Assessing Reservoir Depositional Environments to Develop and Quantify Improvements in CO_2 Storage Efficiency: A Reservoir Simulation Approach (DEEP)

Project Number: DE-FE0009612

Roland Okwen, Scott Frailey, and Hannes Leetaru

Illinois State Geological Survey

U.S. Department of Energy
National Energy Technology Laboratory
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Developing the Technologies and Infrastructure for CCS
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Acknowledgments

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- The MGSC is a collaboration led by the state geological surveys of Illinois, Indiana, and Kentucky.
- Through a university grant program, Landmark Software was used for the reservoir and geologic modeling.

Presentation Outline

- Project benefit to CO_2 program
- Project goals and objectives
- Project approach
- Outcomes
- Accomplishments to date
- Summary

Benefit to the Program

CARBON STORAGE PROGRAM MAJOR GOALS

- Support industry’s ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.
- Develop and validate technologies to ensure 99 percent storage permanence.
- Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness.

BENEFITS STATEMENT

This project will address Area of Interest 3, Field Methods to Optimize Capacity and Ensure Storage Containment. The identification of field techniques to improve storage efficiency above the baseline CO_2 storage efficiency in specific geologic formation classes of different depositional environments identified by DOE as promising storage formations will provide better regional assessment estimates and site screening criteria. The research will contribute to the program’s effort of estimating CO_2 storage capacity in geologic formations.

Project Overview:

Goals

- Quantify storage efficiency for different depositional systems;
  - DOE’s “High” and “Medium” storage potential ratings
- Identify methods to
  - Improve *E*;
  - Control CO_2 plume footprint

Project Overview: Objectives

- Select Illinois Basin (ILB) formations representing different depositional systems
- Develop rigorous geologic and geostatistical models of selected formations
- Conduct numerical simulations
  - Estimate *E*
  - Depict CO_2 plume distribution within formation flow units
  - Determine depositional system-based strategies to improve *E*

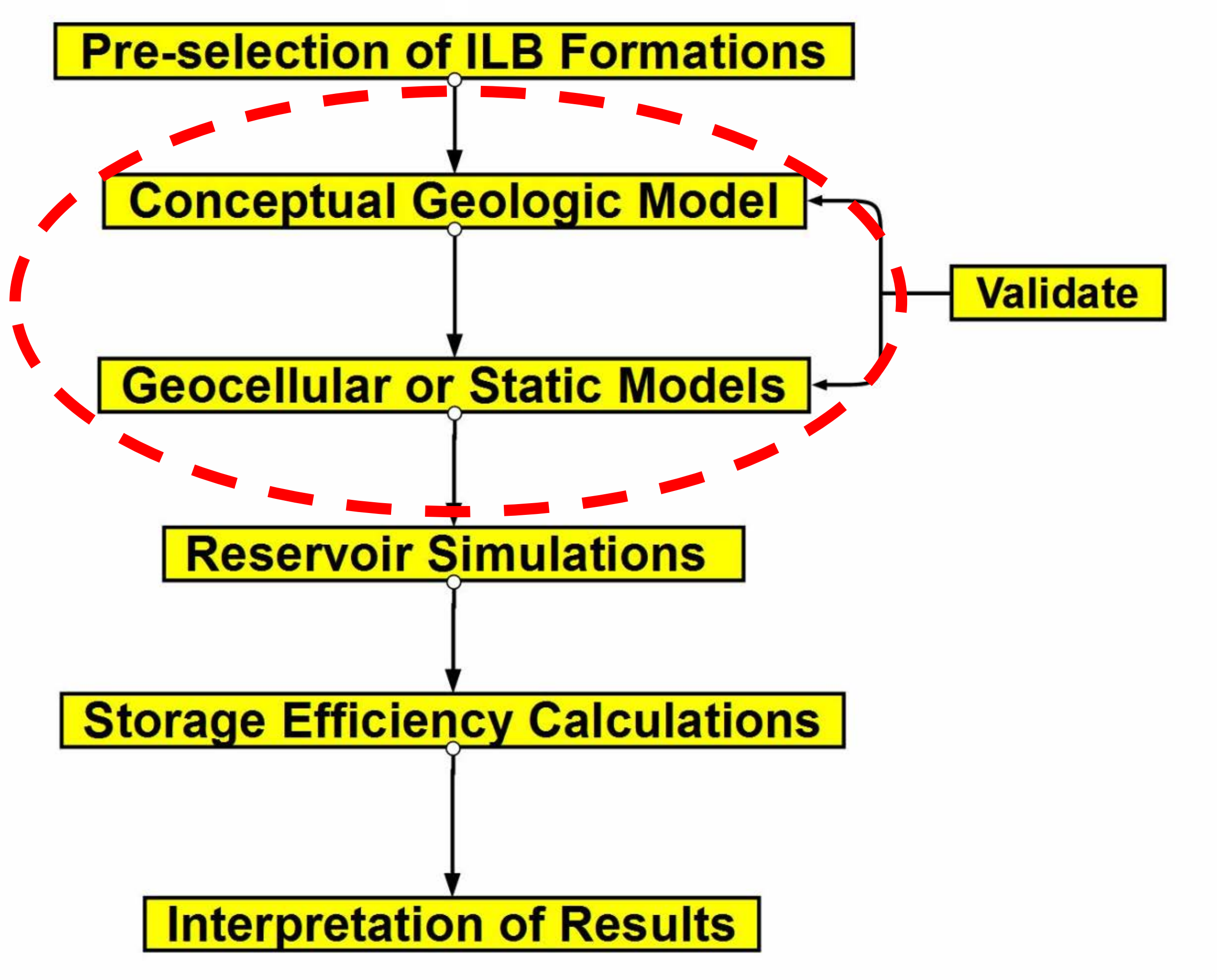
Background

- CO_2 storage potential Matrix (NETL, 2010)
- Large Scale, Small Scale and Characterization are DOE defined groups

Matrix of Field Activities in Different Depositional Environment

Depositional Environment	High Potential					Medium Potential				Low or Unknown Potential	
	Deltaic	Shelf Clastic	Shelf Carbonate	Strandplain	Reef	Fluvial Deltaic	Eolian	Fluvial & Alluvial	Turbidite	Coal	Basalt (LIP)
Large Scale	–	1	–	–	1	3	–	1	–	–	–
Small Scale	3	2	4	1	2	–	–	2	–	5	1
Characterization	1	–	8	6	–	3	3	2	2	–	1

Approach for each depositional environment



Pre-selection of ILB Formations

Conceptual Geologic Model

Validate

Geocellular or Static Models

Reservoir Simulations

Storage Efficiency Calculations

Interpretation of Results

Depositional Environments

Depositional Environment	Storage Potential (DOE's Rating)	ILB Formation	Other US Basin formations
Deltaic	High	Benoist	Frontier Formation (Rocky Mountain basins)
Shelf Clastic	High	Cypress	Tapeats Sandstone (Colorado Plateau) Hamilton and Martinez (Sacramento Valley Basin)
Shelf Carbonate	High	Ste. Genevieve	Naco and Martin (Colorado Plateau); Knox (Illinois and Michigan Basins); Arbuckle (Ozark Plateau)
Strandplain	High	Upper Mt. Simon	Fleming Group (Gulf of Mexico Basin); Pottsville, Parkwood, and Hartselle (Black Warrior Basin)
Reef	High	Racine	Cisco-Canyon (Permian Basin)
Fluvial Deltaic	Medium	Bridgeport	Domengine (Sacramento Valley Basin); Fleming Group
Fluvial & Alluvial	Medium	Lower Mt. Simon	Tuscaloosa (Gulf Coast Basin); Stockton and Passaic (Newark Basin)
Turbidite	Medium	Carper	Puente (Los Angeles Basin)

Conceptual and Geocellular Models

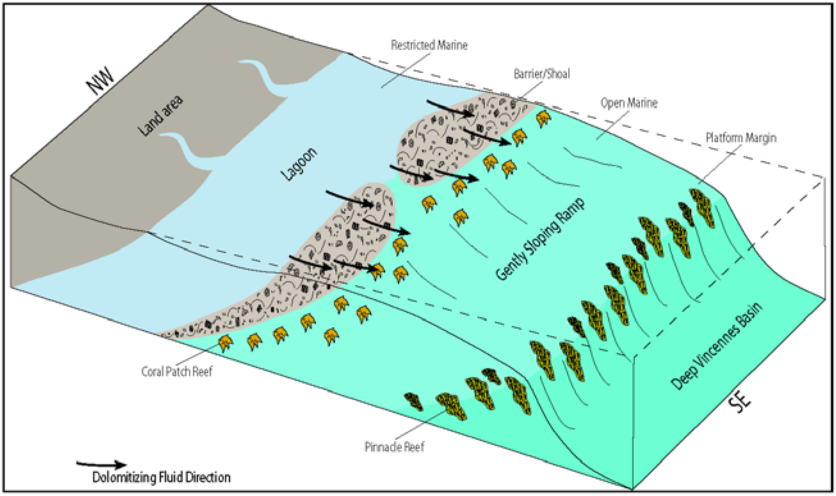
- Conduct geologic mapping
  - Available Data
    - Logs: spontaneous potential, neutron-density, openhole, and casedhole
    - Core
    - Outcrops
- Results
  - Cross sections
  - Isopach maps
  - Structure maps
  - Block diagram of the depositional environment

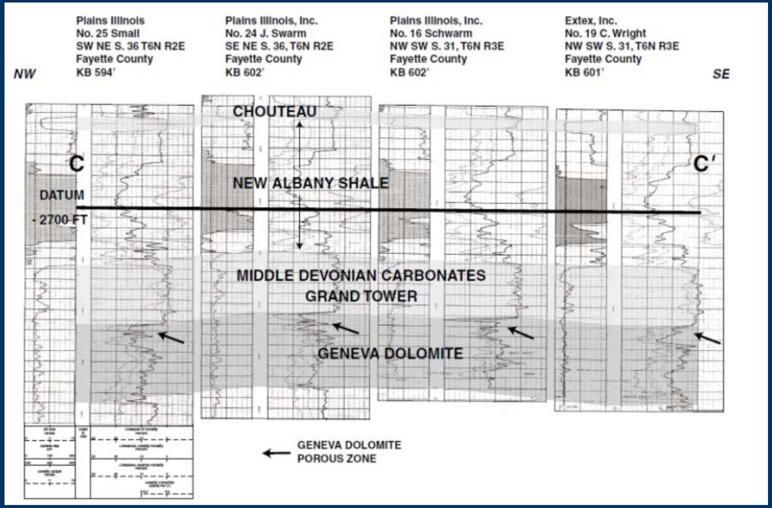
- Software: Geographix and Petra

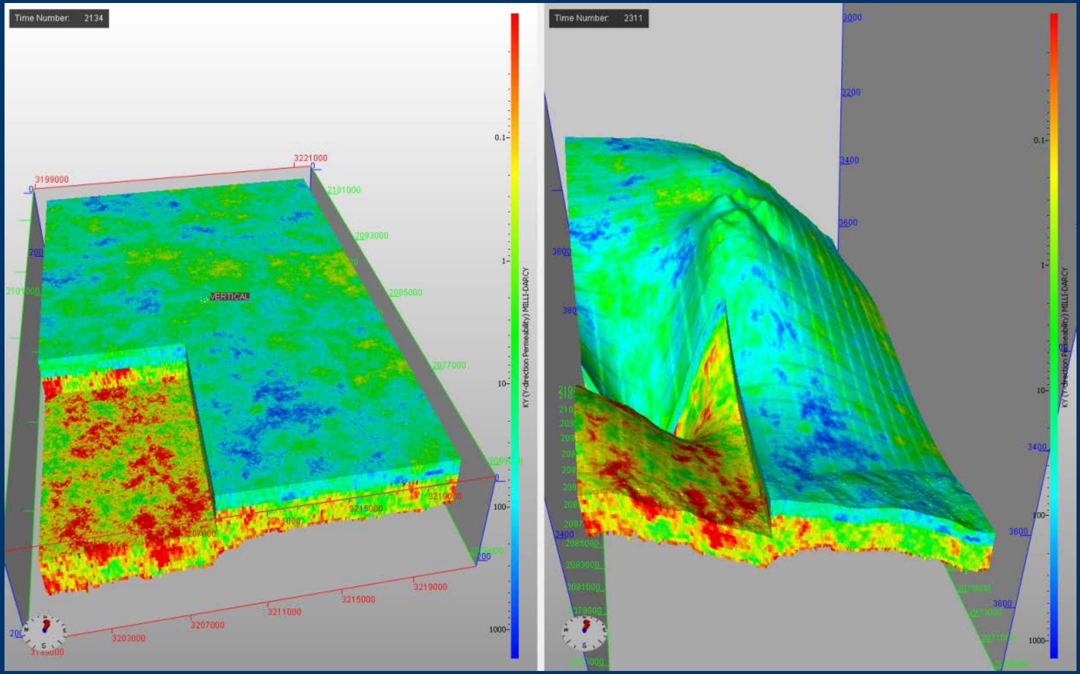
Conceptual and Geocellular Models (cont.)

- Conduct geostatistical analyses using
  - Conceptual geologic model
  - Digitized logs
  - Core data
  - Surface maps
- Build geocellular model (4 distributions)
  - Porosity
  - Permeability
  - Thickness
  - Facies
- Flat, no structure
- Software: Isatis

Example: Shelf Carbonate

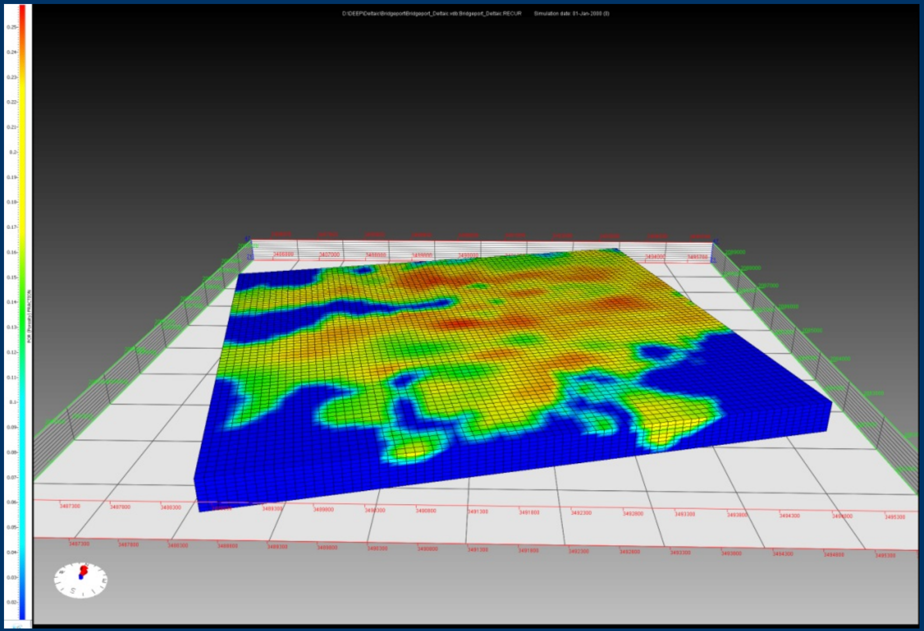


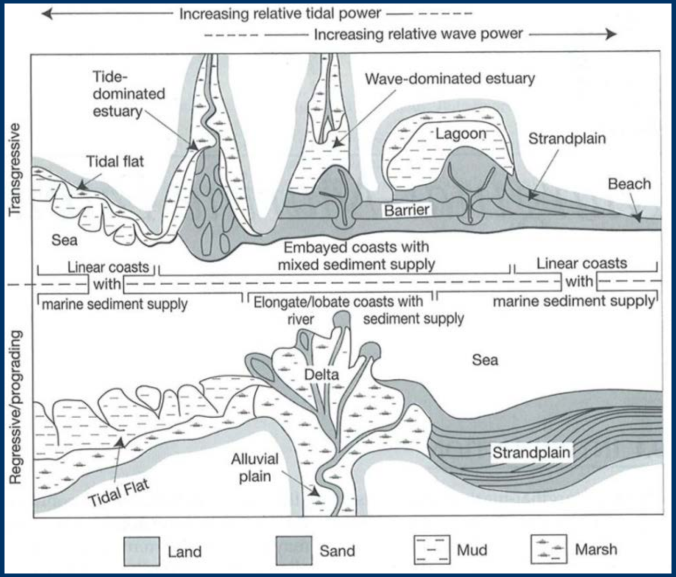


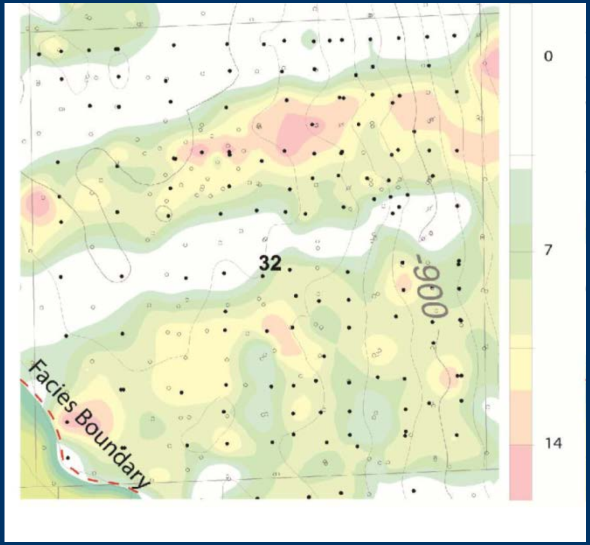


Model Permeability distribution (0.1–1000 mD)

Example: Deltaic







- Permeability distribution (5−300 mD)
- Model area covers isopach map (Seyler et al., 2012)

Reservoir Simulations

Input and initial conditions

- Reservoir and PVT properties
- End-point saturations and relative permeabilities
- Initial conditions

$$P_{res} > P_{CO_{2,crit}} : 1100 \text{ psi}$$

$$T_{res} > T_{CO_{2,crit}} : 90\ {}^{o}\text{F}$$

- Injection rate :

18,854 Mscf/d (1 tonne/d)

- No pressure constraint

- Software: Landmark Nexus

End-point saturations & rel. permeability

Parameter	Sandstone	Limestone
S_{wr}	0.50	0.50
$k_{rw,max}$	1.00	1.00
$S_{g,c}$	0.30	0.20
$k_{rg, max}$	0.25	0.25
m	2.00	2.00
n	3.00	4.00

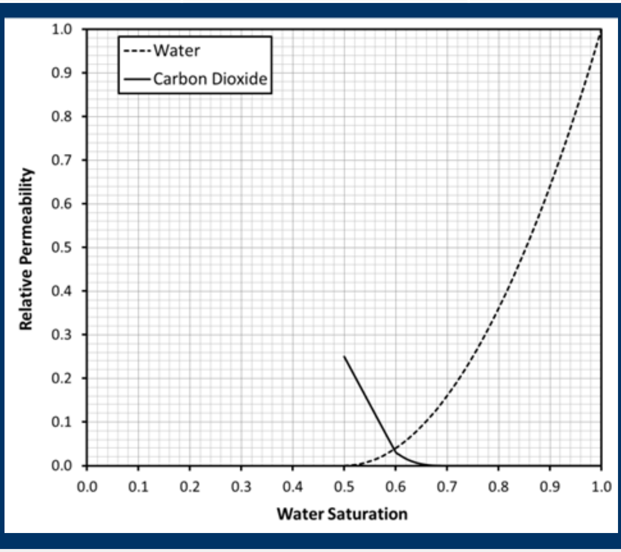


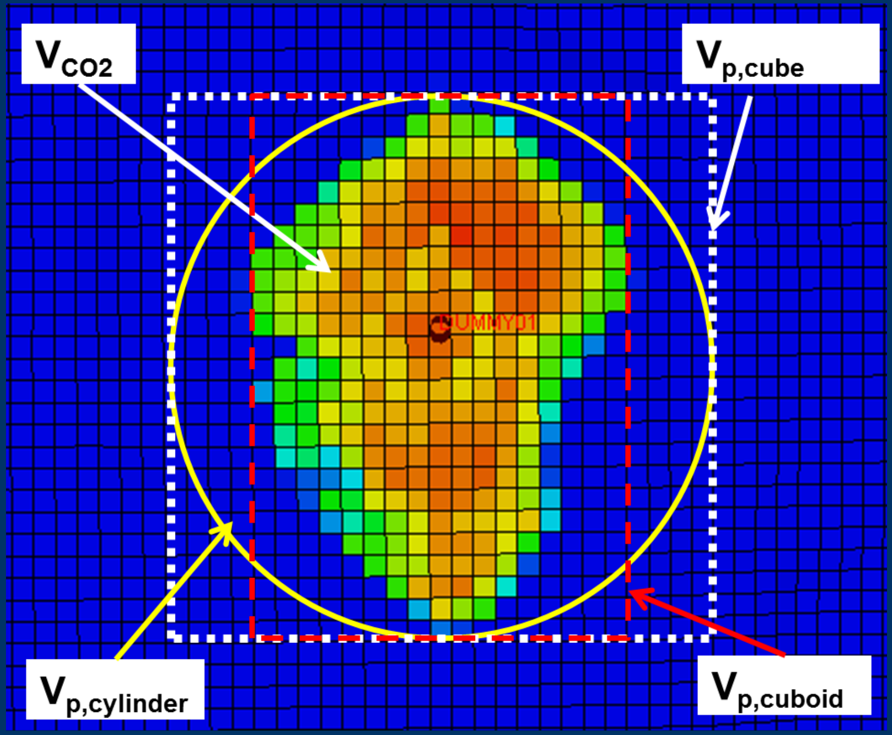
Fig.: Sandstone relatively curve

Reservoir Simulations, cont.

Storage Efficiency (E)

$$E = \frac{V_{CO_2}}{V_p}$$

- V_{CO2} : reservoir pore volume contacted by CO_2.
- V_p : pore volume available for storage



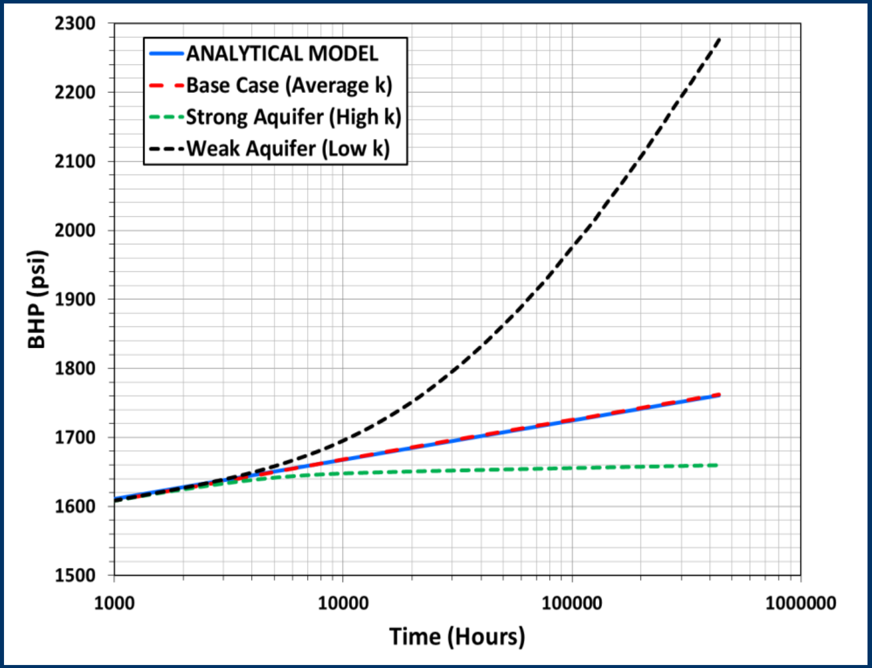
Warmer colors indicate higher CO_2 saturation and blue indicates water

Reservoir Simulations

- Sensitivity studies
  - Infinite acting aquifer (analytical vs. numerical model)
    - Wellblock permeability
    - Aquifer permeability averaging method
    - Water influx vs outflux

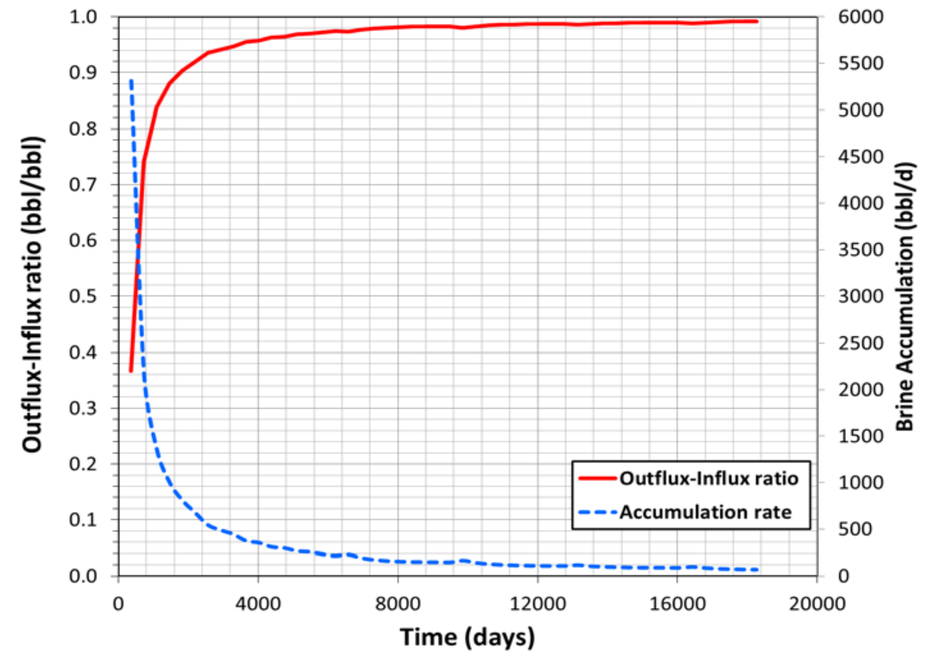
Aquifer permeability averaging method

Aquifer strength on BHP



- Average reservoir k closely exhibit infinite-acting aquifer behavior.

Fluid outflux vs. influx



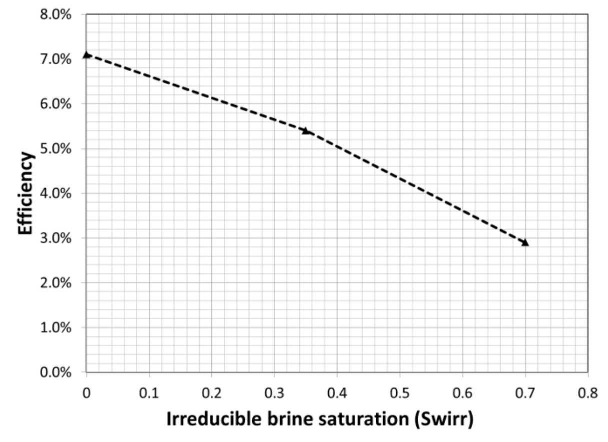
- Outflux-Influx ratio approaches 1.0 over time.

Reservoir Simulations

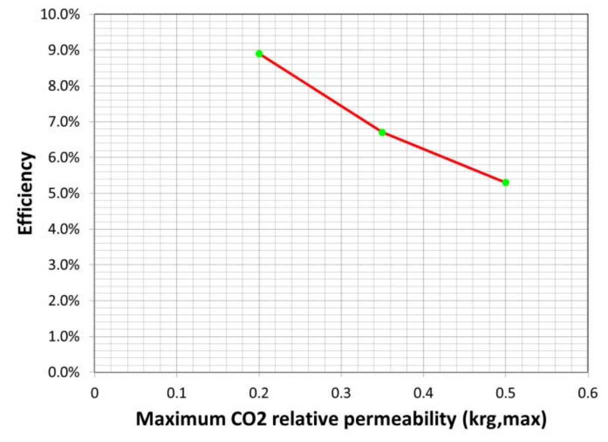
- Sensitivity studies (continued)
  - End-point saturations and relative permeabilities
    - S_{wirr} : irreducible brine saturation
    - S_{gc}, : critical CO_2 saturation
    - $k_{rg,max}$: maximum CO_2 relative permeability

End-point Saturations and relative permeability Effects

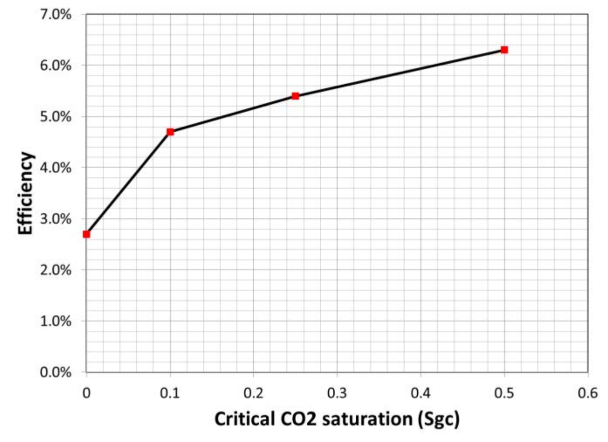
S_{wirr}



$K_{rg,max}$

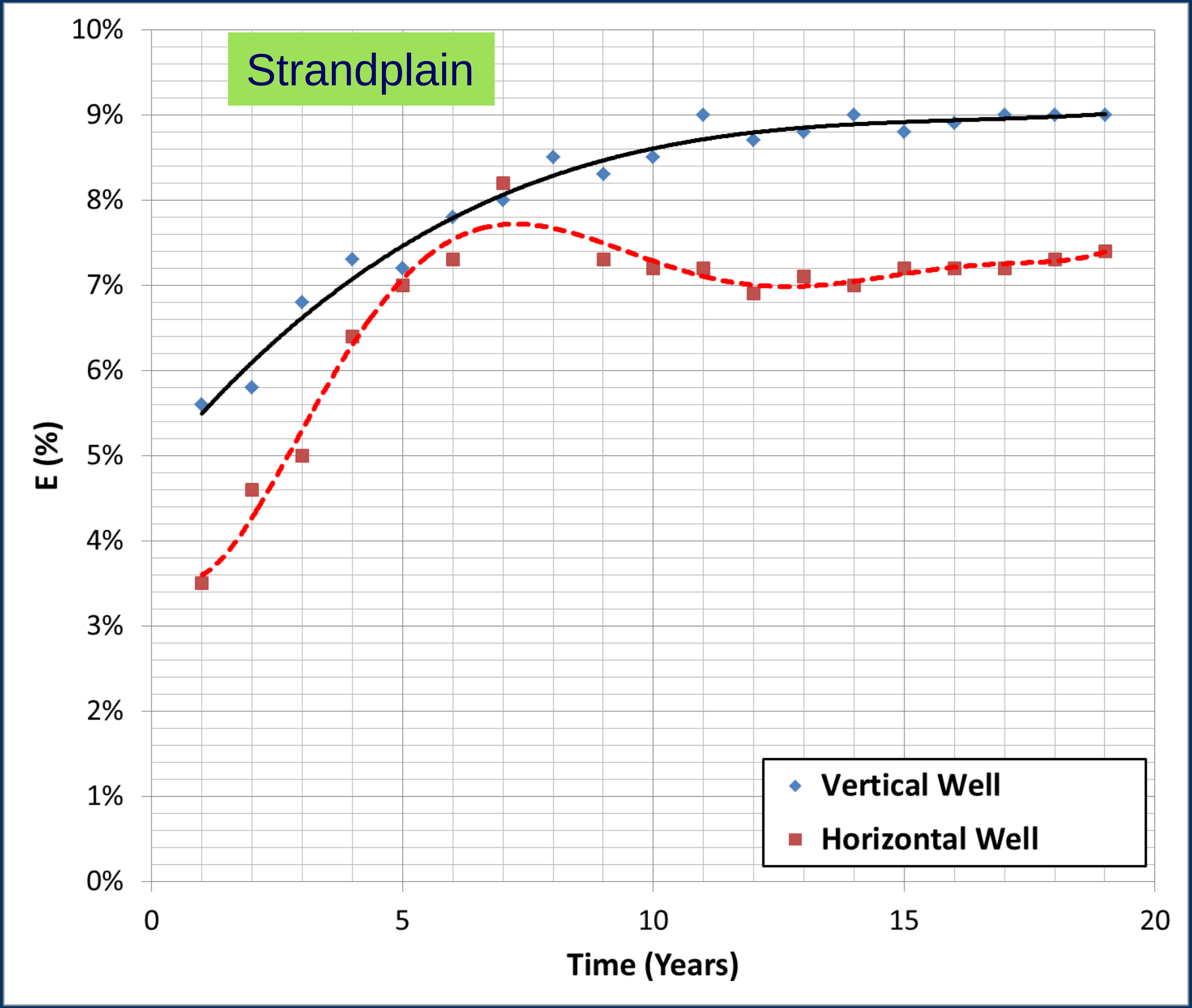


S_{gc}



- E declines as S_{wirr} or $k_{rg,max}$ increase
- E increases with S_{gc}

Example: Storage Efficiency profile

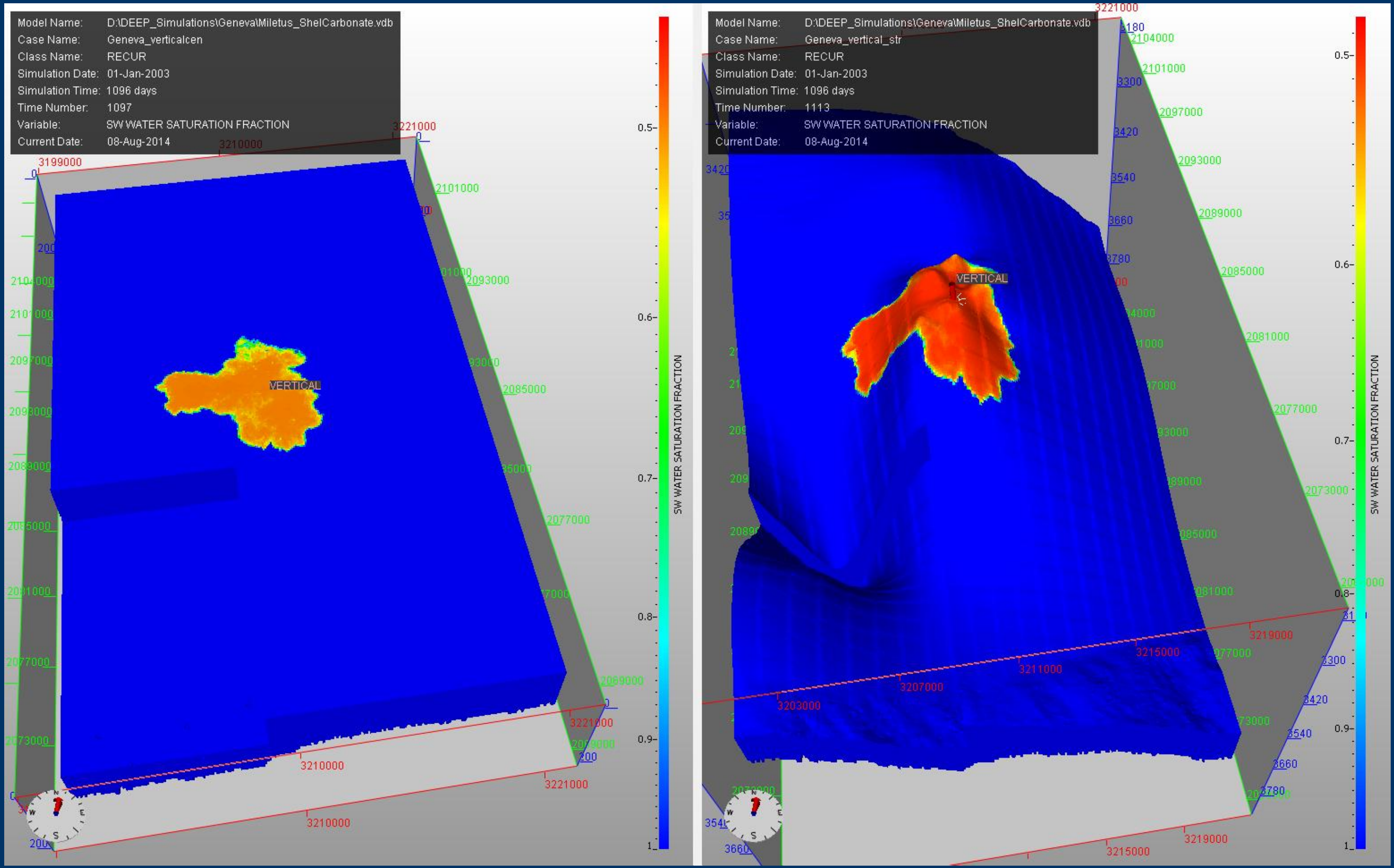


Example: shelf carbonate

- Cells: 1,209,748

CO_2 plume distribution (3 years)

CO_2 plume distribution (1 year)



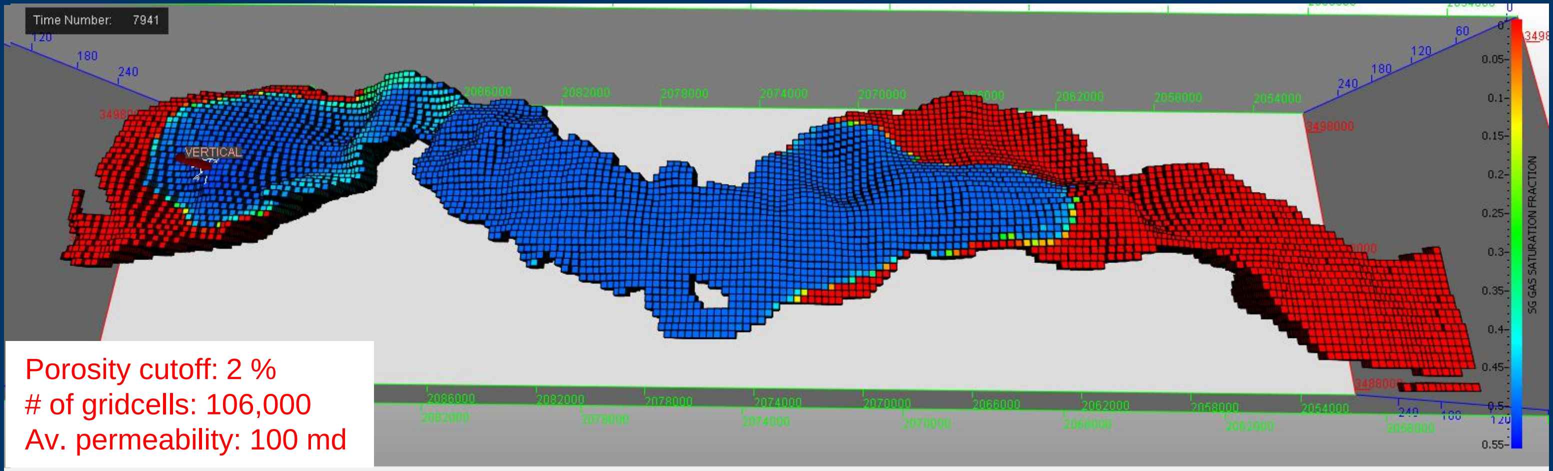
Model Name: D:\DEEP_Simulations\Geneva\Miletus_ShelCarbonate.vdb
Case Name: Geneva_verticalcen
Class Name: RECUR
Simulation Date: 01-Jan-2003
Simulation Time: 1096 days
Time Number: 1097
Variable: SW WATER SATURATION FRACTION
Current Date: 08-Aug-2014

Model Name: D:\DEEP_Simulations\Geneva\Miletus_ShelCarbonate.vdb
Case Name: Geneva_vertical_str
Class Name: RECUR
Simulation Date: 01-Jan-2003
Simulation Time: 1096 days
Time Number: 1113
Variable: SW WATER SATURATION FRACTION
Current Date: 08-Aug-2014

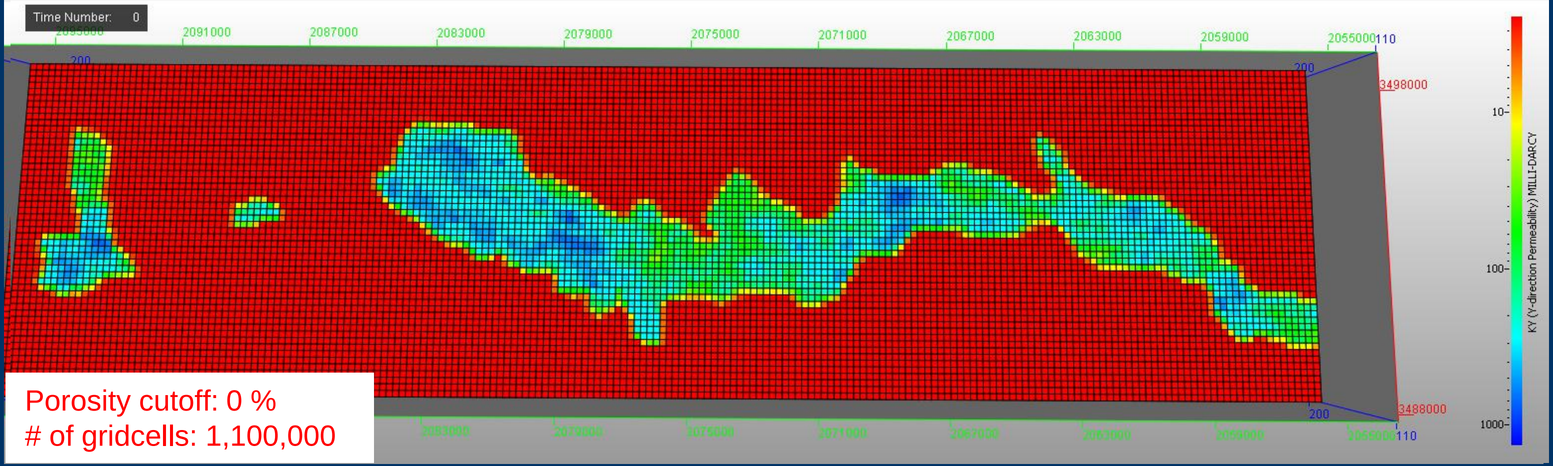
Example: Fluvial Deltaic

- Channel System
- Cells: 127,500, k_{av}: 100 md

CO_2 plume distribution (50 year)



Porosity cutoff: 2 %
# of gridcells: 106,000
Av. permeability: 100 md



Porosity cutoff: 0 %
# of gridcells: 1,100,000

Normalize baseline efficiencies

- Normalize for effect of relative permeability and end-point saturations

$$(1)\ E_v = \frac{E}{\bar{S}_g}$$

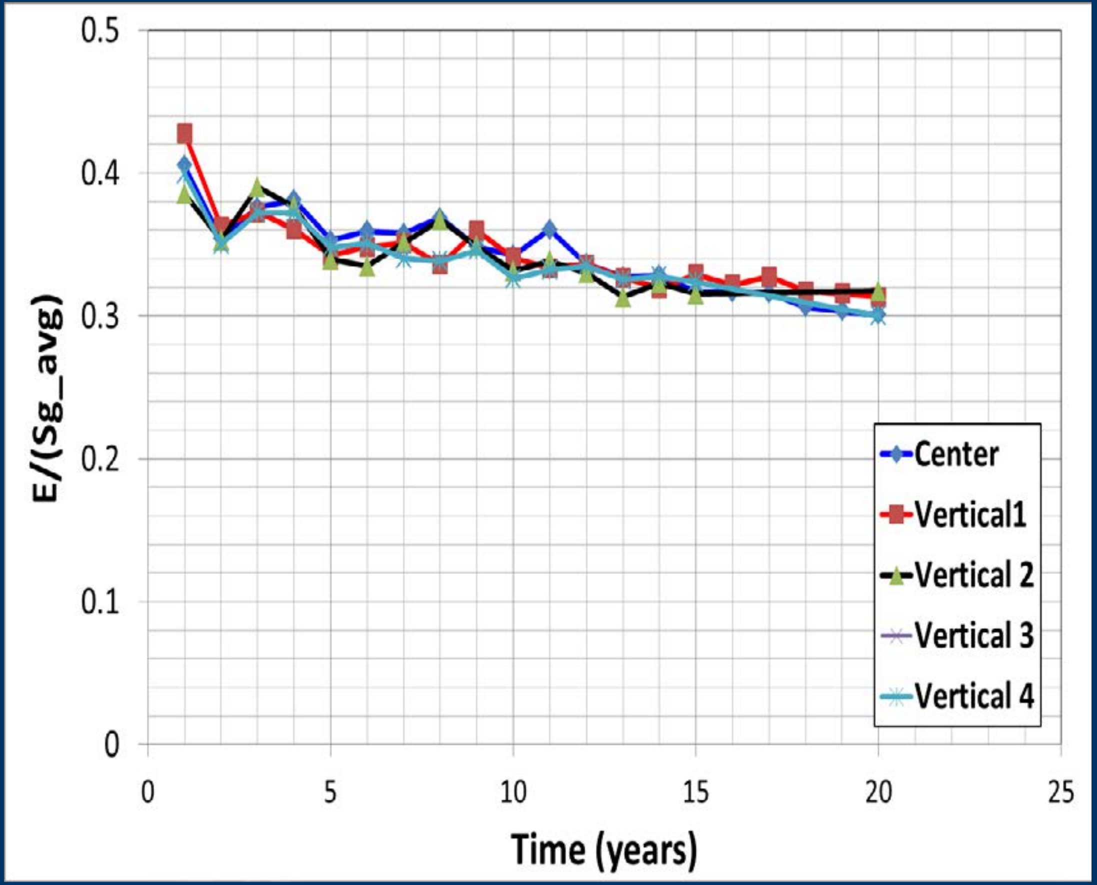
$$(2)\ E_v = \frac{E}{\bar{S}_g} k_{rg}(\bar{S}_g)$$

$$(3)\ E_v = \frac{E\,(1 - S_{wirr})}{\bar{S}_g}$$

$$(4)\ E_v = \frac{E\,(1 - S_{wirr} - S_{gc})}{\bar{S}_g}$$

$$(5)\ E_v = \frac{E\,(1 - \bar{S}_g)}{\bar{S}_g}$$

$$(6)\ E_v = \frac{E\,(1 - S_{wirr})}{\bar{S}_g - S_{gc}}$$



Outcomes

Normalize baseline efficiencies

Depositional Environment		Baseline E_V (%)		% Change (effect of geologic structure)
	ILB formation	Stratigraphic	Structural	
Deltaic	Sandstone	23 — 41	23 — 43	0.0 — 4.8
Shelf clastic	Sandstone	17 — 41	20 — 52	18 — 26
Shelf carbonate	Limestone	9.5 — 26	10 — 28	5.3 — 7.7
	Dolomite	7.5 —19	9.0 — 19	0.0 — 20
Fluvial deltaic	Sandstone	36 — 52	36 — 51	0.0 — 1.9
Strandplain	Sandstone	16 — 32	30 — 43	34 — 88*
Reef	Limestone	14 — 53	13 — 56	5.7 — 7.1
Fluvial and alluvial	Sandstone	11 — 52	17 — 58	12 — 55

*Large structure, low dip angle and thick reservoir

Min: Median: Max
0% : 7.4% : 88%

E and E_v increase with size of geologic structure.

Storage Potential vs. Efficiency Matrix

- CO_2 storage potential Matrix (NETL, 2010)

CO_2 storage potential Matrix (NETL, 2010)

Geologic Formation Classes	High Potential					Medium Potential			
	Deltaic	Shelf Clastic	Shelf Carbonate	Strandplain	Reef	Fluvial Deltaic	Eolian	Fluvial & Alluvial	Turbidite
Ranking	1	2	3	4	5	6	7	8	9

CO_2 storage Efficiency Matrix

Geologic Formation Classes	High Potential					Medium Potential			
	Deltaic	Shelf Clastic	Shelf Carbonate	Strandplain	Reef	Fluvial Deltaic	Eolian	Fluvial & Alluvial	Turbidite
Ranking	2	4	8	5	6	1	—	7	3

Classification is based on E_v of simulation using stratigraphic geologic models

Note: High E ≠ high storage capacity (potential).

Summary

- Key Findings
  - Formations studied exhibit a mixture of depositional environments with one having a dominating presence.
  - Depositional systems in cratonic and non-cratonic US Basins exhibit similar characteristics but differ in scale of geologic features.
- Lessons Learned
  - Effect of geologic structure on storage efficiency is dependent on:
    - Size
    - Dip angle
    - Reservoir thickness
- Future Plans
  - Developed database tool to estimate *E* from simulation data.

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MGSC

Midwest Geological
Sequestration Consortium
www.sequestration.org

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GEOLOGICAL SURVEY
PRAIRIE RESEARCH INSTITUTE

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

ISGS Staff

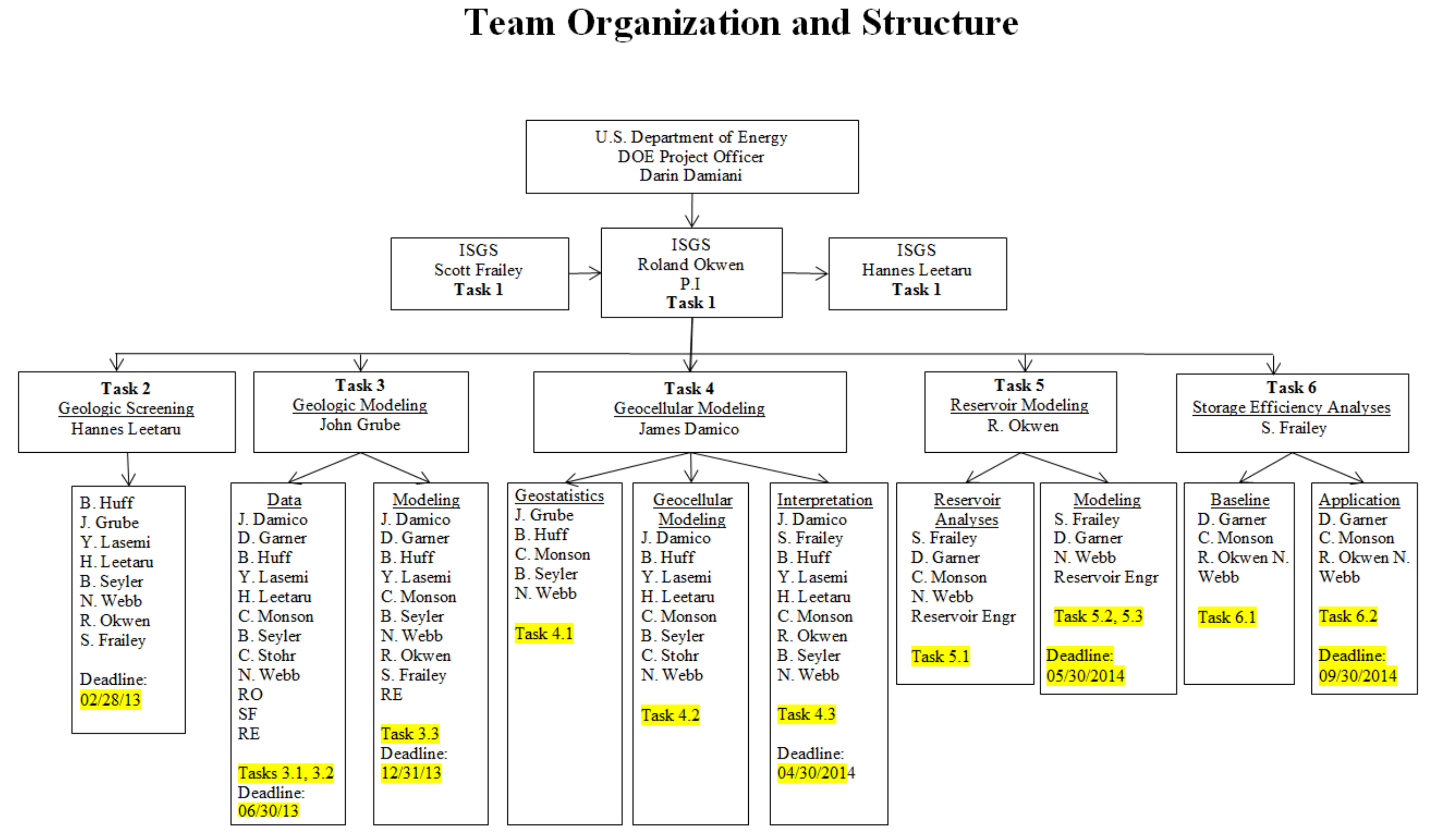
- Reservoir Engineers:
  - Roland Okwen
  - Scott Frailey
- Sub-contractor (Schlumberger) :
  - John Grube
  - Beverly Seyler
- Database specialist
  - Damon Garner

- Geologists:
  - Hannes Leetaru
  - Yaghoob Lasemi
  - Nathan Webb
  - James Damico
  - Charles Monson
- Editor:
  - Dan Klen

Appendix

- These slides will not be discussed during the presentation, but are mandatory

Organization chart



Team Organization and Structure

U.S. Department of Energy
DOE Project Officer
Darin Damiani

ISGS
Scott Frailey
Task 1

ISGS
Roland Okwen
P.I
Task 1

ISGS
Hannes Leetaru
Task 1

Task 2
Geologic Screening
Hannes Leetaru

B. Huff
J. Grube
Y. Lasemi
H. Leetaru
B. Seyler
N. Webb
R. Okwen
S. Frailey

Deadline:
02/28/13

Task 3
Geologic Modeling
John Grube

Data
J. Damico
D. Garner
B. Huff
Y. Lasemi
H. Leetaru
C. Monson
B. Seyler
C. Stohr
N. Webb
RO
SF
RE

Tasks 3.1, 3.2
Deadline:
06/30/13

Modeling
J. Damico
D. Garner
B. Huff
Y. Lasemi
C. Monson
B. Seyler
N. Webb
R. Okwen
S. Frailey
RE

Task 3.3
Deadline:
12/31/13

Task 4
Geocellular Modeling
James Damico

Geostatistics
J. Grube
B. Huff
C. Monson
B. Seyler
N. Webb

Task 4.1

Geocellular Modeling
J. Damico
B. Huff
Y. Lasemi
H. Leetaru
C. Monson
B. Seyler
C. Stohr
N. Webb

Task 4.2

Interpretation
J. Damico
S. Frailey
B. Huff
Y. Lasemi
H. Leetaru
C. Monson
R. Okwen
B. Seyler
N. Webb

Task 4.3

Deadline:
04/30/2014

Task 5
Reservoir Modeling
R. Okwen

Reservoir Analyses
S. Frailey
D. Garner
C. Monson
N. Webb
Reservoir Engr

Task 5.1

Modeling
S. Frailey
D. Garner
N. Webb
Reservoir Engr

Task 5.2, 5.3

Deadline:
05/30/2014

Task 6
Storage Efficiency Analyses
S. Frailey

Baseline
D. Garner
C. Monson
R. Okwen N. Webb

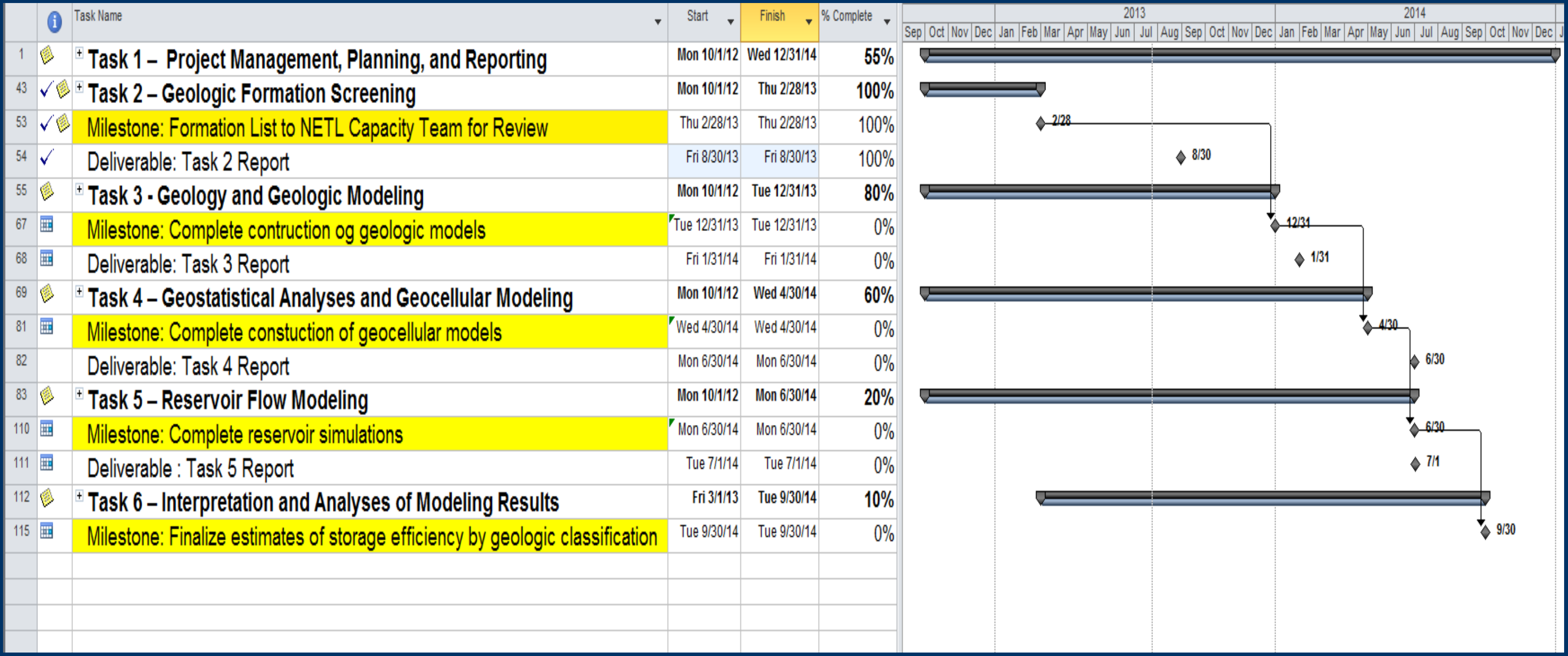
Task 6.1

Application
D. Garner
C. Monson
R. Okwen N. Webb

Task 6.2

Deadline:
09/30/2014

Gantt Chart



		Task Name	Start	Finish	% Complete
1		**Task 1 – Project Management, Planning, and Reporting**	**Mon 10/1/12**	**Wed 12/31/14**	**55%**
43	✓	**Task 2 – Geologic Formation Screening**	**Mon 10/1/12**	**Thu 2/28/13**	**100%**
53	✓	Milestone: Formation List to NETL Capacity Team for Review	Thu 2/28/13	Thu 2/28/13	100%
54	✓	Deliverable: Task 2 Report	Fri 8/30/13	Fri 8/30/13	100%
55		**Task 3 - Geology and Geologic Modeling**	**Mon 10/1/12**	**Tue 12/31/13**	**80%**
67		Milestone: Complete contruction og geologic models	Tue 12/31/13	Tue 12/31/13	0%
68		Deliverable: Task 3 Report	Fri 1/31/14	Fri 1/31/14	0%
69		**Task 4 – Geostatistical Analyses and Geocellular Modeling**	**Mon 10/1/12**	**Wed 4/30/14**	**60%**
81		Milestone: Complete constuction of geocellular models	Wed 4/30/14	Wed 4/30/14	0%
82		Deliverable: Task 4 Report	Mon 6/30/14	Mon 6/30/14	0%
83		**Task 5 – Reservoir Flow Modeling**	**Mon 10/1/12**	**Mon 6/30/14**	**20%**
110		Milestone: Complete reservoir simulations	Mon 6/30/14	Mon 6/30/14	0%
111		Deliverable : Task 5 Report	Tue 7/1/14	Tue 7/1/14	0%
112		**Task 6 – Interpretation and Analyses of Modeling Results**	**Fri 3/1/13**	**Tue 9/30/14**	**10%**
115		Milestone: Finalize estimates of storage efficiency by geologic classification	Tue 9/30/14	Tue 9/30/14	0%

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3) Okwen, R., F. Yang, and S. Frailey, accepted (in prep), Effect of geologic depositional environment on CO_2 storage efficiency: Energy Procedia.

4) Okwen, R., C. Monson, Y. Lasemi, and N. Grigsby, accepted (in prep), Quantifying CO_2 storage efficiencies of geologic depositional environments: poster to be presented at the 42nd annual AAPG Eastern Section meeting, London, ON, September 27–October 1, 2014.

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7) Okwen, R., J.D Damico, N. Webb, Y. Lasemi, C. Monson, and N. Grigsby, 2014, Assessing depositional environments in the Illinois Basin: poster presented at the annual Illinois Oil and Gas Association meeting, March 6–7.

8) Okwen, R., S. Frailey, and H. Leetaru, 2013, Assessing depositional environments to improve CO_2 storage efficiency, poster presented at the US DOE Carbon Storage R&D Project Review Meeting, Pittsburgh, PA, August 20–22

Outcomes

Baseline Storage efficiencies

$$E = \frac{V_{CO_2}}{V_p}$$

Depositional Environment	Lithology	Baseline E (%)		% Change
		Stratigraphic	Structural	
Deltaic	Sandstone	9.5 — 18	10 — 20	5.3 — 11
Shelf clastic	Sandstone	5.6 — 15	6.6 — 19	18 — 26
Shelf carbonate	Limestone	3.1 — 9.0	3.3 — 9.9	6.5 — 10
	Dolomite	3.0 — 8.2	3.8 — 7.5	8.0 — 27
Fluvial deltaic	Sandstone	13 — 22	15 — 22	0.0 — 15
Strandplain	Sandstone	6.1 — 13	11 — 17	31 — 80*
Reef	Limestone	4.8 — 19.7	4.7 — 21.3	2.0 — 8.1
Fluvial and alluvial	Sandstone	8.0 — 19	9.9 — 22	16 — 24
Turbidite	Fine Sandstone	6.5 — 24	7.0 — 25	4.2 — 7.6

*Large structure