Optimizing CO_2 Sweep based on Geochemical, and Reservoir Characterization of the Residual Oil Zone of Hess's Seminole Unit

Project Number: **DE-FE0024375**

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National Energy Technology Laboratory

Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 13-16, 2018

Presentation Outline

Technical Status

- Characterization and Role of Capillary Pressures
- Origin of ROZ in the San Andres Formation
- Simulation of optimizing CO_2 sweep during WAG injection into ROZ

Accomplishments to Date

Lessons Learned

Synergy Opportunities

Project Summary

Technical Status

Reservoir Characterization

- 5 continuous cores through the entire reservoir logged, high resolution color scanned, sampled, core plugged (2,400 feet core)
- 6 continuous cores through ROZ reservoir, logged scanned etc. (1,900 feet core)
- Nearly a thousand measurement of capillary pressure and water saturation made on 130 core plugs and over 500 NMR measurements made, relative permeability measurements underway

Petro-physical Measurements

Reservoir Characterization Workflow:

1. Centrifuge Measurement… **capillary pressure v saturation**…. With NMR characterization

1. **Relative Permeability Measurements**… water floods of oil saturated cores

2. **CO_2 floods of cores** previously water flooded with NMR characterization

CO2 Trapping Mechanisms

Structural trapping

Dissolution trapping

Residual trapping

Capillary Trapping

Mineral trapping

Oil Phase trapping

Capillary Pressure Studies

- Experiments measure air/brine, air/oil, or mercury/air capillary pressures versus saturation
- Covert to brine/CO_2 etc. using experimental data on Interfacial Tensions (IFT) and contact angles.
- Issue: **large pressure difference** between **injector well (25 MPa)** and **producer (7.6 MPa)** significantly impact brine CO_2 capillary pressures!

Conversion factor conversion: calculation

We start with **the Young-Laplace equation**

$$P_c = \frac{2\sigma cos\theta}{r}$$

For the a/b and g/b systems, we can write

$$\frac{2\sigma_{a/b}\ cos\theta_{a/b}}{P_{c,a/b}} = \frac{2\sigma_{g/b}\ cos\theta_{g/b}}{P_{c,g/b}}$$

Then,

$$P_{c,g/b} = \frac{\sigma_{g/b}\ cos\theta_{g/b}}{\sigma_{a/b}\ cos\theta_{a/b}} P_{c,a/b} = \frac{36.5 \times cos57^{\circ}}{76 \times cos0^{\circ}} P_{c,a/b} = \frac{36.5 \times 0.54}{76 \times 1} P_{c,a/b} = 0.259 P_{c,a/b}$$

That is,

$$P_{c,g/b} = 0.259 P_{c,a/b}$$

Injector: $P_{c,g/b} = \mathbf{0.319 P_{c,a/b}}$

Producer: $P_{c,g/b} = \mathbf{0.199 P_{c,a/b}}$

Conversion factors differ significantly with fluid pressure

Wang and Tokunaga, 2015	Injector: $P_{c,g/b} = 0.319P_{c,a/b}$ Producer: $P_{c,g/b} = 0.199P_{c,a/b}$
Al-Yaseri et al, 2017	Injector: $P_{c,g/b} = 0.010P_{c,a/b}$ Producer: $P_{c,g/b} = 0.172P_{c,a/b}$

The main uncertainty is the contact angle of CO2-brine-dolomite at the injector side (25 MPa, 377 K)

IMPACT OF CO2/BRINE CAPILLARY PRESSURES ON CO2 STORAGE

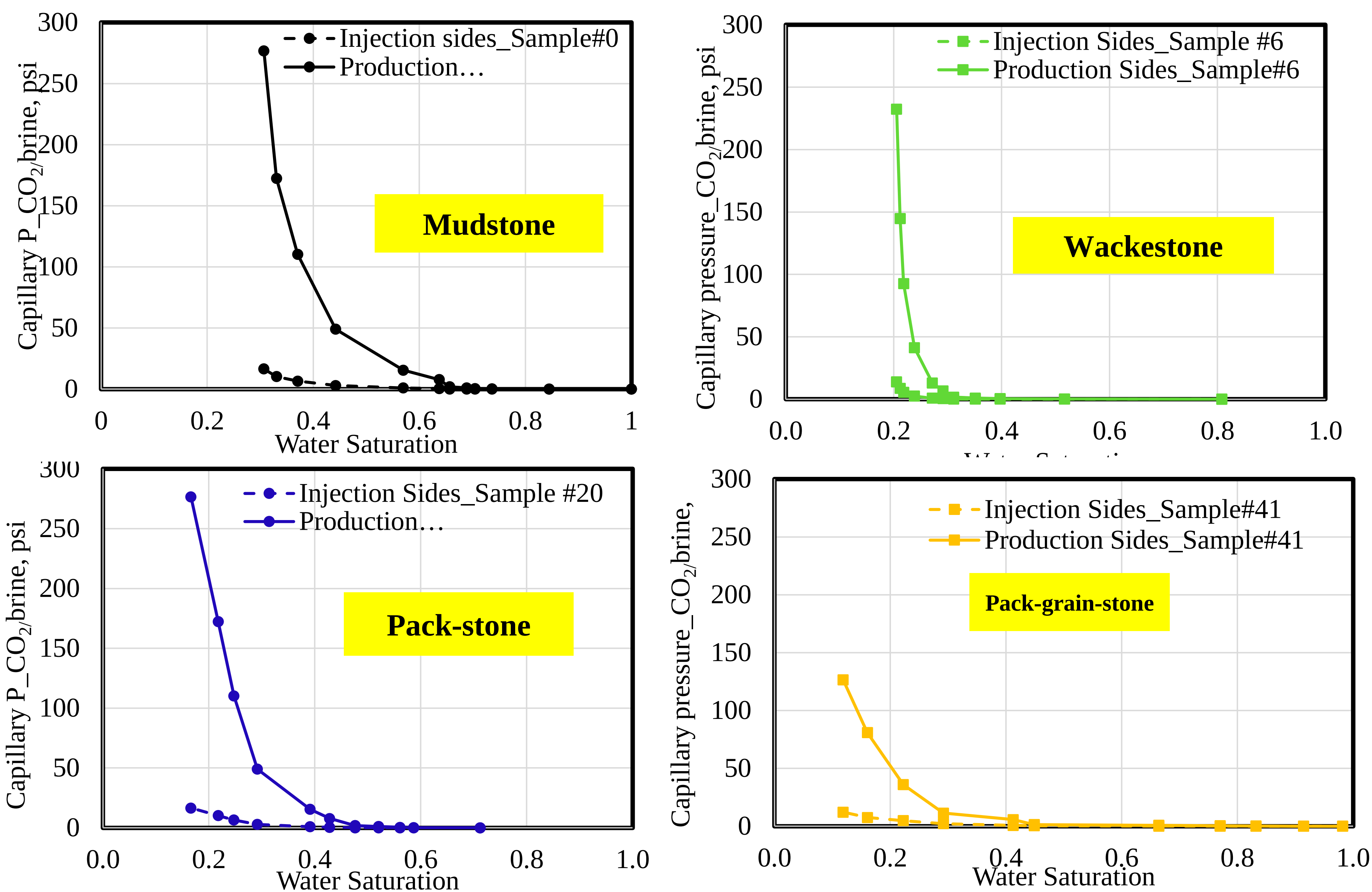
Some preliminary estimates:

Near production well …. maximum CO_2 saturation from capillary trapping is **~ 15 %**

Near injection well … maximum CO_2 saturation from capillary trapping is **~ 6.5 %**

IMPACT OF LITHOFACIES ON CAPILLRY PRESSURES

Representative CO_2/brine Capillary Pressure Curves



MULTIPHASE FLUID FLOW SIMULATIONS

1. Simulations of origin of ROZ

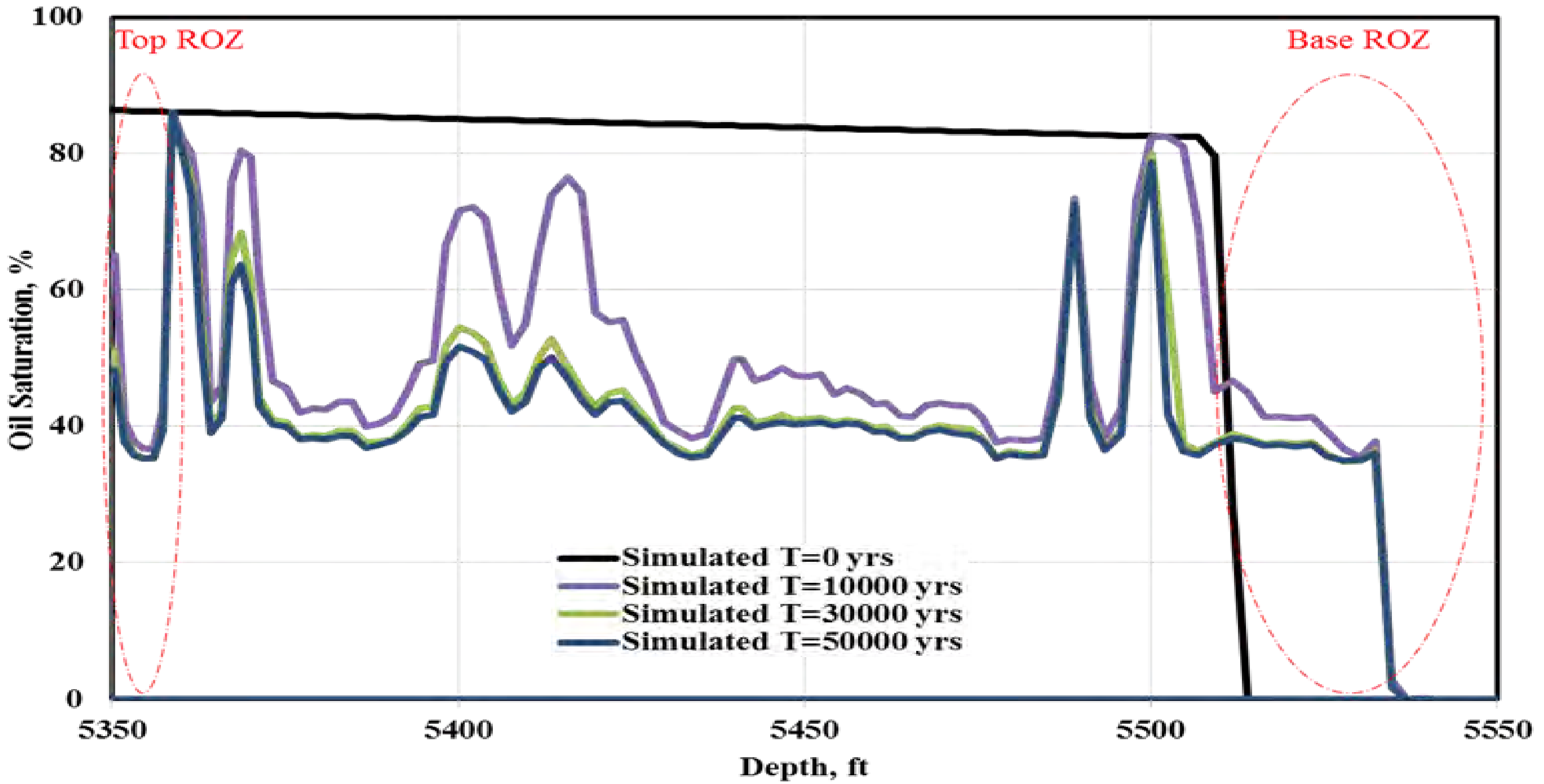
2. Simulations of WAG injections into ROZ with varying reservoir heterogeneity

3. NEXT generation modelling using **Intercept/Echelon** on TACC Supercomputers…

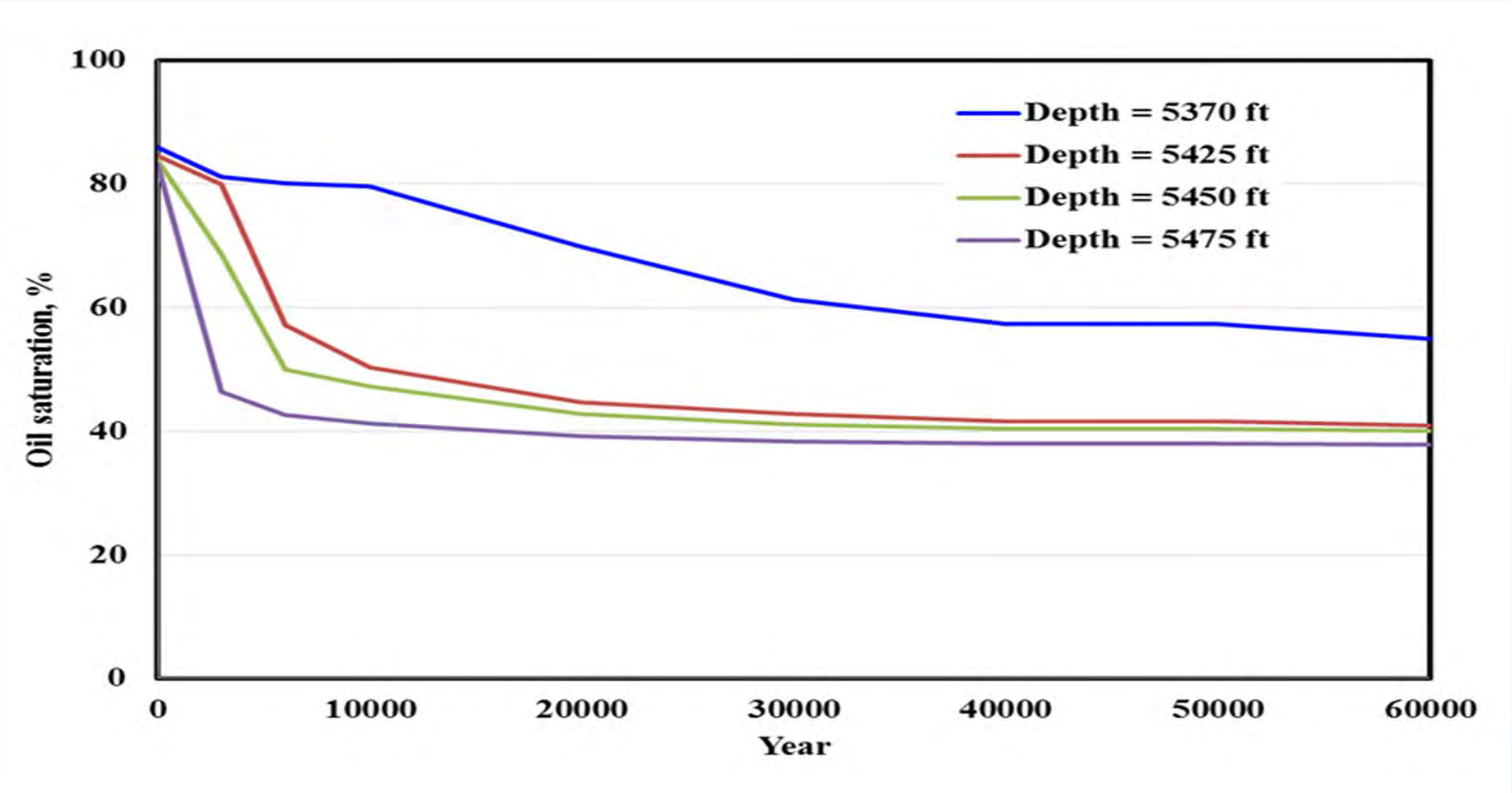
Simulations of origin of ROZ

- Using Eclipse full physics simulator
- Assumes aquifer flow model proposed by Melzer and others…
- Examines impact of varying aquifer flow rate and time scale of increased aquifer flow rates
- Compares resultant predicted oil saturation with depth to data for Seminole reservoir published by Hess.

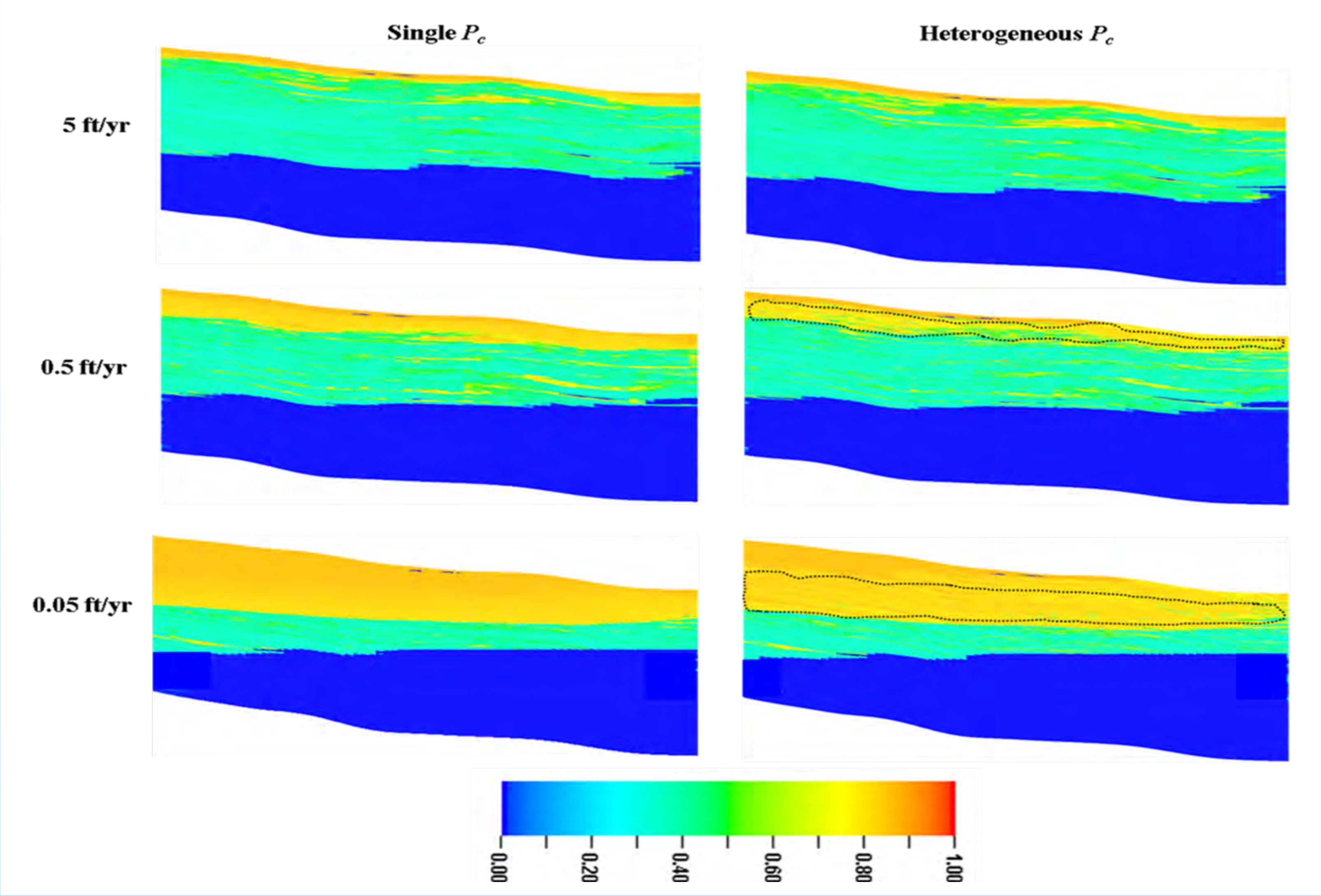
Simulated ROZ Oil Saturation over Time



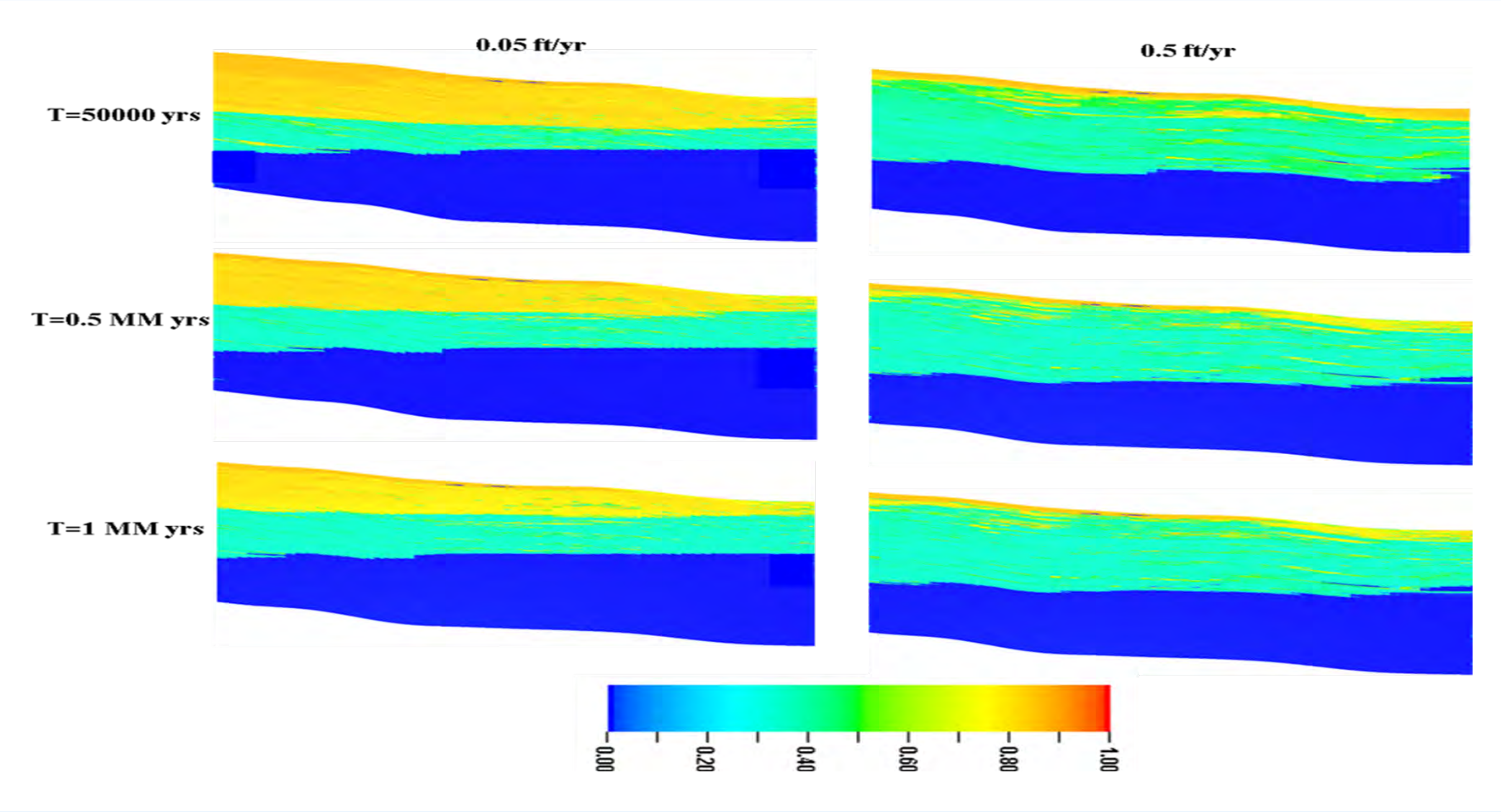
Change in Oil Saturation at Specific Reservoir Depths over Time



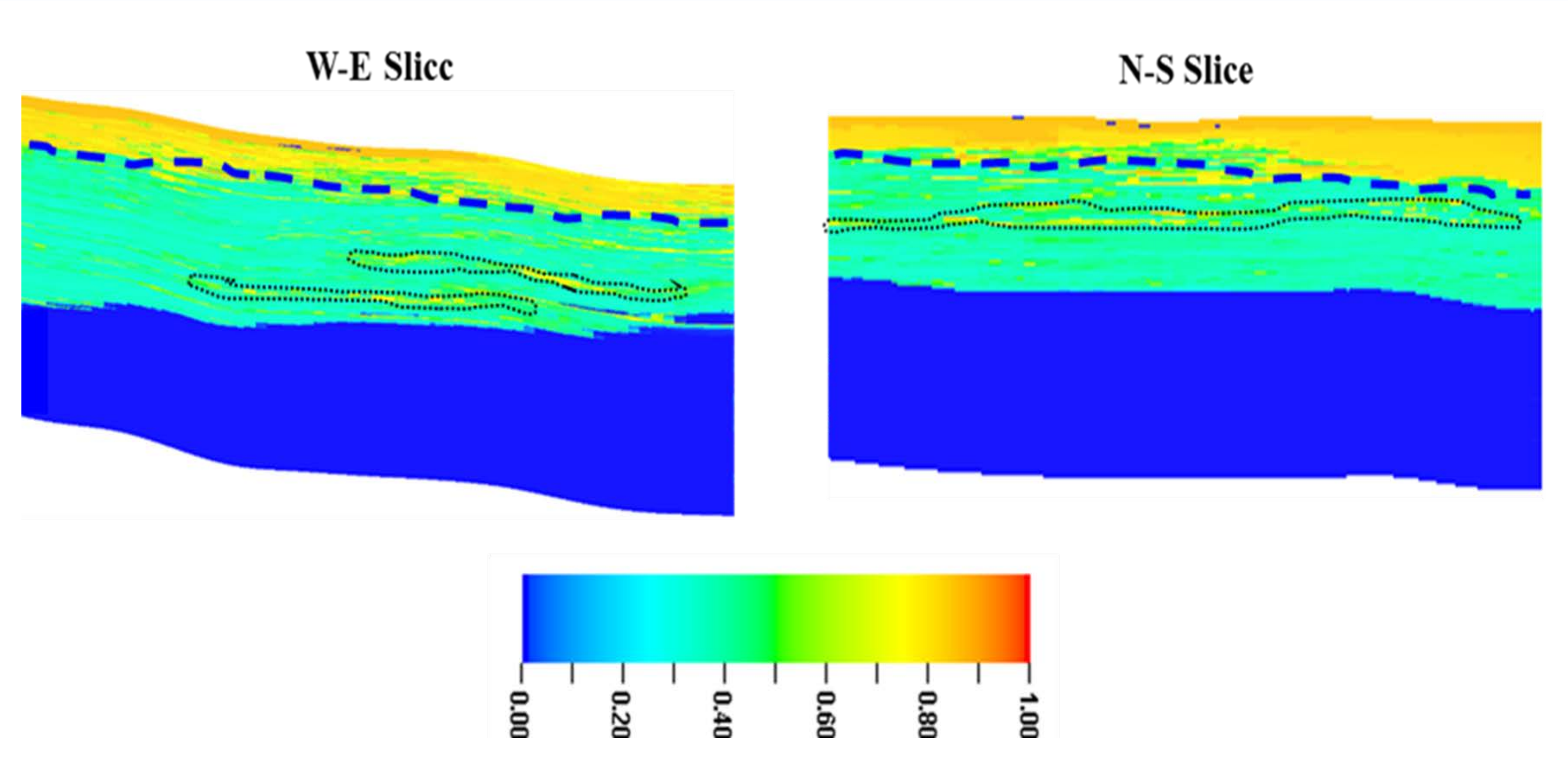
Impact of Heterogeneous Capillary Pressures on the Nature of ROZ Development



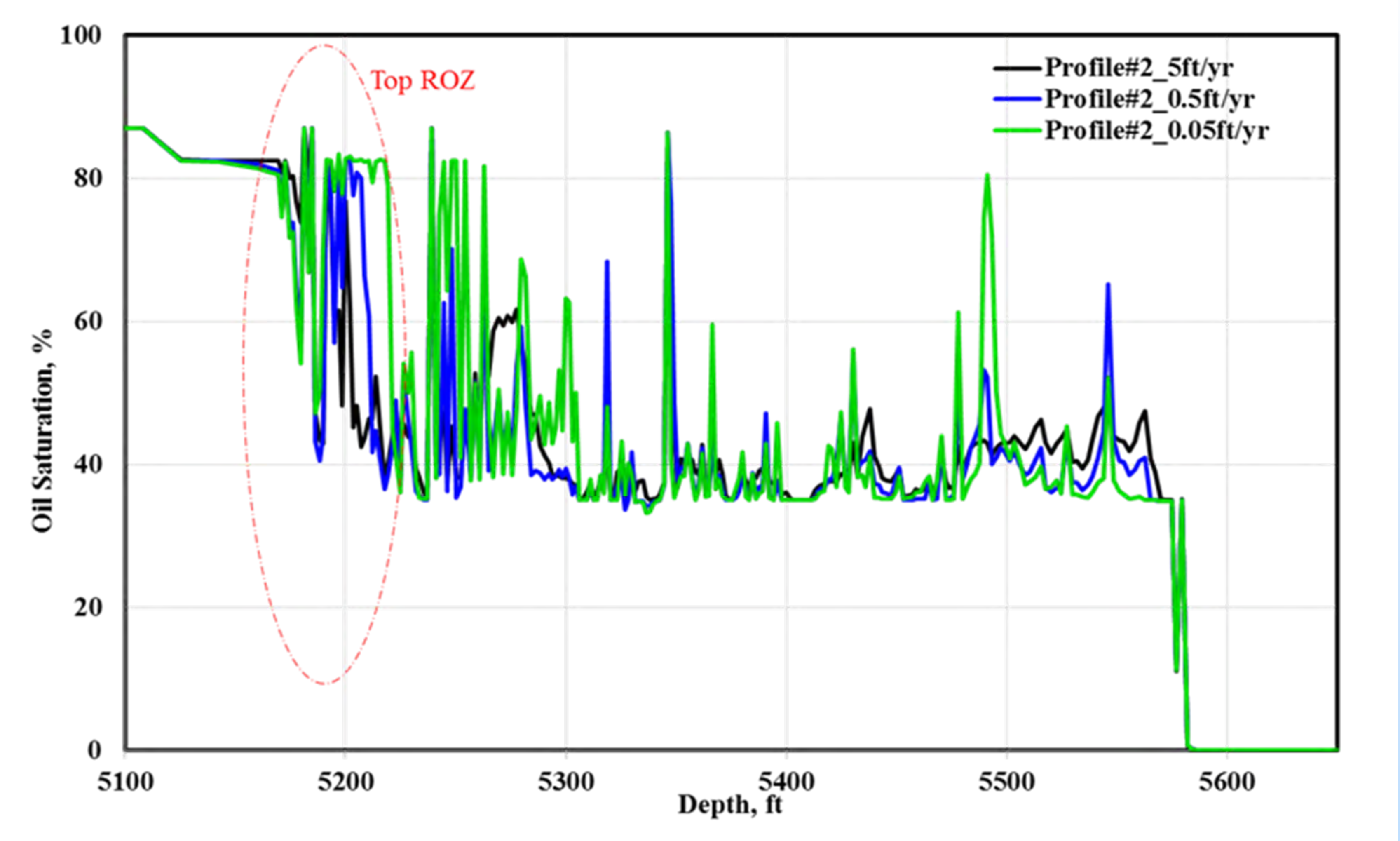
ROZ Oil Saturations as a Function of Flowrate



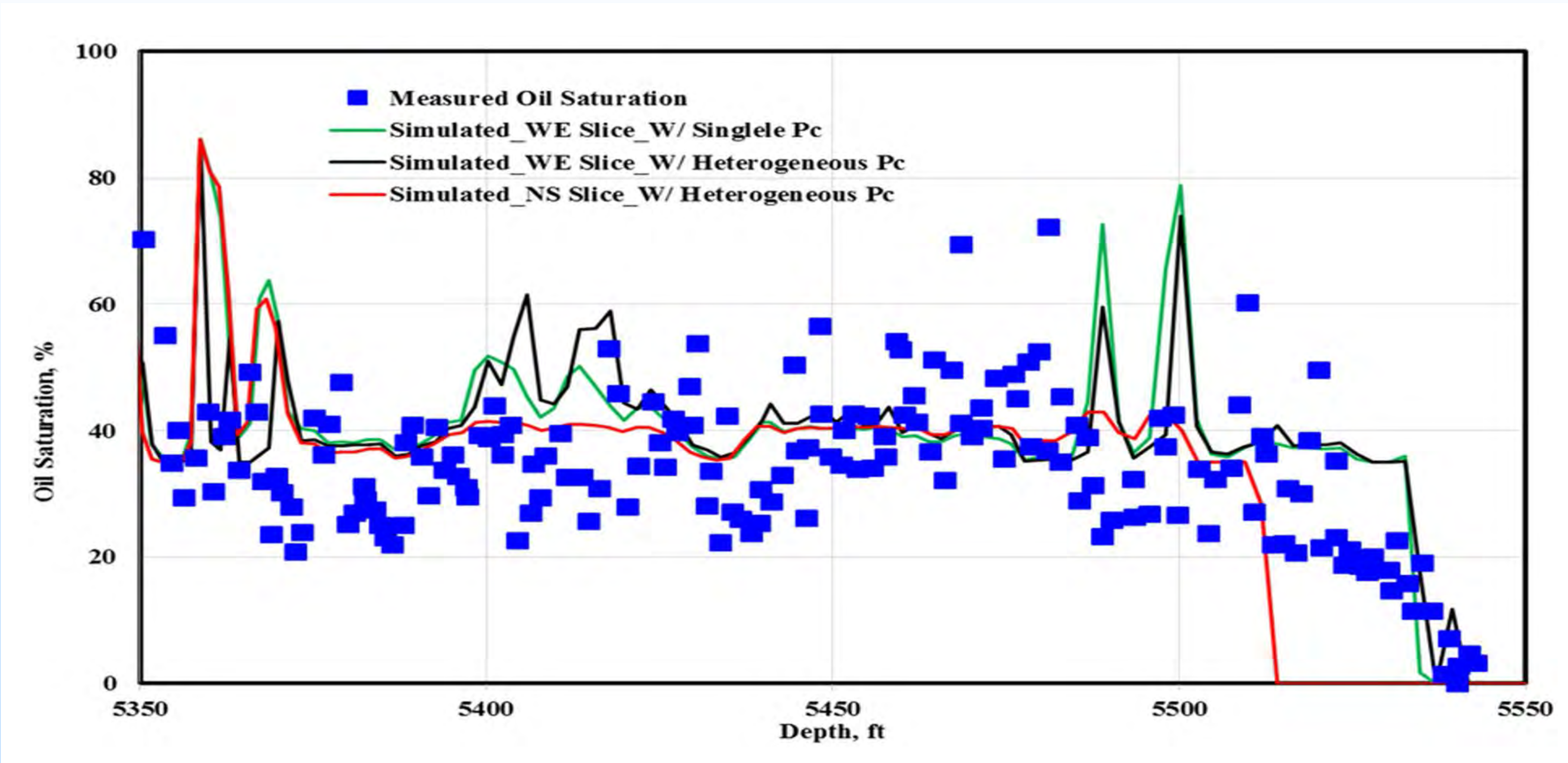
High Oil Saturation Zones within ROZ



ROZ Oil Saturation Profiles with Variable Aquifer Flow Rates



Simulated ROZ Oil Saturation versus Well Measurements

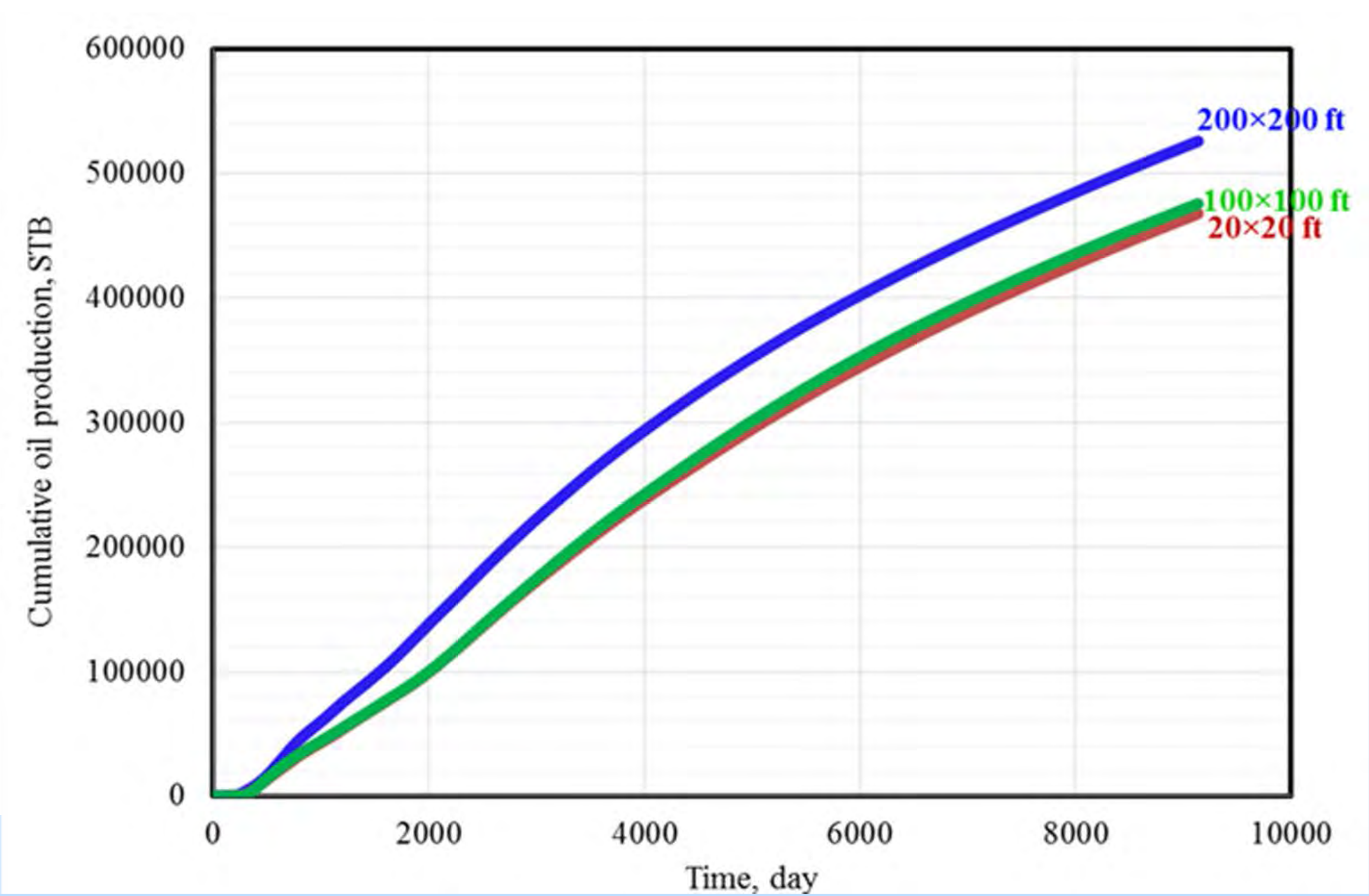


SIMULATION OF WAG OIL PRODUCTION AND ASSOCIATED CO_2 STORAGE FROM ROZ

First Generation Simulations

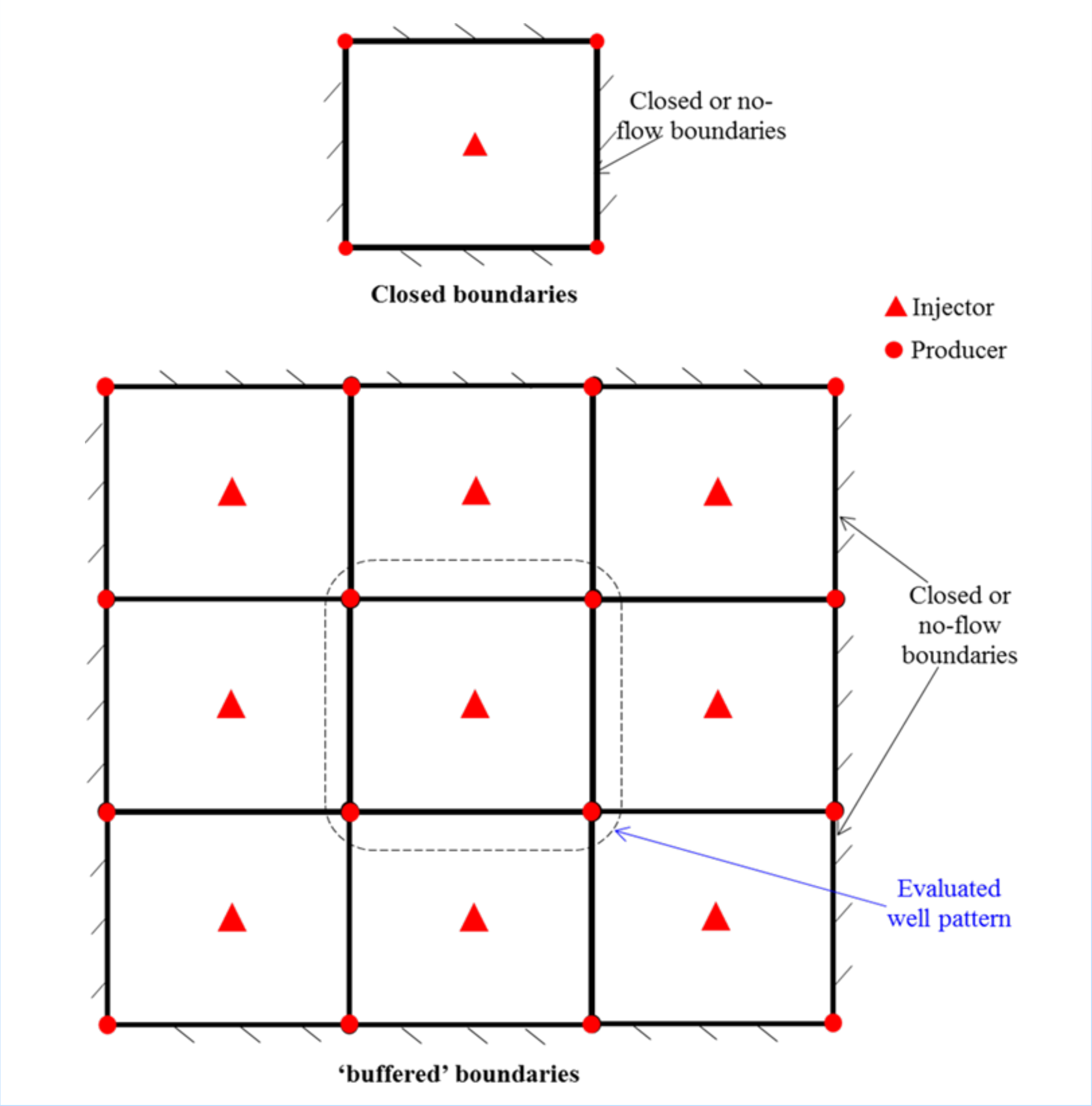
- Using Eclipse full physics simulator
- First established **optimum cell size**
- Tested a variety of **boundary conditions**
- Examined **impact of WAG ratio** (water to gas ratio)
- Investigated **impact of heterogeneity** by using test volumes from different parts of the reservoir

Cumulative Oil production Versus Cell Size

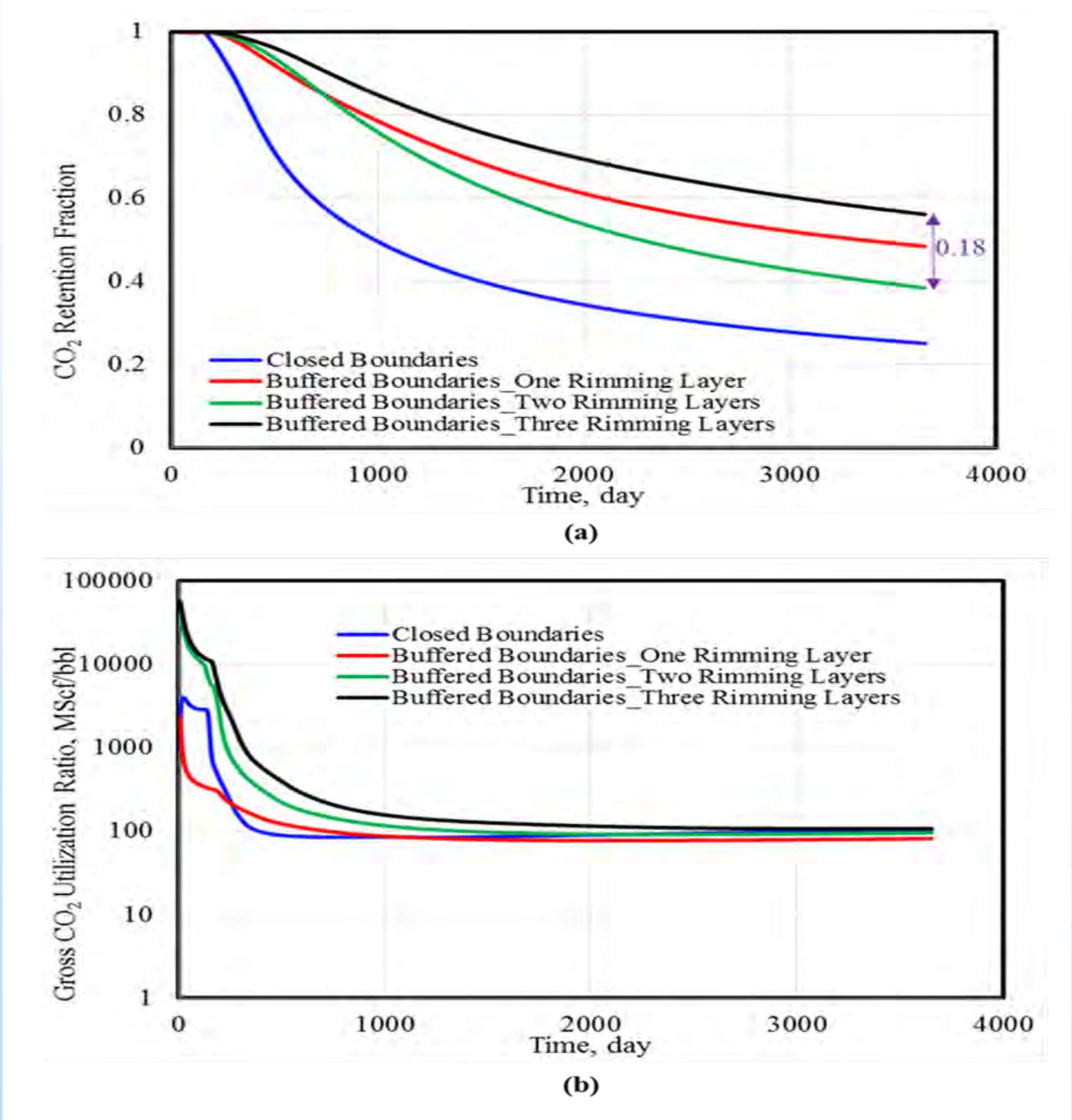


Impact of Boundary Conditions

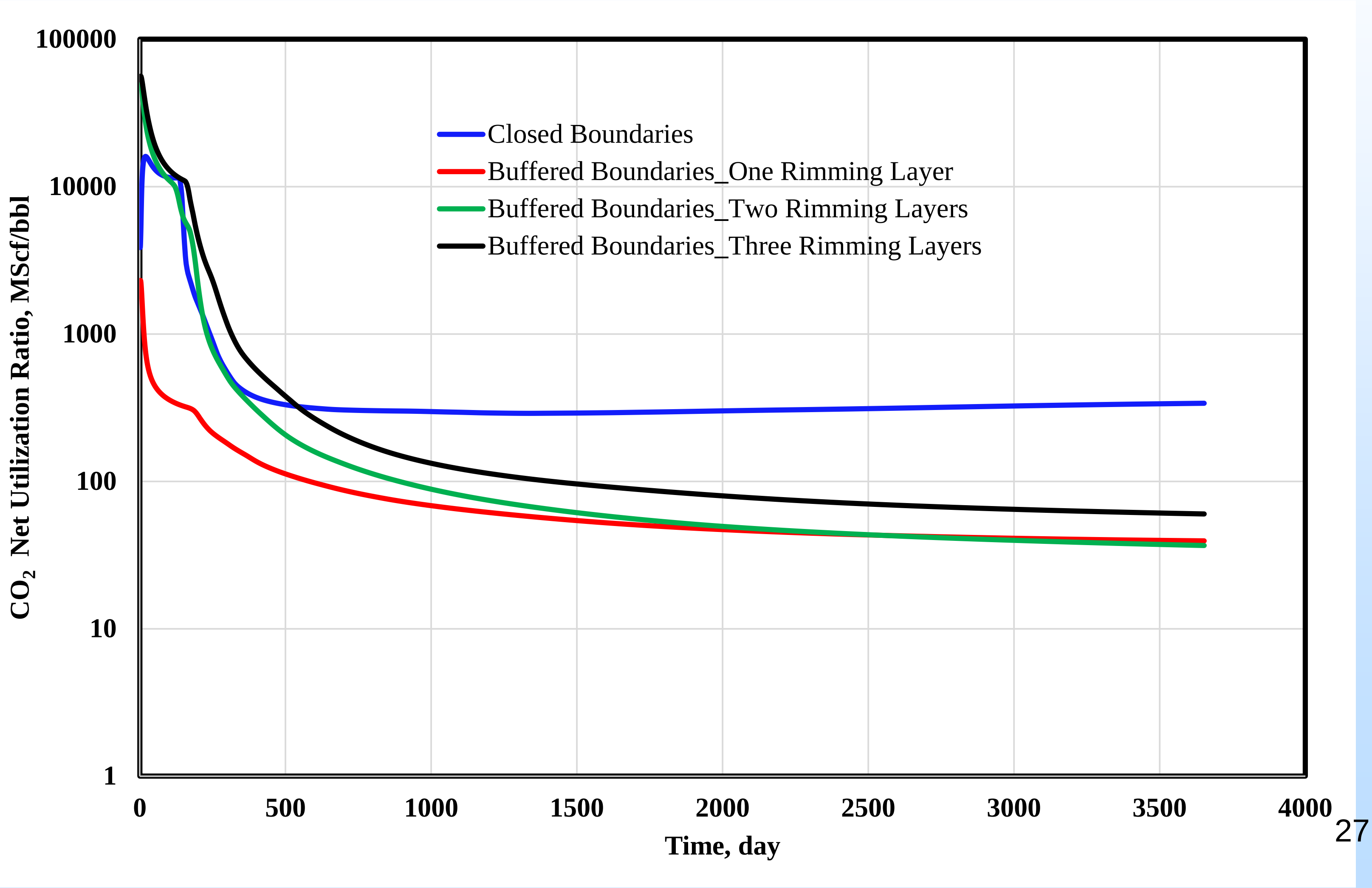
Boundary Conditions for ROZ Sweep Efficiency



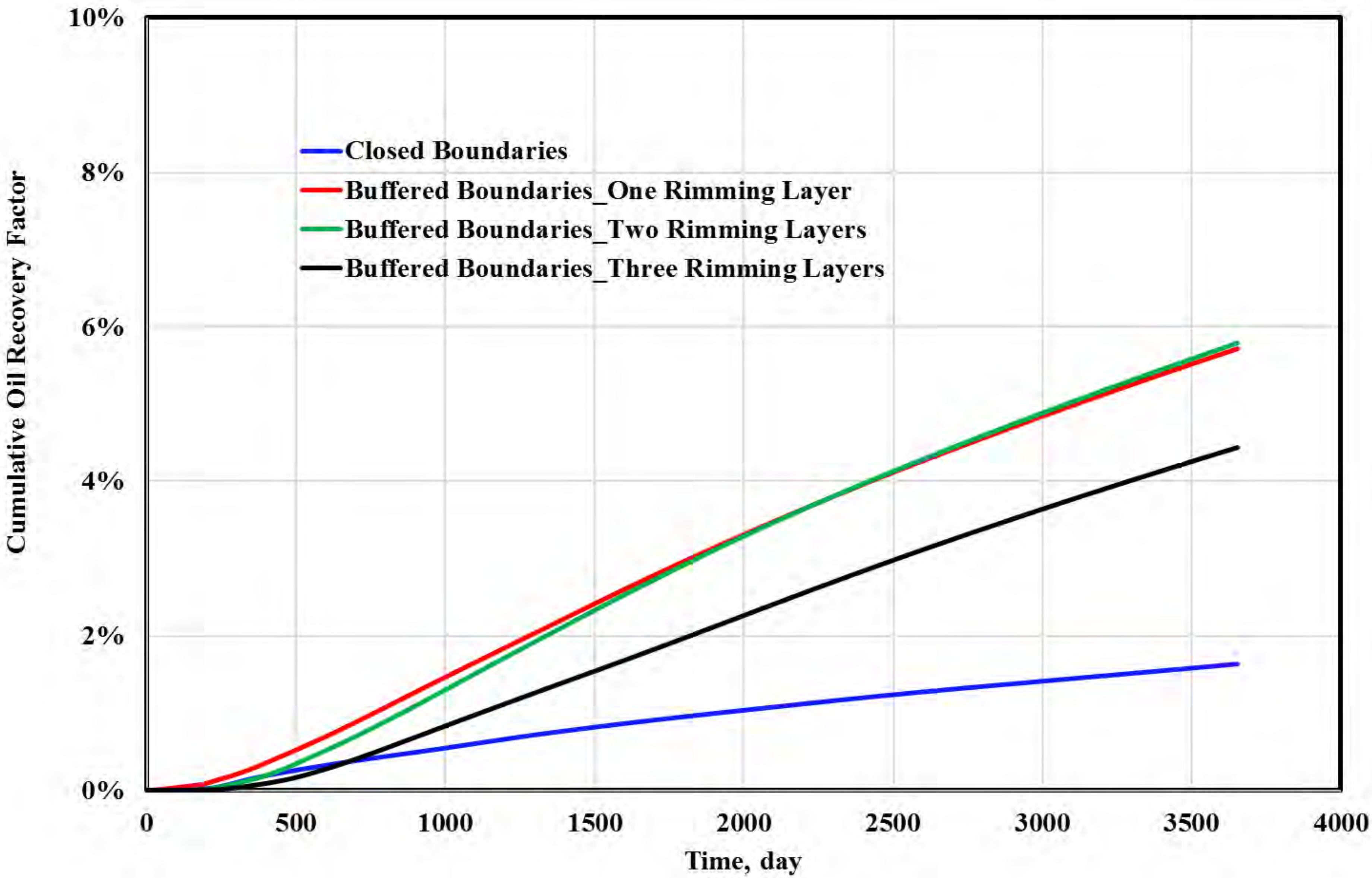
Impact of Boundary Conditions on CO_2 Metrics



Impact of Boundary Conditions on CO_2 Net Utilization Ratio

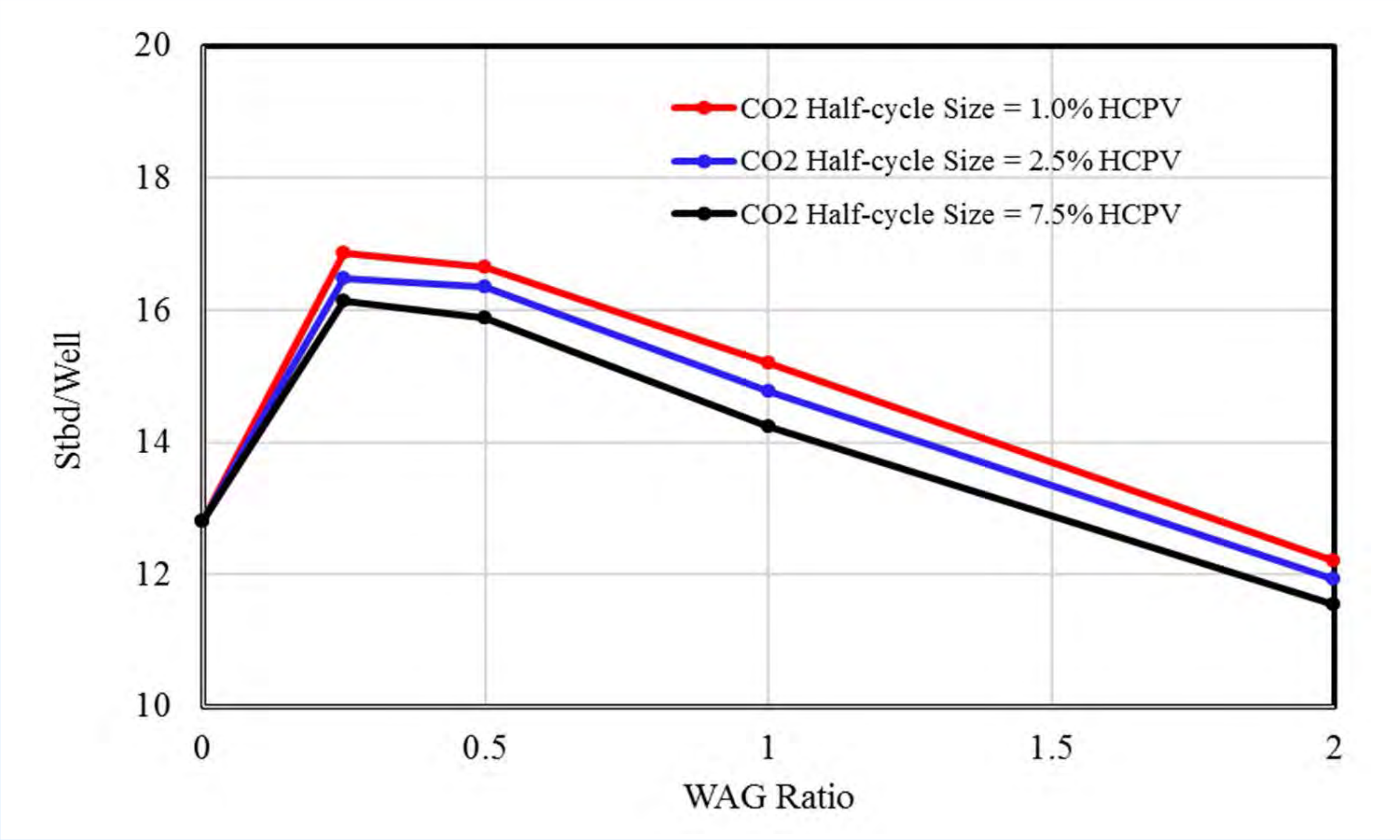


Impact of Boundary Conditions on oil recovery

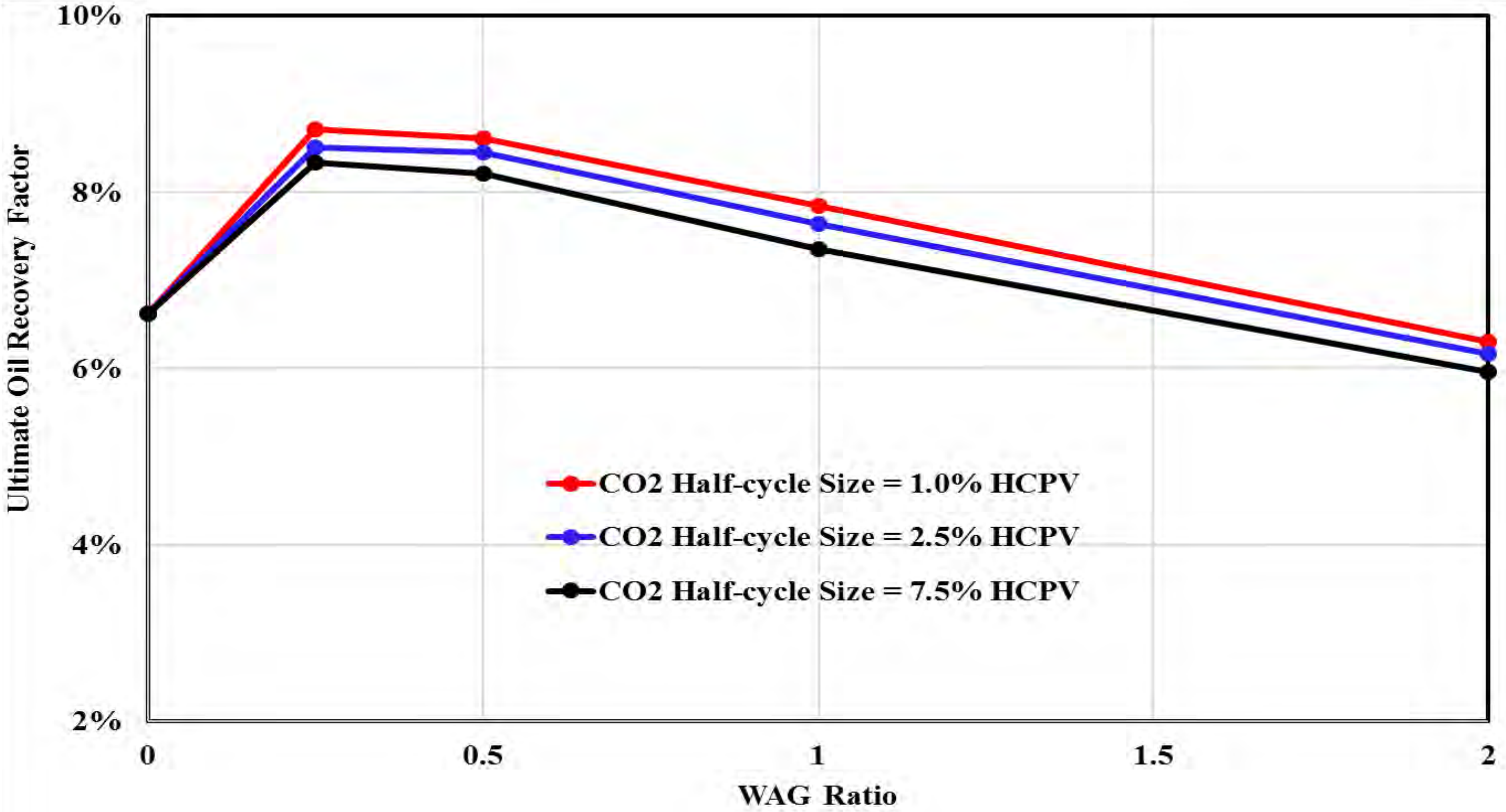


Impact of WAG (water to gas) Ratio

Oil Production as a Function of WAG Ratio

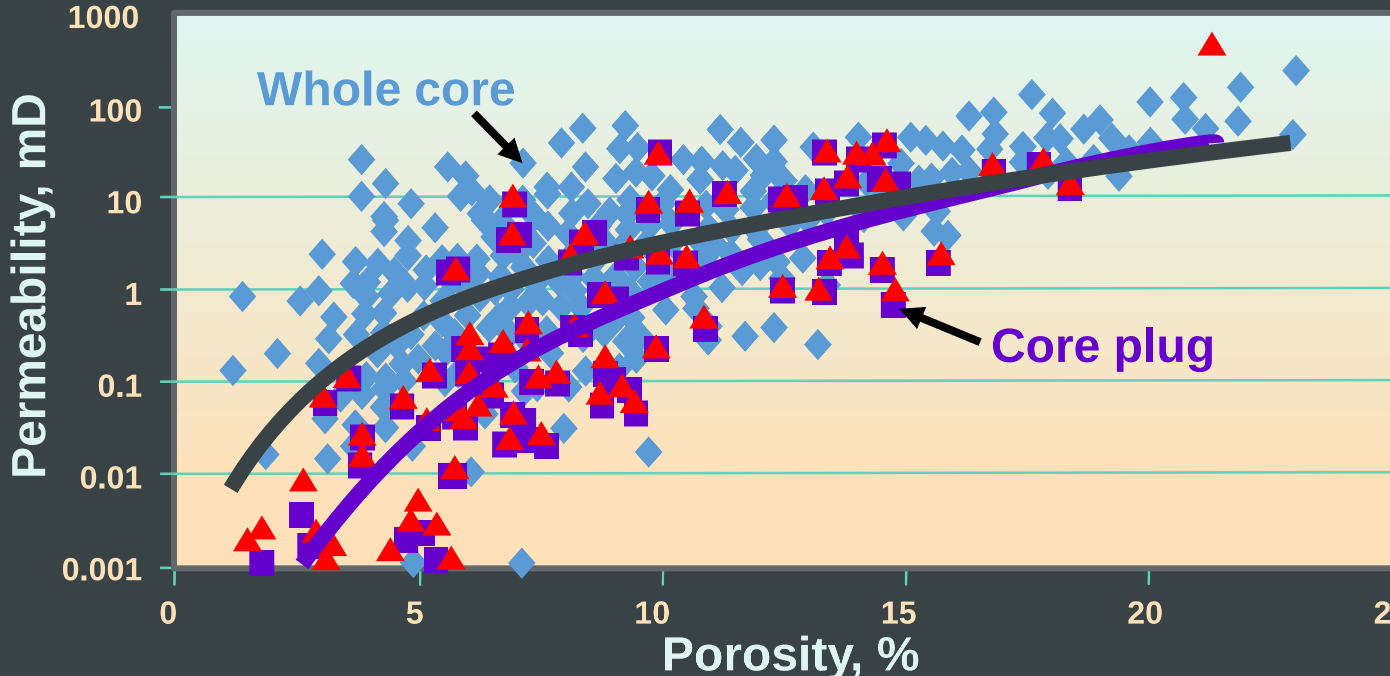


Ultimate Oil Recovery Factor as a Function of WAG Ratio



IMPACT OF PERMEABILITY ON WAG INJECTIONS

Whole Core vs. Plug Porosity-Permeability



Source: SPE, 2010, Honarpour, M. M., and others
QAe4803

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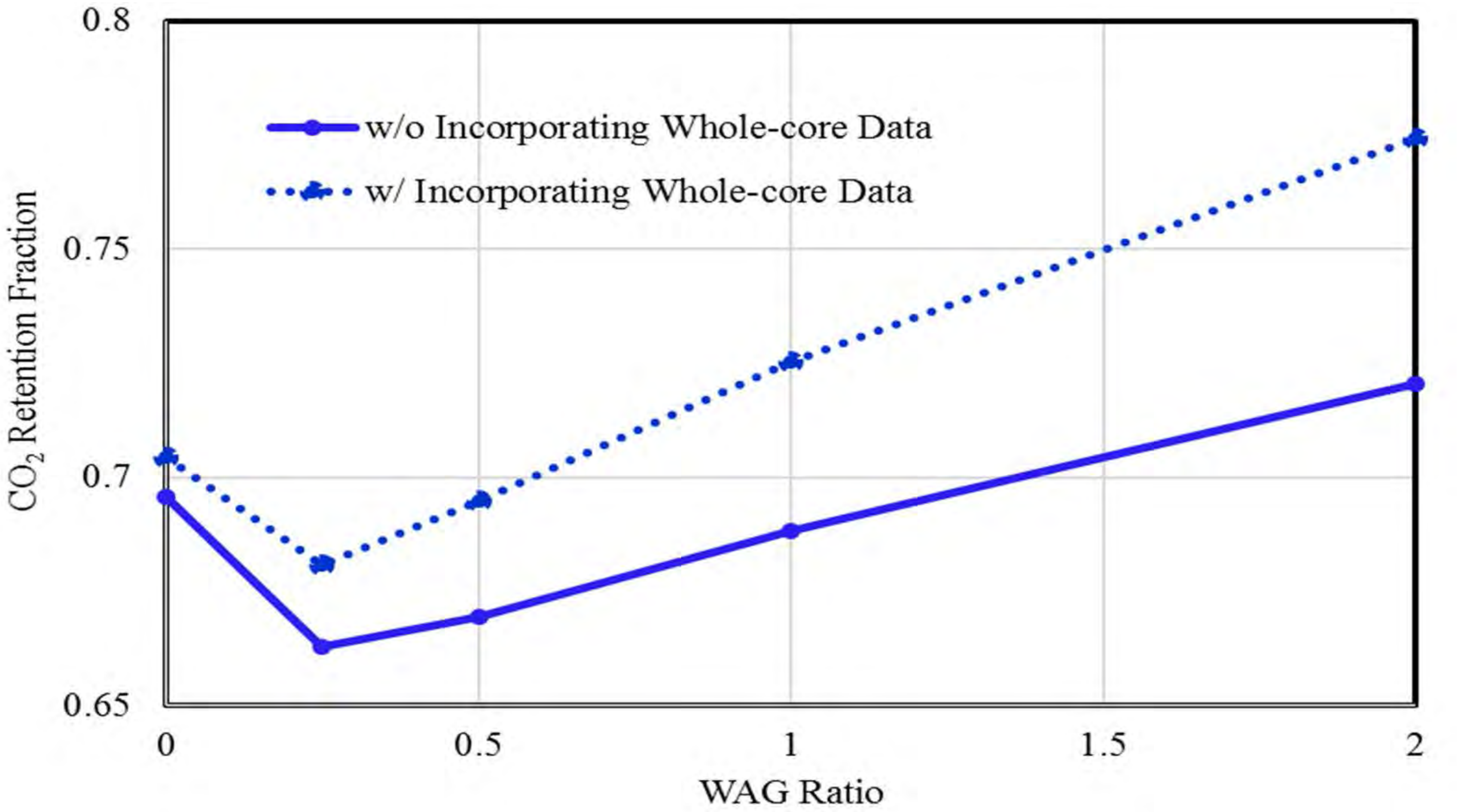
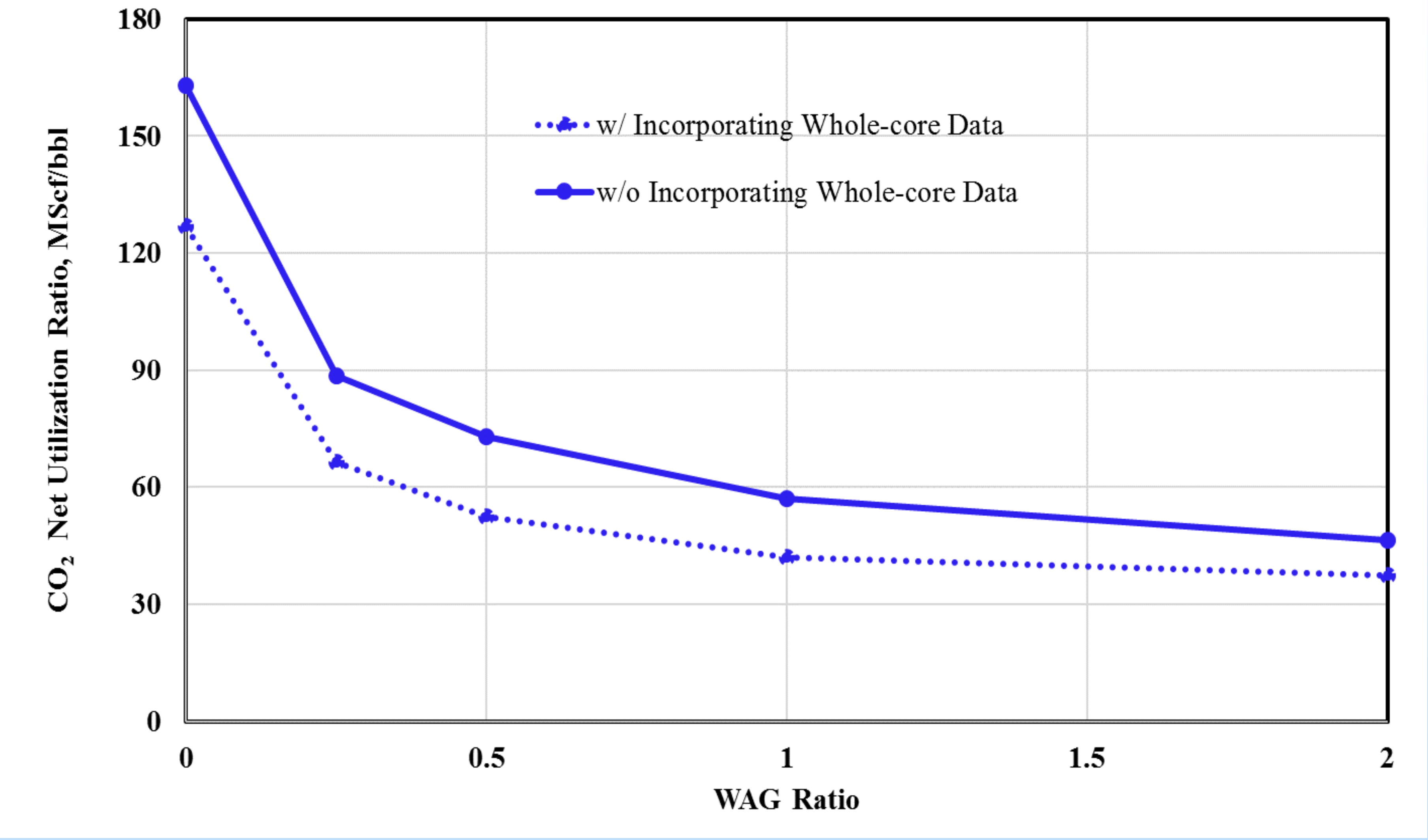
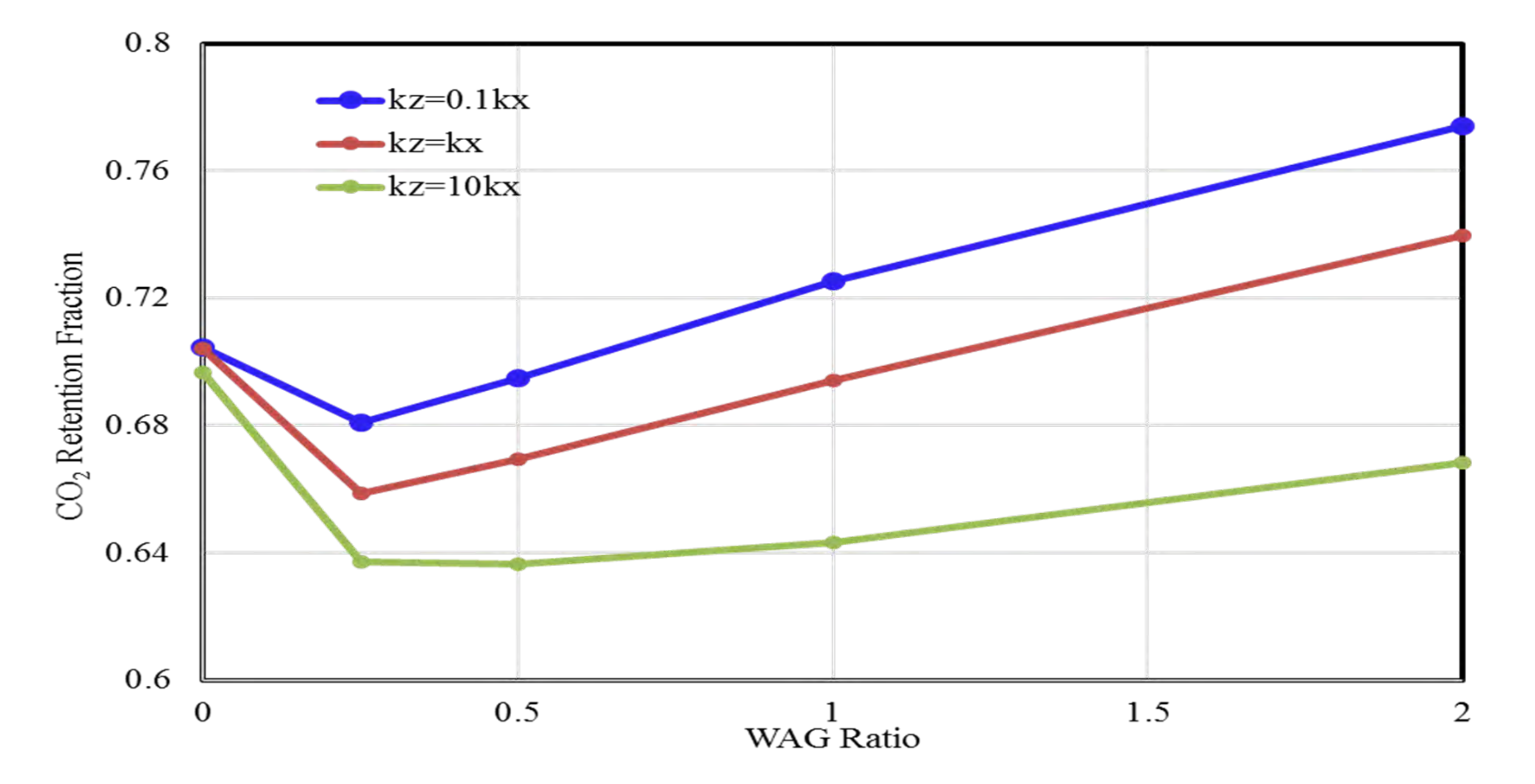
Impact of Permeability on CO_2 Retention During WAG



Impact of Permeability on CO2 Net Utilization During WAG

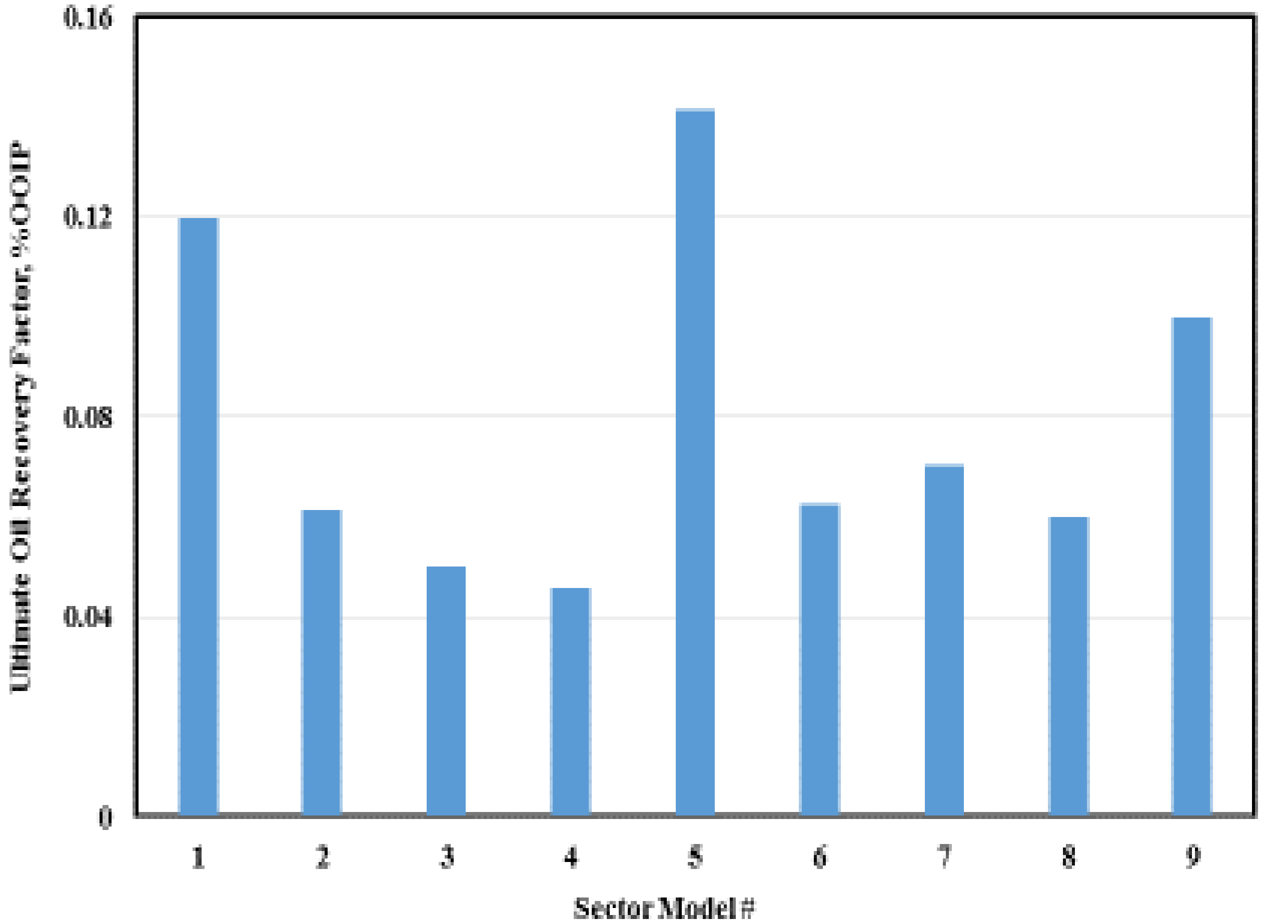


Impact of Anisotropic Permeability on CO_2 Retention During WAG

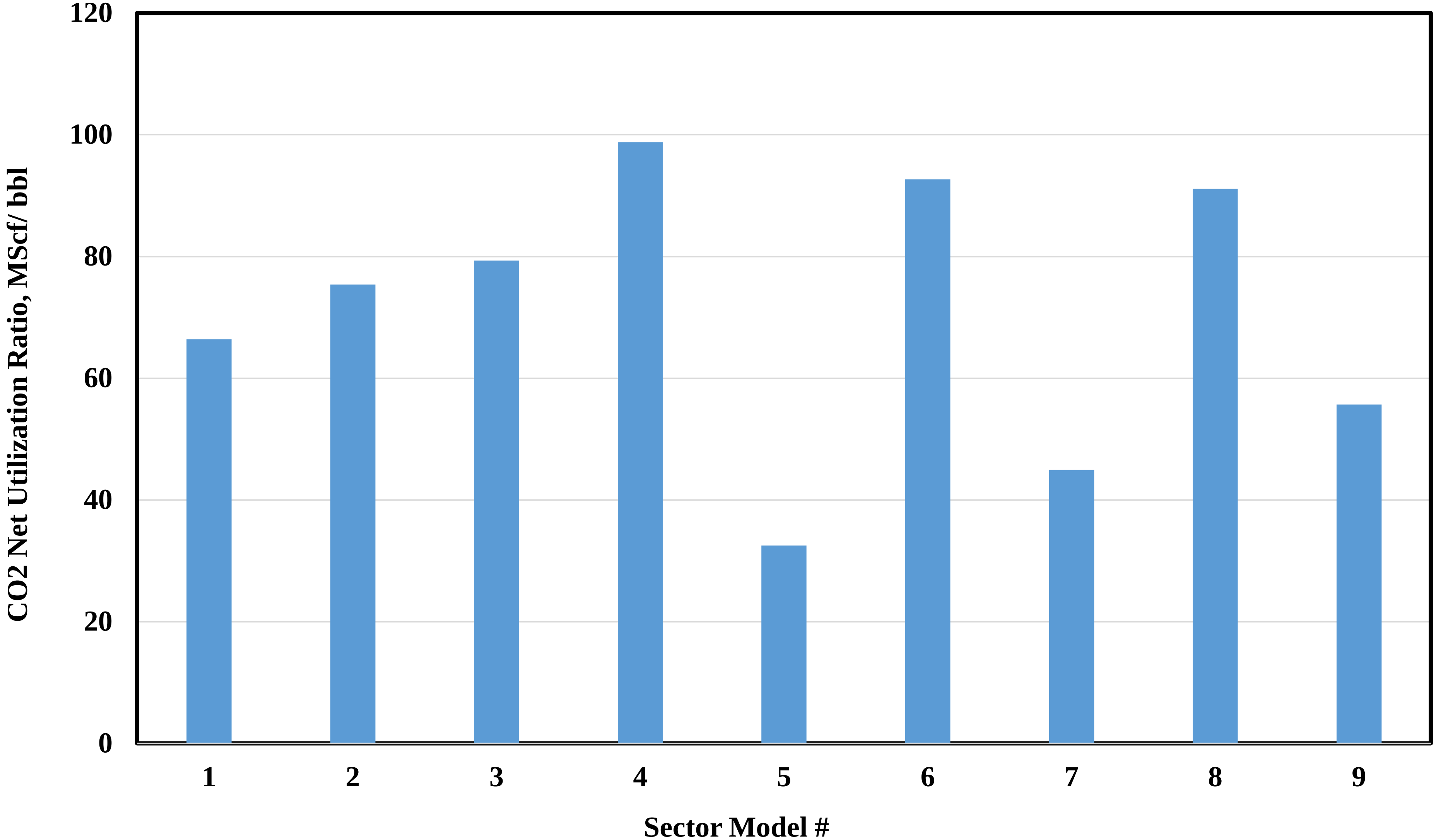


IMPACT OF RESEVOIR HETEROGENEITY

Ultimate Oil Recovery Factors for Different Sectors during WAG



CO_2 Net Utilization Ratios for Different Sectors during WAG



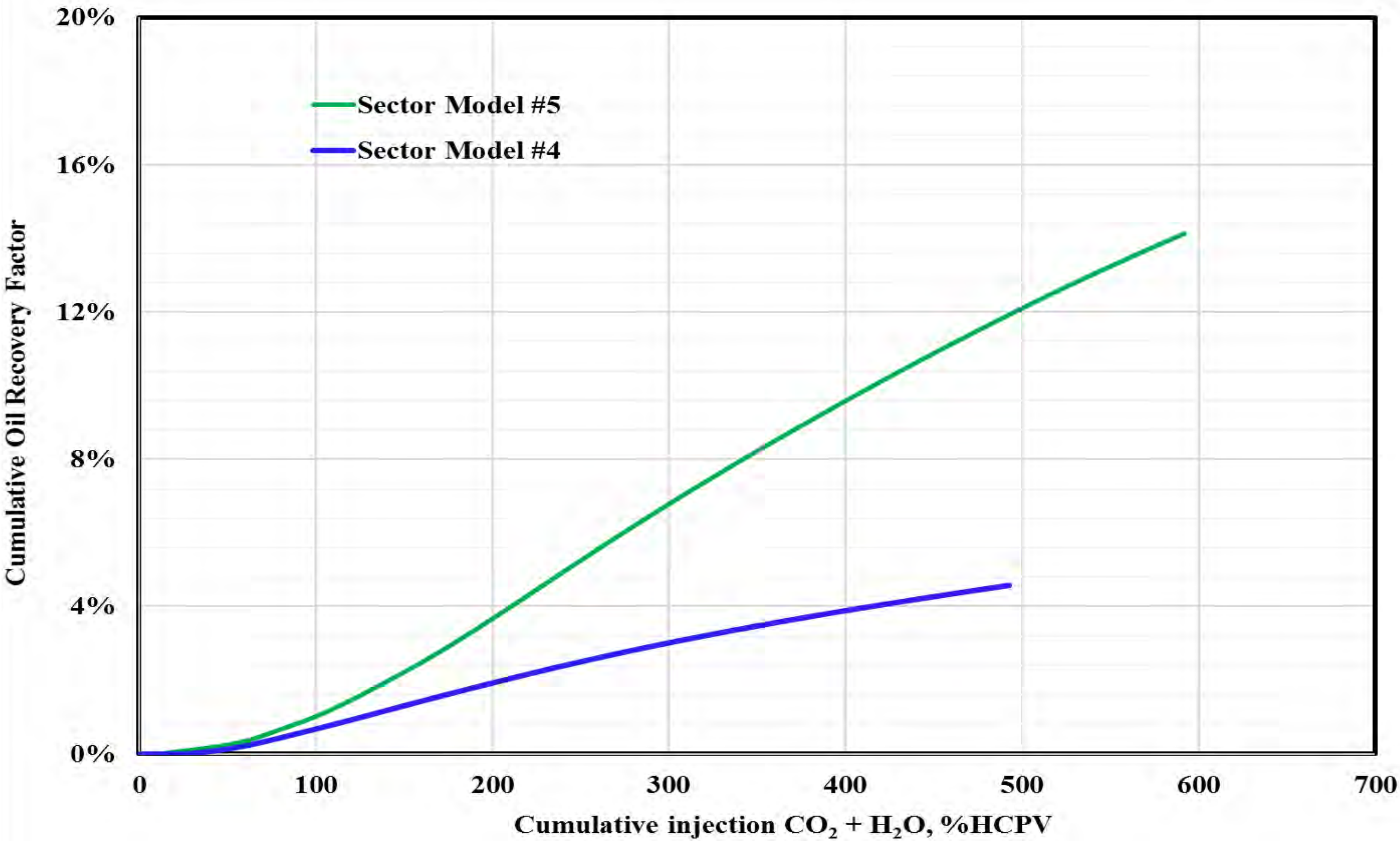
In the following we will focus on:

Area 4 (high heterogeneity)

and

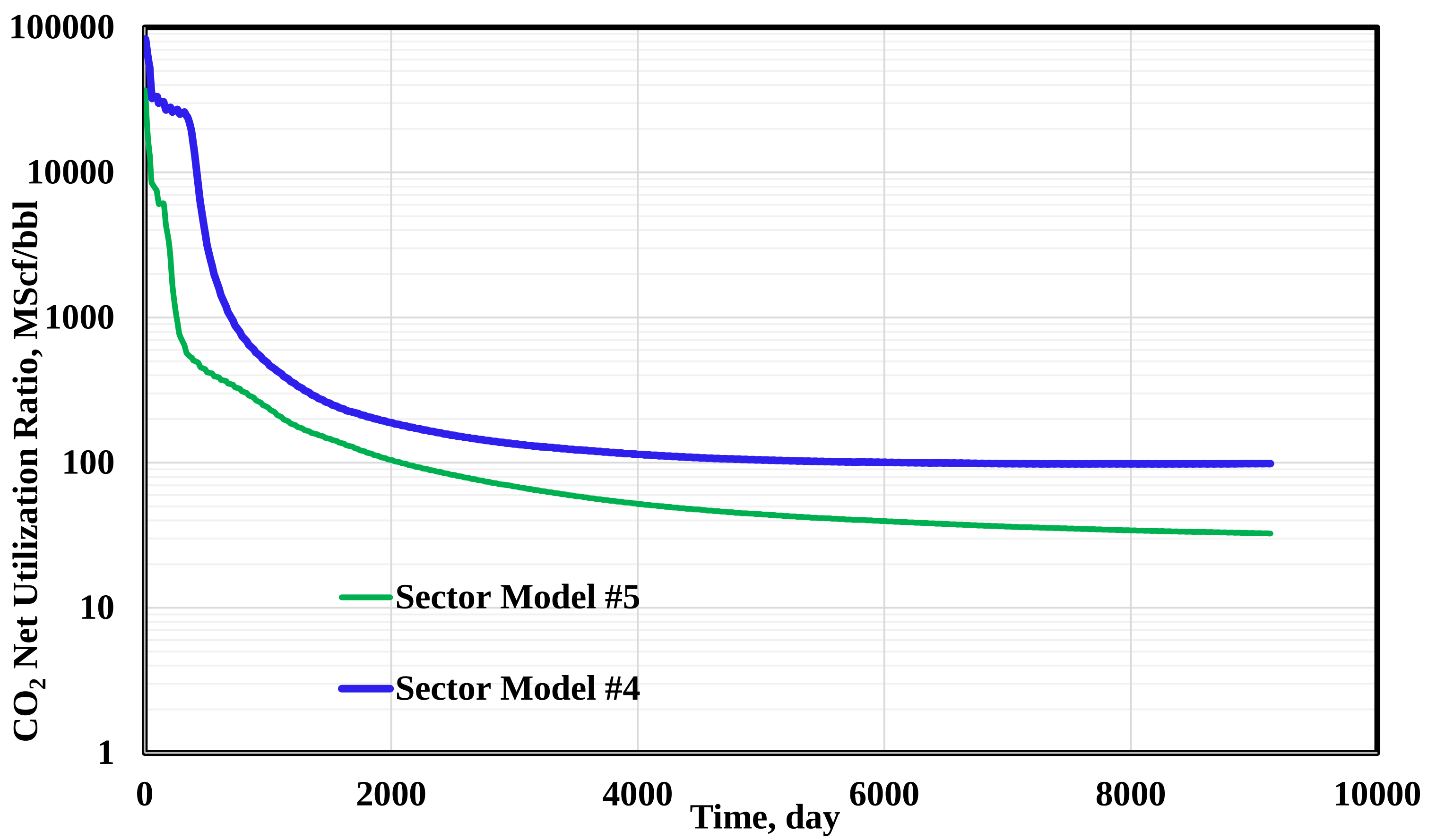
Area 5 (lower heterogeneity)

Cumulative Oil Recovery Factor over Time



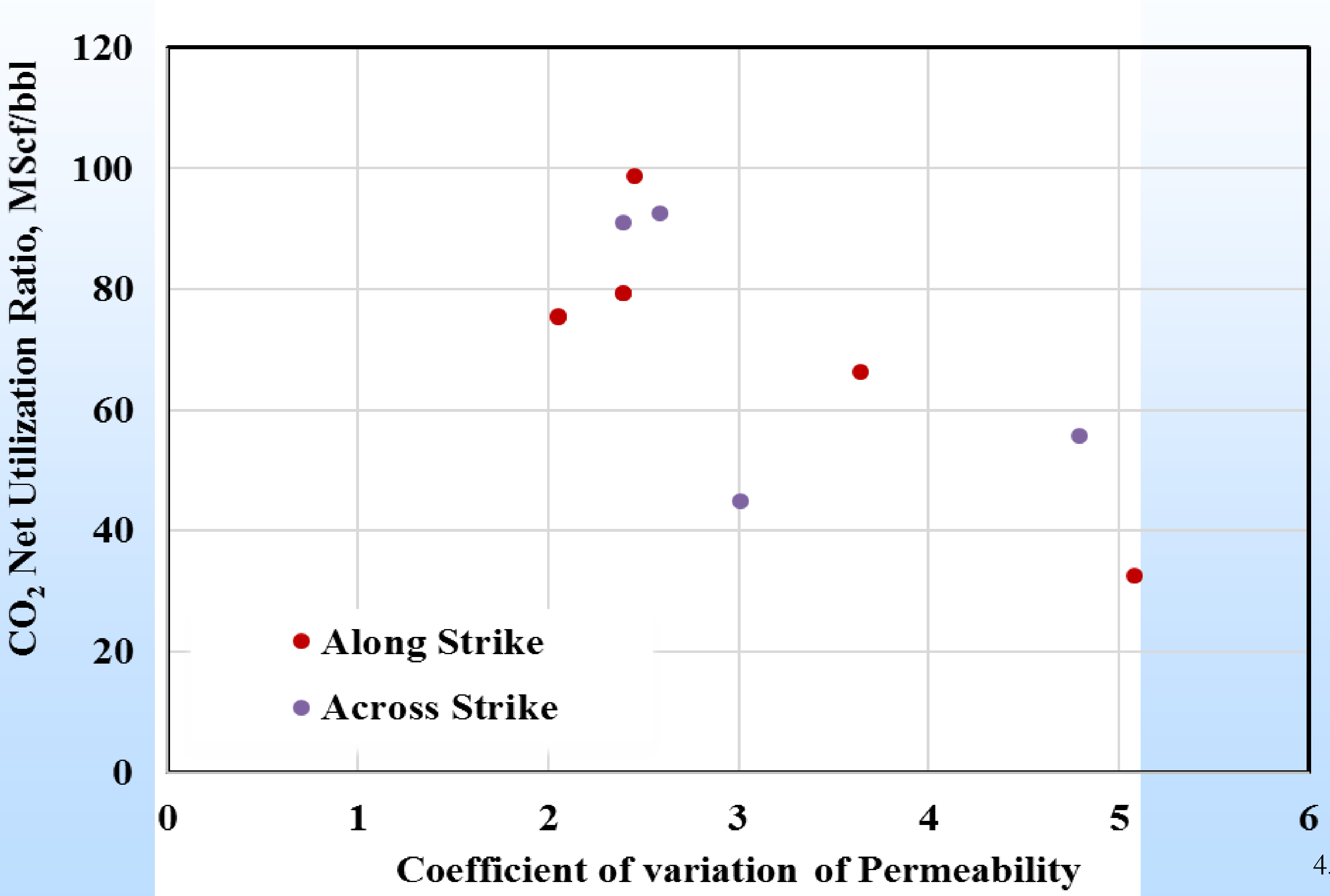
High heterogeneity less oil production

CO2 Net Utilization Ratio over Time in ROZ for Two Extremes in Heterogeneity

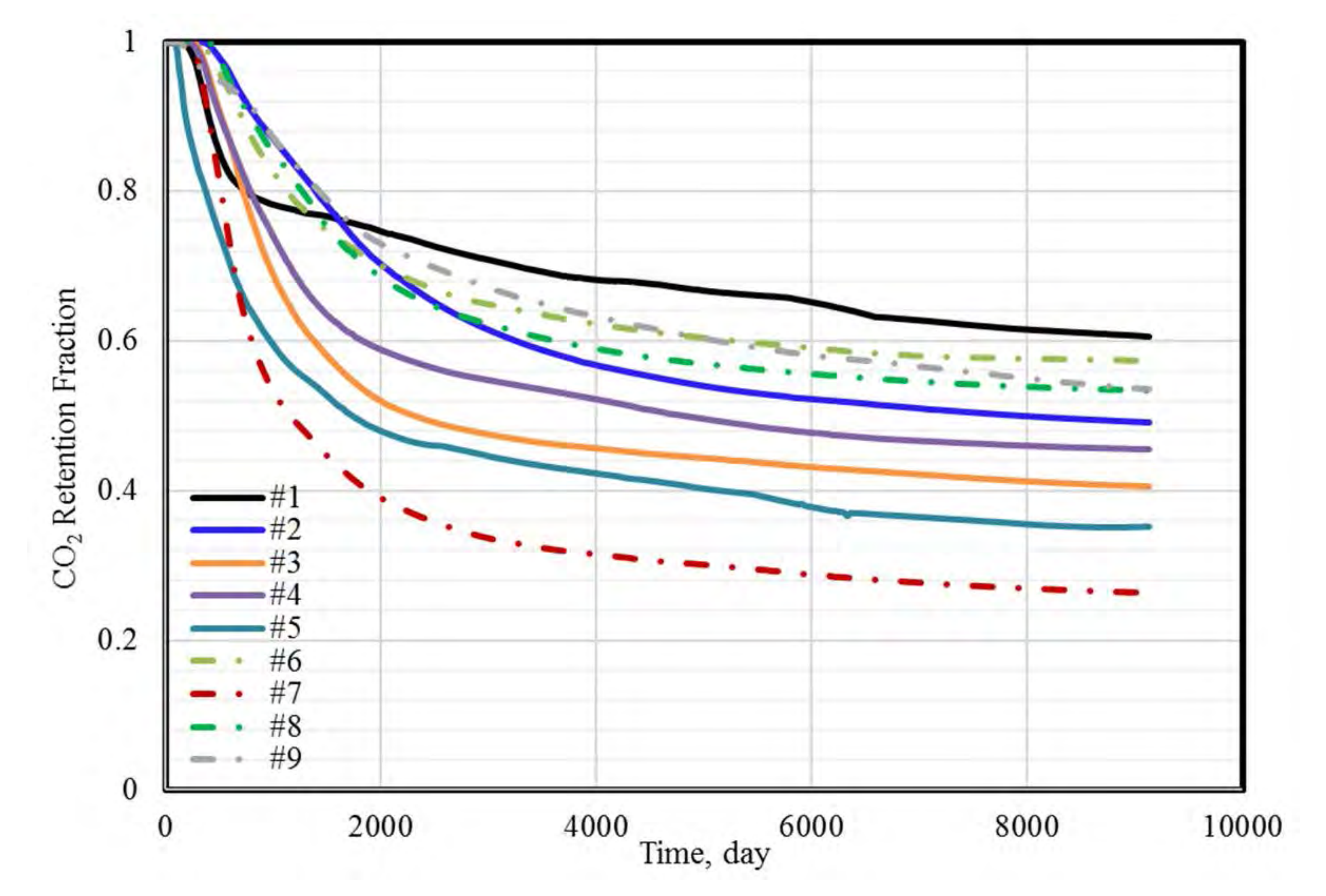


Higher heterogeneity higher CO_2 utilization

CO_2 Retention as Function of Coefficient of Variation of Permeability

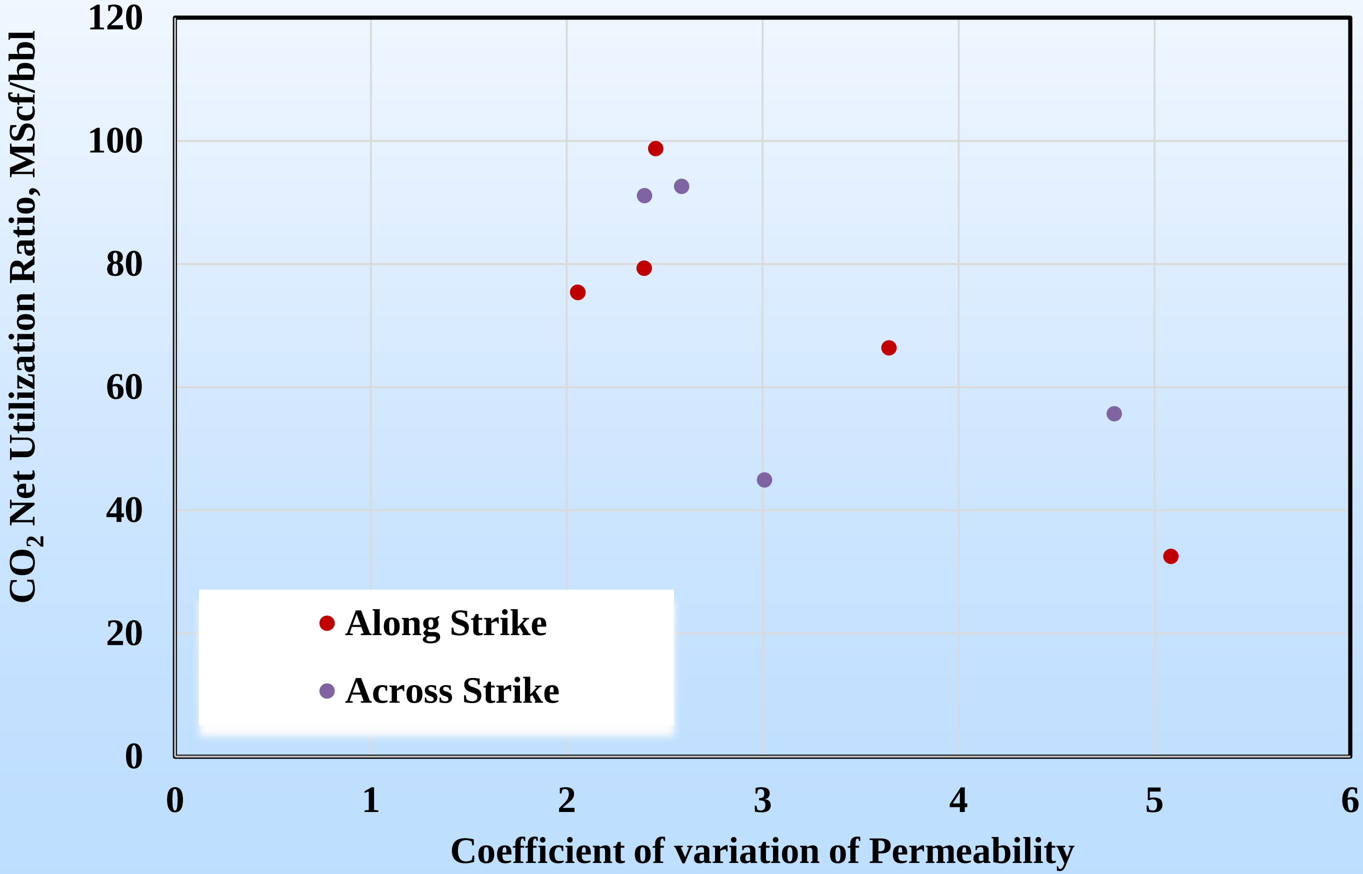


CO_2 Retention over Time in ROZ with Differing Heterogeneity



CO_2 Net Utilization Ratio as Function of Heterogeneity of Permeability

CO_2 utilization ratio vs. coefficient of variation



Higher heterogeneity, higher CO_2 retention

NEXT GENERATION SIMULATORS

- NEXT generation modelling using **Intercept/ Echelon** on TACC Supercomputers…
- Expect up to 100 times lower run times with Echelon that runs on Massively parallel GPU hardware
- Just acquired a new workstation with 2 Titan GPU arrays for prototyping Echelon runs and Intercept jobs to run on TACC

RATIONALE FOR FASTER SIMULATORS

- Simulation of higher spatial resolution reservoir models
- Modeling impact of capillary pressures and relative permeability as function of litho-facies and pressure
- Resolving spatial variation of CO_2 trapping volumes from different mechanisms

Accomplishments to Date

- Second Generation Static Reservoir Model completed
- Completion centrifuge measurements of capillary pressure versus brine saturation in core plugs
- Initiated water and CO_2 flooding of oil saturated core plugs to measure relative permeability
- First pass wireline log calibration/interpretation completed
- Analysis of all production and injection data completed by well by pattern and by phase
- Partitioning of production and injection data between ROZ and MPZ
- Eclipse simulation of formation of ROZ and of optimizing WAG injections into ROZ using full static reservoir model

Lessons Learned

Research gaps and challenges

1. Nature of Green Field ROZ
2. What factors control distribution of ROZ
3. Establishing best way of setting boundary conditions, and role of underling aquifer in BC.
4. It has been a challenge to conduct a sufficiently large experimental program to measure petro-physical flow parameters and pore/storage properties due to equipment breakdown, personnel changes etc.

Lessons Learned

Unanticipated research difficulties.

1. Issues understanding and implementing the role of boundary conditions for simulations
2. Need to have orders of magnitude more computer power to carry out the kind of simulations needed to made reliable models of CO_2 sequestration in ROZ.
3. Higher pressure centrifuge runs were fracturing core plugs

Synergy Opportunities

- Our study will provide the first detailed publically available study of a ROZ….. We are interested in collaborating with other projects.

Project Summary

Key Findings

1. Simulation of aquifer driven ROZ formation confirm that this mechanism can create ROZ with similar characteristics to those observed in Seminole Field.
2. Metrics for CO_2 storage and oil production from of WAG injections into ROZ vary with boundary conditions, WAG ratio, permeability, and reservoir heterogeneity.
3. CO_2/brine capillary pressures vary considerably with lithofacies and pressure which impacts CO_2 storage

Project Summary

Next Steps

1. **Using Next-Generation Intercept and Eclipse/ Echelon simulations** to compare to analysis of efficiency in the context of reservoir metrics such as CO_2 Efficiency and CO_2 Cumulative Storage
2. Using these high capacity simulations to **study impact of variation in capillary pressure with litho-facies and pressure to model CO2 storage during WAG injection**
3. Calibration of Advanced Wireline Logs with core measurements such as NMR, resistivity…
4. Building upgraded third generation static reservoir model integrated with new petro-physics data

Appendix

Benefit to the Program

- Supports DOE's Programmatic goal No. 2, to "Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness".

Project Overview

Goals and Objectives

Project objective: “To improve the understanding of how much CO_2 can be stored in residual oil zones (ROZ) given current practice and how much this could be increased, by using strategies to increase sweep efficiency”.

These same strategies will increase the efficiency of oil production.

Organization Chart

<table>
<tr><td colspan="2">Project Director

Ian Duncan</td></tr>
<tr><td>Task 1
Management</td><td>Task 2 through 6</td></tr>
<tr><td>Task Leader/Back-up
Duncan/Ambrose</td><td>Task Leader/Back-up
Duncan/Ambrose</td></tr>
</table>

Gantt Chart

	Yr1 Q1	Yr1 Q2	Yr1 Q3	Yr1 Q4	Yr2 Q1	Yr2 Q2	Yr2 Q3	Yr2 Q4	Yr3 Q1	Yr3 Q2	Yr3 Q3	Yr3 Q4
2	X	X	X	X	X	X	X	X	X	X D7	X	
2.1	x	x	x D3	x	x	x	x	x				
2.2		x	x	x	x	x D11	x	x				
2.3			x	x	x	x	x	x	x			
2.4				x	x	x	x	x D8				
2.5				x	x	x	x	x	x	x D9		
3		X	X	X	x D4							
4		X	X	X	X	X	x D5	X	x D6	X	X	
4.1				x	x	x						
4.2			x	x	x	x	x					
5		X	X	X	X	X	X	X	X	X	X D10	
6						X	X	X D12	X	X	X	X D13

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