[PS]Quantifying CO_2 Storage Efficiency of Geologic Depositional Environments*

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Abstract

Storage efficiency (E), the ratio of the injected volume of CO_2 to the accessible pore volume, quantifies CO_2 storage potential in a reservoir. Storage efficiency is used to make storage resource assessments and to determine distribution of the CO_2 at geological carbon storage sites. A single range of E is typically applied to all depositional environments. This work is intended to improve site selection and screening processes by using numerical modeling to quantify E ranges for eight depositional environments, namely deltaic, shelf clastic, reef and non-reef shelf carbonate, strandplain, fluvial deltaic, fluvial-alluvial, and turbidite. Depositional environments were interpreted from core and geophysical log data, and geologic models were developed based on selected Illinois Basin formations. For example, three unique models for non-reef shelf carbonates were created based on the Mississippian Ste. Genevieve Limestone, the Devonian Geneva Dolomite, and the Silurian Moccasin Springs Formation at Johnsonville, Miletus, and Tilden Fields, respectively. At Johnsonville, the Ste. Genevieve contains northeast-southwest trending, elongated oolite shoals and microcrystalline dolomite layers which both form reservoirs. The Geneva at Miletus consists of a regional high-porosity interval with secondary porosity formed through dolomitization and dissolution, possibly enhanced on paleotopographic highs over Silurian reefs. At Tilden, the reservoir is a coral and stromatoporoid reef body in the Moccasin Springs. However, the models were designed to be representative of the different depositional environments and not of any particular field. Features in cratonic and non-cratonic basins differ in scale but exhibit similar reservoir characteristics, allowing comparisons between depositional environments in the Illinois Basin and other United States basins. Geologic and petrophysical data from these fields were used as constraints in the development of geocellular models, which were upscaled for flow simulations. Geologic structures such as domes were removed from the geocellular models because they influence fluid movement and limit lateral flow of CO_2, significantly increasing E regardless of the depositional environment. Reservoir simulation of CO_2 storage in the different depositional environments is ongoing. Preliminary simulation results predict that baseline E can be increased using operational injection and well completion techniques optimized for CO_2 storage.

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Introduction

CO_2 storage efficiency (E)—the ratio of the injected volume of fluid to the accessible pore volume—provides a means to quantify storage resource. This study uses numerical modeling to quantify E for eight depositional environments.

Prodedure

- A seven-step process (Figure 1) was used to identify and characterize depositional environments and characterize their storage efficiency.
- The Formation Selection, Conceptual Geologic Model, and Geocellular Model stages were iterative and rigorous to validate that the resulting static reservoir model was representative of the depositional environment.

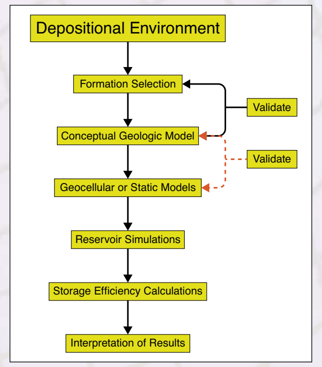


Figure 1. Flow chart of the processes involved in estimation of storage efficiency for each depositional environment.

- Storage efficiency calculations were based on different injection well placement scenarios and three different pore volume types, expressed as ranges of efficiency.
- Features in cratonic and noncratonic basins differ in scale but exhibit similar reservoir characteristics, allowing comparisons between depositional environments in the Illinois Basin (the Basin) and other United States basins (Table 1).

Table 1: Examples of formations in US basins with similar depositional environments.

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

Geologic Models: Reefs and Shelf Carbonates

- Geologic models were designed to represent different depositional environments (Figure 2) and not specific fields. Models were developed based on selected Illinois Basin formations but field-specific results (such as uncharacteristically high porosity and permeability) were adjusted when necessary to make the models more broadly representative of each depositional environment.
- Facies and depositional environments for the selected formations were interpreted from cores and geophysical logs.
- Models for two different types of depositional environments—reef and shelf carbonate (ooid grainstones and dolomite)—are compared here as illustrations of our methodology.
  - The Silurian Moccasin Springs Formation at Tilden Field was the basis of the Reef model (Figure 3).
  - Shelf Carbonate models were based on two oil fields: the Devonian Geneva Dolomite at Miletus Field, which produces from a vuggy, sucrosic dolomite (Figures 4 and 5), and the Mississippian Ste. Genevieve Formation at Johnsonville Field, which produces from ooid grainstones and dolomites (Figures 6 and 7).

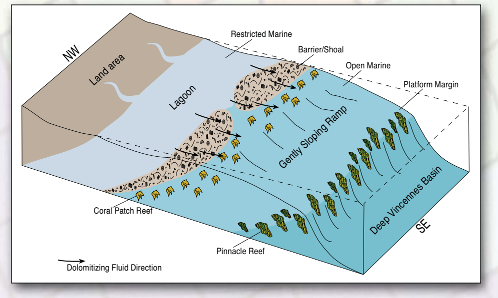


Figure 2. Generalized depositional model of a shelf carbonate with reefs (modified from Lasemi, 2009, and Lasemi et al., 2010).

Reef (Tilden Field)

- Tilden Oil Field (Figure 3) is part of a pinnacle reef bank trend along the platform margin in southern Illinois and into Indiana, and is similar to productive Silurian pinnacle reefs in the Michigan Basin.
- Cross sections across the field indicate that the reef structures change laterally to deeper marine inter-reef facies.
- The clean carbonate facies in productive areas of the field is mainly composed of coral and stromatoporoid buildups.

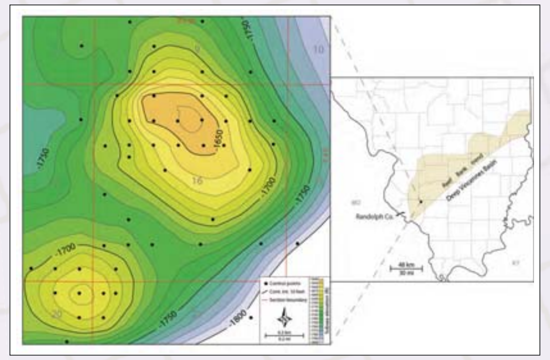


Figure 3. Structure contour map of two Silurian reef structures in Tilden Field, showing closure to 30.5 m (100 ft) of closure.

Shelf Carbonate-Dolomite (Miletus Field)

- Miletus Oil Field lies on an anticlinal structure with a steep east flank and localized arcuate geometry which may reflect an underlying atoll-like reef (Figure 4).
- The Geneva is a vuggy and sucrosic dolomite which is brecciated and has enhanced porosity and permeability due to postdepositional dolomitization and dissolution of fossils (example of correlative formation shown in Figure 5).
- The Geneva play is similar to the Ordovician Red River play in the Williston Basin and the Mississippian Madison Group of the Rocky Mountain and Northern Great Plains regions.

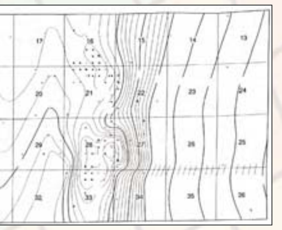


Figure 4. Structure map on top of the Devonian Geneva Dolomite at Miletus Field.

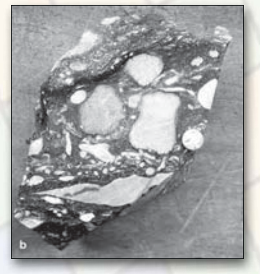
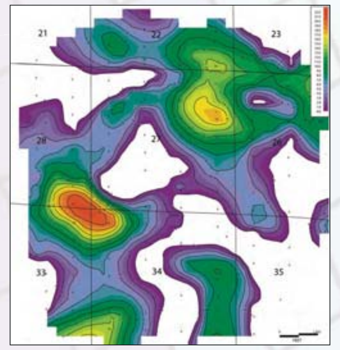


Figure 5. The Jeffersonville Limestone from Scott Quarry in Indiana (Seyler et al., 2003). The Jeffersonville is equivalent to the Geneva Dolomite. The fossil allochems (e.g. corals and bryozoans) are abundant and diverse indicating deposition within a normal marine environment, but, unlike the Geneva, the Jeffersonville has not been altered by dolomitization and dissolution.

Shelf Carbonate—Ooid Grainstones (Johnsonville Field)

- The majority of the Johnsonville Oil Field production is from the Mississippian Ste. Genevieve Formation.
- The primary Ste. Genevieve reservoir bodies are ooid grainstones (Figures 6 and 7) believed to be similar to those currently forming on the Bahama Banks. Stratigraphic trapping of fluids in these grainstones is caused by the interbar muds which encompass the clean oolite packstones at the heart of the thicker shoals.
- Ste. Genevieve ooid shoals are generally oriented either northeast-southwest (tidal channels perpendicular to paleoshoreline) or northwest-southeast (barrier bars along shoreline). They are generally less than 0.4 km (0.25 mi) wide, 3.2 km (2 mi) long, and 3.0 m (10 ft) thick, but often occur in subparallel swarms and may coalesce to form thicker or broader reservoir bodies (Figure 6).
- Dolomitization can occur at the base of the shoals and in the interbar mudstones (lower image). These dolomite reservoirs (Figure 7) have high porosity and permeability, but tend to be more localized than ooid grainstones.
- The Ste. Genevieve marine ooid grainstones are similar to parts of the Cretaceous on the Gulf Coast and Jurassic in the U.S. Eastern and Central Gulf of Mexico.

Figure 6. Net isopach map of an ooid grainstone layer (Fredonia Member, Mississippian Ste. Genevieve Formation) at Johnsonville Consolidated Field



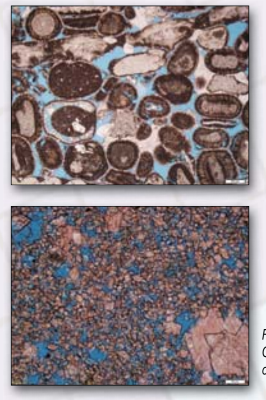


Figure 7. Ooid grainstones (top image) from the primary Ste. Genevieve reservoir bodies, with secondary production from dolomites (lower image).

General Geocellular Development

- Geologic models and digital well log and core data were used to develop geocellular models.
- Structural maps and isopachs were used to delineate top and bottom of each reservoir.
- Marker beds were used to define a stratigraphic datum and remove the influence of geologic structures, such as domes, in order to isolate the effect of the depositional environment on E.
- Data from digital well logs were used to create variograms and condition sequential Gaussian simulations, in order to create porosity distributions for each depositional environment.
- Core data were used to create porosity to permeability transform equations for each model (example shown in Figure 8). In all cases the transform was selected using available data and geologists' expectations based on reservoir characteristics found in similar reservoirs.
- The realization most representative of the depositional environment was upscaled and used in reservoir simulations (Figures 9, 10, and 11).
- Statistics for the upscaled shelf carbonate and reef geocellular models are shown in Table 2.

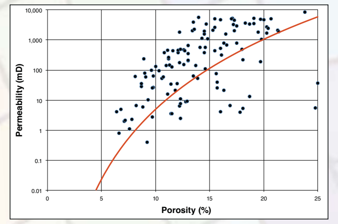


Figure 8. A plot of porosity (x-axis) vs permeability (y-axis) data from core analysis reports from Johnsonville Field. The equation defining the line was used to transform simulated porosity values to permeability. Very high permeability values were suspected to be the result of fractured plugs, so a line was imposed to create the desired permeability–porosity relationship.

Reef

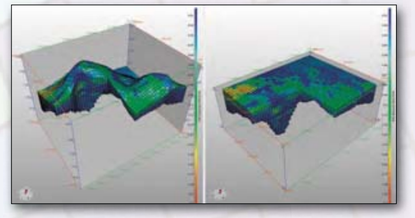


Figure 9. Porosity distribution of the structural (left) and stratigraphic (right) reef geocellular models (foreground corner removed to reveal internal distribution). The models match the conceptual geologic model and capture the two dome structures (interpreted as pinnacle reefs) and compartmentalized very porous and permeable zones of varying lateral and vertical extent.

Dolomite (Shelf Carbonate)

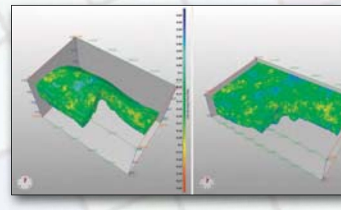


Figure 10. Porosity distribution of the structural (left) and stratigraphic (right) dolomite shelf carbonate geocellular models (foreground corner removed to reveal internal distribution). The model contains widespread moderate porosity (green).

Ooid Grainstone (Shelf Carbonate)

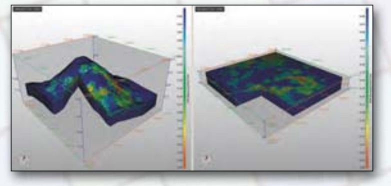


Figure 11. Porosity distribution of the structural (left) and stratigraphic (right) ooid geocellular models (foreground corner removed to reveal internal distribution). The model contains compartmentalized highly porous and permeable reservoirs (representing elongated oolite shoals) within impermeable limestone and dolomite (blue).

Storage Efficiency Calculations

- Storage efficiency is calculated using the following equation:

$$E = \frac{V_{CO_2}}{V_{P,\,type}}$$

Where V_{CO2}, and $V_{p,\,type}$ represent storage volume of CO_2 injected and available pore volume respectively.

- Three approaches (Figure 12 and Table 3) were adopted to estimate $V_{p,\,type}$: cylinder, cuboid, and cube.
- E is expected to increase initially and plateau over time. The first derivative of E (dE/dt) is also expected to approach zero as E plateaus (Figure 13).
- Storage efficiency of a simulation scenario is determined when E stabilizes.
- The time interval during which E stabilizes is different for each model based on the permeability and model size.
- The size of some models was increased so that E could stabilize and be estimated.

Figure 12. Different methods used to estimate the available pore area (Vp) for calculating storage efficiency. Warmer colors indicate higher CO_2 saturation and blue indicates water.

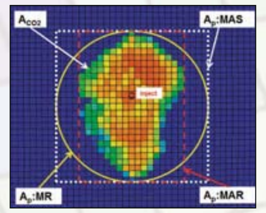


Table 3: Description of parameters in storage efficiency calculation.

Parameter	Definition	Applications
V_{CO2}	Reservoir pore volume contacted by CO_2	Area and pore space
V_p, cube	Pore volume of cube	Area of review
V_p, cuboid	Pore volume of rectangular cuboid	Area of review
V_p, cylinder	Pore volume of cylinder	Pore space utilization over time
E_{static}	–	Area of review
$E_{dynamic}$	–	Pore space utilization over time

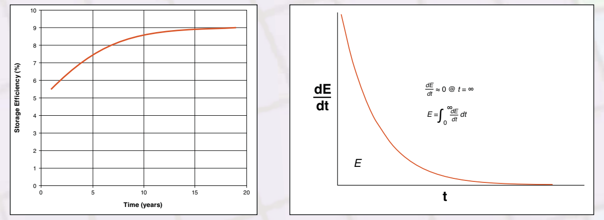


Figure 13. Conceptual representation of changes in E as a function of time.

Properties of the Reef and Shelf Carbonate Geocellular Models

Table 2: Statistics for the dimensions and petrophysical properties for each geocellular model.

Model	Shelf Carbonate (Dolomite)	Shelf Carbonate (Limestone)	Reef
Gridcells in x-direction	215	65	36
Gridcells in y-direction	350	70	44
Gridcells in z-direction	23	23	57
Δx (ft)* (Δx = Δy)	100	200	200
Δz (ft)	3	3	3
Area (ft^2)	7.53×10^8	1.82×10^8	6.34×10^7
Total gridcells	1.73×10^6	1.05×10^5	9.03×10^4
Total volume (ft^3)	5.19×10^{10}	1.26×10^{10}	1.08×10^{10}
Number of active cells	1.21×10^6	3.82×10^4	4.54×10^4
Total active volume (ft^3)	3.63×10^{10}	4.58×10^9	5.45×10^9
Depth (min/max) (ft)	3,197/3,911	2,516/2,730	1,626/1,913
Porosity (min/max/mean)	0/0.27/0.14	0.05/0.25/0.12	0/0.20/0.03
Permeability (min/max/mean) (mD)	0.0/1,717/13.3	0.02/5,772/211	0/1,041.62/2.35

Results

- A range of storage efficiencies for each depositional environment model was determined from CO_2 injection simulations at five different vertical well locations using three methods of estimating pore volume.
- Simulations were conducted using both stratigraphic and structural models (Figures 14, 16, and 18).
- Models show CO_2 plume distribution over time for the reef and shelf carbonate models (Figures 14, 16, and 18).
- Model predicts the storage efficiency profiles for the reef and shelf carbonate formations (Figures 15, 17, and 19).

Reef

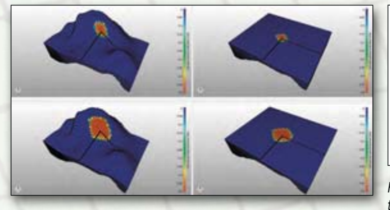


Figure 14. Extent of the CO_2 plume in the structural (left) and stratigraphic (right) reef models at 20 years (top) and 50 years (bottom). Storage efficiencies ranged from 14-53% for the stratigraphic model and 13-56% for the structural.

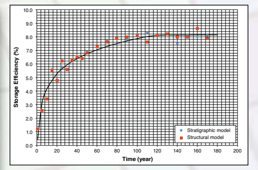


Figure 15. Storage efficiency as a function of time for the reef depositional environment using the cube pore volume estimation method. For this example, structure had no effect on E.

Dolomite (Shelf Carbonate)

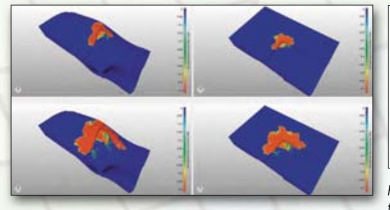


Figure 16. Extent of the CO_2 plume in the stratigraphic (right) and structural (left) ooid grainstone models at 182 days (top) and 456 days (bottom). Storage efficiencies ranged from 9.5-26% for the stratigraphic model and 10-28% for the structural.

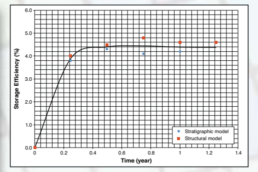


Figure 17. Storage efficiency as a function of time for dolomite shelf carbonate using the cube pore volume estimation method. For this example, structure had very slight effect on E.

Ooid Grainstone (Shelf Carbonate)

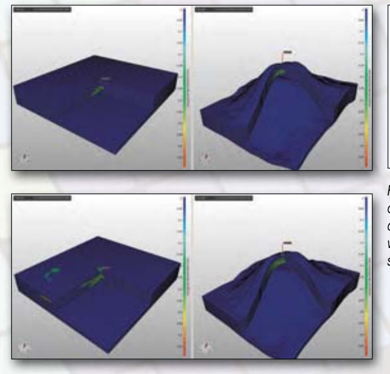


Figure 18. Extent of the CO_2 plume in the stratigraphic (left) and structural (right) ooid grainstone models at 182 days (top) and 456 days (bottom). Storage efficiencies ranged from 9.5-26% for the stratigraphic model and 10-28% for the structural.

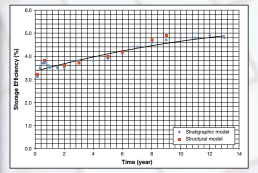


Figure 19. Storage efficiency as a function of time for the limestone shelf carbonate depositional environment using the cube pore volume estimation method. For this example, structure had no effect on E.

Please visit ***www.co2sinkefficiency.org*** for more information.

Storage Efficiency Normalization

- The storage efficiency of formations is dependent on relative permeability and end-point saturations. As a result, the estimated *E* for each depositional environment was normalized using $\bar{S}_g$, the average CO_2 saturation within the plume using:

$$E_v = \frac{E}{\bar{S}_g}$$

- The normalized efficiency is equivalent to volumetric displacement efficiency (E_V).
- To estimate E, the values of E_V in Table 4 are multiplied by the $\bar{S}_g$ of the formation.
- The depositional environments have been ranked based on the estimated E_V (Table 5). Fluvial deltaic depositional environment has the highest predicted E_V while shelf carbonate has the least.

Table 4: The volumetric displacement efficiency, E_V, for each depositional environment is listed below, ranging from 7.5% at the lowest to 53% at the highest.

Depositional Environment	Lithology	E_V (%)		% Change
		Stratigraphic	Structural	(effect of geologic structure)
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*

Table 5: Normalized CO_2 volumetric efficiency ranking by depositional environment.

Depositional Environment	Fluvial Deltaic	Deltaic	Turbidite	Shelf Clastic	Strandplain	Reef	Fluvial and Alluvial	Shelf Carbonate
E_V Ranking	1	2	3	4	5	6	7	8

Conclusions

- Storage efficiency (E_V) ranges from 8 to 50% for eight different and unique depositional environment models.
- Fluvial Deltaic has the highest storage efficiency and Shelf Carbonate has the lowest.
- Presence of structure had no effect on some models and almost doubled the storage efficiency for one depositional model.

References

Seyler, B., J. P. Grube, and Z. Lasemi. 2003. *The Origin of Prolific Reservoirs in the Geneva Dolomite (Middle Devonian), West-Central Illinois Basin.* Illinois Petroleum 158. Champaign: Illinois State Geological Survey.

Lasemi, Y. 2009a. "Carbonate Sequence Stratigraphy and Reservoir Development: The Middle Silurian Racine Formation in the Sangamon Arch, West-Central Illinois." *AAPG Eastern Section Meeting Program and Abstracts*: 42–43.

Lasemi, Y. 2009b. "Oil Potential seen in Silurian Reef-Related Reservoirs in Illinois Sangamon Arch." *Oil and Gas Journal* 107 (29): 36–40.

Lasemi, Y. 2009c. "A Prominent Unconformable Boundary within the Upper Niagaran Racine Formation: Record of a Major Middle Silurian Tectono-Eustatic Event in the Sangamon Arch, West-Central Illinois." Abstract. *GSA Abstracts with Programs* 41: 26.

Lasemi, Y., B. Seyler, Z. Lasemi, and Z. A. Khorasgani. 2010. *Sedimentology and Reservoir Characterization of the Silurian Deposits in the Mt. Auburn Trend of the Sangamon Arch, West-Central Illinois*. Circular 577. Champaign: Illinois State Geological Survey.

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