Optimizing and Quantifying CO_2 Storage Capacity/Resource in Saline Formations and Hydrocarbon Reservoirs

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U.S. Department of Energy

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Carbon Storage R&D Project Review Meeting
Transforming Technology through Integration and Collaboration
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Presentation Outline

- Benefit to the program
- Project overview
- Technical status
- Accomplishments to date
- Synergy opportunities
- Summary

Benefit to the Program

- Second, third, and fourth goals of Carbon Storage Program:
  - Improve reservoir storage efficiency while ensuring containment effectiveness.
  - Predict CO_2 storage capacity.
  - Develop best practices manuals (BPMs).
- CO_2 storage resource estimation methodologies will be evaluated and refined, if necessary, for saline and hydrocarbon reservoirs.
- Storage efficiency values will be available for various depositional environments.
- Lessons learned will be presented in a BPM.

Project Overview

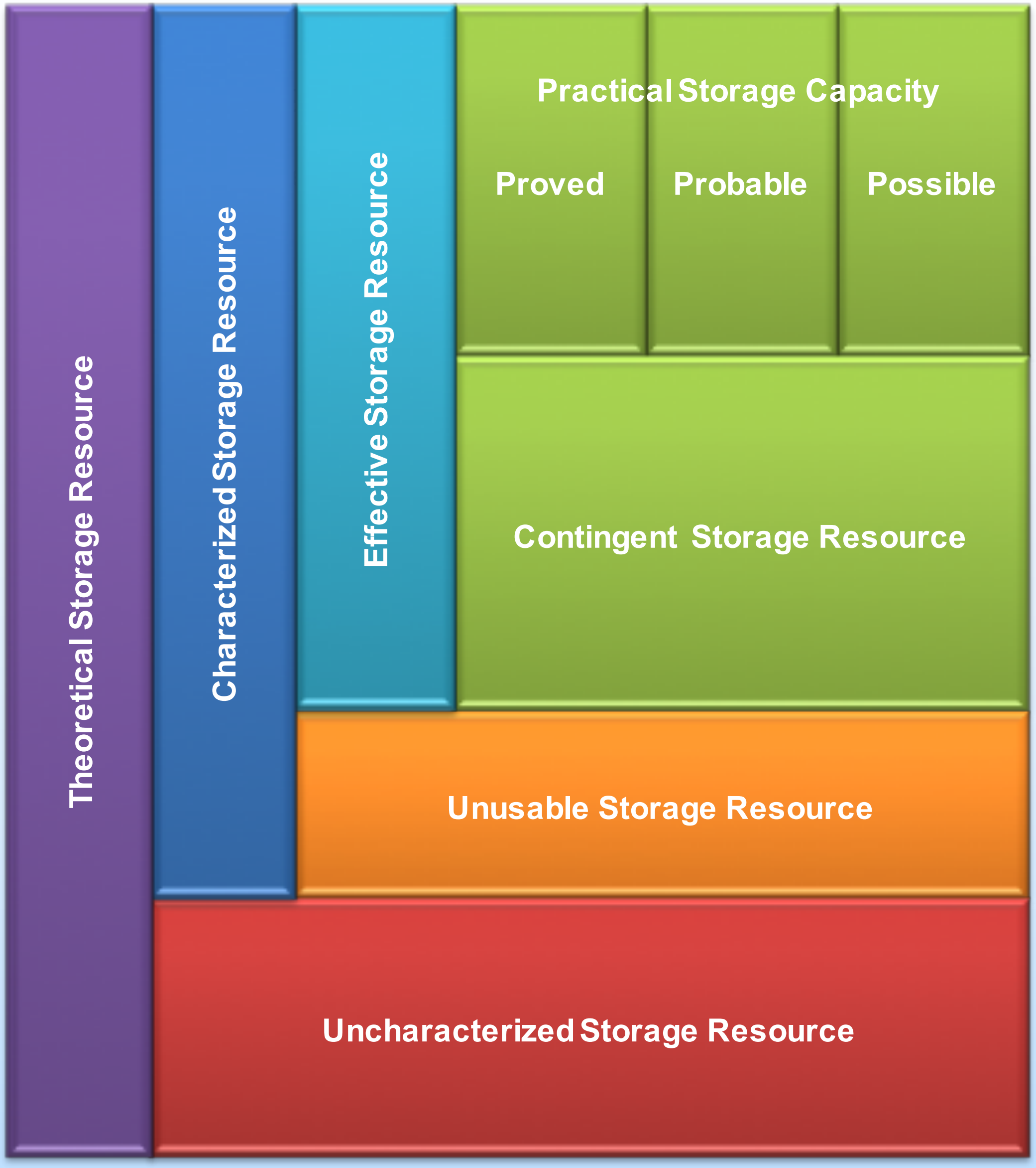
Goal

- To refine current methods and terms used to estimate CO_2 storage resource in saline formations and hydrocarbon reservoirs.

Objectives

- Review literature and industry data
- Construct models, perform simulations
- Evaluate storage efficiency
  - By depositional environment (saline formations)
  - During CO_2 enhanced oil recovery (EOR)

CO_2 Storage Resource/Capacity

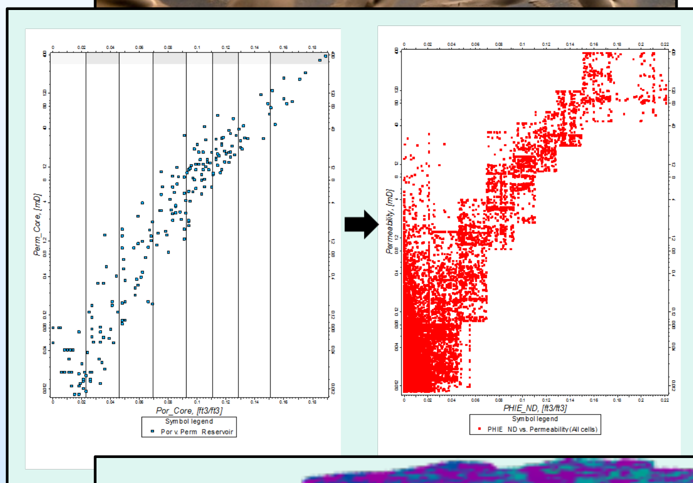


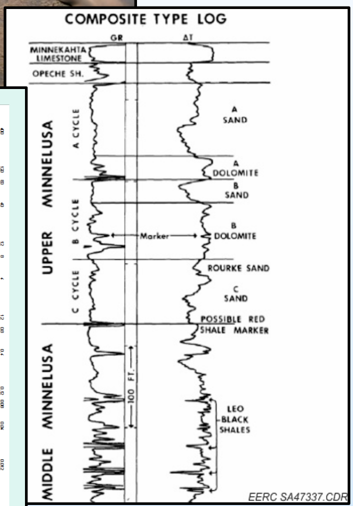
Adapted from IEA Greenhouse Gas R&D Programme, 2009, Development of storage coefficients for CO_2 storage in deep saline formations: 2009/12, October 2009.

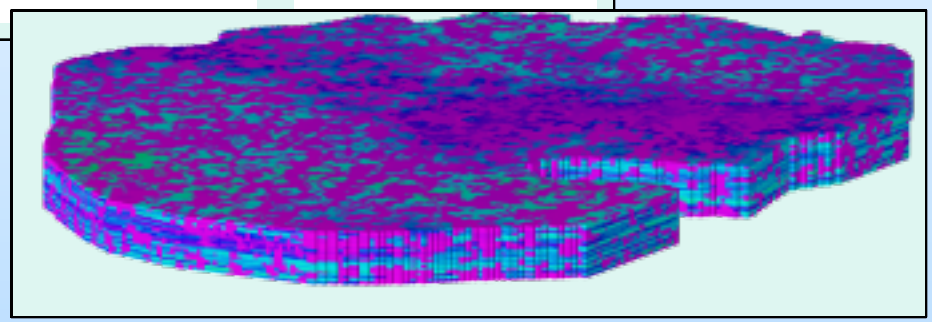
Saline Formations: Modeling

Approach

- Construct regional- to basin-scale geocellular models representing various depositional environments (primary and secondary).
- Use actual saline formations as a guide and data source.
- Supplement petrophysical properties using the Average Global Database (AGD).





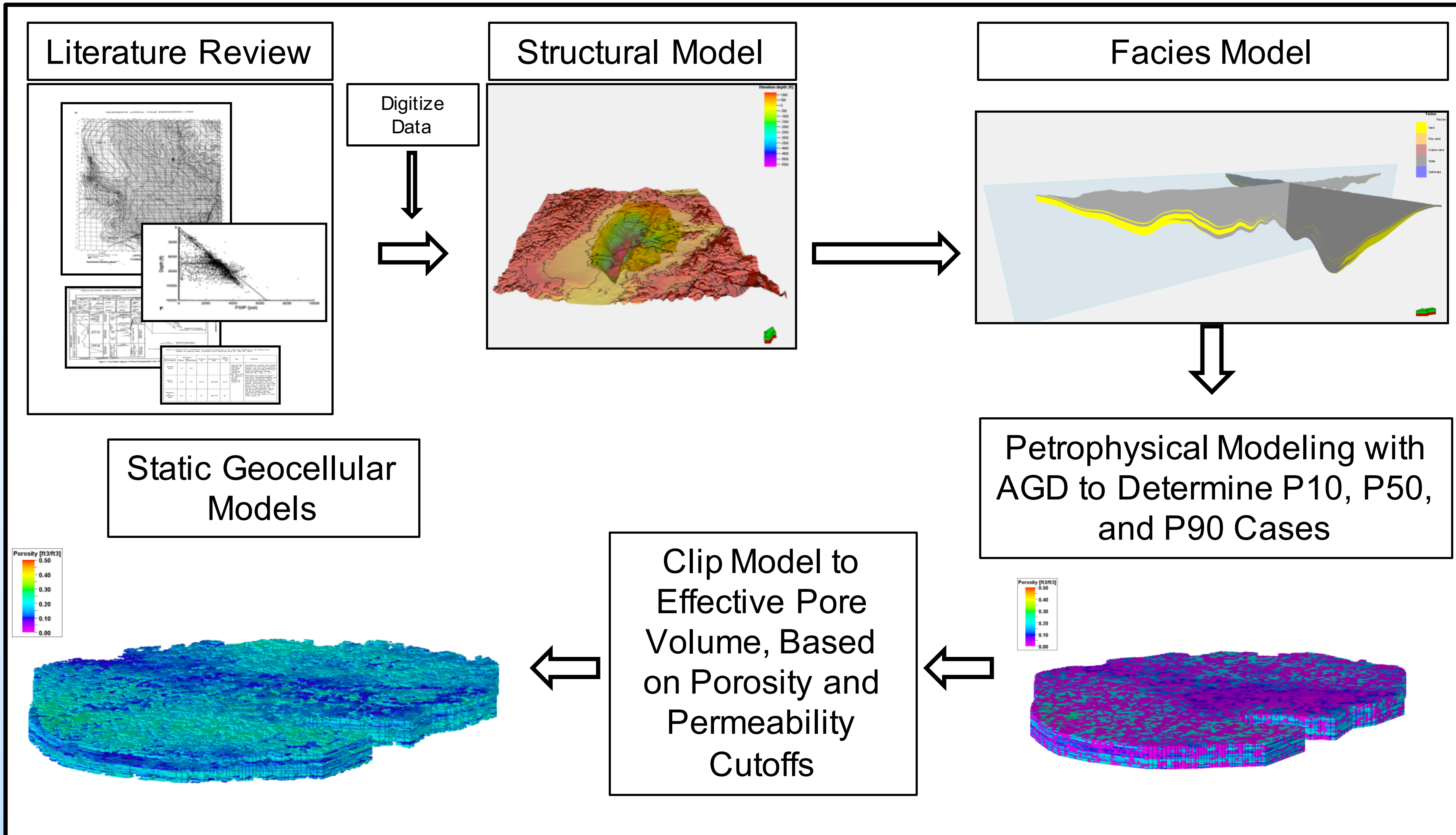


Schlumberger

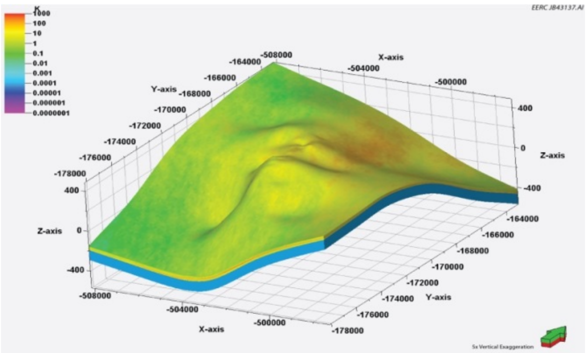
Saline Formations Selected

Saline Formations and Depositional Environments Selected		
Model Structural Basis	Primary Depositional Environment	Secondary Depositional Environment
Broom Creek	Eolian	N/A
Inyan Kara	Delta	Fluvial
Leduc	Reef	Carbonate Shelf
Minnelusa	Eolian	N/A
Mission Canyon	Carbonate Shelf	Peritidal
Qingshankou and Yaojia	Lacustrine	Fluvial
Stuttgart	Fluvial	Delta
Utsira	Clastic Slope	Strand Plain
Utsira	Clastic Shelf	Strand Plain
Winnipegosis	Reef	Carbonate Shelf

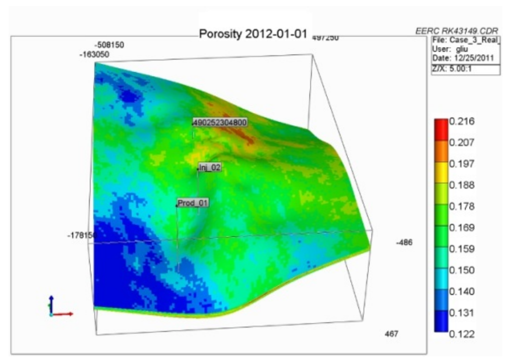
Modeling Workflow



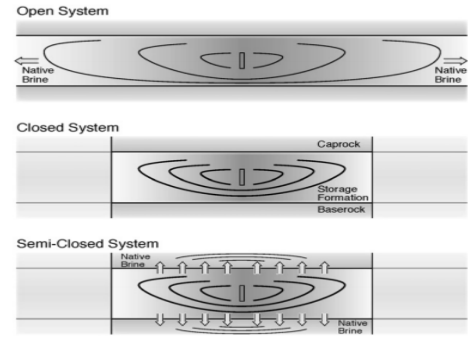
Simulation Workflow



Geocellular Models with High-, Mid-, and Low-Pore Volume

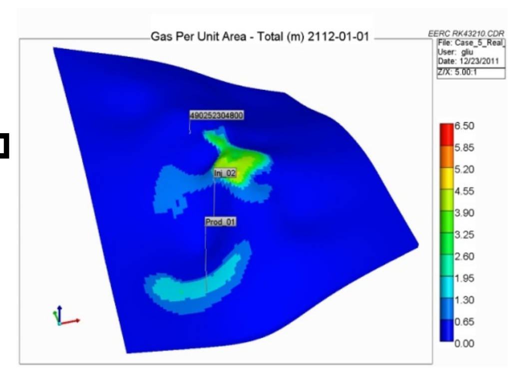


Injection Simulation Design



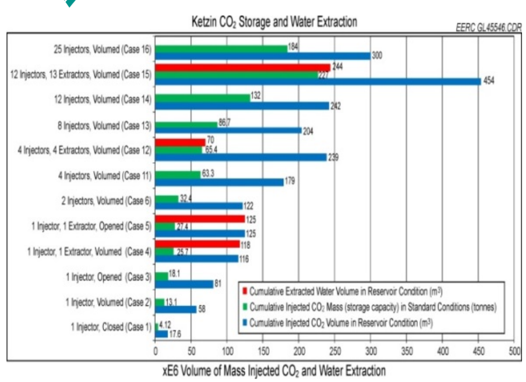
Boundary Condition Testing

http://esd.lbl.gov/files/research/programs/gcs/projects/storage_resources/journal_3_NETL_zhou_etal_IJGGC.pdf

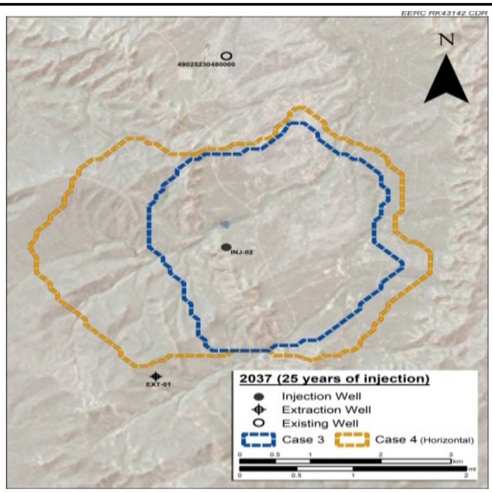


Operational Storage Capacity Enhancement

COMPUTER MODELLING GROUP LTD.



Dynamic Storage Efficiency Estimates



Storage Efficiency Comparisons and Analysis

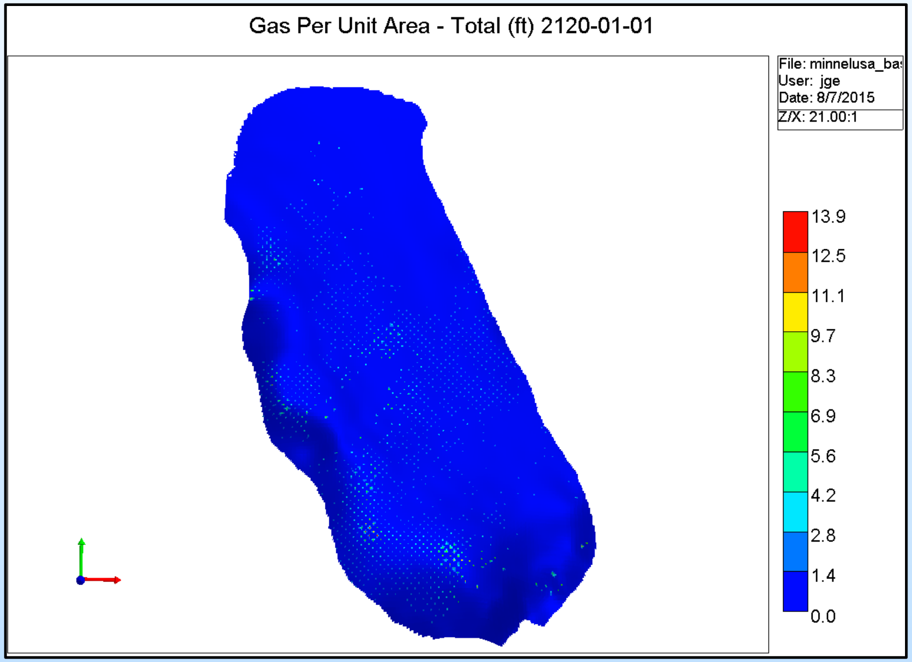
Base Case Simulation Results

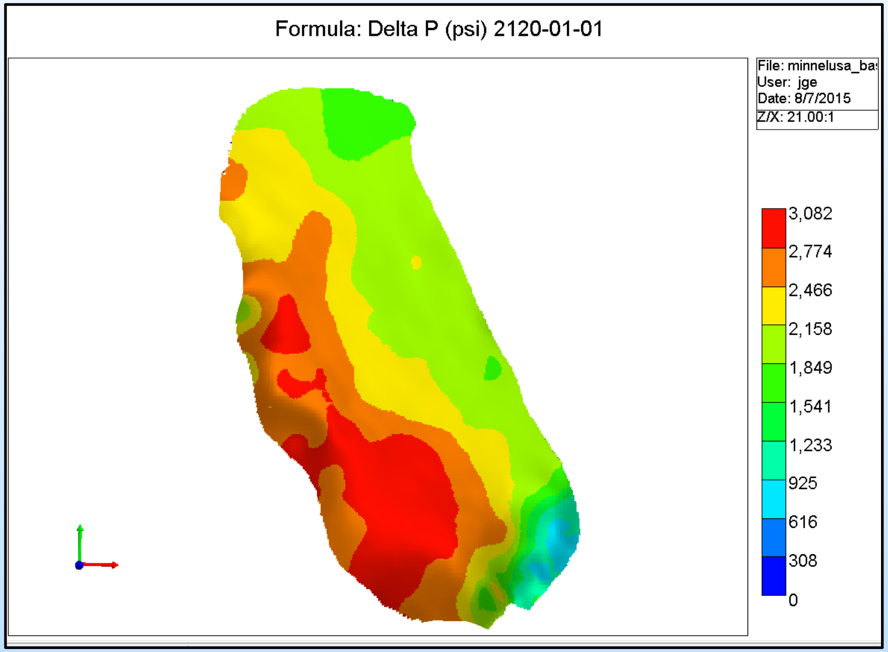
Model	1st Depositional Environment	2nd Depositional Environment	Injection Wells	Stored CO_2, Mt	Average CO_2 Stored, Mt/well
"Broom Creek"	Eolian		138	6143	45
"Inyan Kara"	Delta	Fluvial	106	5595	53
"Leduc"	Reef	Carbonate shelf	39	167	4
"Minnelusa"	Eolian		637	1757	3
"Mission Canyon"	Carbonate shelf	Peritidal	1521	34,008	22
"Qingshankou and Yaojia"	Lacustrine	Fluvial	277	19,934	72
"Stuttgart"	Fluvial	Delta	122	10,473	86
"Utsira Clastic Slope"	Clastic slope	Strand plain	391	27,959	72
"Utsira Clastic Shelf"	Clastic Shelf		109	9110	84
"Winnipegosis"	Reef	Carbonate shelf	1	0.25	0.3

- Base case simulations and stored volume are not meant to represent actual storage in these formations; the properties that were used in each depositional model were from the P50 properties from the AGD. The goal is to look at storage efficiency in different depositional environments.

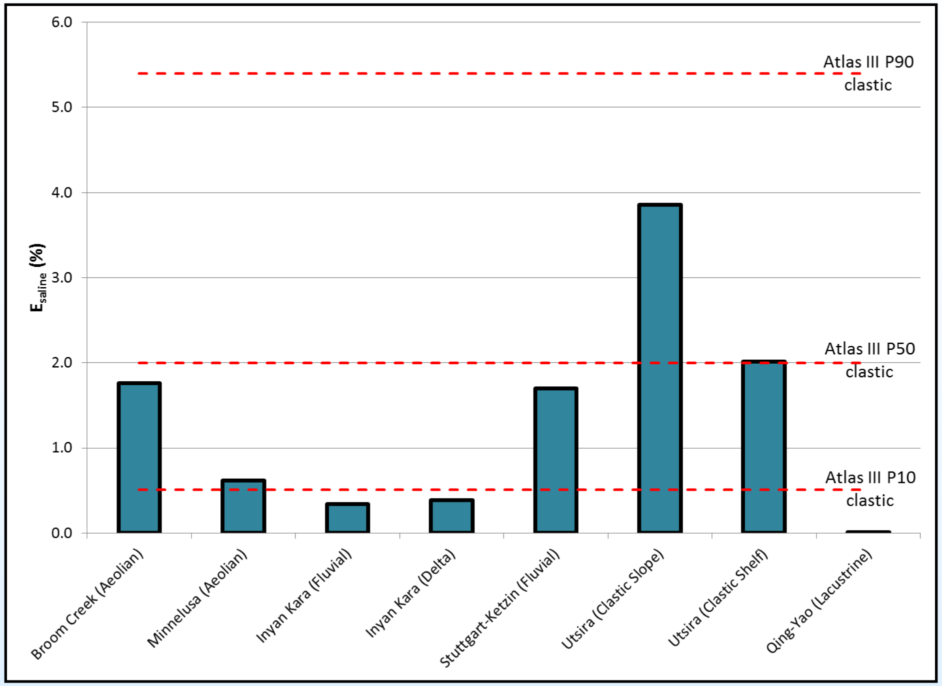
Optimization Case Simulation

- Closed-boundary simulations were conducted for P10, P50, and P90 realizations.
- Semi-closed-boundary simulations (infinite-acting aquifer laterally, infinite-acting cap rock vertically) were conducted for the P50 models.
- Multiple scenarios (e.g., water extraction, horizontal wells) were designed to maximize storage resource and determine the impact of site-specific factors and depositional environment on CO_2 storage resource.





Optimization Case Simulation Results



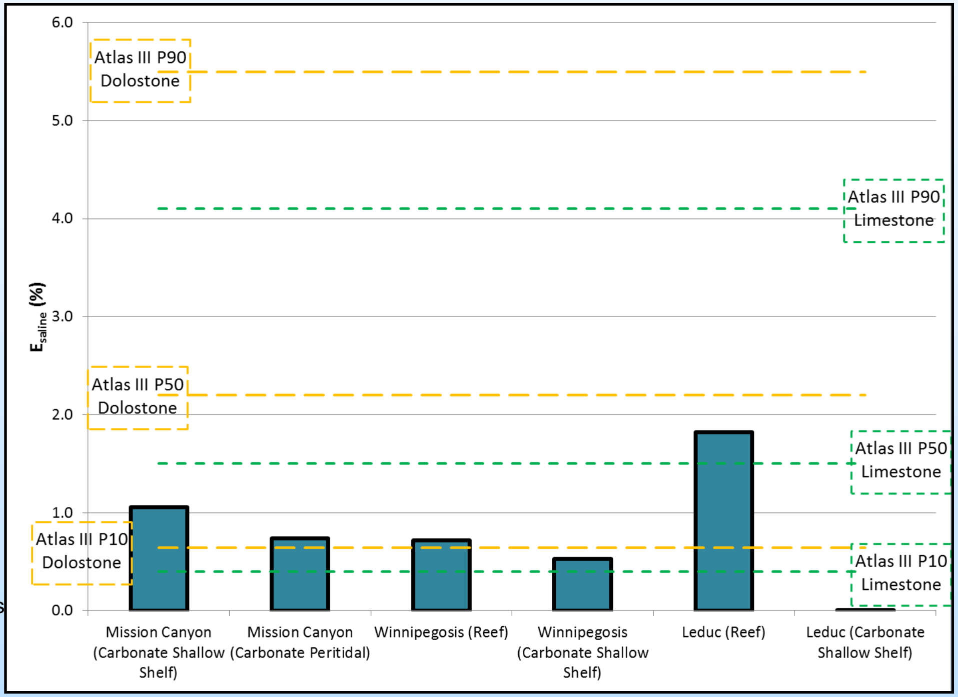
Dashed lines show efficiency values from the U.S. Department of Energy (DOE) Atlas III.

Saline Formation Efficiency Factors for Geologic and Displacement Terms

$$E_{saline} = E_{An/At} E_{hn/hg} E_{\phi e/\phi tot} E_v E_d$$

Lithology	P_{10}	P_{50}	P_{90}
Clastics	0.51%	2.0%	5.4%
Dolomite	0.64%	2.2%	5.5%
Limestone	0.40%	1.5%	4.1%

Table from DOE National Energy Technology Laboratory, 2010. Carbon sequestration atlas of the United States and Canada (3rd ed.).



Hydrocarbon Reservoirs: Data Review

- A literature review of current storage estimation methodologies in oil and gas reservoirs was performed.
- Data were collected from existing oil fields and ongoing CO_2 EOR projects.
- A statistical analysis was performed for 31 CO_2 EOR sites.

Hydrocarbon Reservoirs: Industry Data

Summary

- The P10, P50, and P90 at 300% hydrocarbon pore volume injection (HCPVI) estimates for:
  - CO_2 retention = 23.1, 48.3, and 61.8% retention
  - Incremental oil recovery = 5.3, 12.1, and 21.5% original oil in place (OOIP)
  - Net CO_2 utilization = 4.5, 8.7, and 10.5 Mscf/stock tank barrel (STB)

A paper with these findings was published in the *International Journal of Greenhouse Gas Control*.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journal homepage: www.elsevier.com/locate/ijggc

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CO_2 storage associated with CO_2 enhanced oil recovery: A statistical analysis of historical operations

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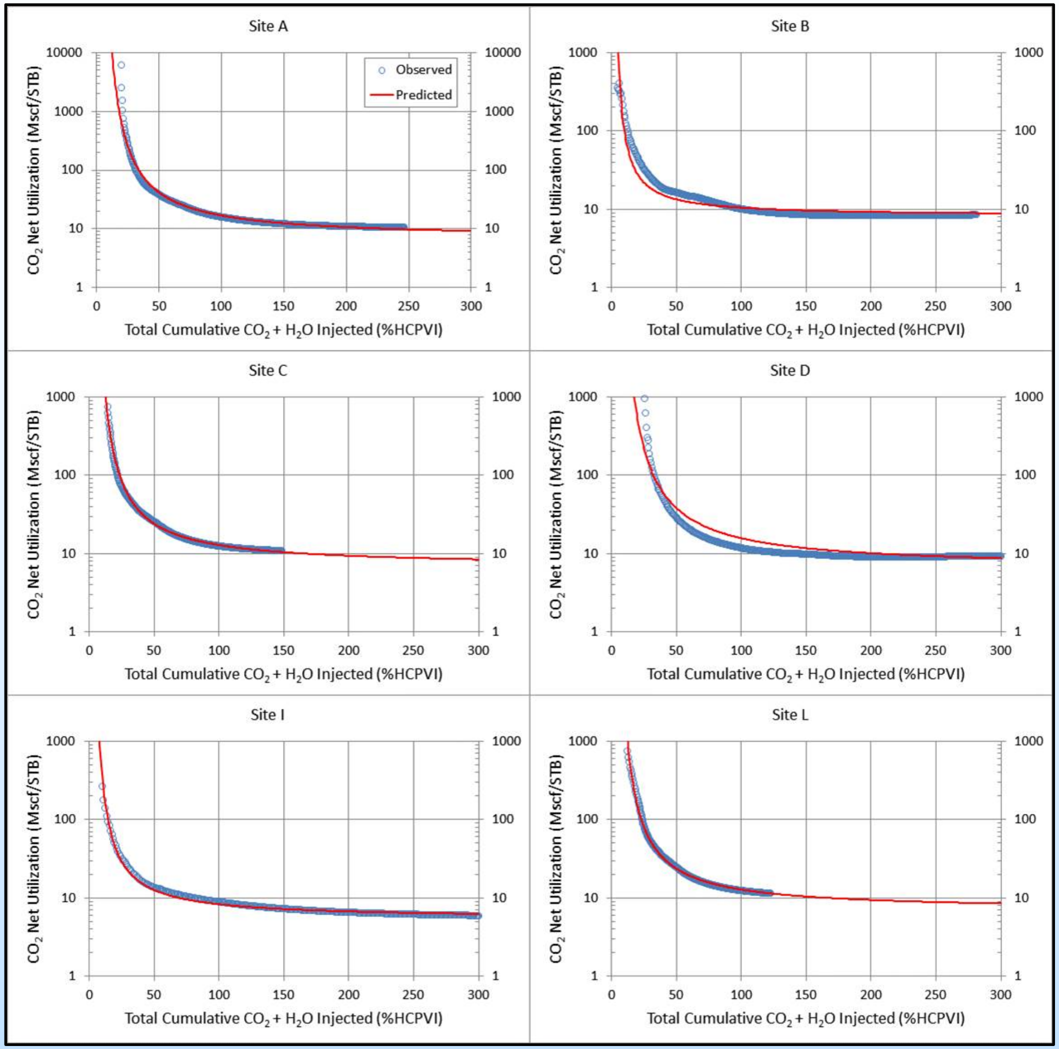
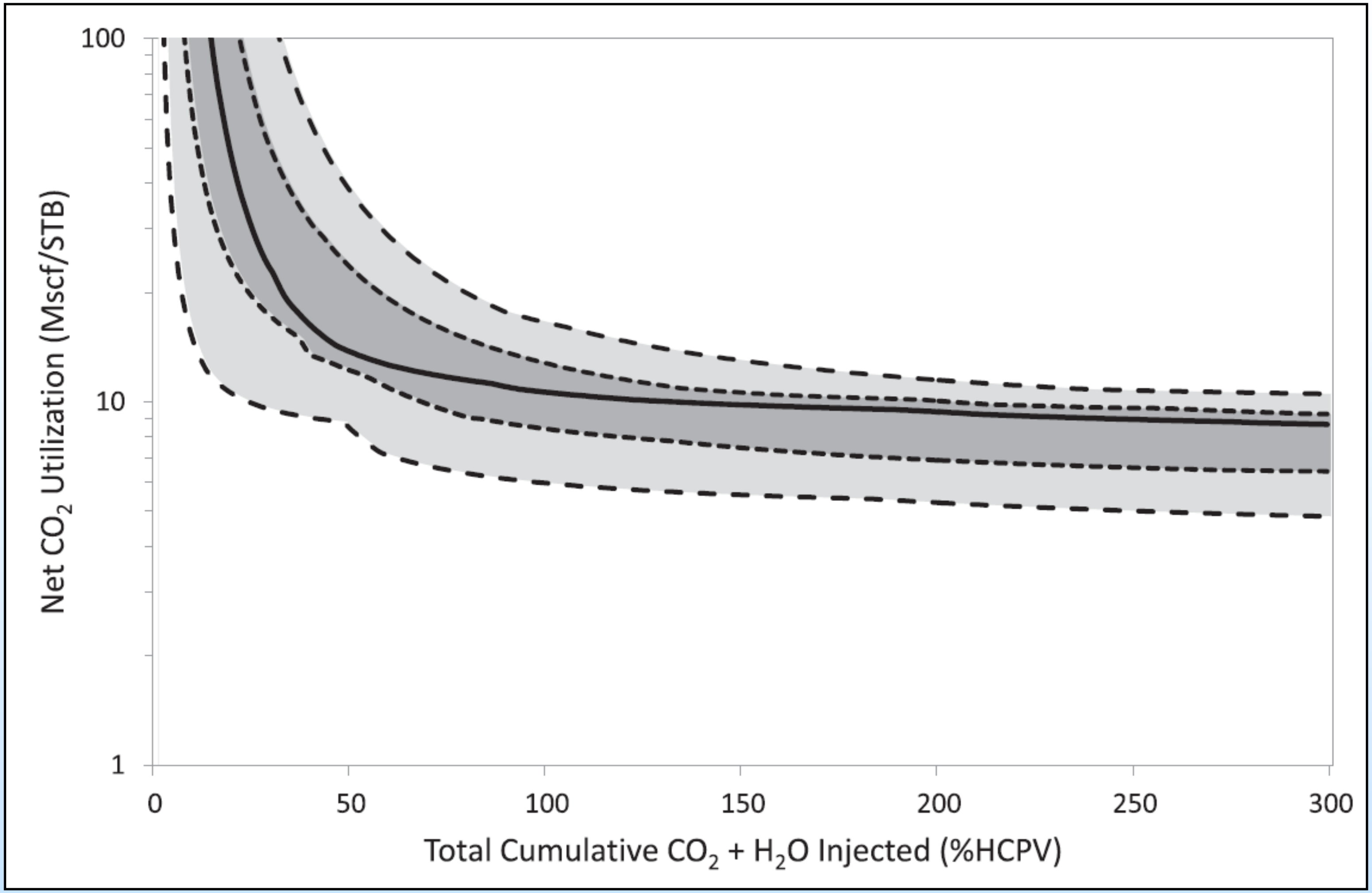
Net CO_2 Utilization Response

Fits of net CO_2 utilization to six representative sites from industry data. The blue line represents observed data; the red line represents the fitted response from a two-parameter asymptotic model.



Uncertainty Quantification: Net CO_2 Utilization P10, P50, and P90



Hydrocarbon Reservoirs: Modeling

Approach

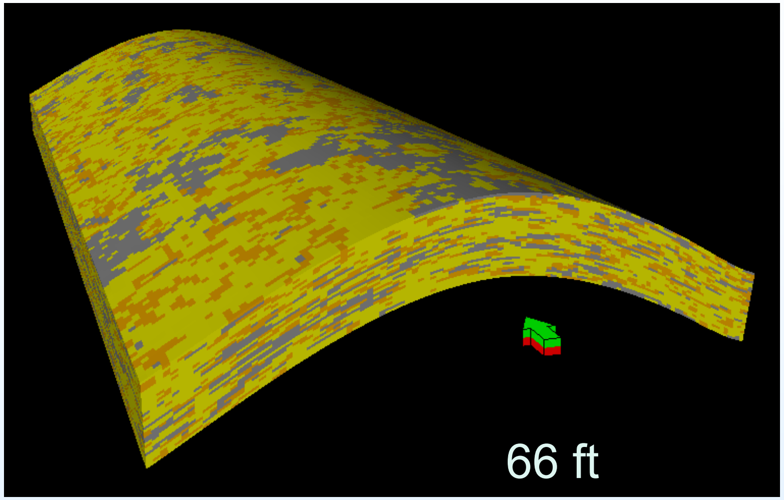
- Construct 12 field-scale models (2 miles x 4 miles) representative of existing oil fields.
- Structure for P10, P50, and P90 models derived from actual EOR oil fields.
- Geologic properties populated into each model from the AGD.

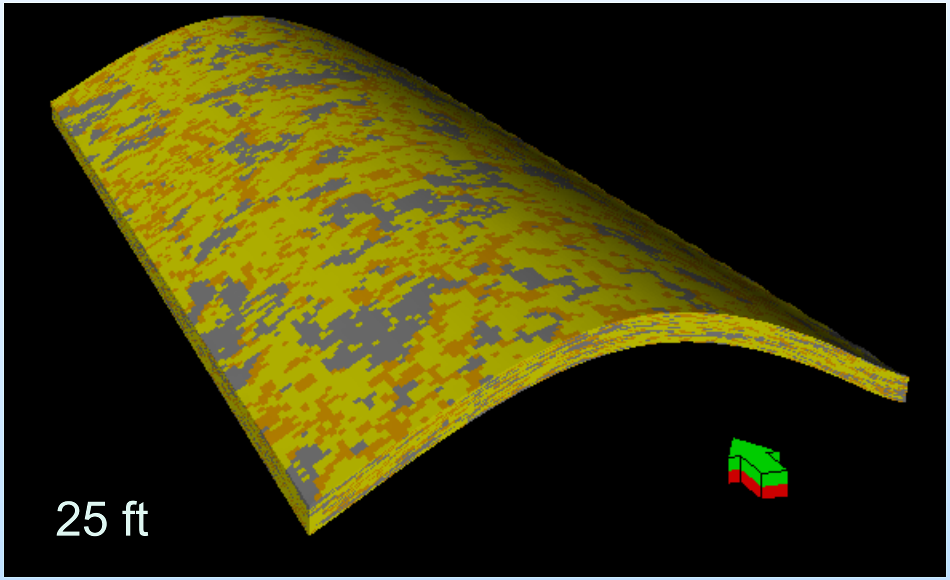
Hydrocarbon Reservoir Model Characteristics

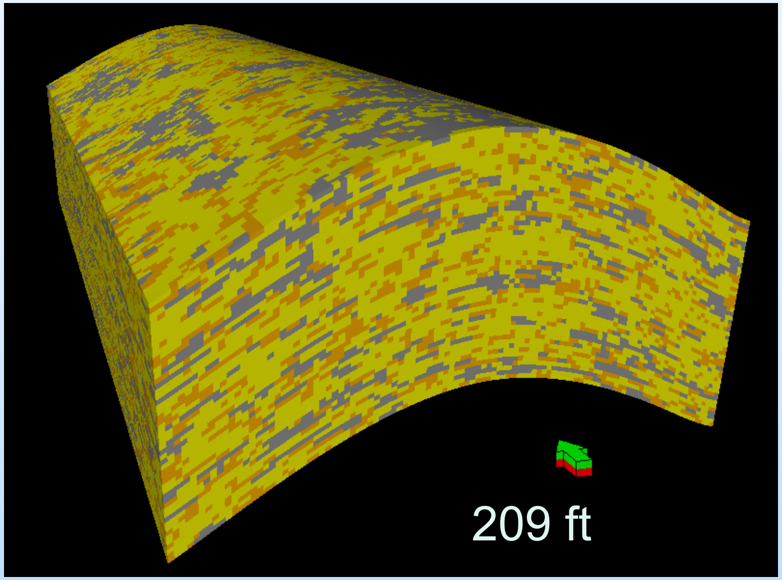
Case No.	Lithology/Environment	Depth (ft)	Thickness (ft)	P10	P50	P90	P50_WAG
1	Fluvial - Clastic	4000	25		Complete		Complete
2	Fluvial - Clastic	4000	66	Complete	Complete	Complete	Complete
3	Fluvial - Clastic	4000	209		Complete		
4	Fluvial - Clastic	8000	25		Complete		
5	Fluvial - Clastic	8000	66	Complete	Complete	Complete	
6	Fluvial - Clastic	8000	209		Complete		Complete
7	Shallow Shelf Carbonate	4000	25		Complete		Complete
8	Shallow Shelf Carbonate	4000	66	Complete	Complete	Complete	Complete
9	Shallow Shelf Carbonate	4000	209		Complete		
10	Shallow Shelf Carbonate	8000	25		Complete		
11	Shallow Shelf Carbonate	8000	66	Complete	Complete	Complete	
12	Shallow Shelf Carbonate	8000	209		Complete		Complete

Hydrocarbon Reservoirs: Structural Modeling

- Anticline structures with 100-ft closure were used with reservoir thicknesses of 25, 66, and 209 ft, based on statistics of operating CO_2 EOR projects.

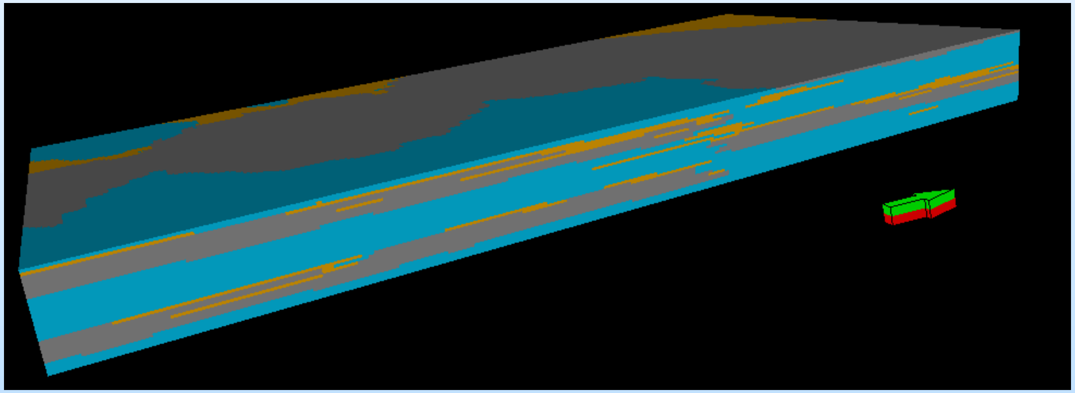






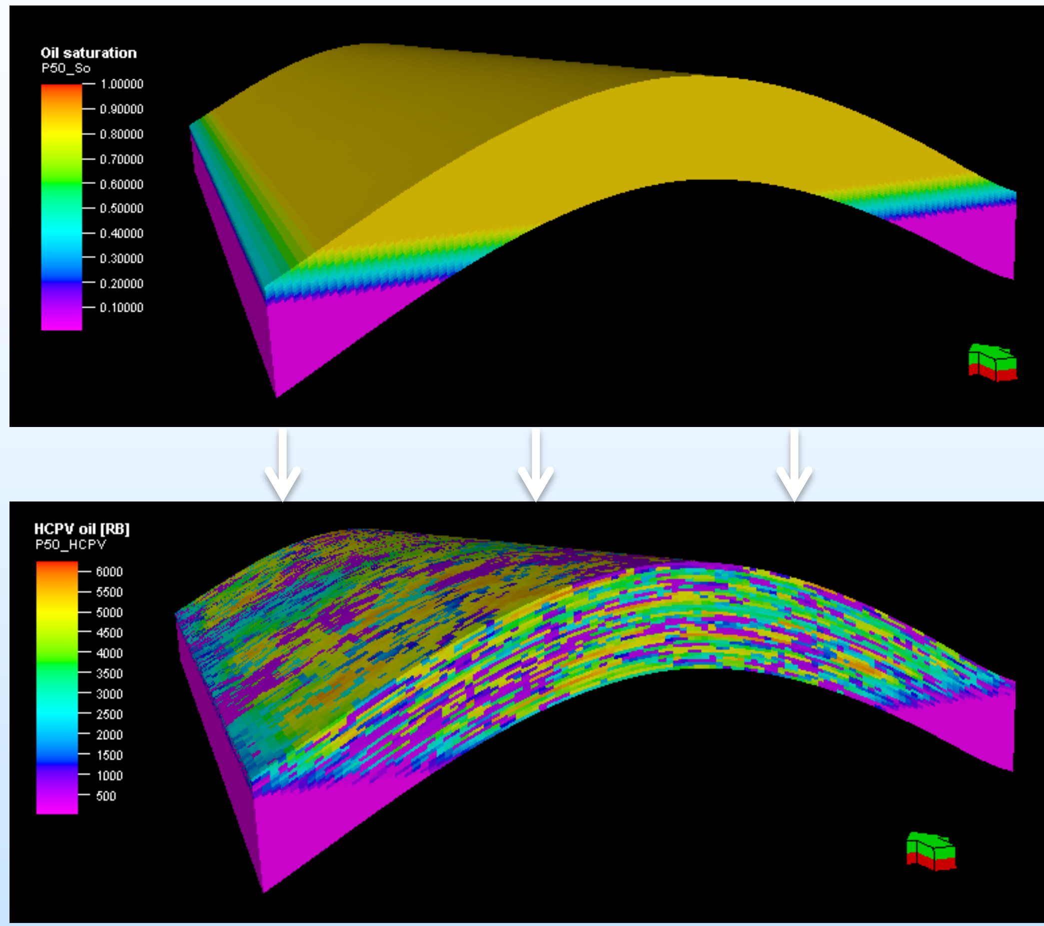
Hydrocarbon Reservoir Facies

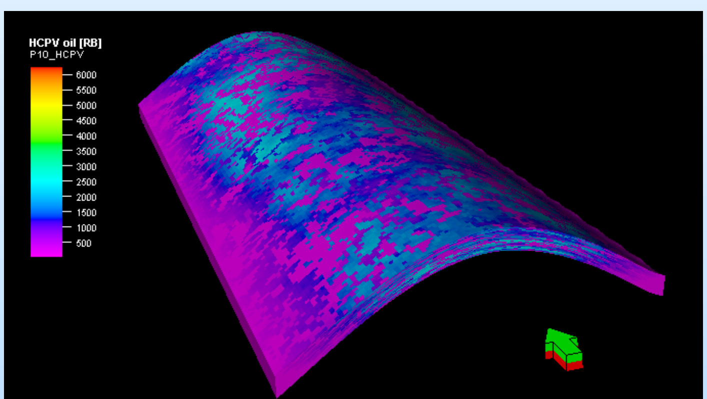
- Shallow shelf-carbonate
  - Populated using a multiple-point statistical algorithm.
  - Training image based on carbonate shelf block model and log from Central Vacuum Unit, New Mexico.
- Fluvial-clastic
  - Populated using a combined object-modeling/multiple-point statistical algorithm.
  - Training image was based on sections of the Platte River in Nebraska and logs from the Weber Sandstone, Rangely Field, Colorado.
- Three subcategories were defined: reservoir, poor reservoir, and shale.



Hydrocarbon Reservoirs: Model Saturations

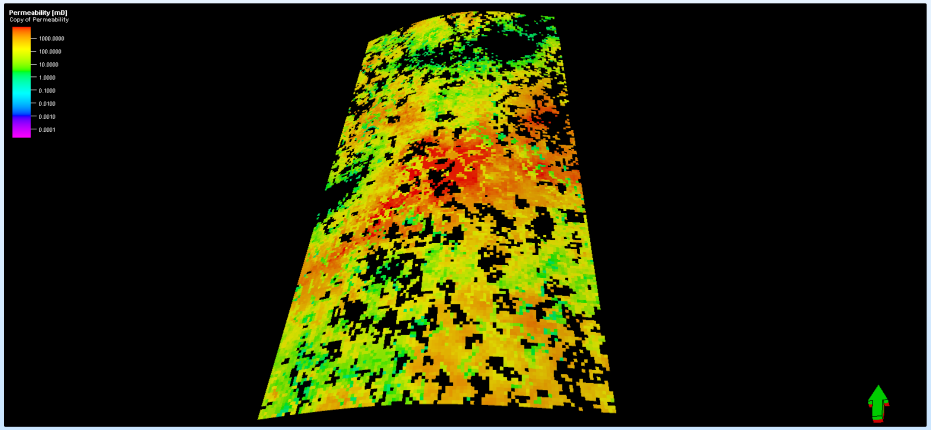
- Oil saturations were incorporated to match statistics of OOIP from the CO_2 EOR database.
- Oil–water contact and maximum saturation were adjusted to fit the target value (75% oil saturation).

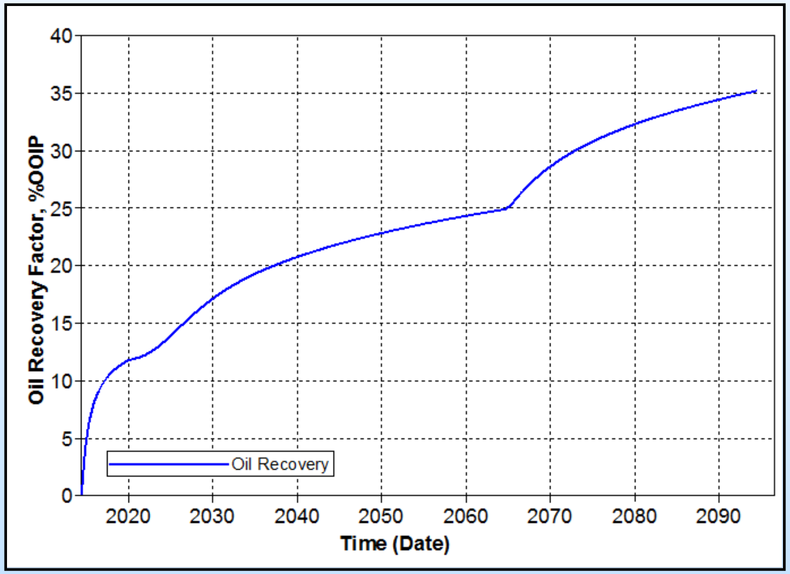




Hydrocarbon Reservoirs: Simulation

- Perform dynamic simulations, including primary, secondary, and tertiary recovery (CO_2), to evaluate the relationship between CO_2 storage and EOR.
- Utilization and recovery factors were assessed.
- Investigate the balance between associated CO_2 storage and CO_2 EOR.

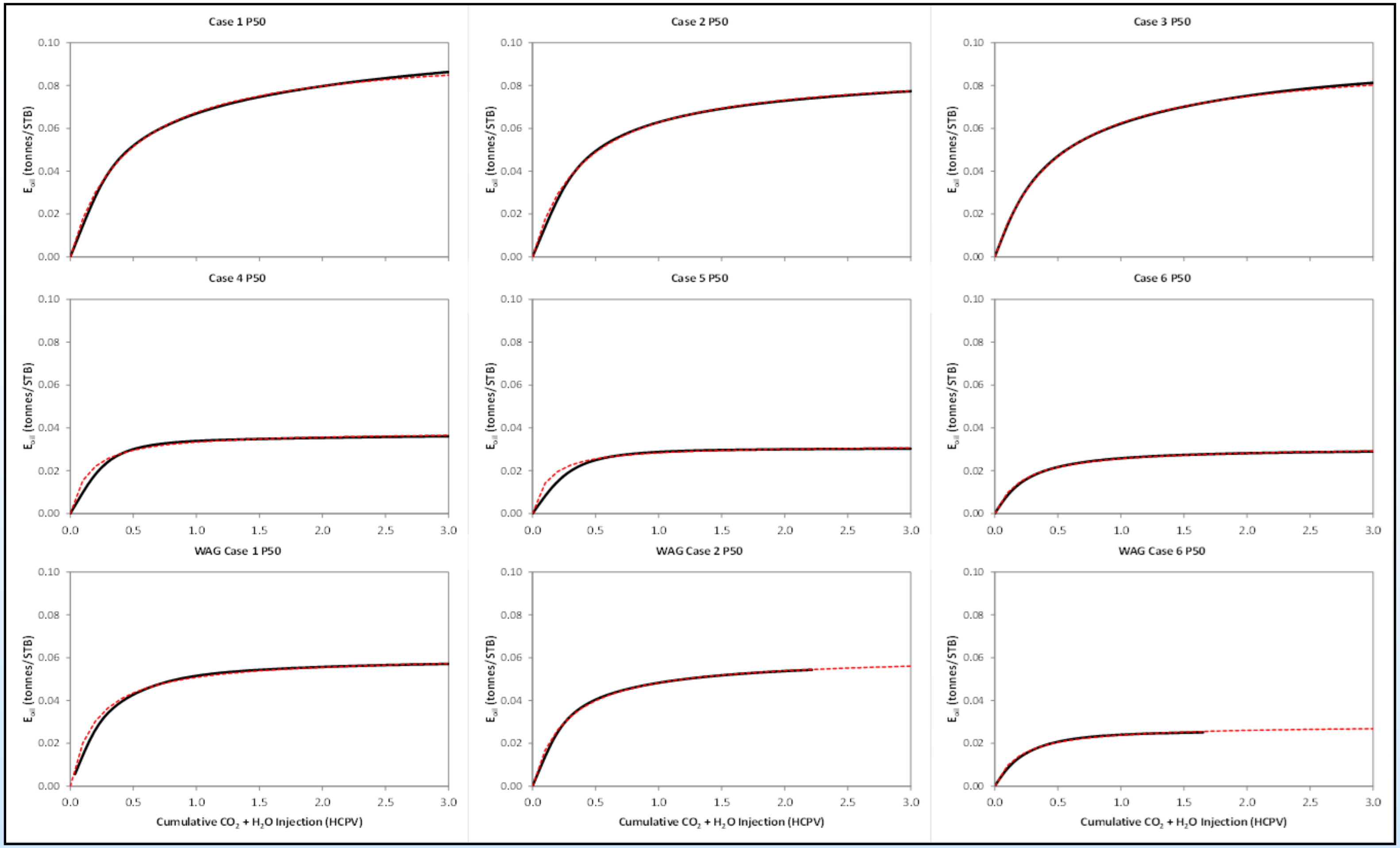




Simulation Results

Continuous CO_2 Injection

WAG



Cumulative CO_2 or CO_2 + H_2O injection (HCPV) versus CO_2 storage efficiency (tonnes/STB) for the fluvial clastic simulation models. The red dashed line represents the fitted Michaelis–Menten model.

Accomplishments to Date

- Saline formations
  - Base case geocellular models completed.
  - Simulations on base case models completed.
  - Optimization cases nearly completed.
  - Storage efficiency calculation by depositional environment for a 100-year time frame is ongoing.
- Hydrocarbon reservoirs
  - Base case geocellular models completed.
  - Simulations for fluvial and shallow shelf reservoirs completed.
  - Journal article published.

Synergy Opportunities

CO_2 Storage Capacity/Efficiency

- Combining an analytical tool with numerical simulations to quantify uncertainty.
- Sharing actual field data across projects would help constrain model properties and simulation results.

Summary

Task 2

- Basin-scale models presented challenges during simulation.
- Depositional environment affects storage efficiency.

Task 3

- The work accomplished to date will allow an efficiency factor for CO_2 storage in conjunction with CO_2 EOR to be identified.

Contact Information

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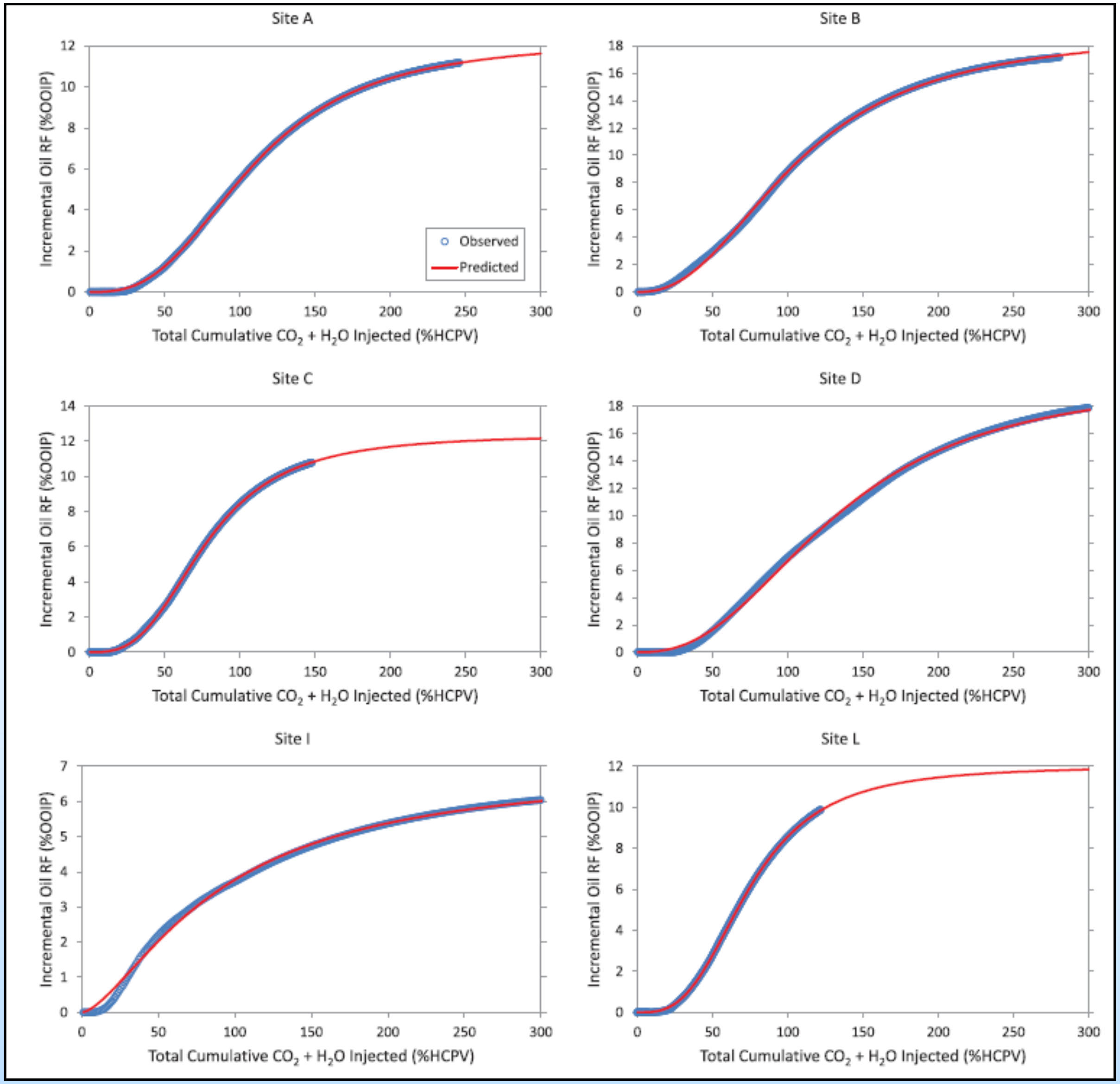
Disclaimer

Appendix

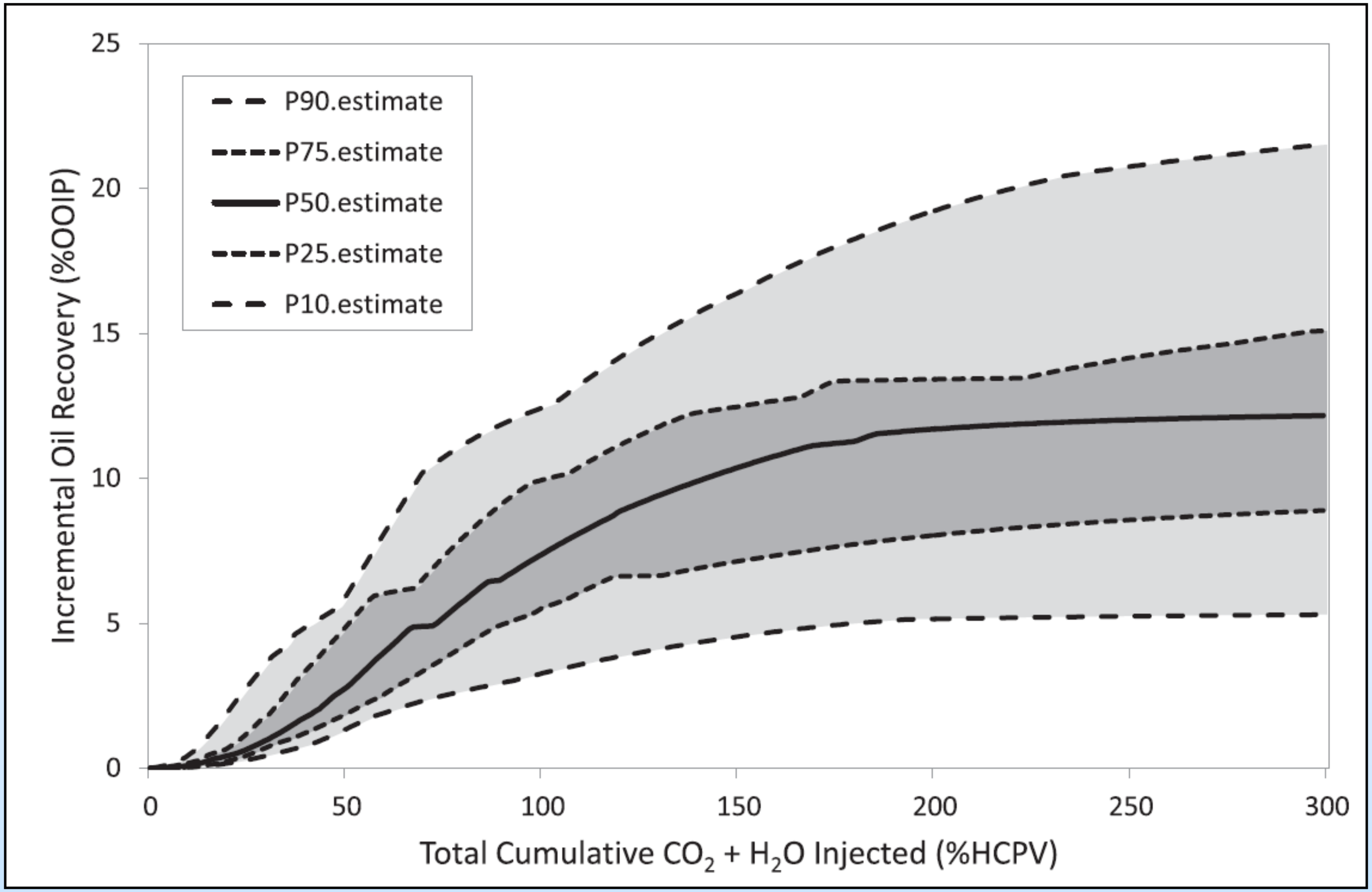
Supplemental Slides

Incremental Oil Recovery

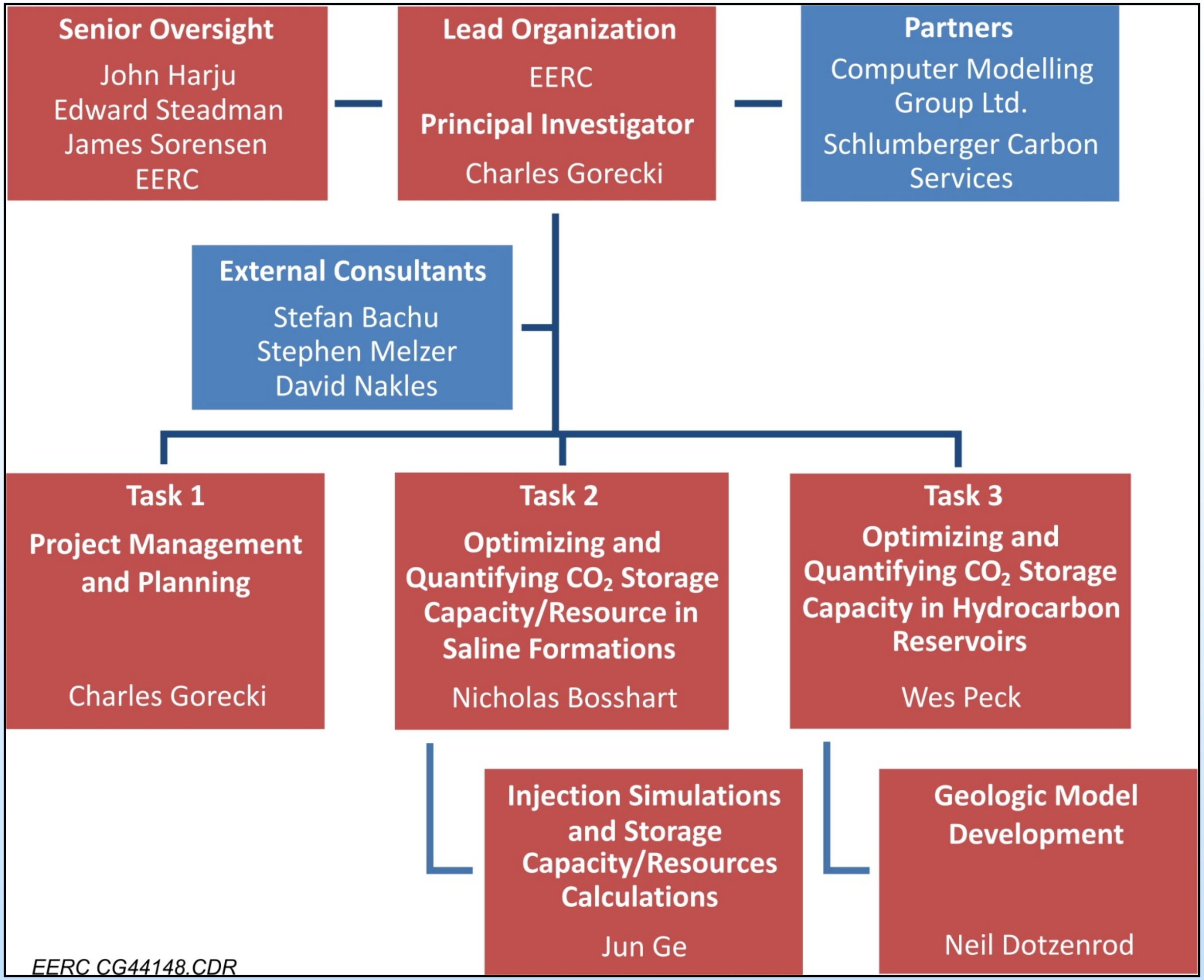
Fits of incremental oil recovery to six representative sites from industry data. Blue line represents observed data; red line represents the fitted response from the four-parameter log-logistic model



Uncertainty Quantification: Incremental Oil RF P10, P50, and P90

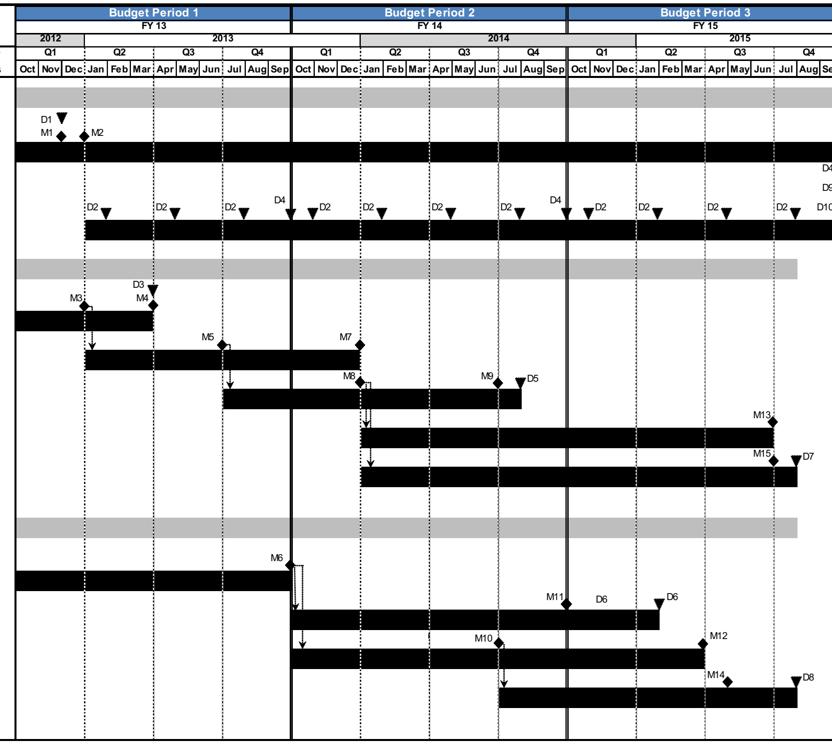


Project Organization Chart



Gantt Chart

	Duration (months)	Start Date	End Date	$ Cost	Labor Hours
Task 1 – Project Management, Planning, and Reporting	**36**	**10/1/2012**	**9/30/2015**	**$ 288,978**	**1384**
1.1 – Perform Project Management	36	10/1/2012	9/30/2015		
1.2 – Project Reporting	33	1/1/2013	9/30/2015		
Task 2 – Optimizing and Quantifying CO_2 Storage Capacity/Resource in Saline Formations	**34**	**10/1/2012**	**7/31/2015**	**$ 701,771**	**1890**
2.1 – Literature Review	6	10/1/2012	3/31/2013		
2.2 – Geologic Model Development	12	1/1/2013	12/31/2013		
2.3 – Simulations to Predict CO_2 Storage Performance	13	7/1/2013	7/31/2014		
2.4 – Optimize CO_2 Storage Efficiency and Resource	18	1/1/2014	6/30/2015		
2.5 – Refine Storage Resource Estimation Methodologies and Storage Coefficients	19	1/1/2014	7/31/2015		
Task 3 – Optimizing and Quantifying CO_2 Storage Resource in Hydrocarbon Reservoirs	**34**	**10/1/2012**	**7/31/2015**	**$ 609,251**	**1460**
3.1 – Literature Review	12	10/1/2012	9/30/2013		
3.2 – Evaluation of CO_2 EOR and CO_2 Storage Relationships	16	10/1/2013	1/31/2015		
3.3 – Hydrocarbon Reservoir Modeling and Simulation	18	10/1/2013	3/31/2015		
3.4 – CO_2 Storage Resource Methodologies in Hydrocarbon	13	7/1/2014	7/31/2015		



Summary Task

Activity Bar

Milestone (M) ◆

Deliverable (D) ▼

Critical Path

Key for Deliverables (D) ▼

D1 – Updated Project Management Plan
D2 – Quarterly Progress/Milestone Report
D3 – Identification of Geologic Formations Selected for Evaluation
D4 – Data Submission to EDX
D5 – Interim Report: Simulation Results for CO_2 Storage Performance
D6 – Interim Report: Balance Between CO_2 EOR and CO_2 Storage
D7 – Manuscript on CO_2 Storage Performance for Submission to Peer-Reviewed Journal
D8 – Manuscript on the Balance Between CO_2 EOR and CO_2 Storage for Submission to Peer-Reviewed Journal
D9 – Best Practices Manual on Optimizing and Quantifying CO_2 Storage Resource in Saline Formations and Hydrocarbon Reservoirs
D10 – Final Report

Key for Milestones (M) ◆

M1 – Updated Project Management Plan Submitted to DOE
M2 – Project Kickoff Meeting Held
M3 – First Saline Formation Selected
M4 – Saline Formations Literature Review Completed
M5 – First Geologic Model Completed
M6 – CO_2 EOR and Associated Storage Literature Review Completed
M7 – All Geologic Models Completed
M8 – First Injection Simulation Completed
M9 – Simulations to Predict CO_2 Storage Performance Completed
M10 – First CO_2 EOR and Storage Simulation Completed
M11 – Reservoir Evaluations Completed
M12 – Field- to Pattern-Sized Geologic Models Completed
M13 – Simulations to Optimize CO_2 Storage Efficiency Completed
M14 – Examination and Refinement of Storage Capacity and Incremental Hydrocarbon Production Completed
M15 – Evaluation and Validation of Estimation Methodologies Completed

Rev. December 17, 2014

Bibliography

- Azzolina, N.A., Nakles, D.V., Gorecki, C.D., Peck, W.D., Ayash, S.C., Melzer, L.S., and Chatterjee, S., 2015, CO_2 storage associated with CO_2 enhanced oil recovery—a statistical analysis of historical operations: International Journal of Greenhouse Gas Control, v. 37, p. 384–397.