25th Annual CO_2 Conference

Theme Session III:
New Gas Compositions, CO_2 Supplies and EOR Case Histories

Optimization of CO2-Enhanced Oil Recovery with CO2 storage in a Mature Oil Field- FWU Case Study

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Outline of Presentation

- Introduction
- FWU Reservoir Description
- Reservoir Simulation Model
- Optimization Process
- Conclusions

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- Introduction
- FWU Reservoir History
- Reservoir Fluid Analysis
- Reservoir Simulation & History Matching
- Prediction Models
- Optimization Process
- Conclusions

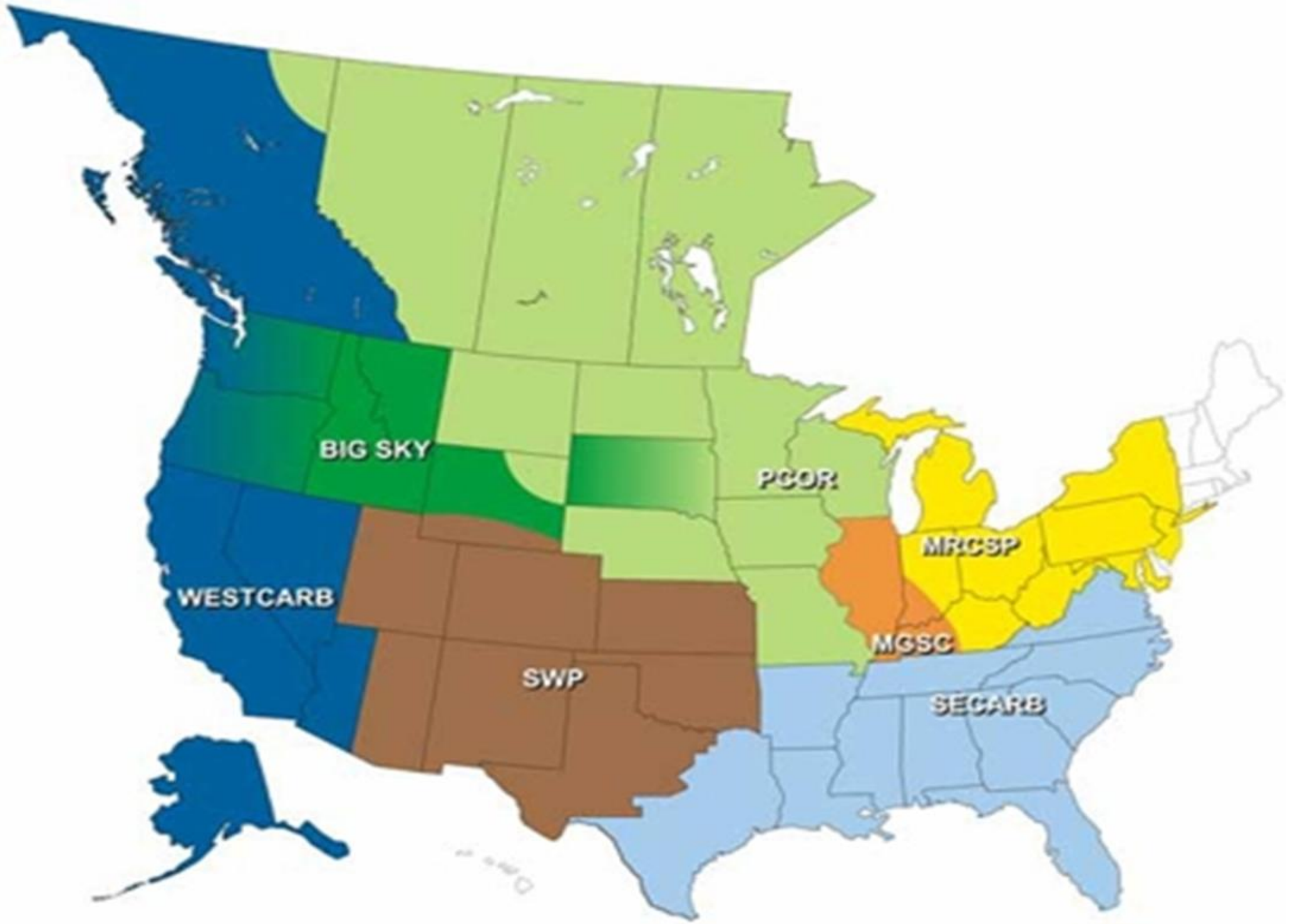
Motivation for this work

- Ampomah et al 2016 (SPE-179528) presented a scenario based model to study different injection strategies effects on oil recovery and CO_2 storage
- Their work showed a possibility of recovering more than **30% of OOIP incremental oil beyond waterflood and storing 75% of purchased CO_2**
- **This work** seeks to use advanced optimization procedure with multi-objective function to improve prediction of CO_2 storage and/or oil recovery

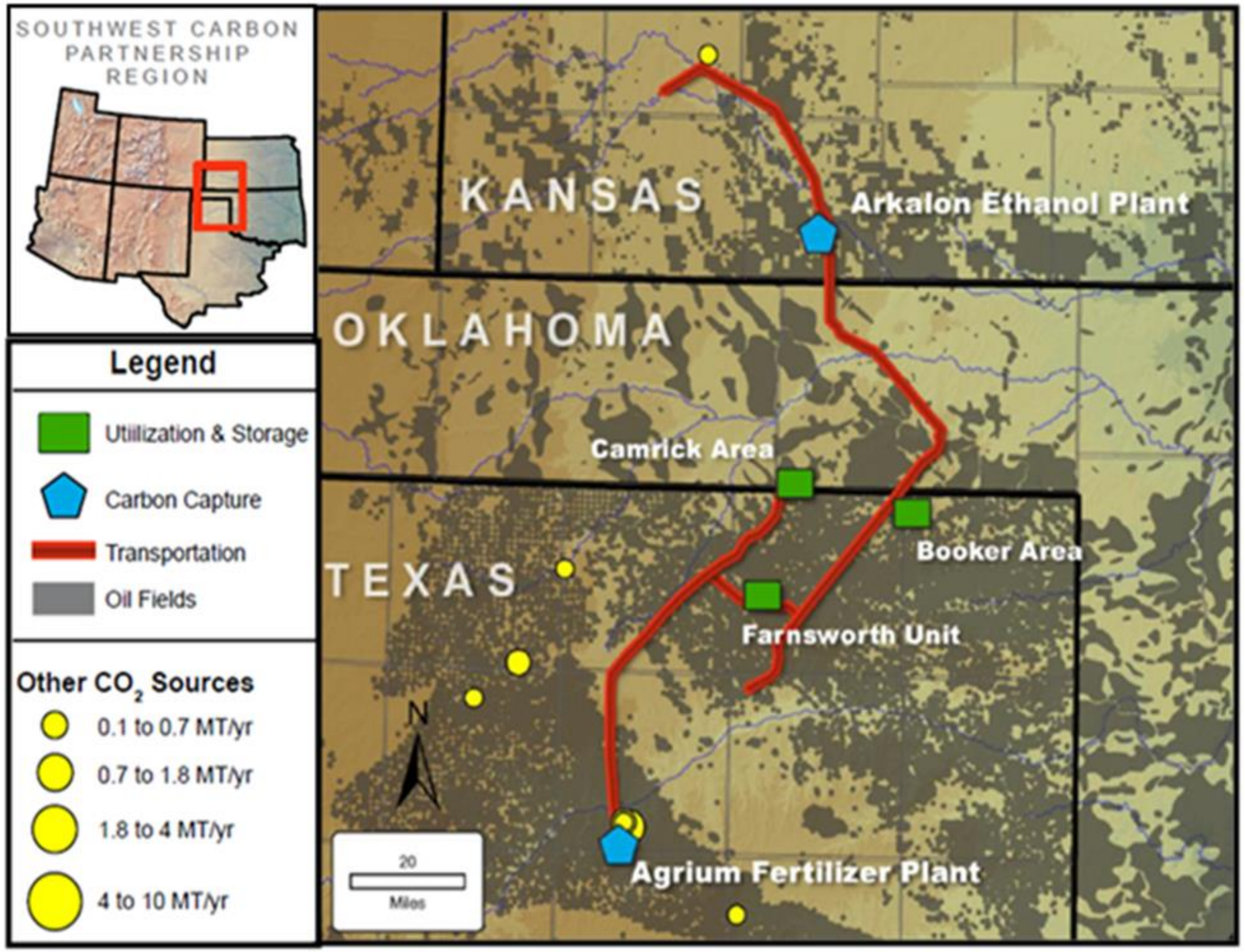
Introduction

DOE Regional Partnerships For Carbon Storage

- 7 Regional partnerships
- Each to inject and store over 1 million tons of anthropogenic CO_2



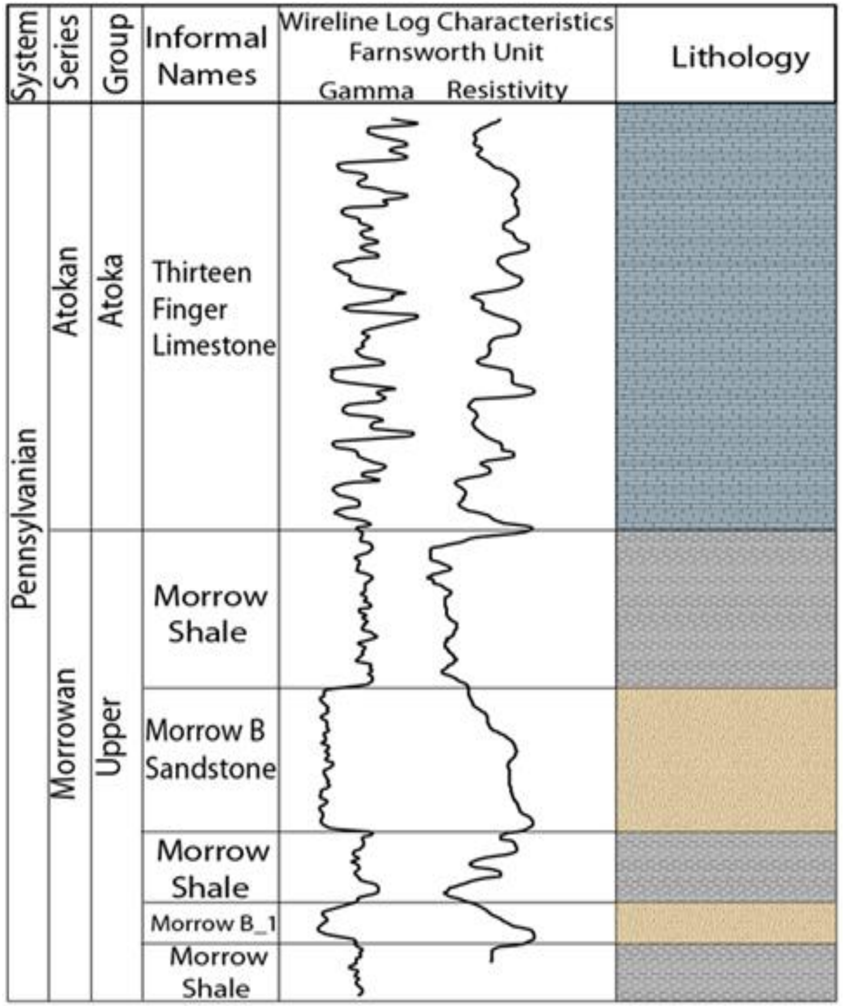
FWU's Large-scale EOR- Carbon Capture, Utilization and Storage (CCUS)

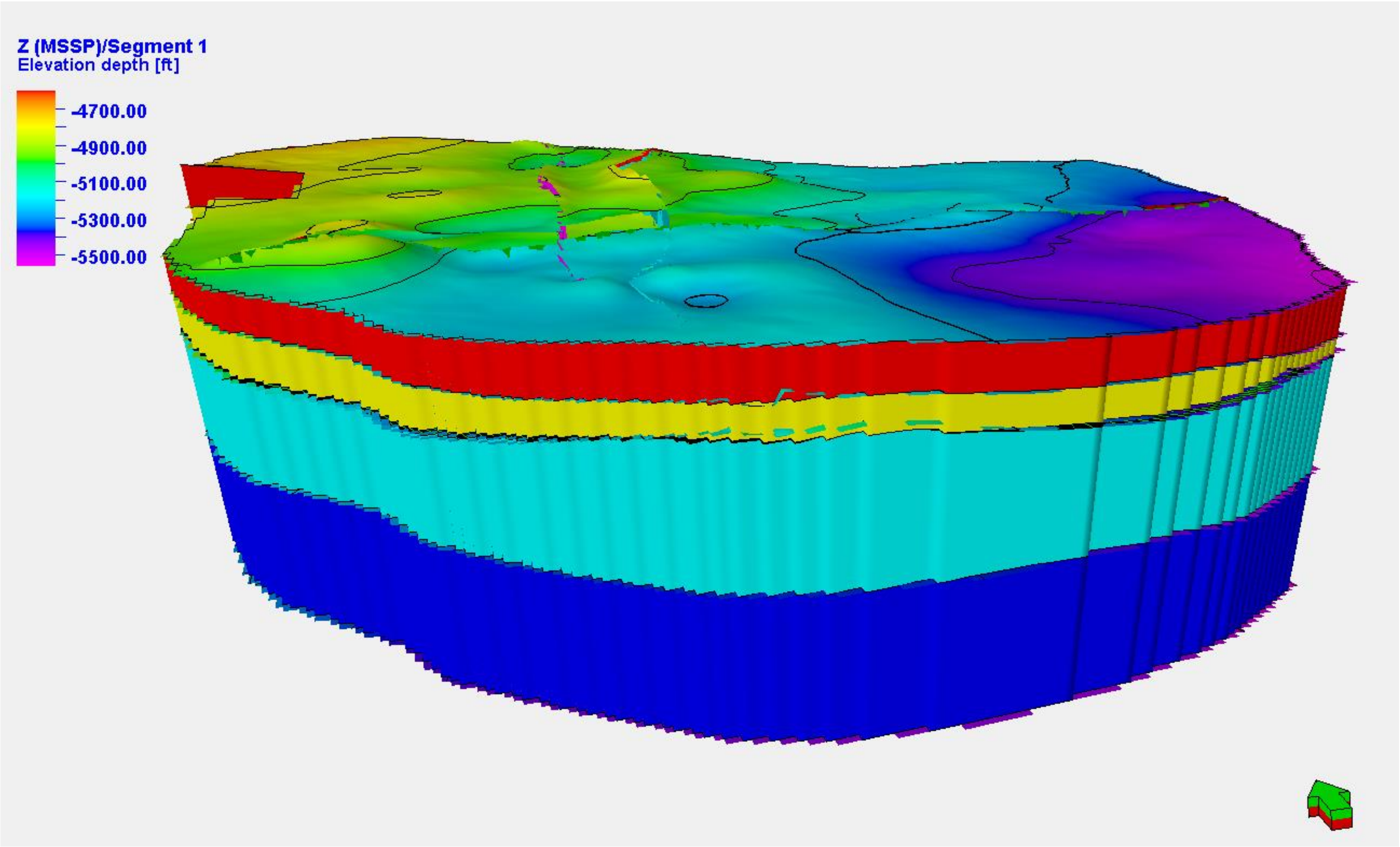


As of June 2019;

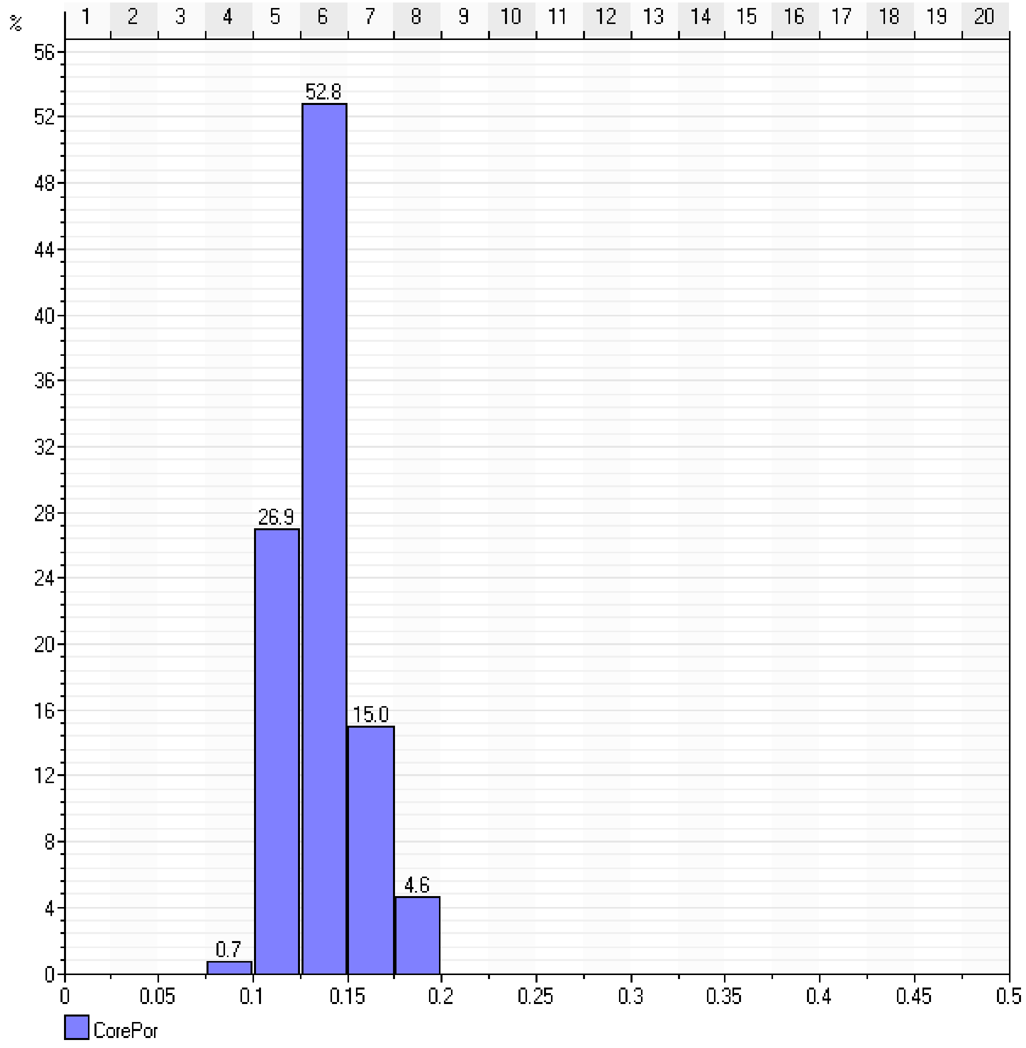
- 1,359,520 metric ton of CO_2 purchased
- 1,281,224 metric ton of purchased CO_2 stored within Morrow B sand
- ~ 94% of purchased CO_2 stored

Model Horizons

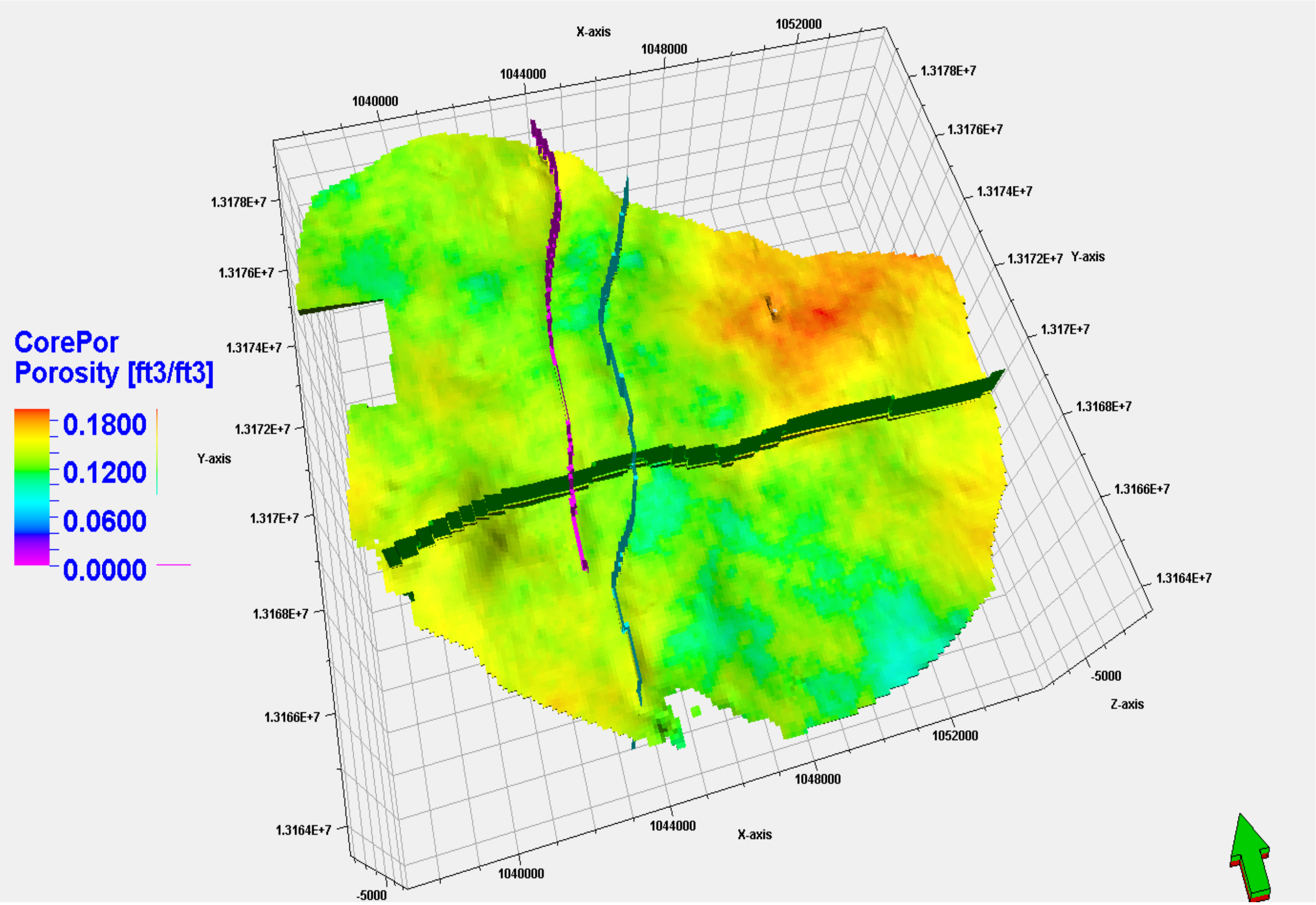




Model Details



Porosity Distribution (Morrow Sand)



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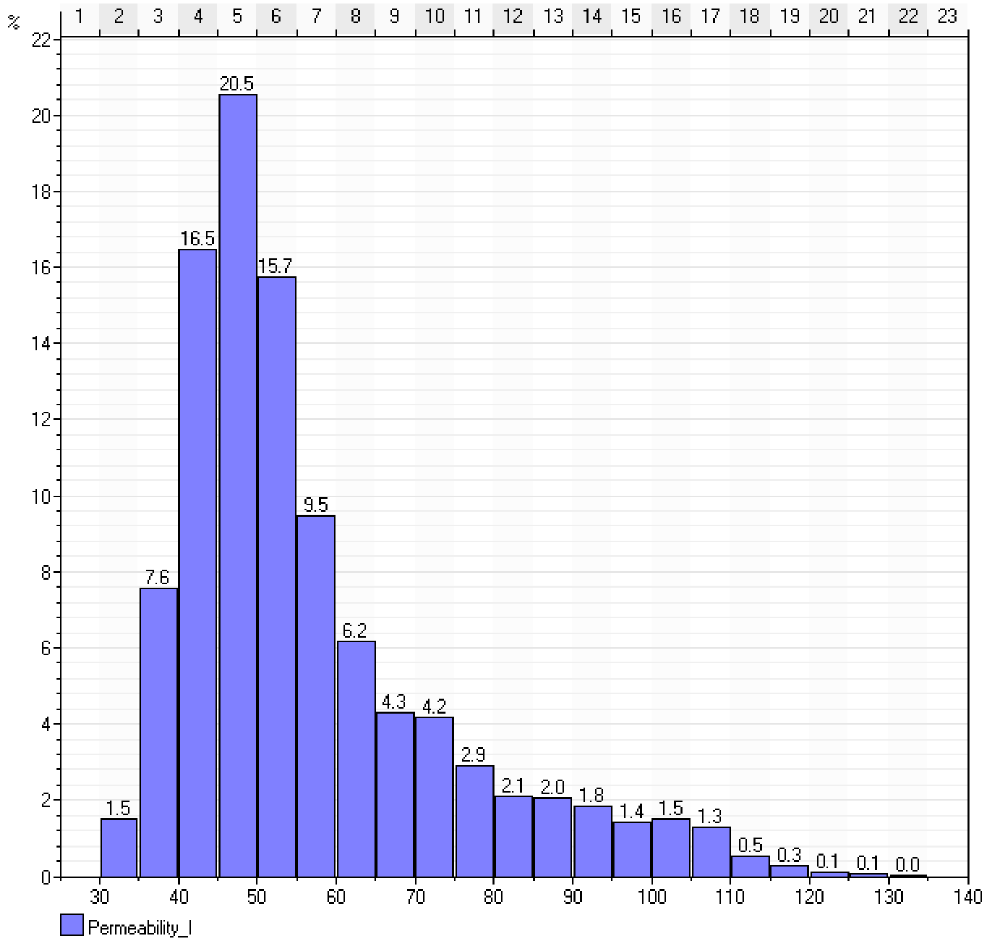
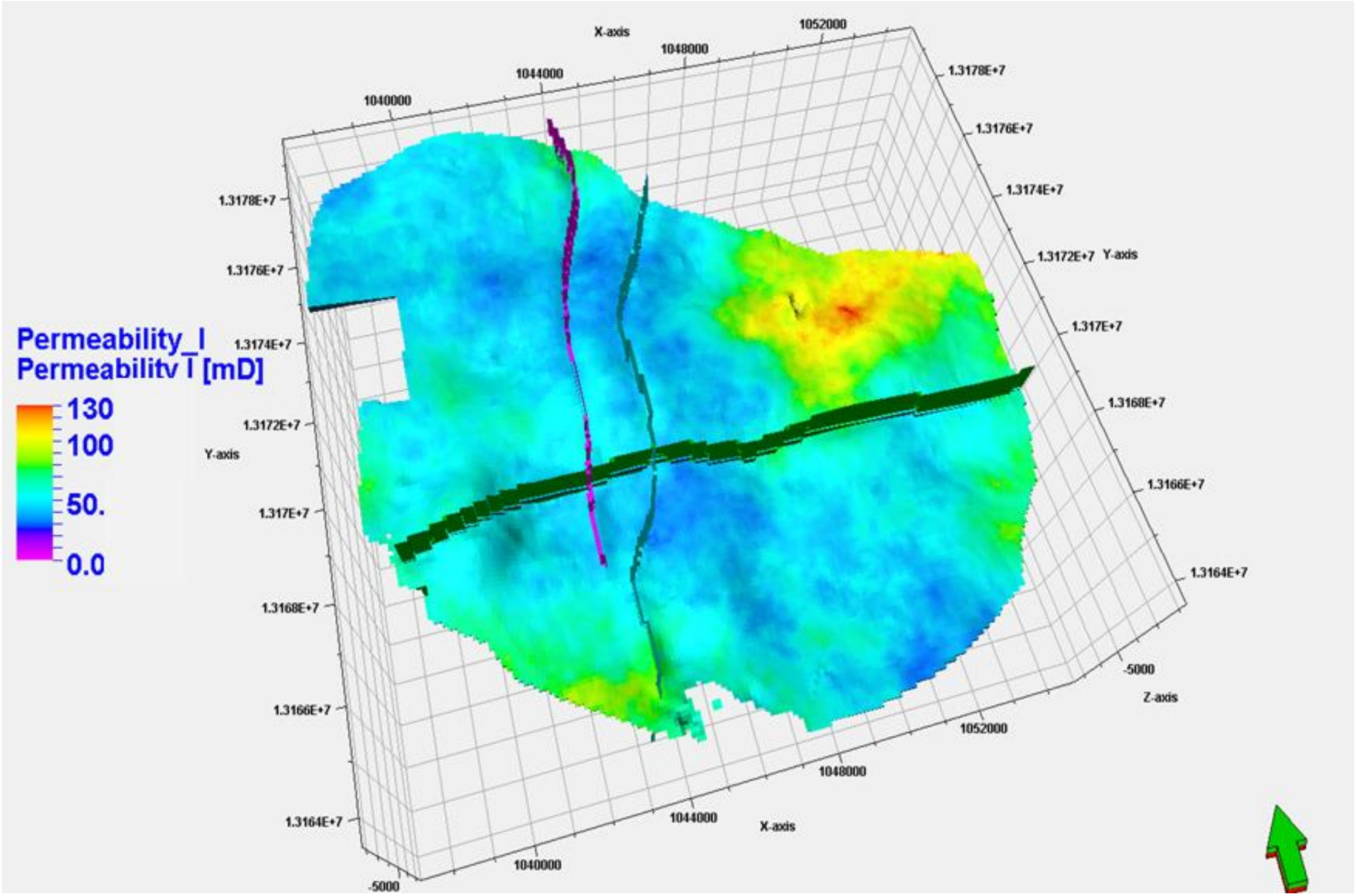
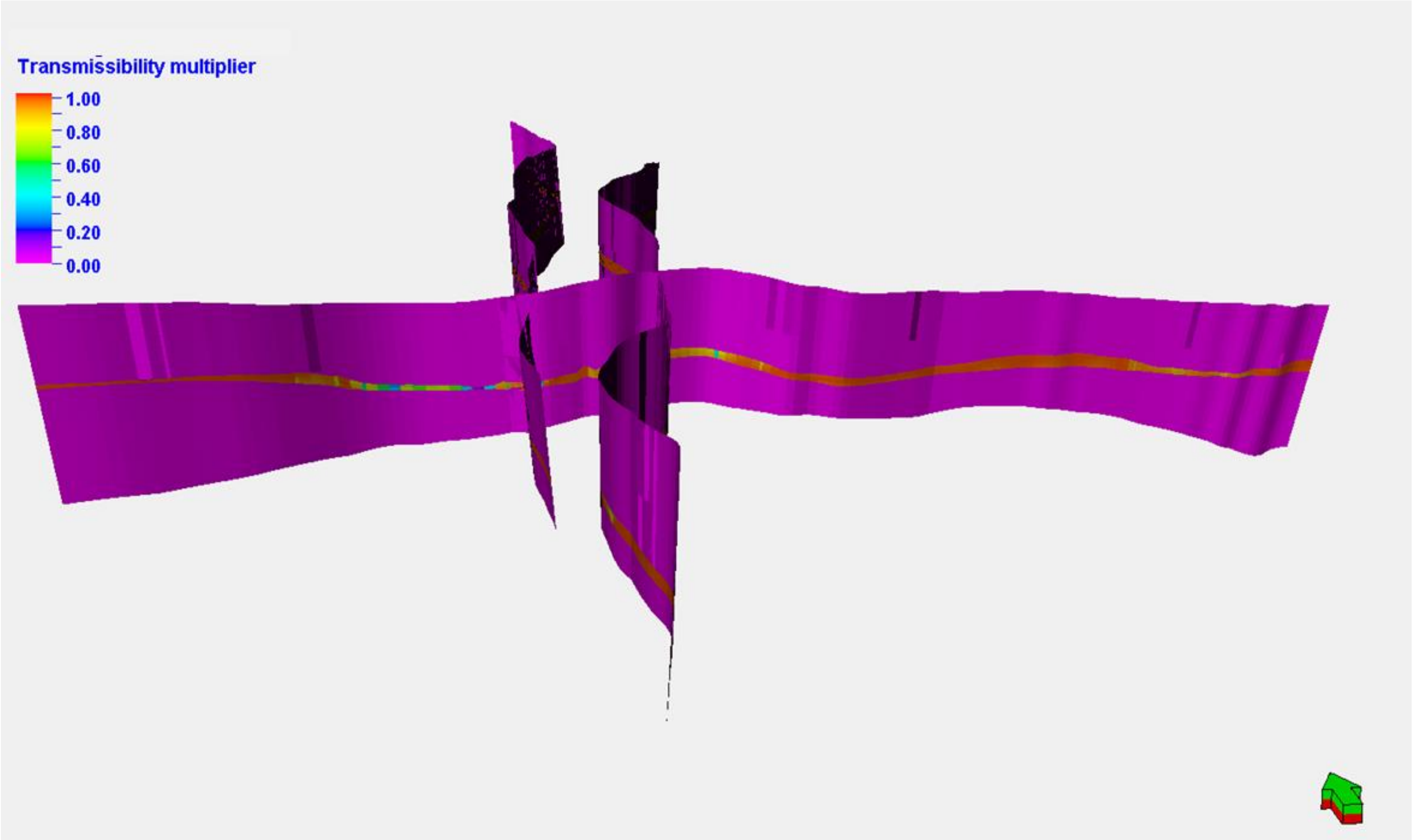


Permeability Distribution (Morrow Sand)



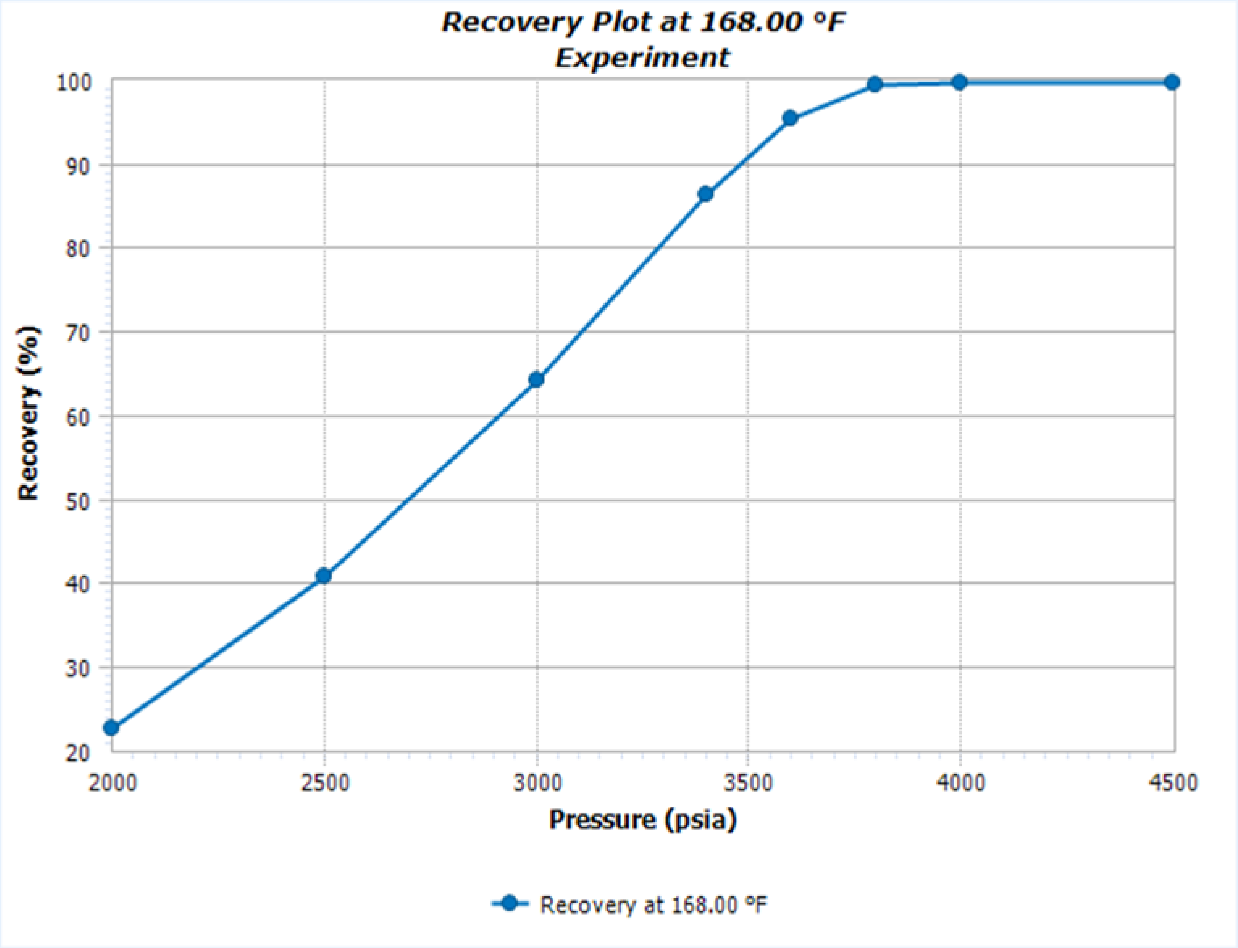
Fault Modeling

- Model : *Sperrivick* Model
- Use Vsh, NGR, Permeability to compute SGR
- High SGR means completely seal fault
- Maximum burial depth: ~3300m
- Maximum depth at time of deformation: 1300m
- Minimum depth at time of deformation: 300m



Fluid Analysis- Regression Summary

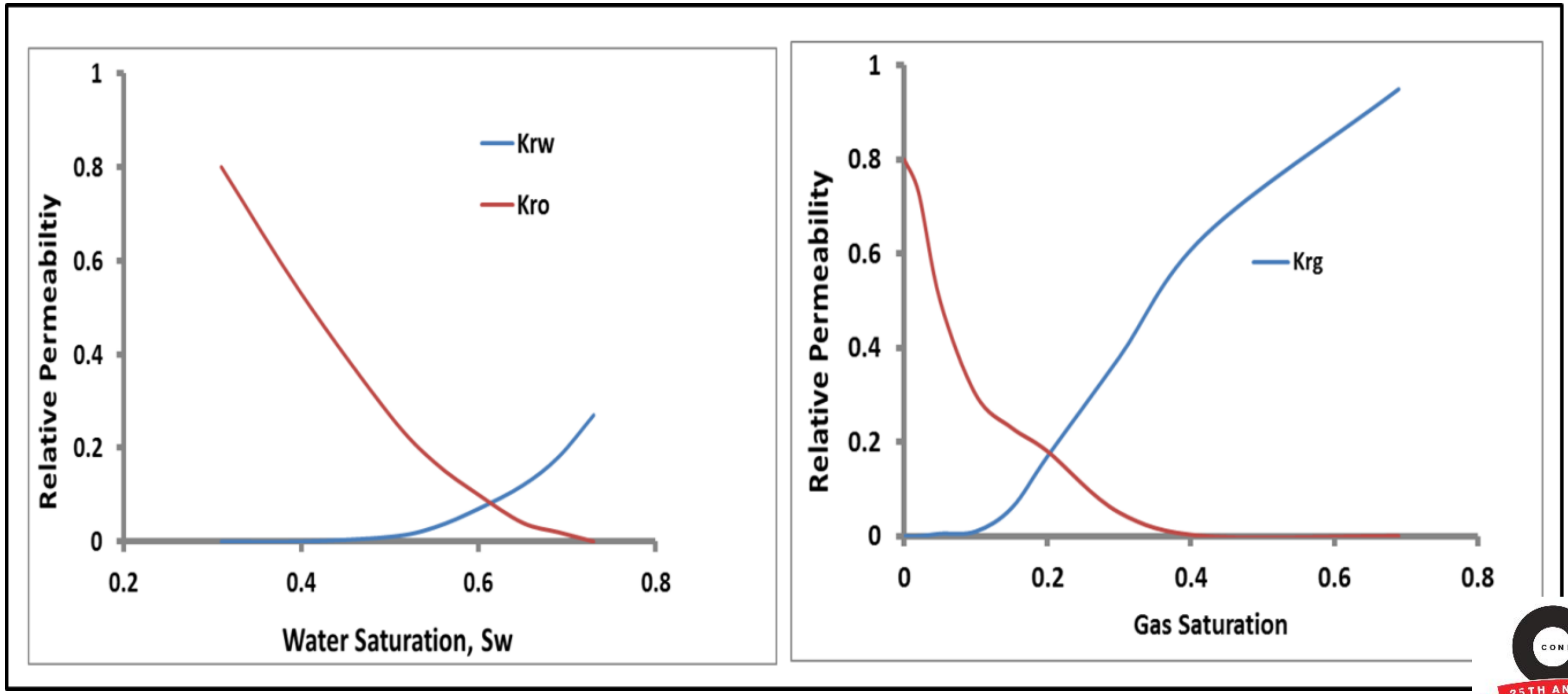
Properties	Units	% Error
Saturation Pressure	psia	2.84
Oil Density	g/cc	1.3
Vapor Z-factor		0.22
GOR	Mscf/stb	1.58
Gas Gravity		2.39
Liquid Viscosity	cp	9.7



Properties	Units	Observed	Before Regression	After Regression	%Error
MMP	psia	4200	3038.4	4008.8	4.5

Reservoir Simulation Base Model

P_{init}, psig @ Datum Depth	2203
P_{bubble}, psig @ Datum Depth	2059
OOIP, MMStb	71
Temperature, °F	168
Initial Water saturation	0.31



History Matching (HM) Process

Objectives

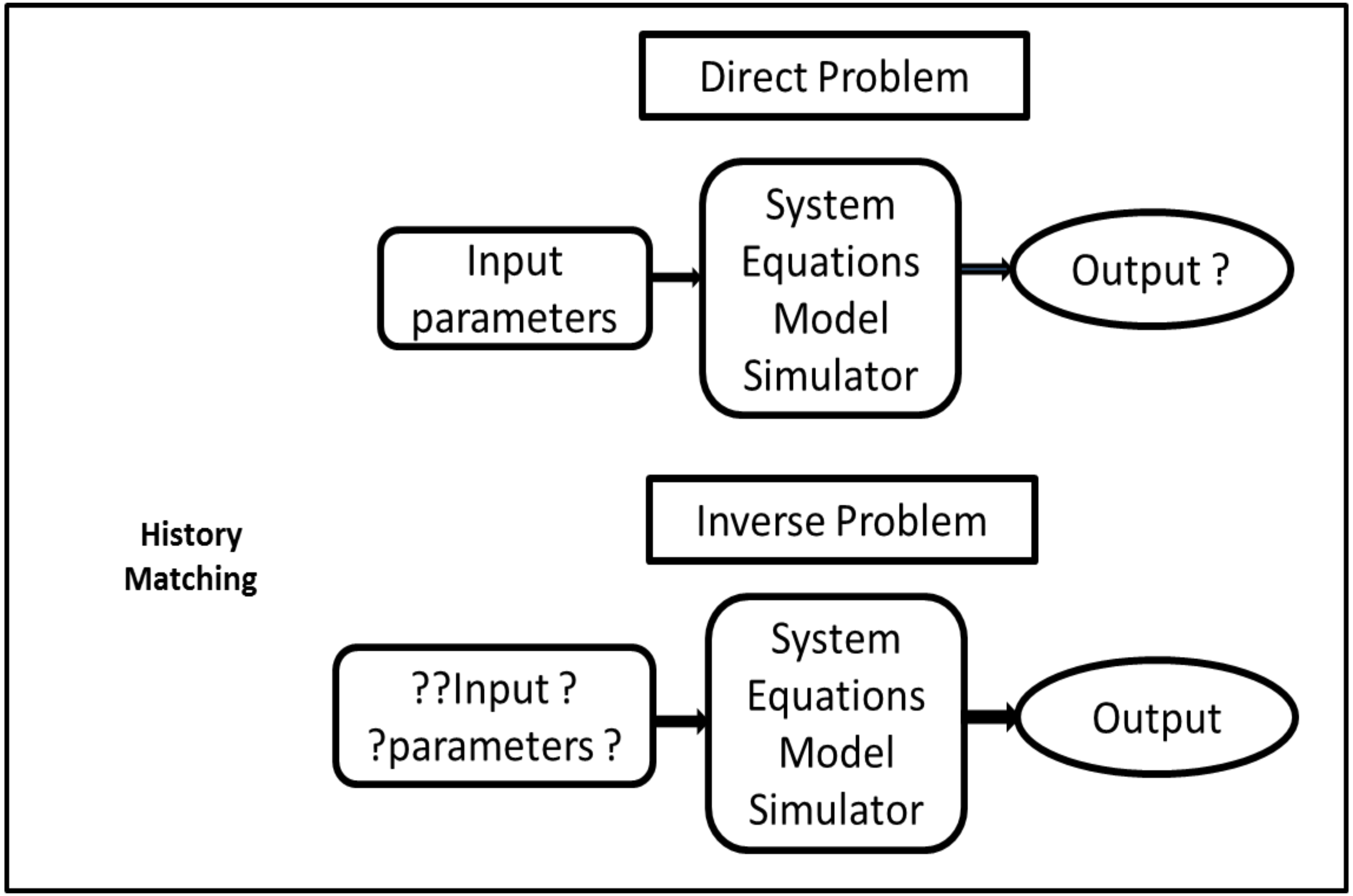
- *To match*

- Field average reservoir pressure

- Field ratios

- Field production rates

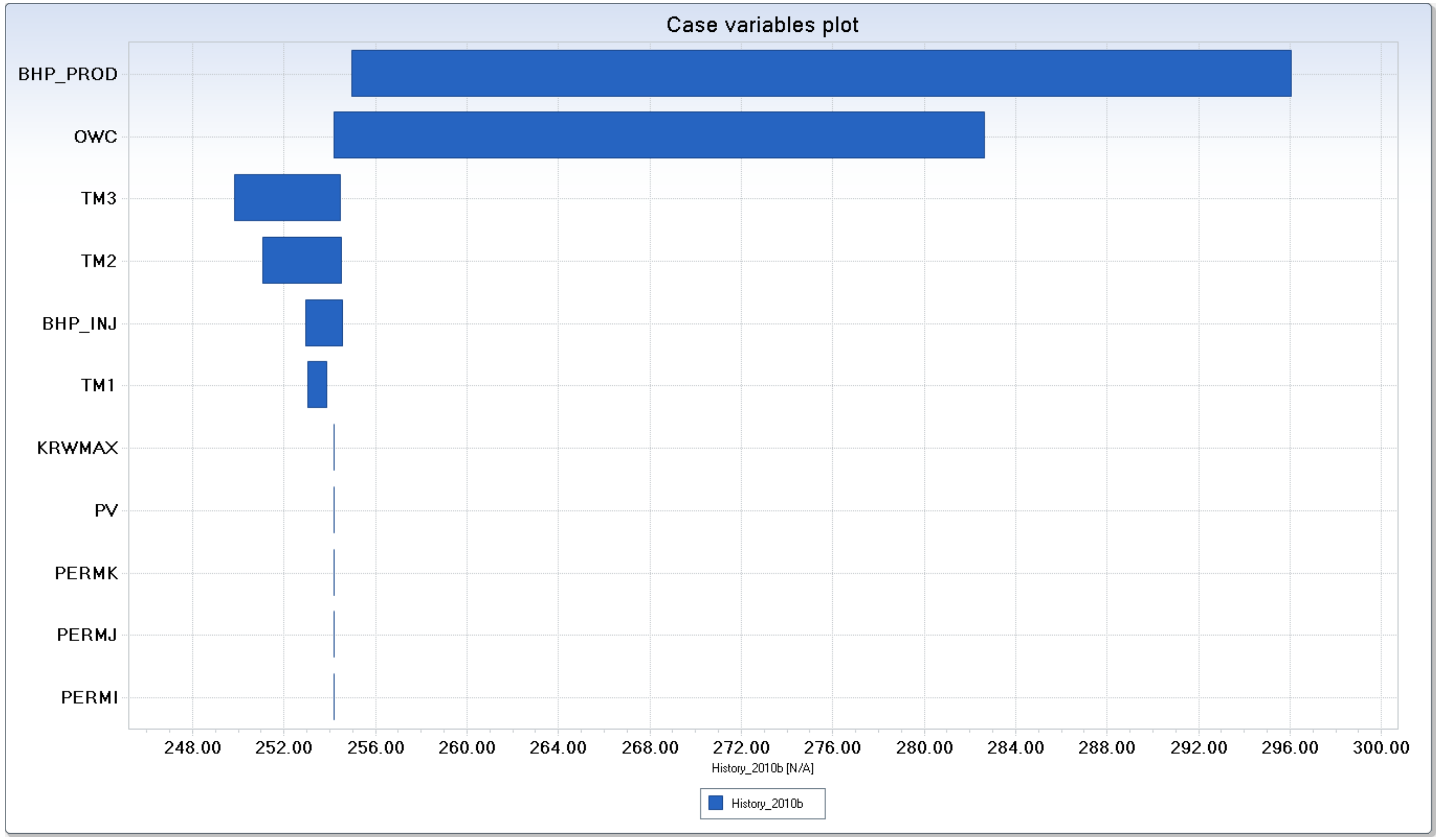
- Well production rates



HM Process

$$RMS = \sqrt{\frac{\sum_1^N (Simulated - Observed)^2}{N}}$$

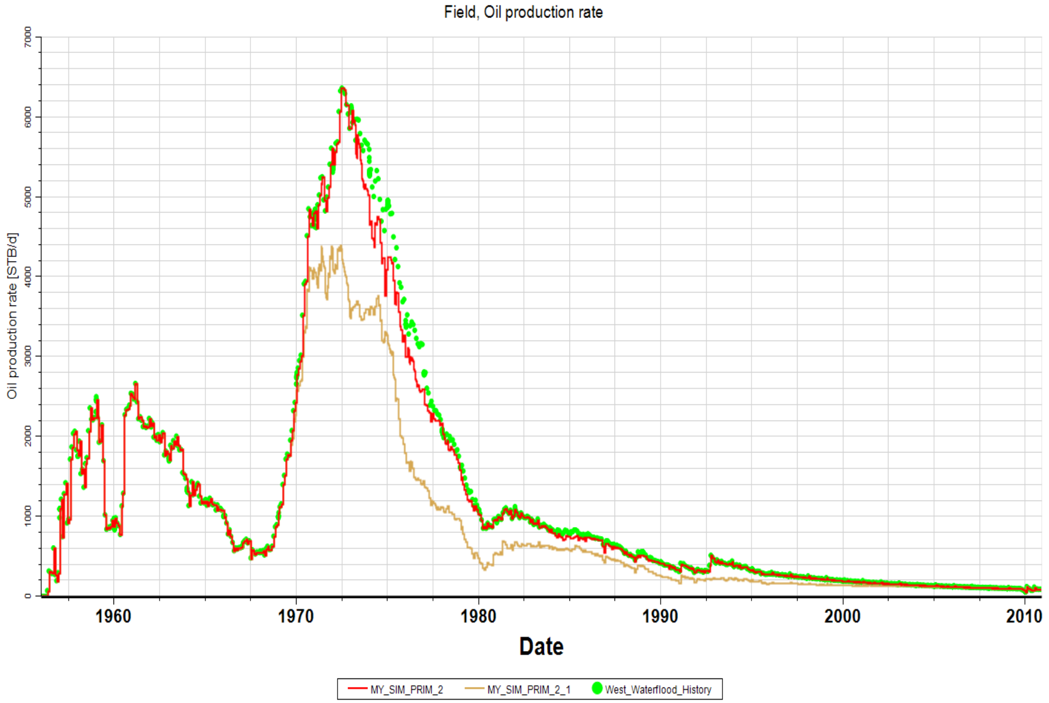
Vector	RMS
Field Oil Production	0.025
Field Water cut	0.03
Field Gas-Oil ratio	0.22



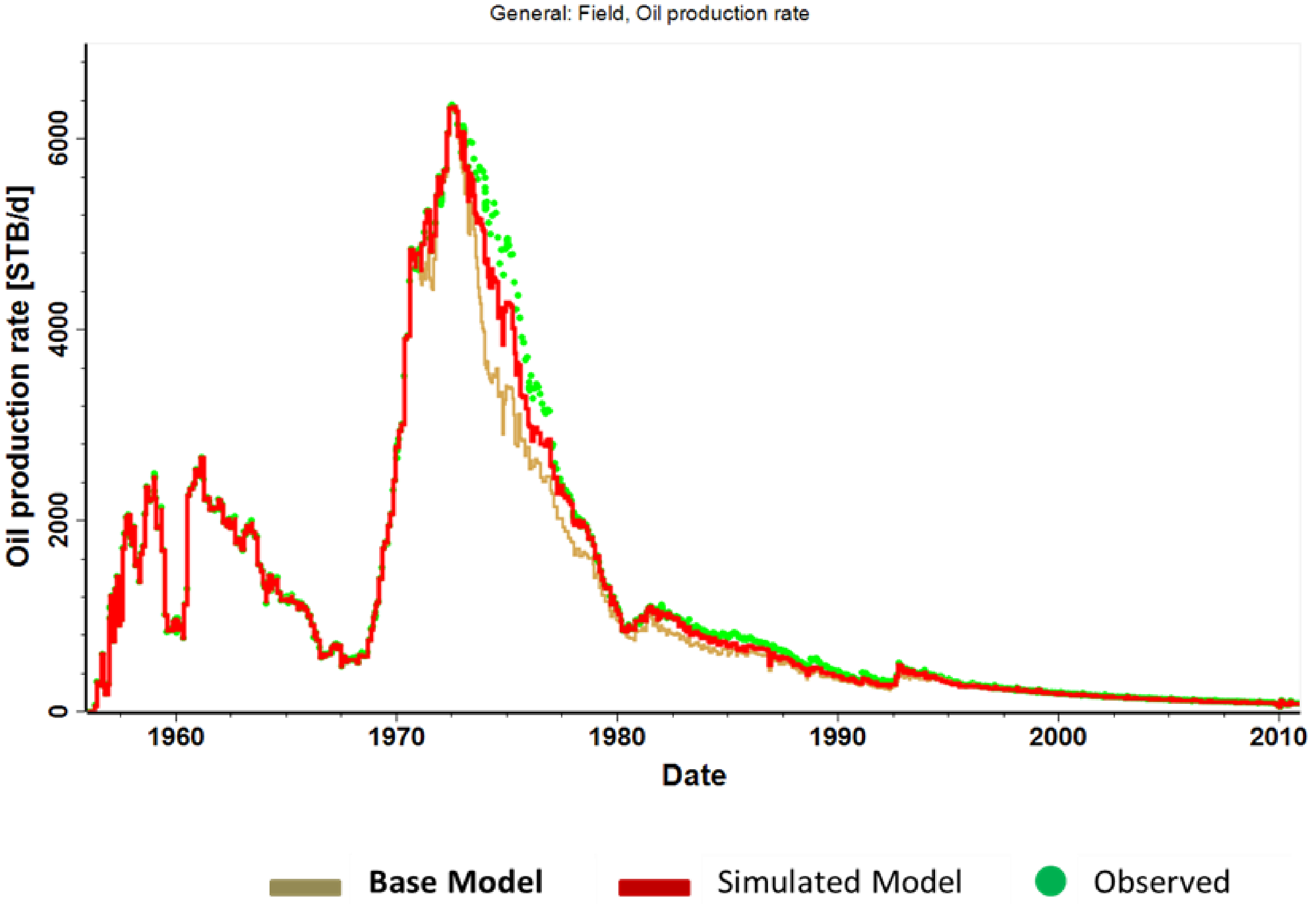
Production History

- *Primary (1956 – 1964)*

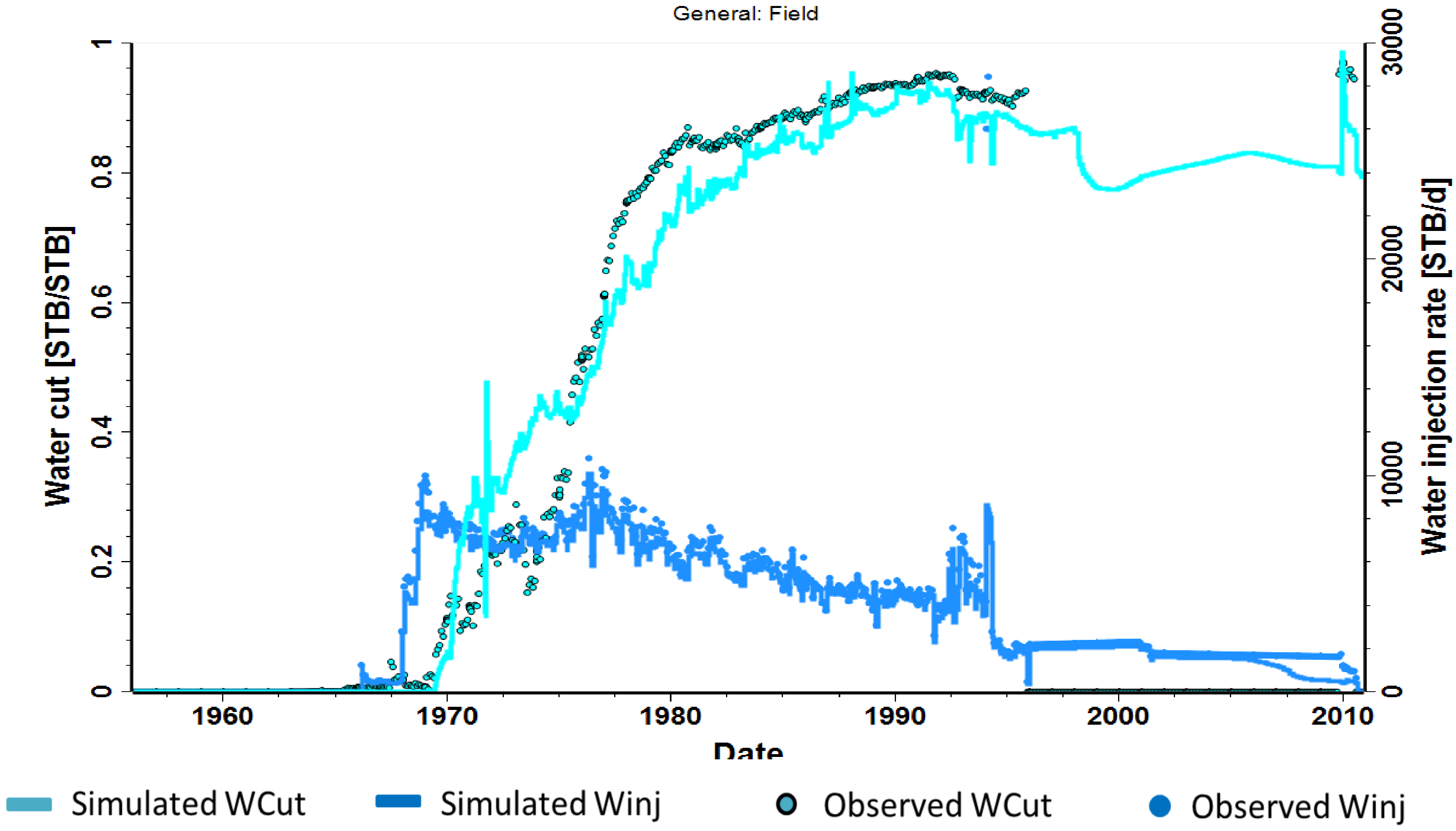
- *Secondary (1964 – 2010)*



Assuming No flow across faults



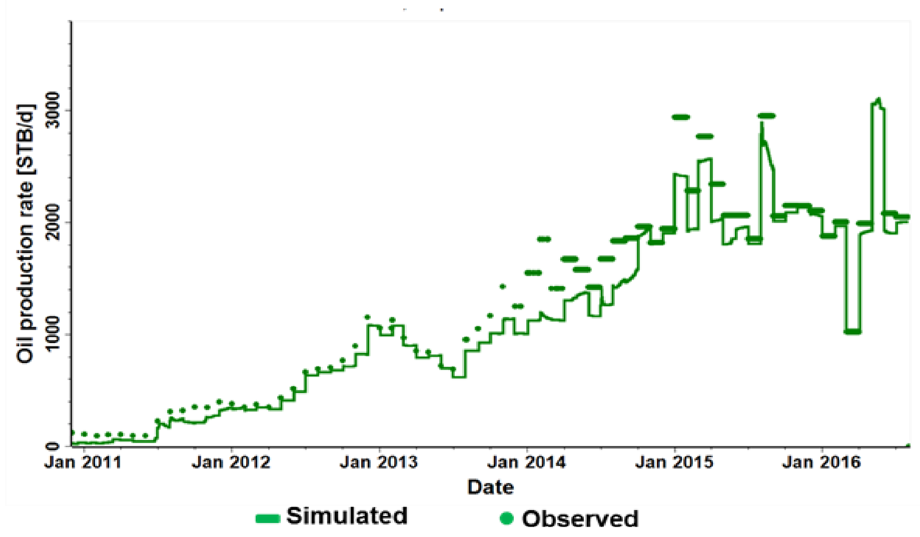
HM Process- Primary & Secondary Recovery

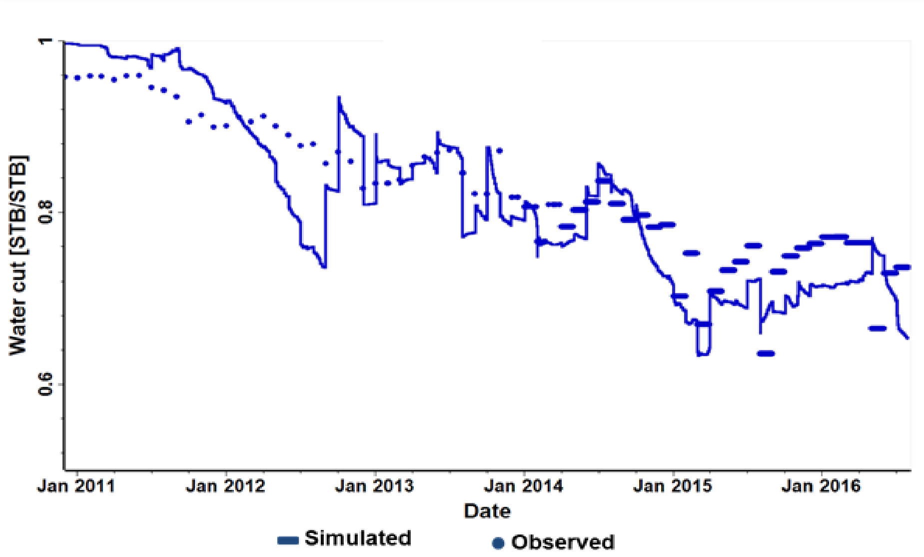


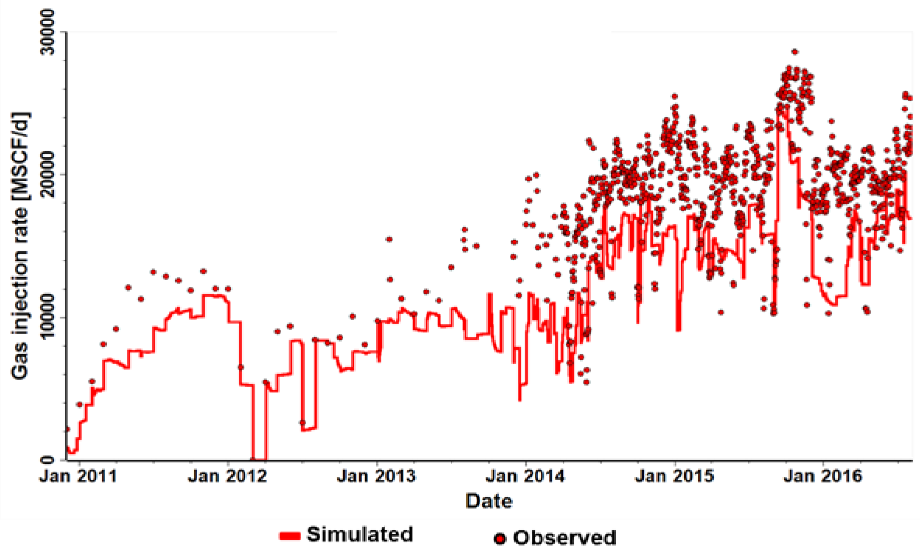
History Match- CO_2-WAG

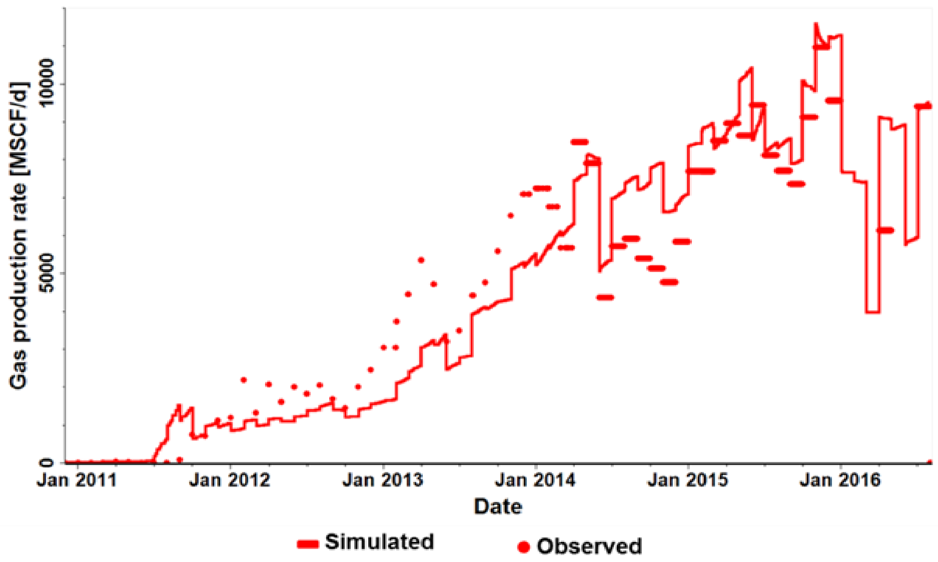
- Initial simulations showed a good match until CO_2 breakthrough
- This was attributed to potential changes in wettability and interfacial tension
- There is a possibility of the Morrow B transitioning into a mixed-wet wettability system
- Corey parameters were adjusted to capture these potential changes to match tertiary recovery process

History Match- CO_2-WAG









Prediction Models

Prediction cases (Aug. 2016 – Jan 2036)

- **Case 1**: Current WAG patterns (12 wells) and adjacent water injectors (7 wells) with constant 10,000 Mscf/d CO_2 purchase in addition to recycle.

- **Case 2**: Convert all injectors to WAG wells (25 wells) with CO_2 purchase and recycle;

A. With constant CO_2 purchase (10,000 Mscf/d).

B. With decreasing CO_2 purchase from 2022 to 2030 and inject only recycled gas after 2030

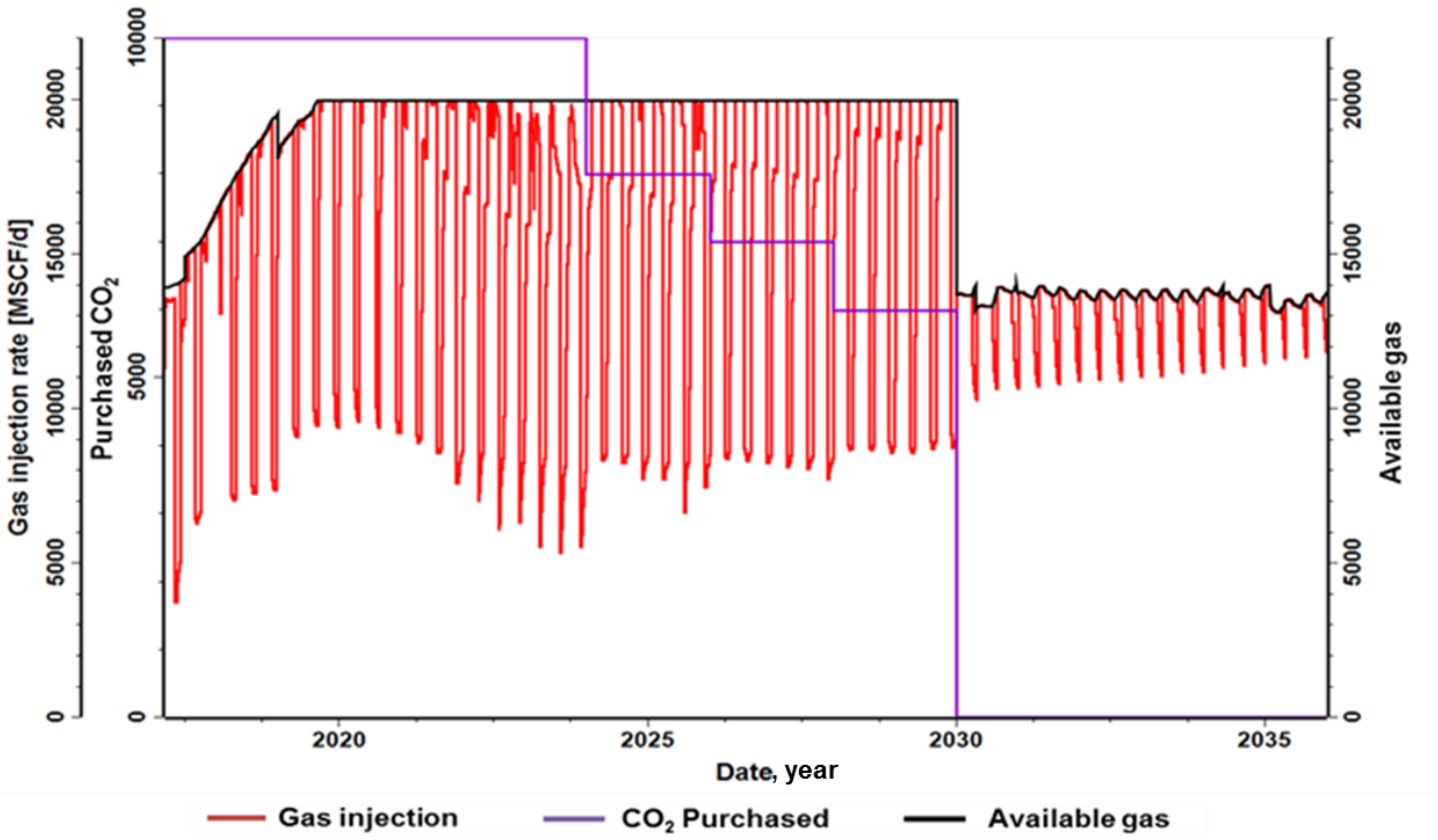
Prediction Models- Additional Conditions

- Compressor capacity ~ 20,000 Mscf/d
- Initial WAG cycle = 3:1
- Production target = 3500 stb/d
- Injection target = CO_2 purchase + Produced (recycled)

Prediction Models- Summary

Results	Units	Case 1	Case 2A	Case 2B
CO_2 Purchased	Bscf	90	90	61
Cumulative CO_2 injected	Bscf	112	123	118
Gross CO_2 Utilization	Bscf/MMStb	8	8	8
Cumulative CO2 Produced	Bscf	72	73	73
CO_2 Recycle	Bscf	22	33	56
Cumulative volume CO_2 stored	Bscf	40	50	45
% Storage	%	45	56	74
Net CO_2 Utilization	Bscf/MMStb	3.0	3.0	3.0
Oil Incremental Recovery	MMStb	14	15	15
% Oil Incremental Recovery	%	19	21	21
Water Injection volume	MMStb	21	14	16

Can the best case be improved?



A possible answer is

OPTIMIZATION

?

Optimization with proxy

- To evaluate the objective function with respect to a set of control parameters, a full simulation must be run. Therefore, the optimization can be a computationally intensive procedure.

- As a simplification, a proxy model can be used to replace the simulations in the optimization process.

- Unless the proxy model is properly validated, the optimization does not have any value.

Objective Function

- To co-optimize CO_2 storage and the oil recovery

- Multi-objective function

$$w_1 \times FOPT + w_2 \times CO_2 \text{ storage}$$

Where

W = weight assigned to vector

FOPT = cumulative oil production

CO_2 storage = CO_2 purchased – CO_2 produced + CO_2 recycle

Selected Control Variables

Control Variables	Units	Minimum	Maximum
Gas cycle Well Group 1(GD1) (2020-2036)	months	2	10
Gas cycle Well Group 2 (GD2) (2020-2036)	months	2	10
Gas cycle Well Group 3 (GD3) (2020-2036)	months	2	10
Gas cycle Well Group 4 (GD4) (2020-2036)	months	2	10
Water Cycle Well Group 1 (WD1) (2020-2036)	months	0	3
Water Cycle Well Group 2 (WD2) (2020-2036)	months	0	3
Water Cycle Well Group 3 (WD3) (2020-2036)	months	0	3
Water Cycle Well Group 4 (WD4) (2020-2036)	months	0	3
Production Group Rate Target (PROD_30)(2020-2036)	stb	500	3500
Well Bottomhole Injection Pressure (BHP_I)	psia	4700	5000
Well Bottomhole Production Pressure (BHP_P2) (2020-2036)	psia	1500	2500

Proxy Modeling

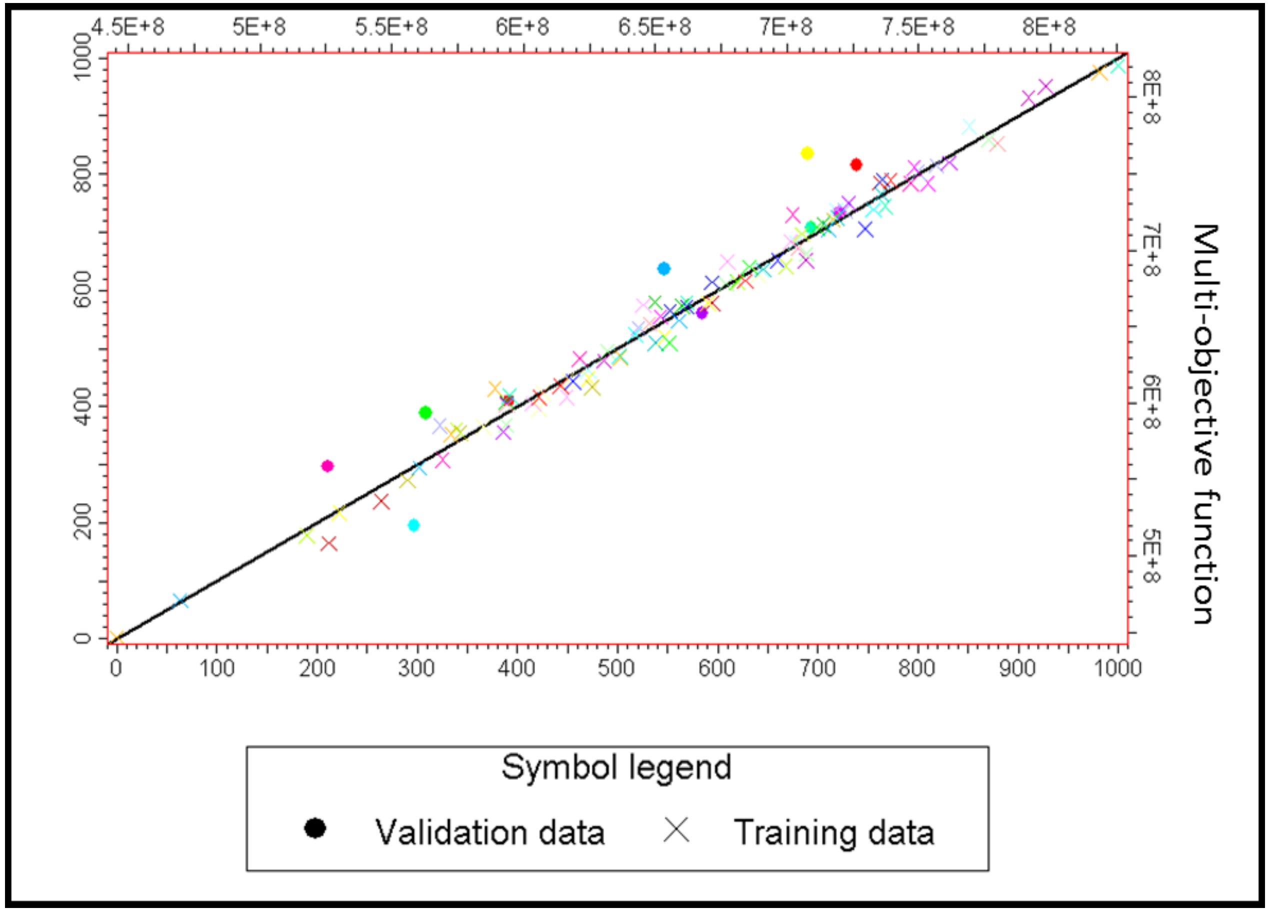
- Polynomial Response surface method

$$y(x) = \beta_0 + \sum_i \beta_i X_i + \sum_i \sum_j \beta_{ij} X_i X_j + \sum_i \beta_{ii} X_i^2$$

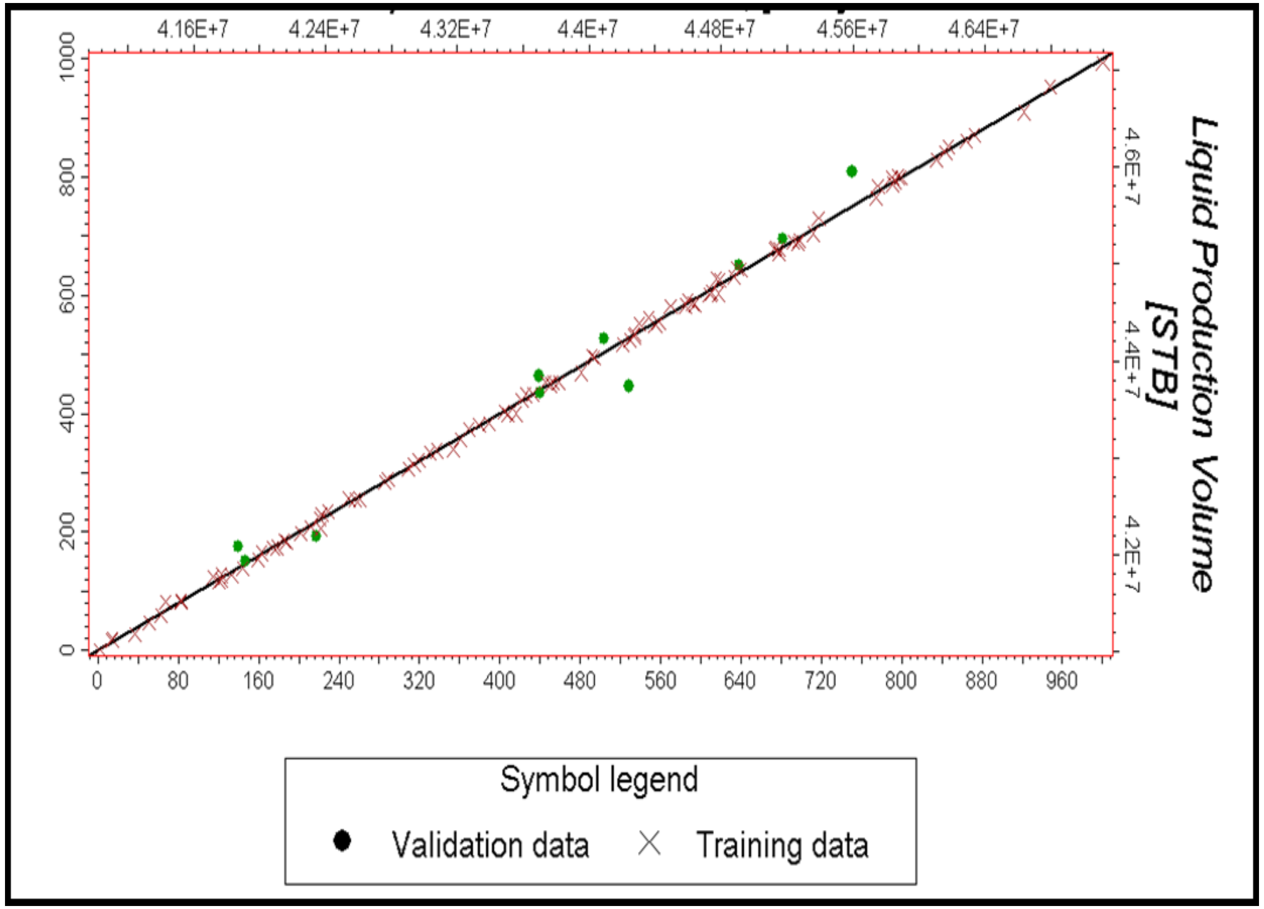
- The quadratic model requires a minimum of (N+1)(N+2)/2
- 100 full simulations for training
- 10 validation simulations
- Using Latin hypercube sampling (DoE) algorithm

Proxy Validation

Multi-Objective function



Oil Production

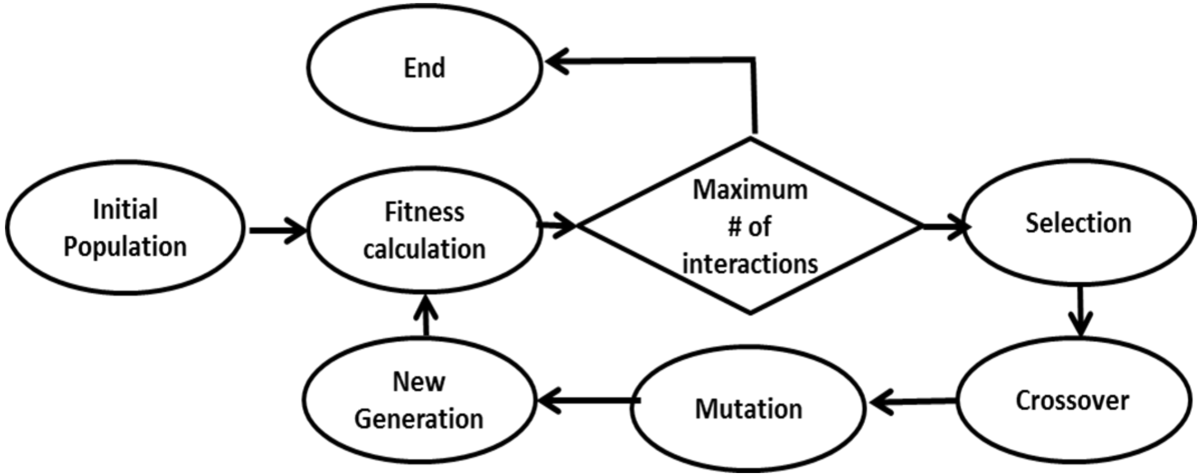


Genetic Algorithm

- Stronger global search capabilities than the Evolution strategy
- Mixed-integer capabilities
- Roulette Wheel used as fitness selection operator
- ***Optimum solution realized at iteration # 1051***

Parameters used in the optimization process

Population	100
Maximum generations	20
Mutation probability	5%
Minimum Iterations	1101



Flowchart of a genetic algorithm

Optimum Surrogate Case Validation

Response Surface Equation Export For Multi-Objective Function 2036-01-01 00:00:00.000

Proxy Name : Response surface proxy

Variables	Min	Max
$BHP_INJ1	4602	4997.24
$BHP_PROD2	1008	2485.62
$GCB1	2.074	9.92
$GCB2	2.02	9.96
$GCB3	2.076	9.95
$GCB4	2.076	9.99
$PROD1	1801	2989.83
$PROD2	1506	2493.69
$WCB1	0.016	2.98
$WCB2	0.028	2.99
$WCB3	0.026	3.00
$WCB4	0.009	2.99

Variables	Input Value
$BHP_INJ1	4585.0
$BHP_PROD2	1735.0
$GCB1	9.5
$GCB2	7.0
$GCB3	9.0
$GCB4	5.8
$PROD1	2318.2
$PROD2	2417.7
$WCB1	0.9
$WCB2	0.4
$WCB3	0.3
$WCB4	0.2

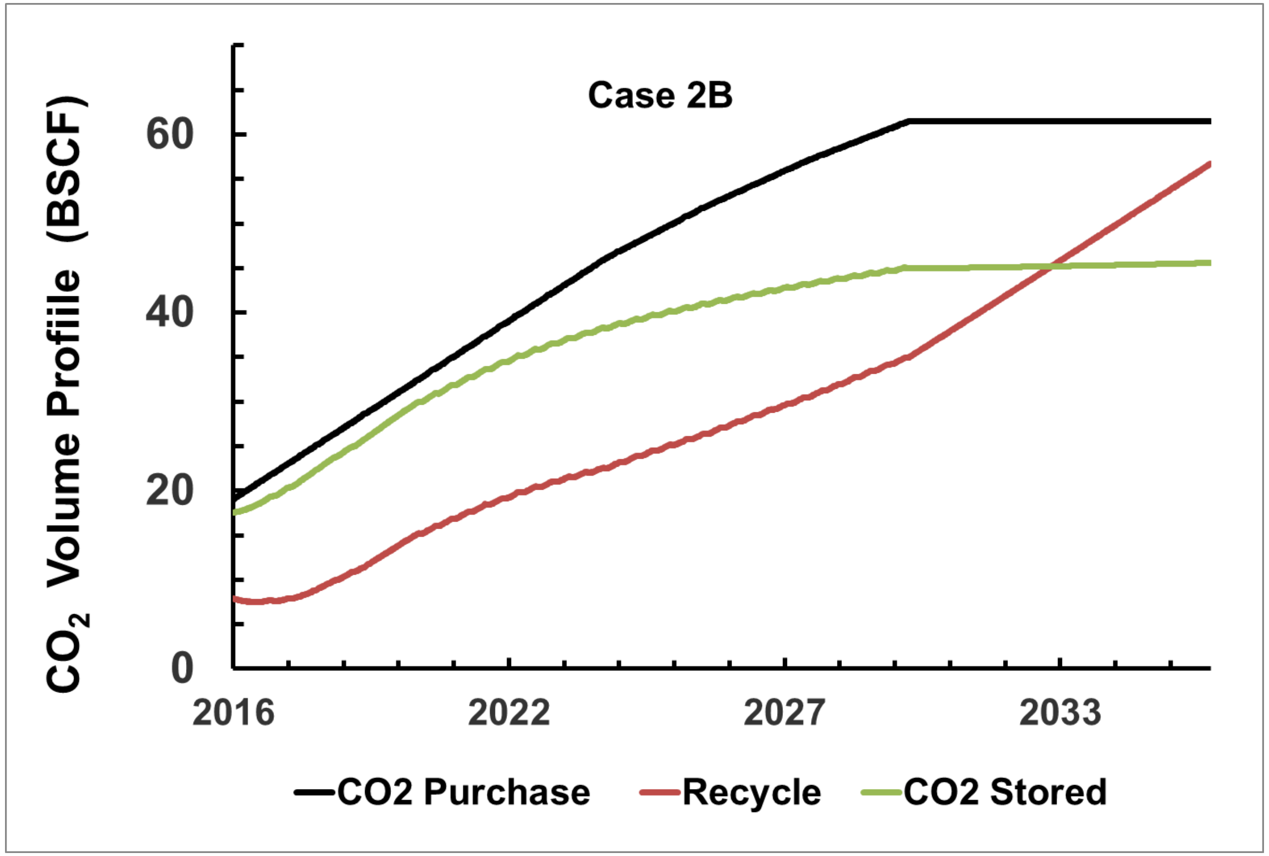
Response	76621657
Simulated	77811411
% Error	**1.53**

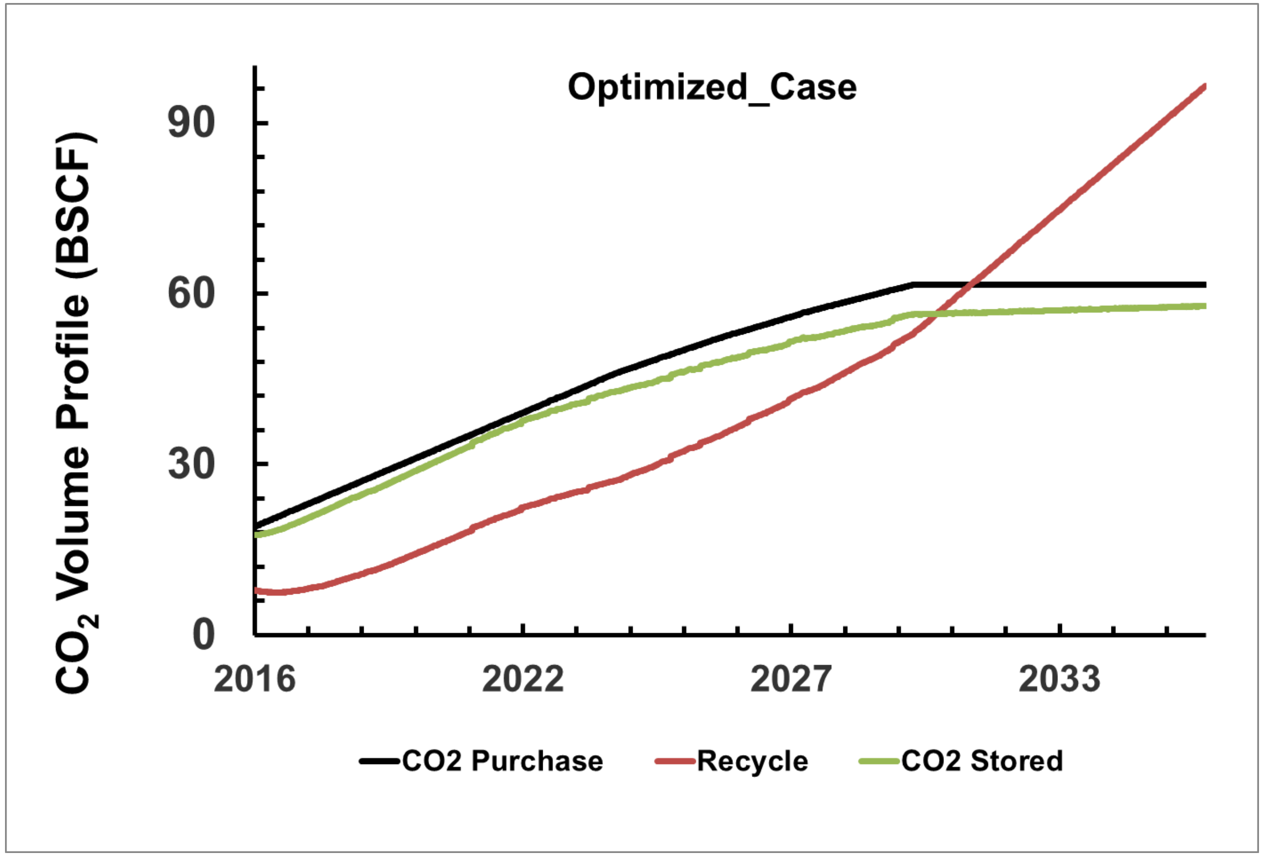
Coefficient Type **Coefficient Value** NOTE: Coefficients are related to the equation in terms of shifted variables. Example: F(X) = F[(X1-X1min),(X2-X2min),...]

Prediction Models- Summary

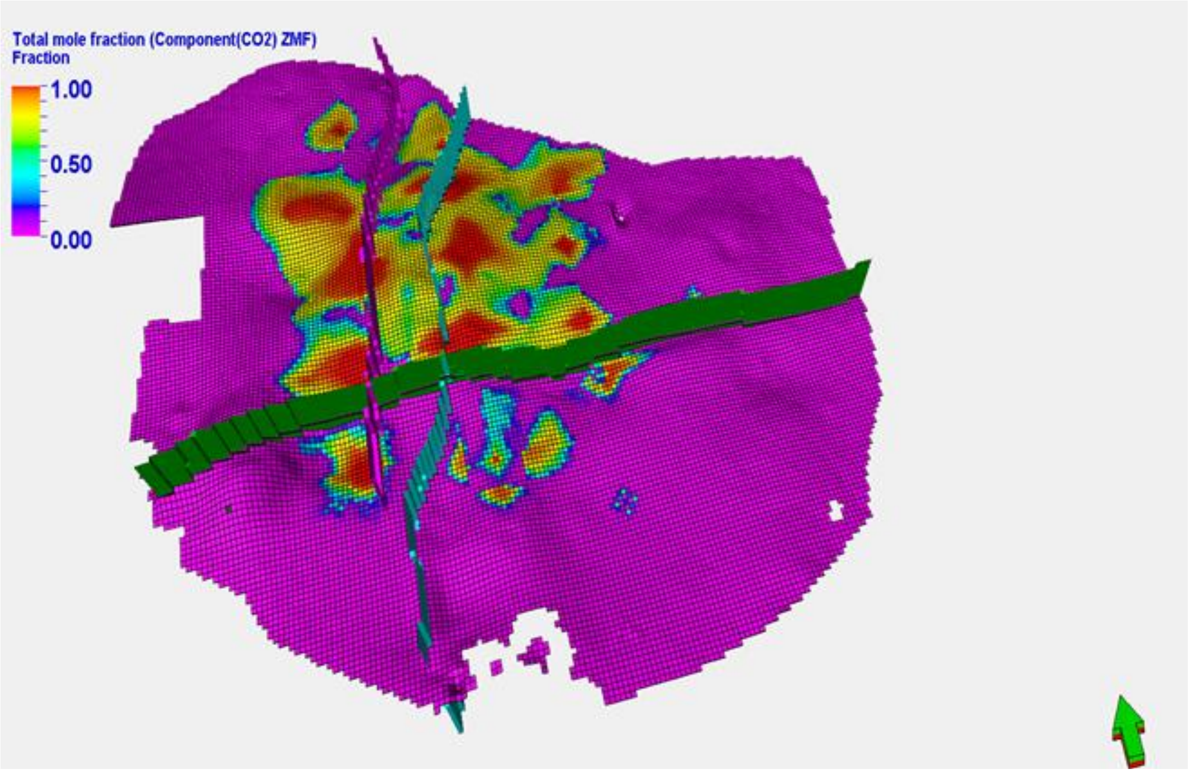
Results	Units	Case 2B	Optimized
CO_2 Purchased	Bscf	61	61
Cumulative CO_2 injected	Bscf	118	158
Gross CO_2 Utilization	Bscf/MMStb	8	7
Cumulative CO2 Produced	Bscf	73	100
CO_2 Recycle	Bscf	56	97
Cumulative volume CO_2 stored	Bscf	45	58
% Storage	%	74	94
Net CO_2 Utilization	Bscf/MMStb	3.0	3.2
Oil Incremental Recovery	MMStb	15	18
% Oil Incremental Recovery	%	21	25
Water Injection volume	MMStb	16	13

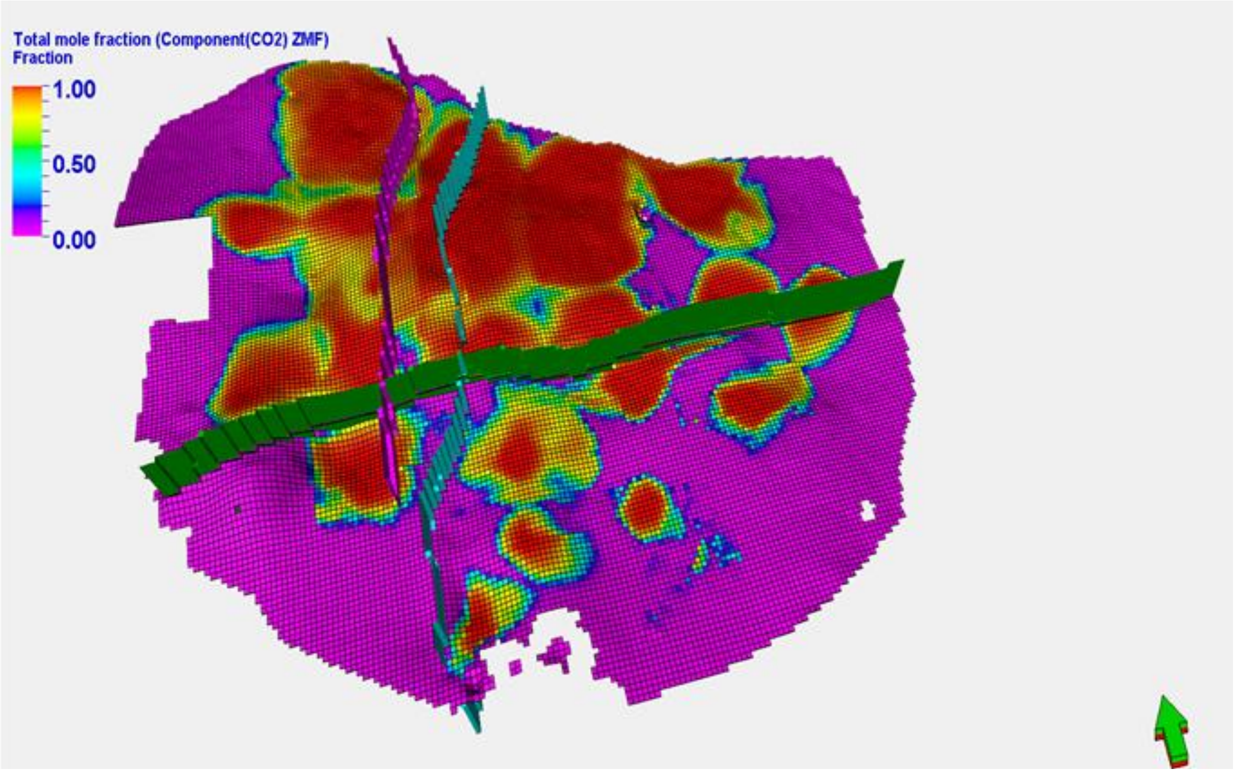
Prediction Models- CO_2 Volume Profile





3D Total Mole fraction of CO_2 distribution





Prediction Models- Simple Economic Model

Assumptions

- Oil price ~ $45/bbl
- Royalty ~ 10%
- Water injection cost ~ $1/bbl
- Recycle CO_2 credit ~ $0.01/ton
- Produced CO_2 charge ~ $0.01/ton
- Taxes (on taxable income) ~ 10%

Prediction Models- Simple Economic Model

Economic Parameters	Unit cost	Case 1	Case 2A	Case 2B	Optimized
Total Oil Revenue ($M)	$ 45/bbl	613	670	676	1138
Royalty (10%)	0.01	6	7	7	11
Recycle CO_2 Credit	$ 0.01	12	17	30	51
Total Revenue ($M)		619	680	699	1177
Purchased CO_2 Cost	$ 40/ton	187	187	128	128
Produced CO_2 Charge	$ 0.01	38	38	38	53
Water injection Cost	1	21	14	16	13
Total Operating Cost ($M)		245	239	182	194
Taxable Income		373	441	517	984
Taxes (10%)	0.01	4	4	5	10
Net Present Value ($M)		370	437	512	974

Conclusions

- This work presented a recent efforts on history matching; scenario based performance assessment and optimization for CO_2 -EOR process in the FWU
- Predicted models showed recycling a high percentage of produced gas, addition of well/patterns, and reduction of CO_2 purchase after some years of operations has a tendency of yielding higher oil recovery and CO_2 storage
- The use of complex multi-objective function resulted in optimum operational variables that yielded 94% of CO_2 storage and more than 25% incremental of OOIP oil recovery beyond waterflood at FWU.
- This work, and ongoing efforts, will serve as blue print for future CCUS project with Anadarko basin and similar geological basins in the world

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