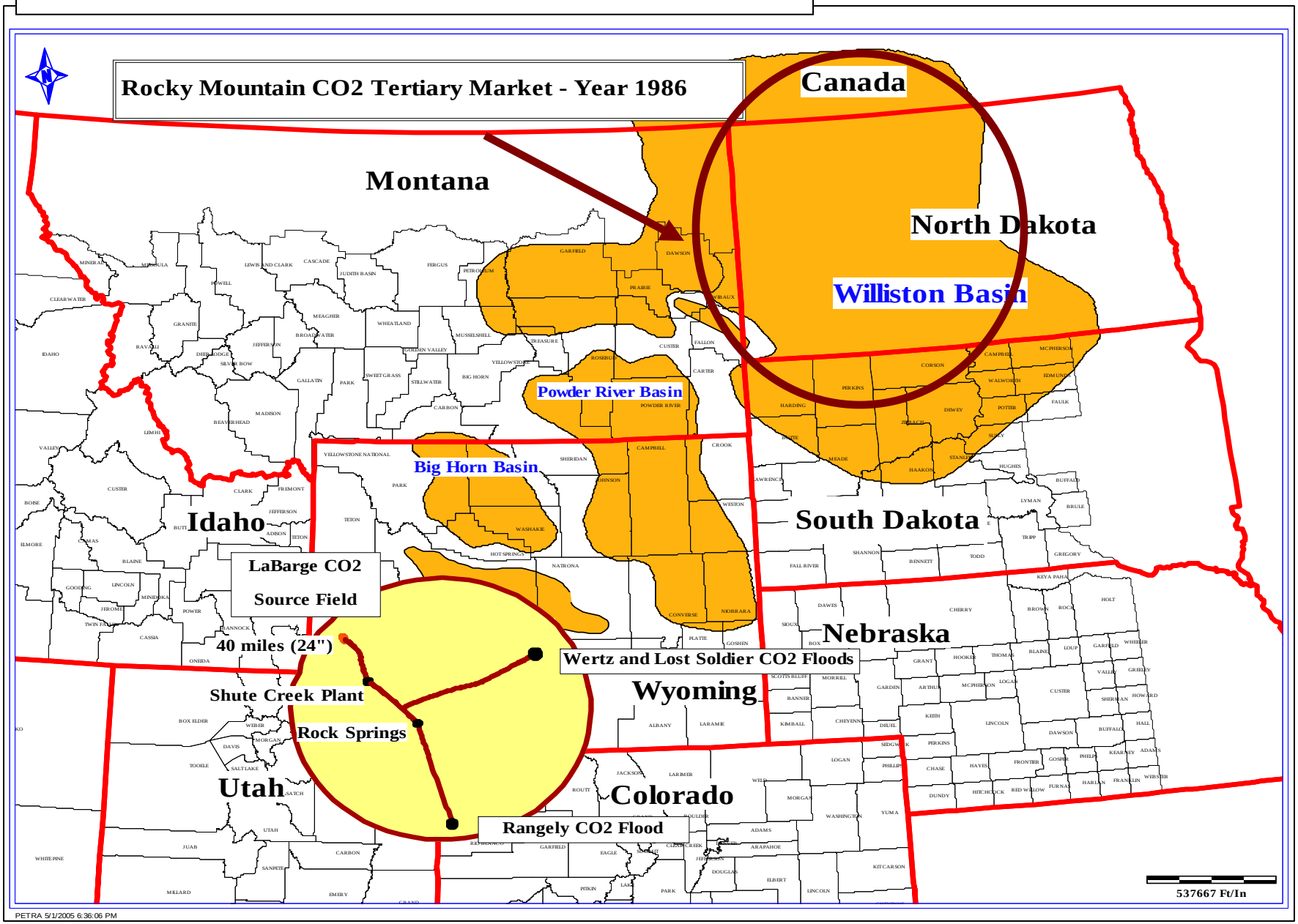




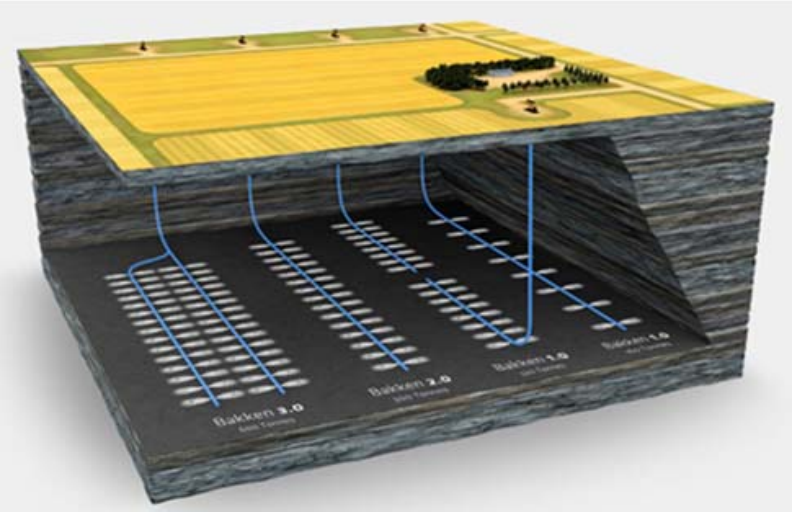


Bakken formation – Shale Oil

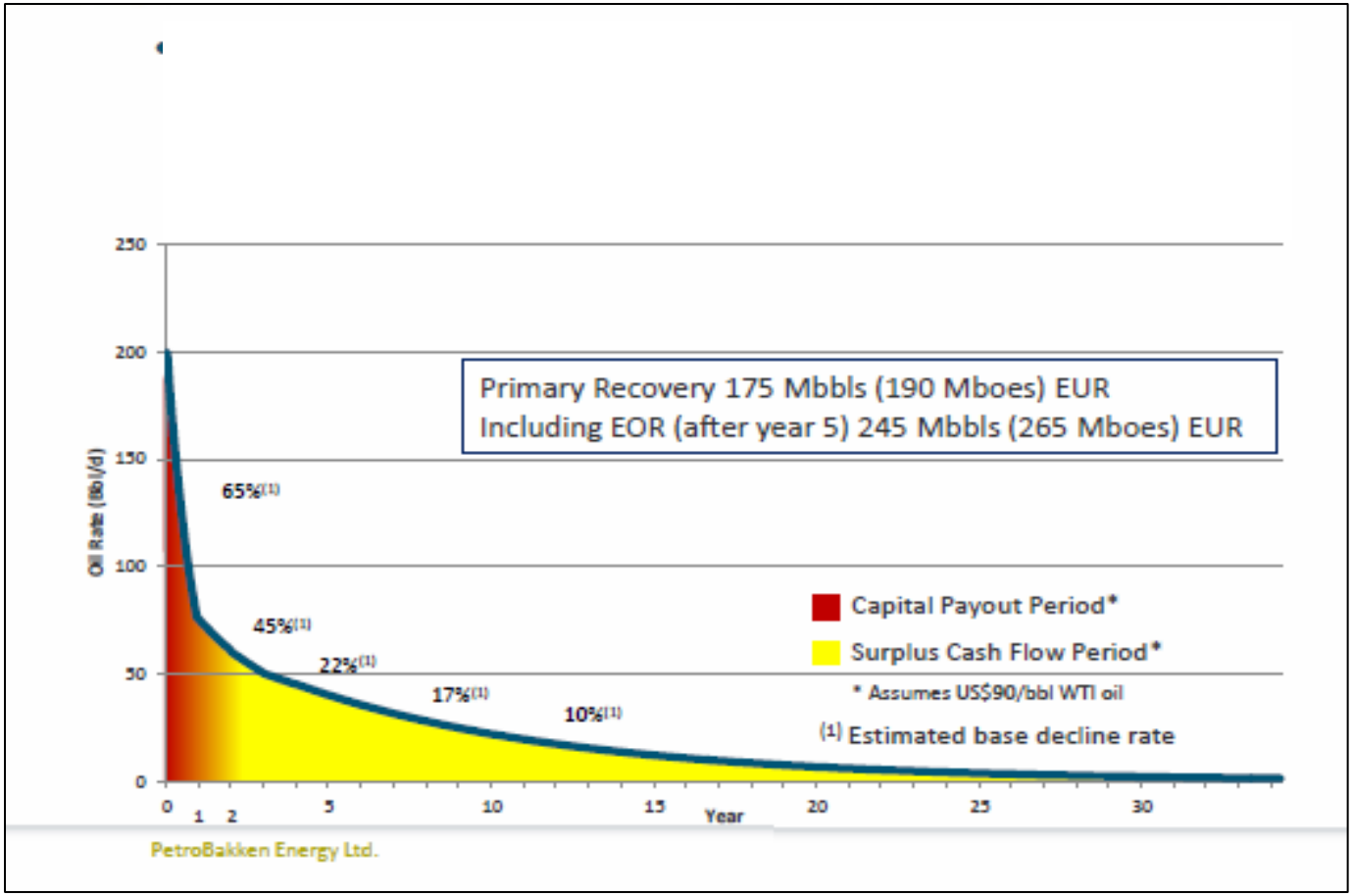


Williston Basin – Bakken Formation – Shale Oil Target

To improve Primary Oil Recovery, operators have resorted from single to bilateral Horizontal Well Completions with massive sand fracture technology to improve Primary Oil Recovery.



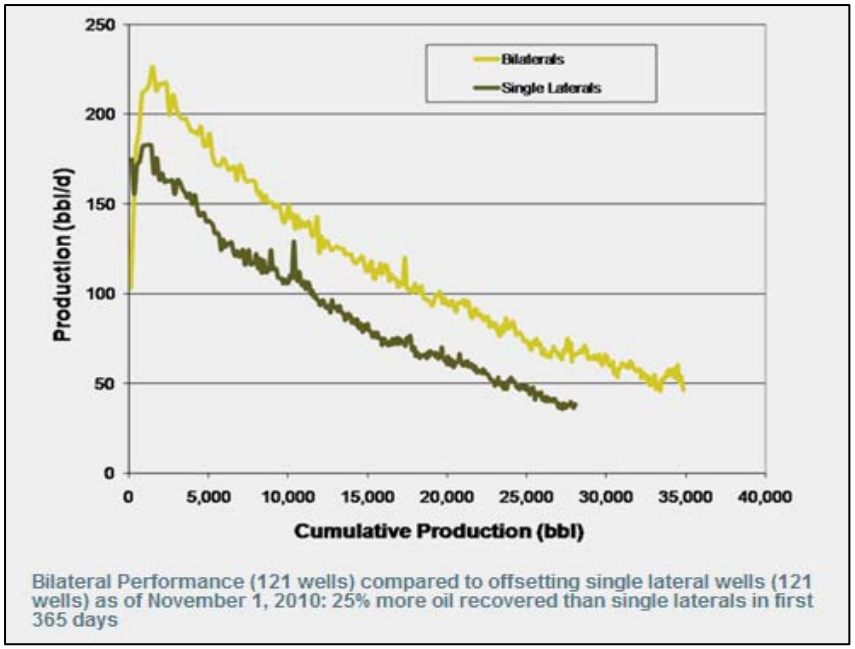
Williston Basin – Bakken Formation

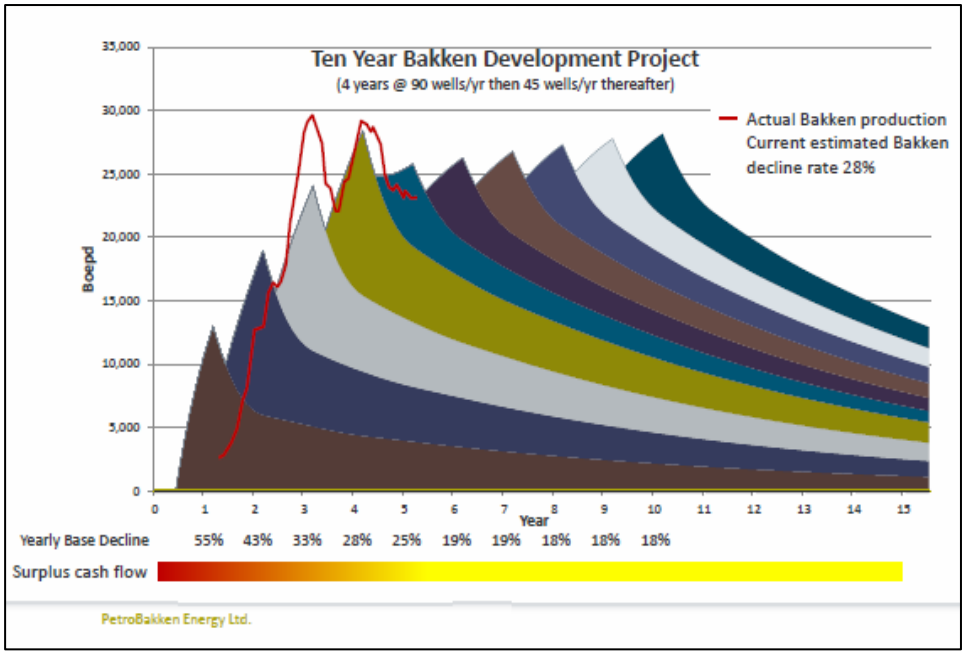


To make this technology work, large investments involving many horizontal wells on steep decline are required to keep a reasonable continuous rate profile. This results in a many well, many year continuous drilling program.

Williston Basin – Bakken Formation

Results of this effort are shown below

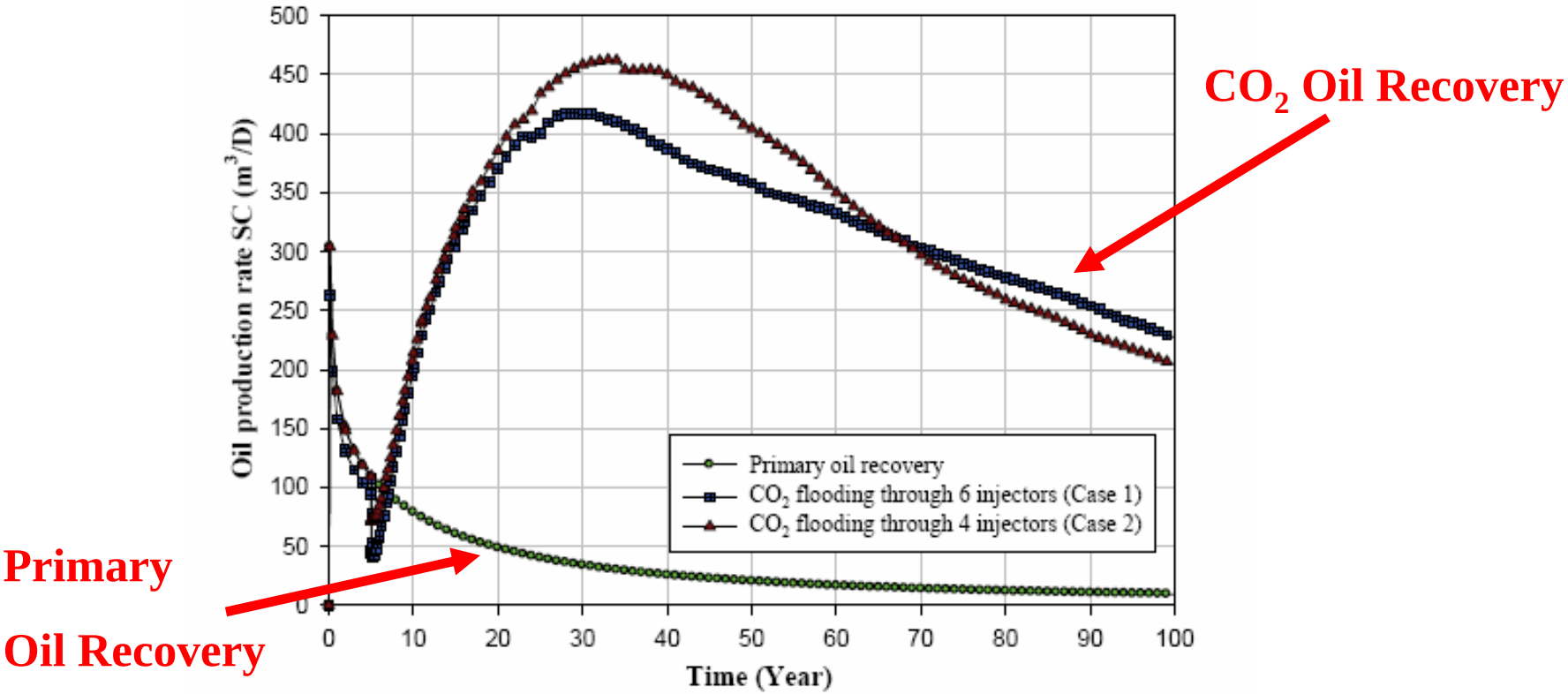




The 10 year Bakken development plan shown above contains 10 one year phases. <u>Ninety wells per phase per year</u> are required for the <u>first four phases</u> with <u>45 wells per phase per year</u> for the <u>last six phases</u>. This results in a total of 635 wells to be drilled over a 10 year period with a single well cost of around 3 million dollars. For other areas of the Bakken drilling costs can exceed 12 million dollars per well.

Williston Basin – Bakken Formation

Reservoir Model Study – CO_2 Tertiary Prediction



Simulation Comparison study results are shown above. Primary recovery was limited to 5 years (3.64% OOIP) with CO_2 Injection over 95 years. Continuous Injection out-performed water injection and other cyclic Huff-n-Puff injection schemes.

Williston Basin – Bakken Formation

Reservoir Model Study – CO_2 Tertiary Prediction

Simulation results of different cases.

No.	Scenario	Oil recovery ($\times 10^6$ m^3)	Oil recovery factor (%)	Gas injected ($\times 10^6$ ton)	Time after injection to breakthrough (year)
1	CO_2 (6 inj.)	11.2	33.0	38.6	0.3
2	CO_2 (4 inj.)	11.7	34.3	4.6	5.0
3	Cyclic CO_2 (4 inj.)	9.8	28.9	3.2	5.0
4	CO_2+CH_4	12.3	36.2	5.9	5.0
5	CO_2+N_2	10.9	32.1	5.4	5.0
6	Water	2.8	8.3	—	35.0
7	Water+CO_2	7.3	21.6	1.9	35.0
8	CO_2 (Hetero model)	10.1	31.5	4.2	5.0

Water flood Recovery

CO_2 Recovery

The simulation results show that CO_2 flooding presents a technically promising method for recovering Bakken oil, but over a very long injection period (95 years of injection). Also, note the long time to breakthrough (several months to many years).

Tertiary CO_2 Flooding

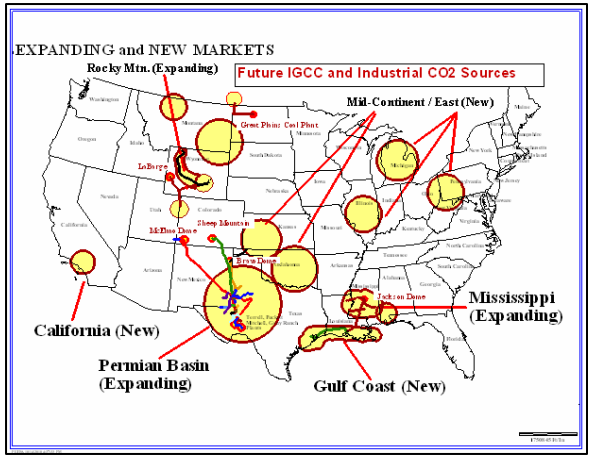
Eight CO_2 Recovery Methods used for Tertiary Oil Recovery in the United States

1. Conventional WAG Recovery (90%+)
2. Residual Oil Zone (ROZ) (Seminole)
3. Gravity Drainage (Yates Field)
4. Double Displacement (Yates Field)
5. Gas Cycling (Denbury, Mississippi).
6. Huff-and-Puff (100+ Projects)
7. Heavy Oil - Calif. (14+ API Gravity)
8. Shale Oil (Bakken) (Under Investigation)

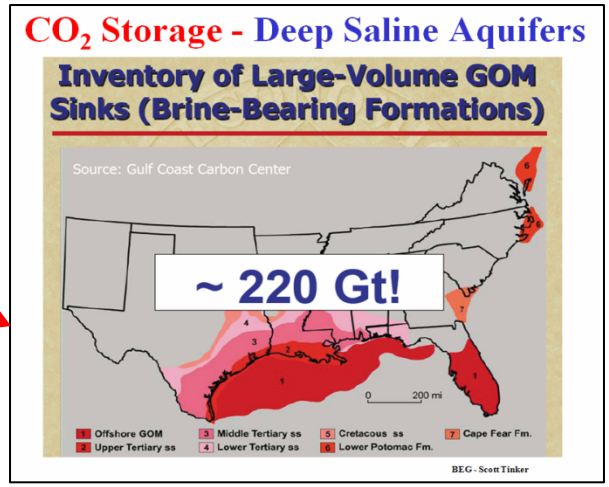
Ninth CO_2 Recovery Method used for EOR and CO_2 Sequestration

Note: Remove both Tertiary Oil and Water

Enhanced Oil Recovery - EOR



CO_2 Storage - Deep Saline Aquifers



Merchant Thanks to Steering Committee!

1995 Reservoir Management in Tertiary CO_2 Floods – SPE 26624

1999 Screening CO_2 Candidate Reservoirs Fundamentals of Pattern Analysis

2000 Setting up the Pieces – What Constitutes a Simulation?

2004 Pattern Performance as a Diagnostic Tool for Reservoir Surveillance

2004 Monitoring the CO_2 Flood - Problem Identification and Solutions

2009 Comparisons of Conventional CO_2 WAG Injection Techniques used in the Permian Basin

2010 Life beyond 80 – A look at Conventional WAG Recovery beyond 80% HCPV in CO_2 Tertiary Floods – SPE 139516

2012 The Energy Gap - "How CO_2 Tertiary Recovery will mark its place in the 21st Century"

Thanks,

Now its your turn?

David H. Merchant

Merchant Consulting

Email: MerchantConsulting@comcast.net

CO_2 Storage Solutions

WEB: www.CO2StorageSolutions.com

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Magnolia, Texas

o 281-374-6330