An Assessment of Geological Carbon Sequestration Options in the Illinois Basin

MGSC Phase I Project Outcomes

MGSC Project Team

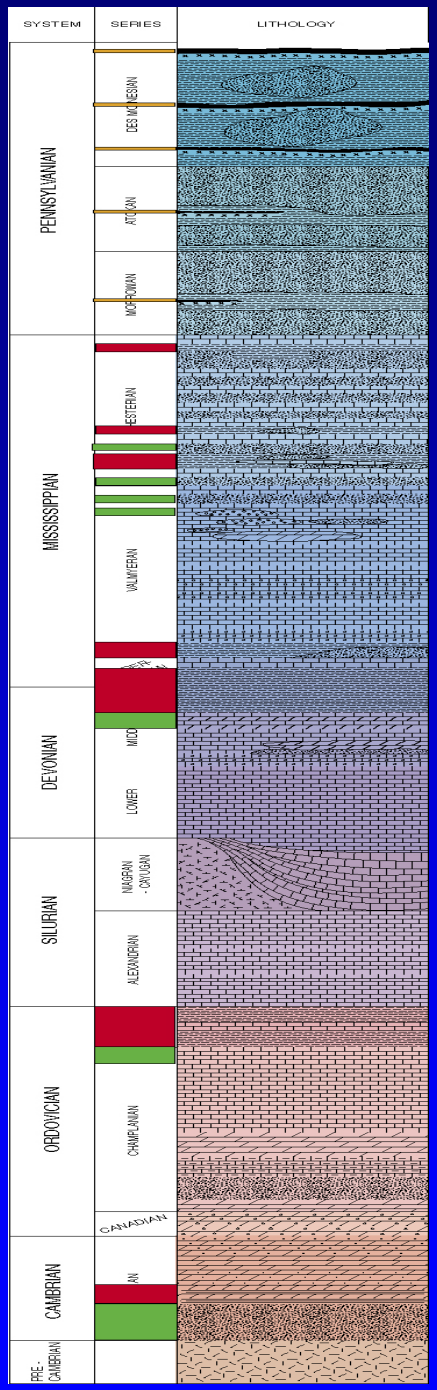
presented by
Robert J. Finley
Illinois State Geological Survey
October 12, 2005

Midwest Geological Sequestration Consortium
www.sequestration.org

Midwest Geological Sequestration Consortium Partners

- Three utility partners: Ameren, Louisville Gas and Electric, and Cinergy
- Five industry partners: American Air Liquide, Peabody Energy, Power Holdings, Aventine Renewable Energy, and LincolnLand Agri-Energy
- Trade groups and consortia: IL, IN, and KY Oil & Gas Associations, ICGA, EPRI, IOGCC
- Illinois Office of Coal Development, DCEO
- Illinois Department of Natural Resources

Illinois Basin Stratigraphic Column



Coals (Sink)

Oil Reservoirs with Shale Seals (Sink)

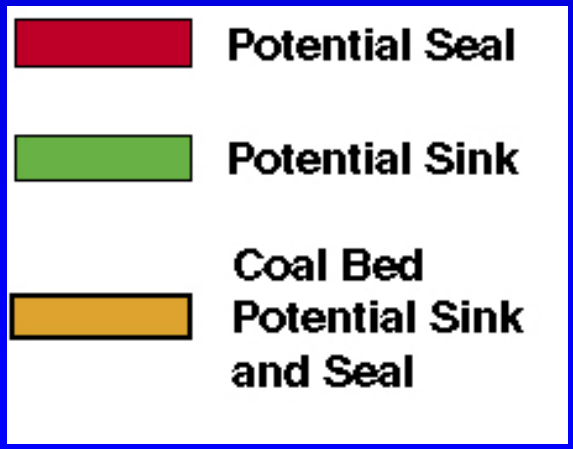
New Albany (Seal) (Sink)

Maquoketa (Seal)

St. Peter (Sink)

Eau Claire (Seal)

Mt. Simon (Sink)



Areas of Emphasis

- Capture and transportation from fixed sources
- Major focus on reservoir characterization for:
  - coal seams
  - mature oil reservoirs
  - deep saline reservoirs
- Structural characterization
- Outreach and web site enhancement
  - www.sequestration.org

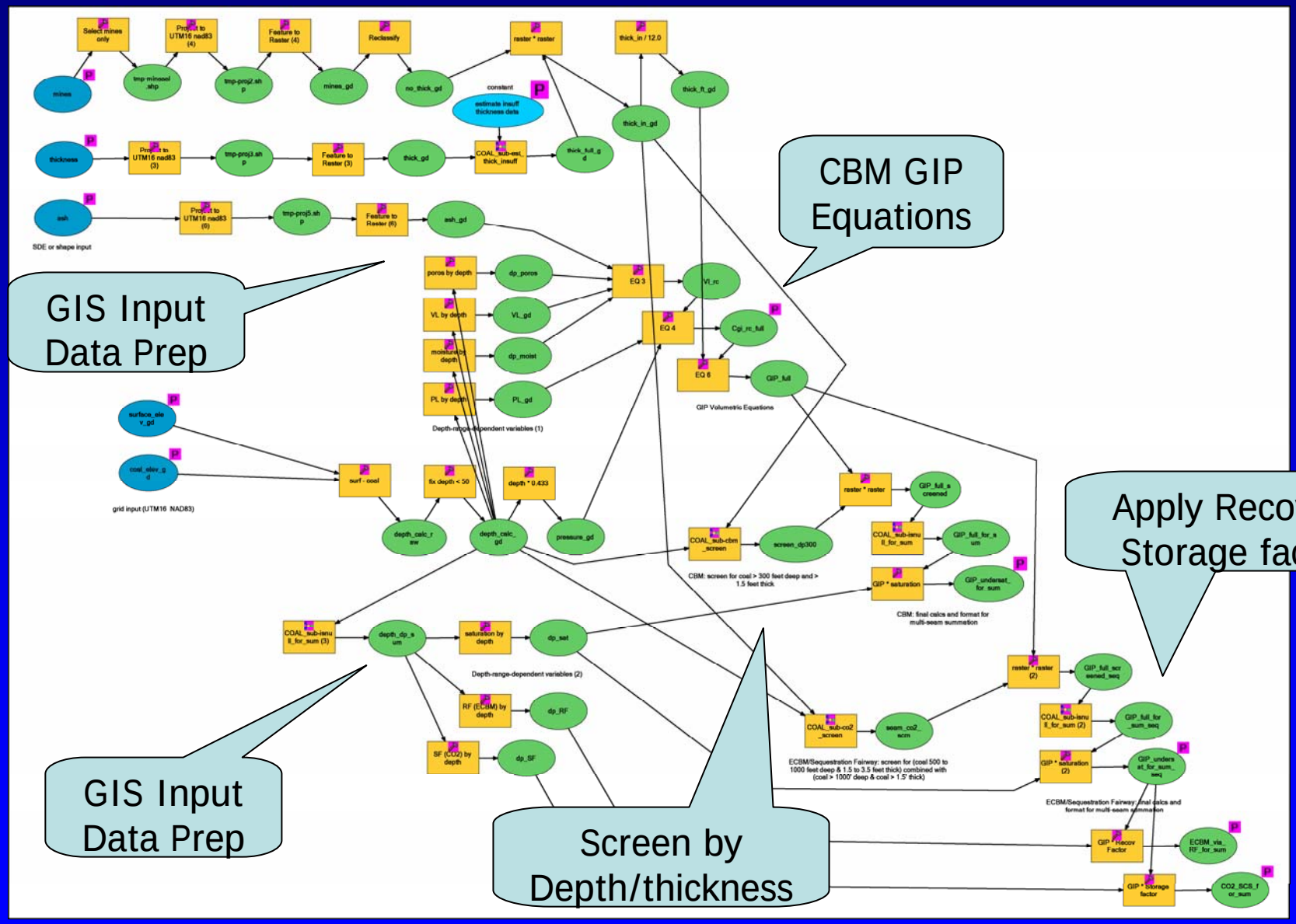
Project Focus at the Conclusion of Phase I

- Geologic modeling (deterministic and geostatistical), reservoir simulations, database, and GIS map products finalized
- Volumetrics and storage capacity estimates
- Depositional character of Mt. Simon Sandstone leads to 2D seismic acquired at two deep structures
- Defining sequestration scenarios by linking sources, transportation, and sinks
- Education and outreach focus intensified with products and seminars; Springfield and Evansville Sept. 27-28
- Documentation in text and figures

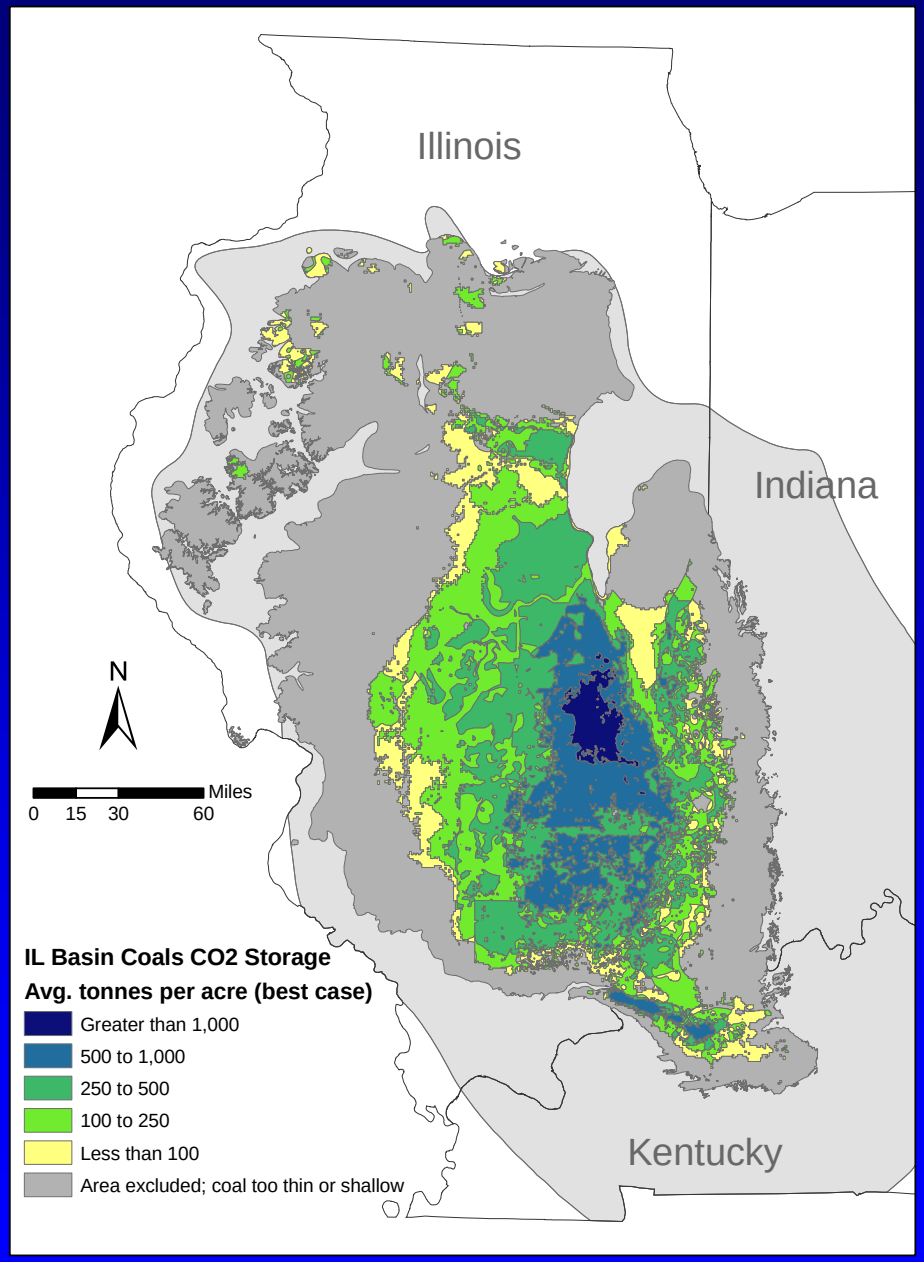
Areas of Emphasis

- Capture and transportation moving toward optimization process
- Major focus on reservoir characterization for:
  - coal seams
  - mature oil reservoirs
  - deep saline reservoirs
- Structural characterization
- Outreach and web site enhancement

MGSC Coal Screening & Gas Calculations GIS Processing Model



Coal Seam Analysis: ECBM Recovery and CO_2 Storage



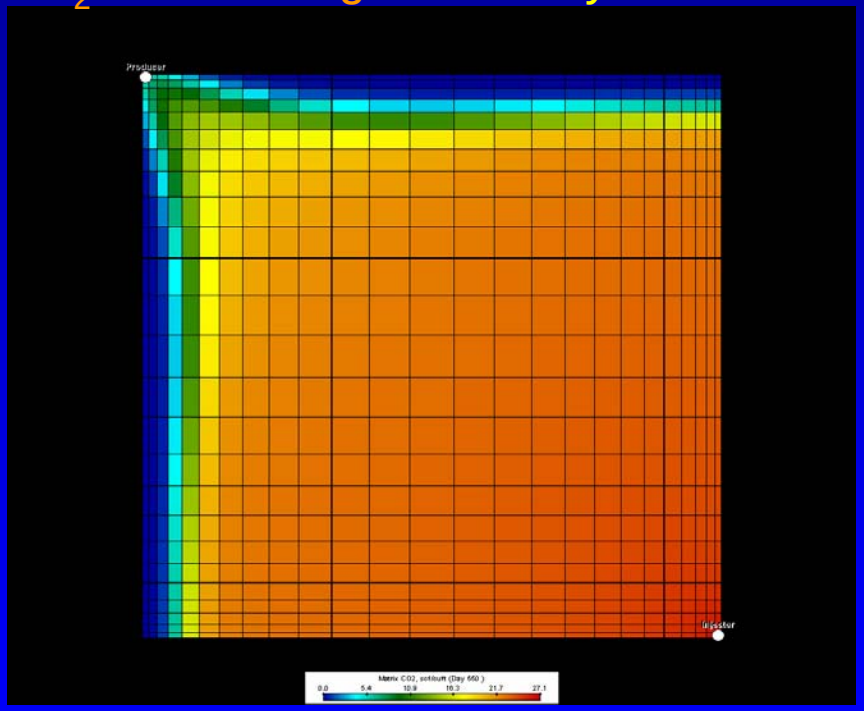
- 7 seams assessed
- "Low / best / high" estimates for each
- 6.7 Tcf total ECBM recoverable
- 3.6 billion tonnes total CO_2 storage potential

Total Coals Potential CO_2 Storage

CBM and ECBM COMET Flow Modeling

High Permeability

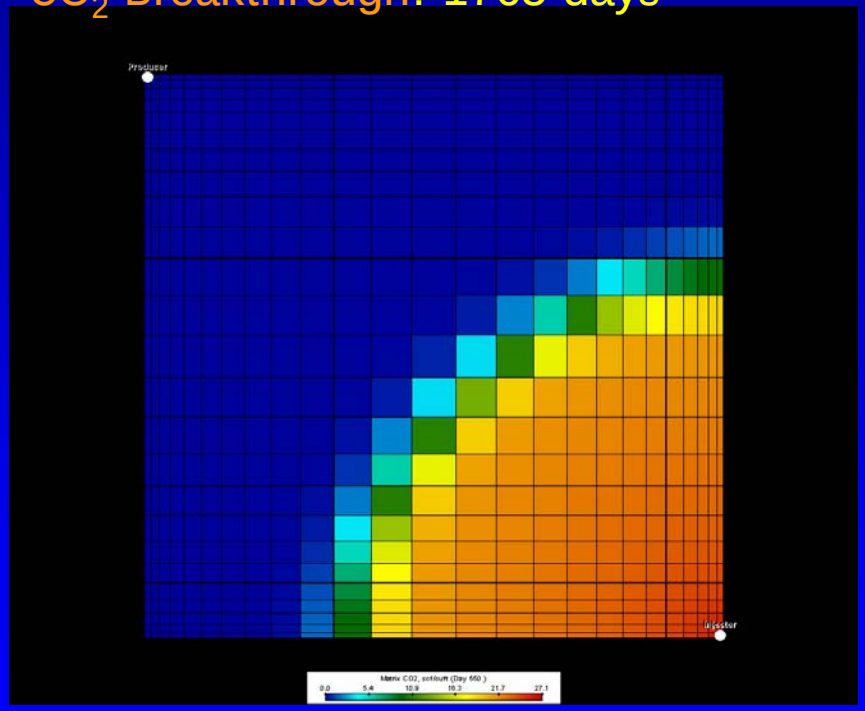
RF: 0.710, SF: 0.890, k: 50 md
CO_2 Breakthrough: 546 days



t: 550 days

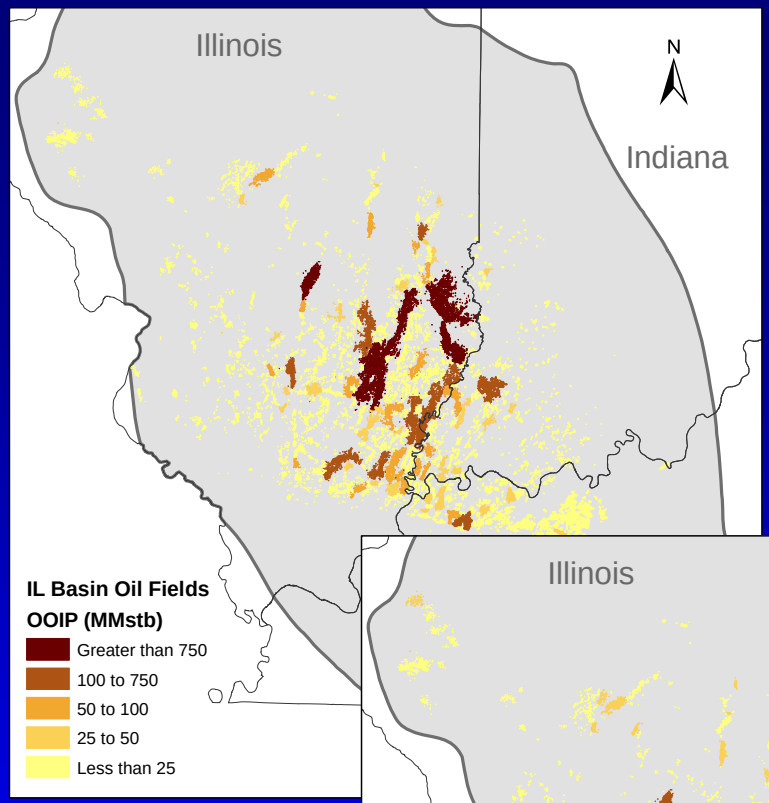
Low Permeability

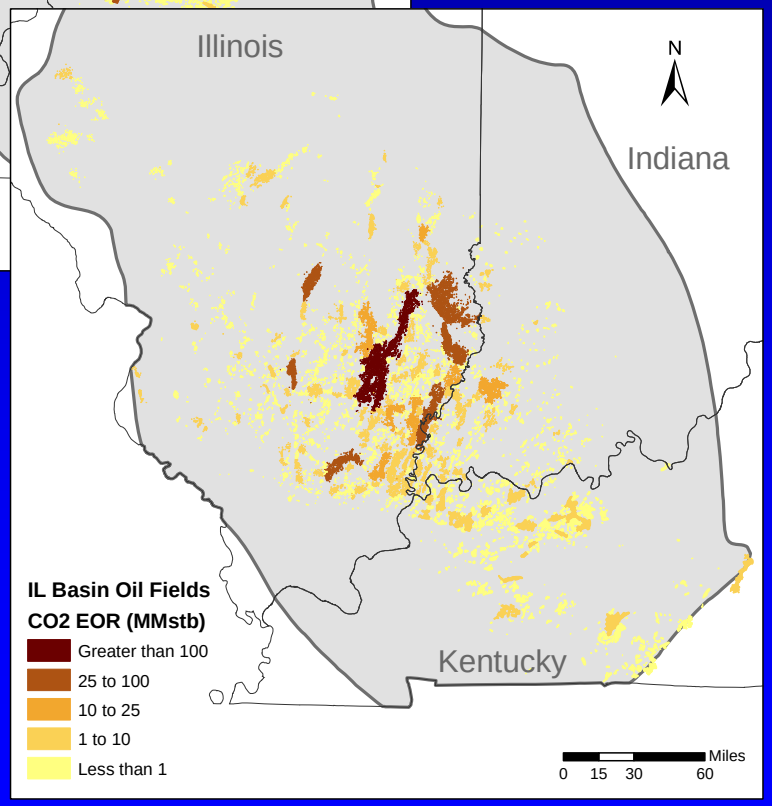
RF: 0.763, SF: 0.894, k: 15md
CO_2 Breakthrough: 1765 days



t: 550 days

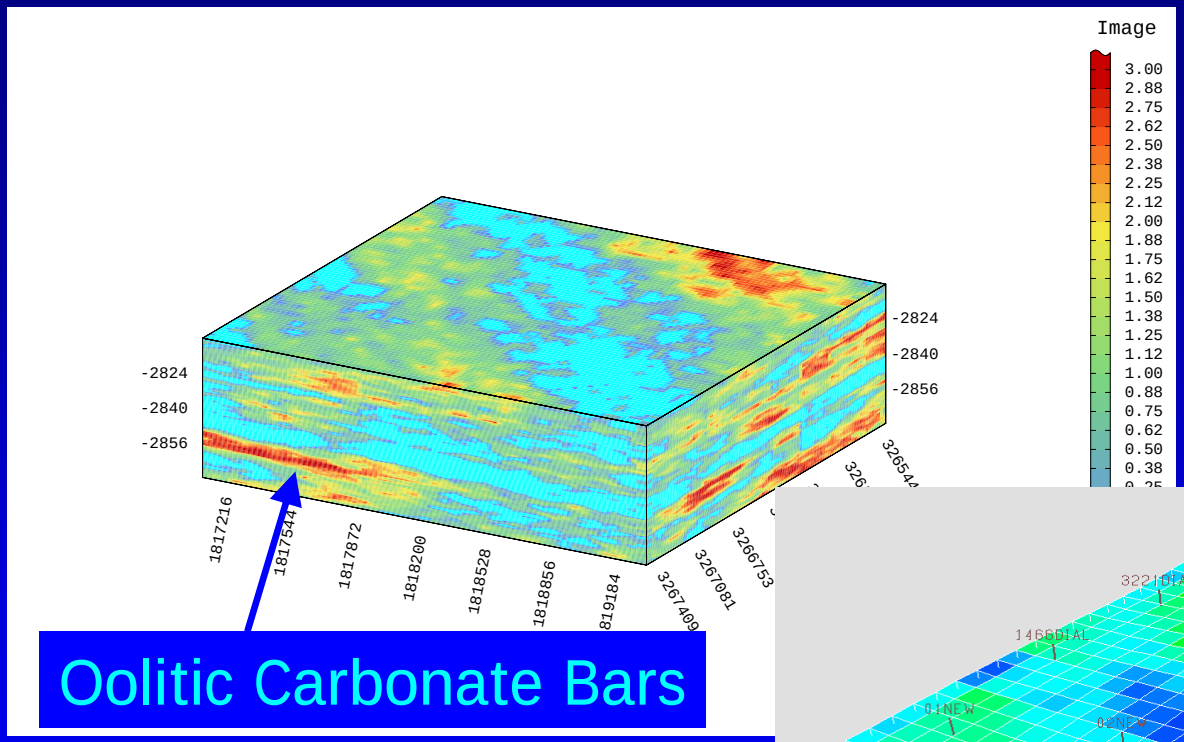
Oil Reservoir Analysis



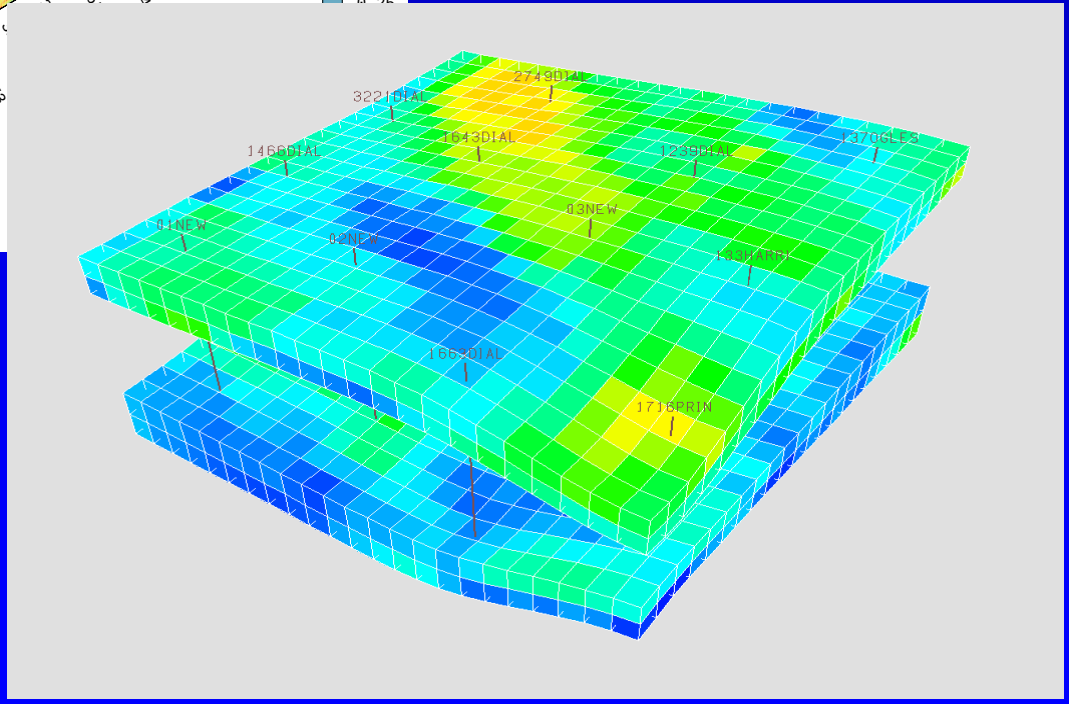


- 14.1 billion bbls (bbbls) total OOIP vs. 12 bbbls previous assessed resource
- 860-1,300 mmbbls EOR resource target
- 140-440 Mt storage capacity

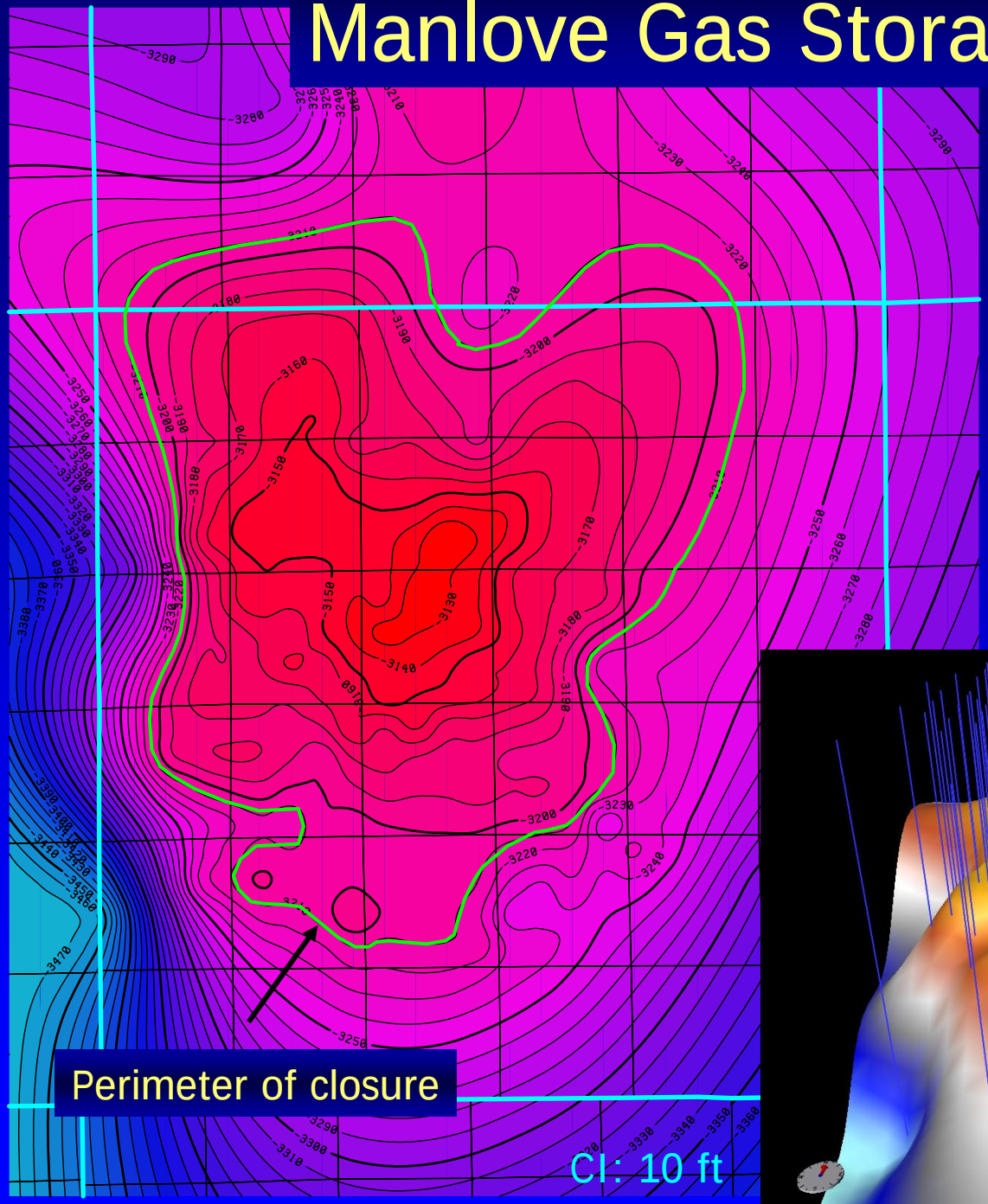
St. Genevieve Reservoir Model



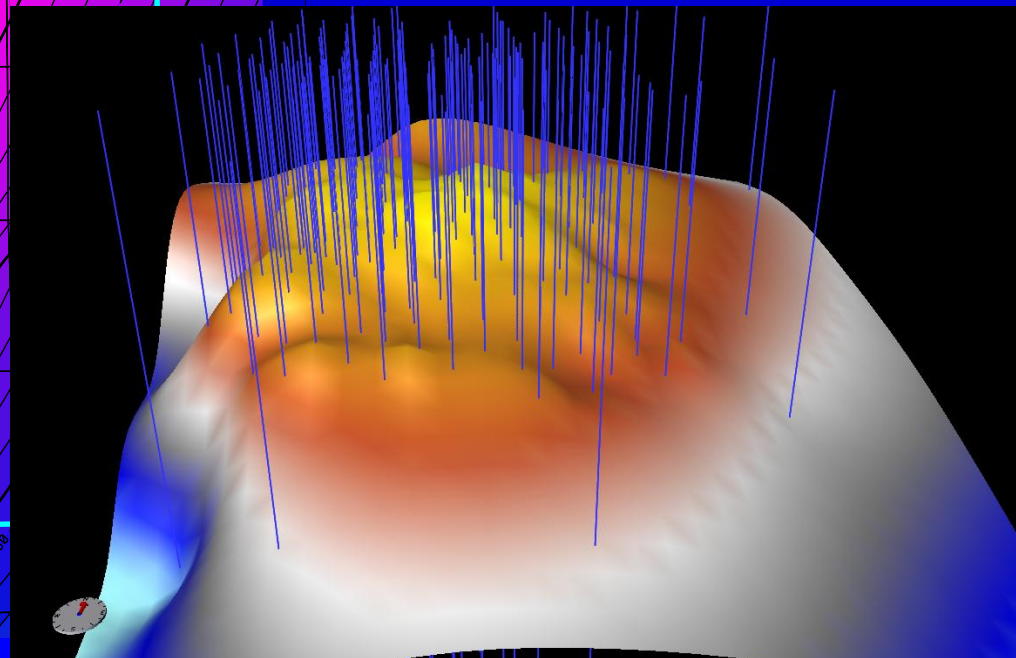
Oolitic Carbonate Bars



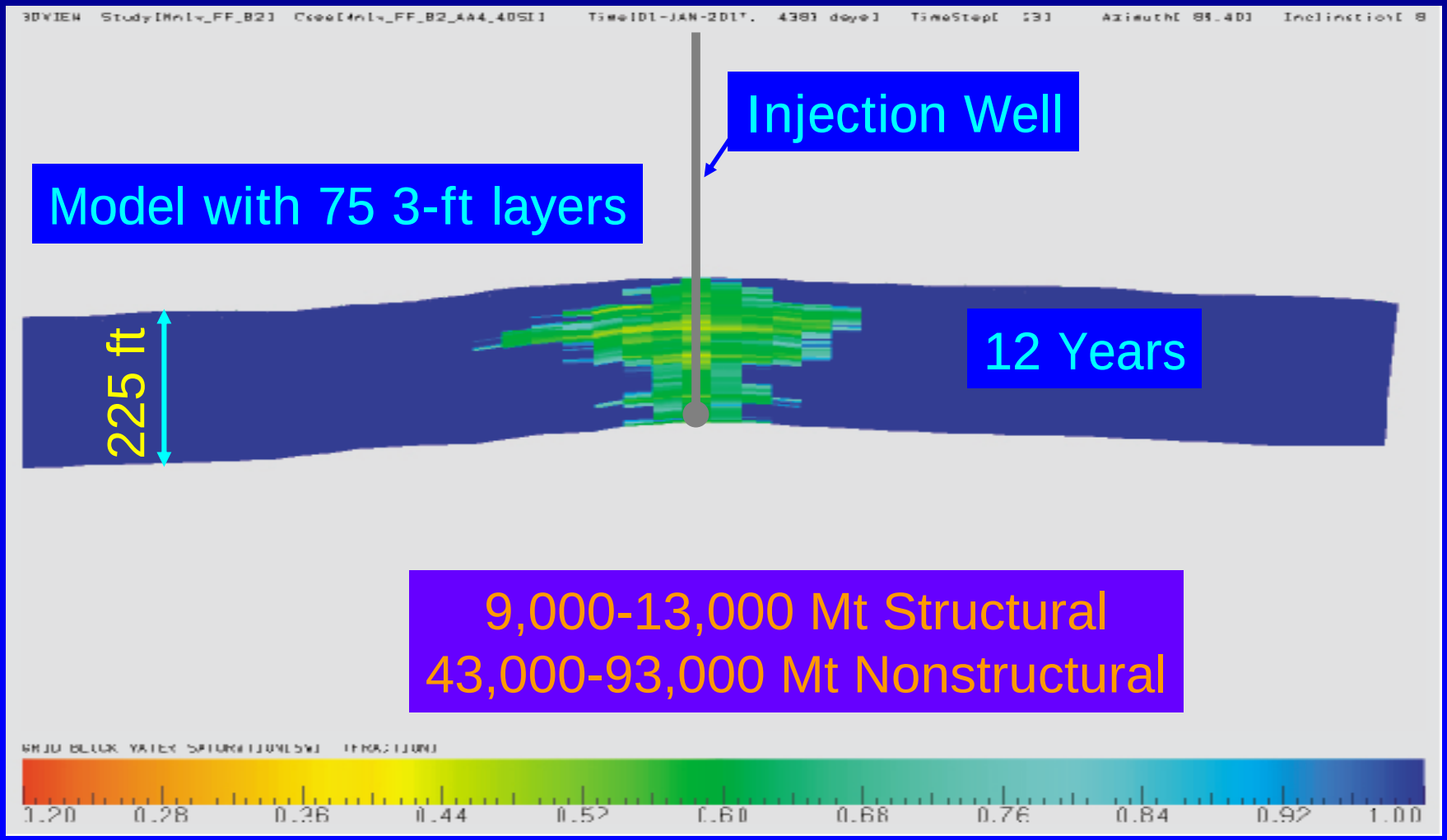
Manlove Gas Storage Project

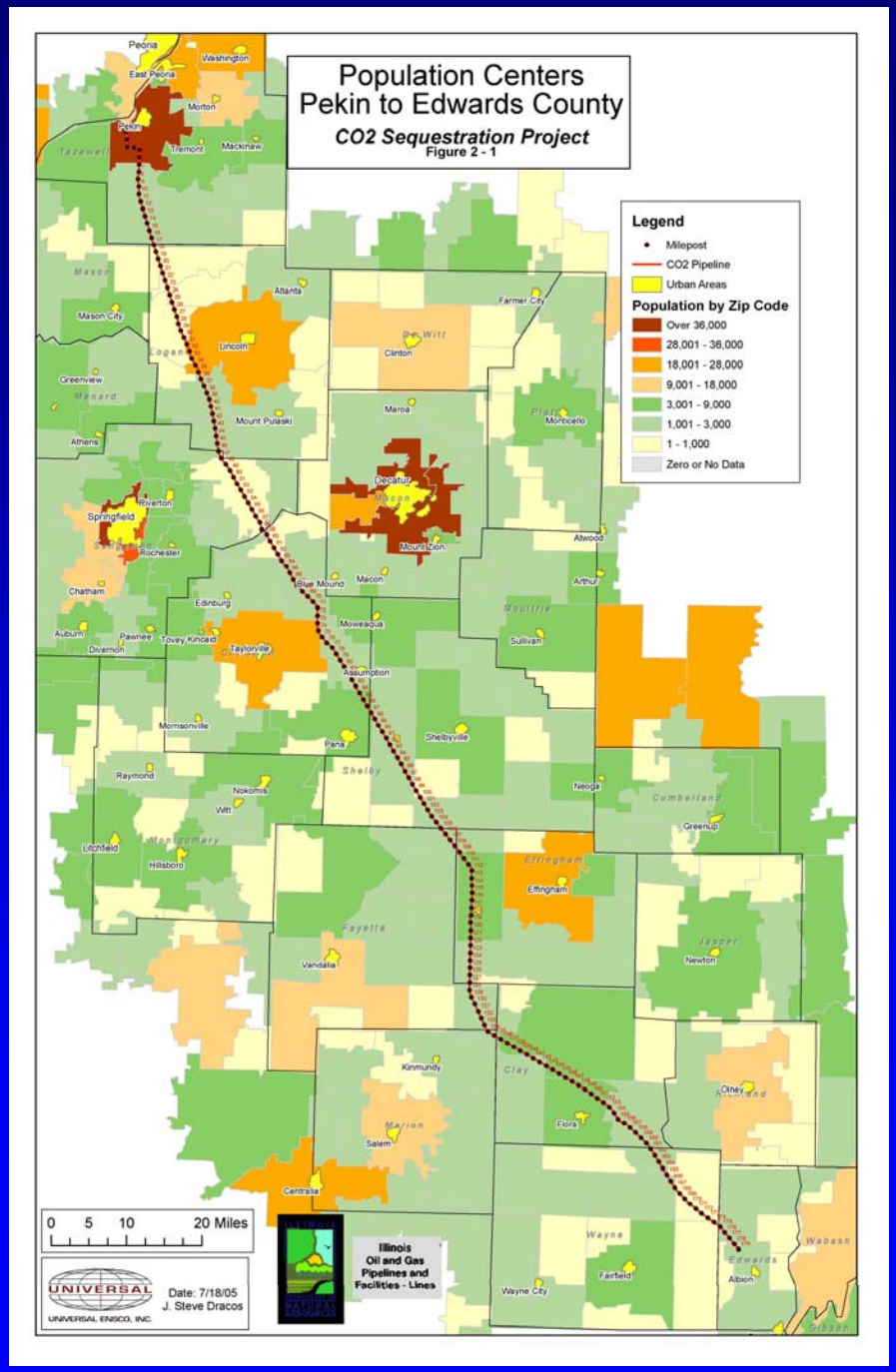


The Manlove Project has
90 feet of closure,
is 5 miles long and 4 miles wide



Mt. Simon Sandstone CO_2 Injection Simulation

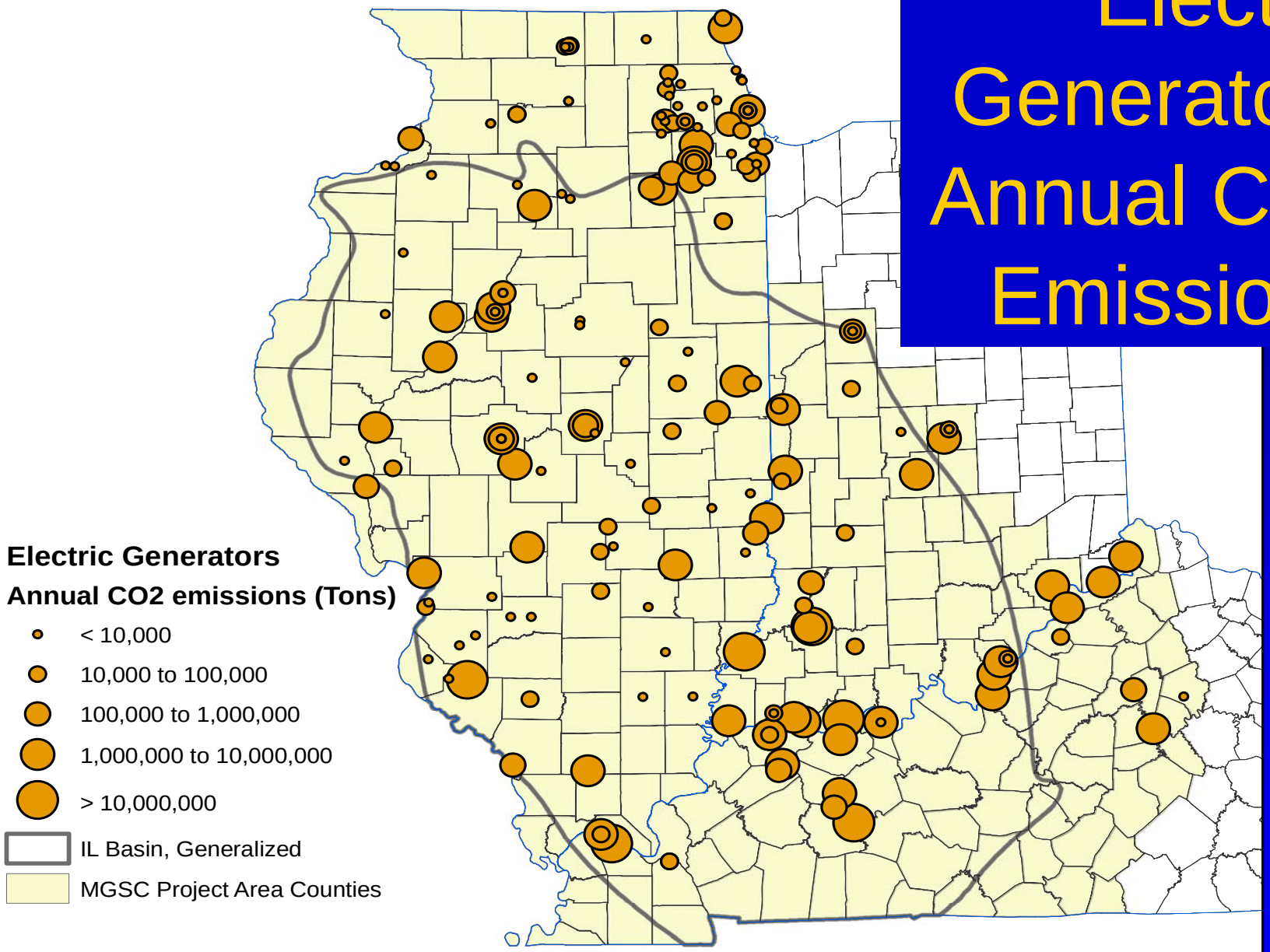




Transportation

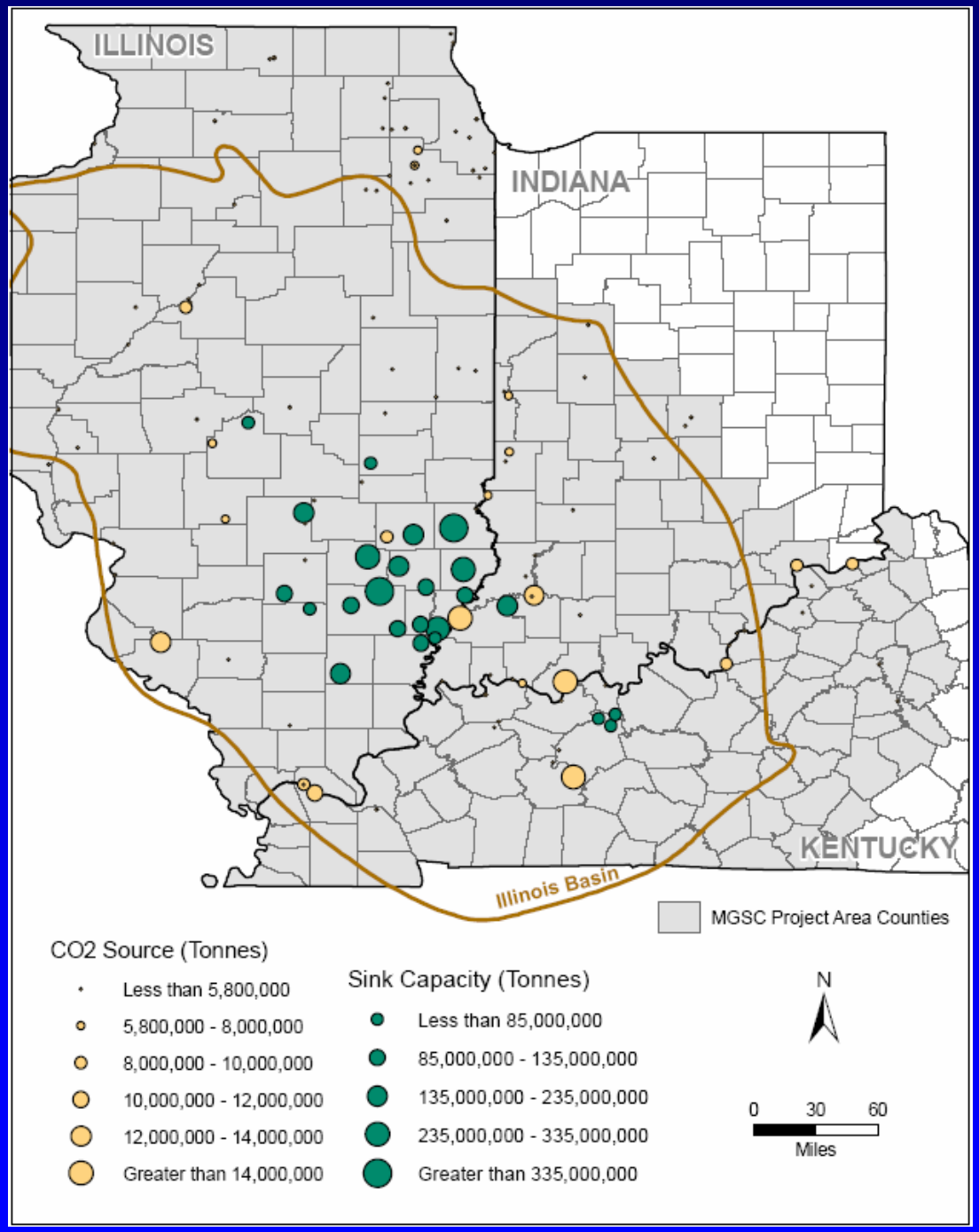
- 180 mile pipeline
- 365 MMscf/d (7.7 Mtonnes/yr) designed pipeline from a "CO_2 EOR" perspective
- Medium pressure (2,300 psig) 18-inch pipe, cost estimate is $779,444/mile
- $144 million installed

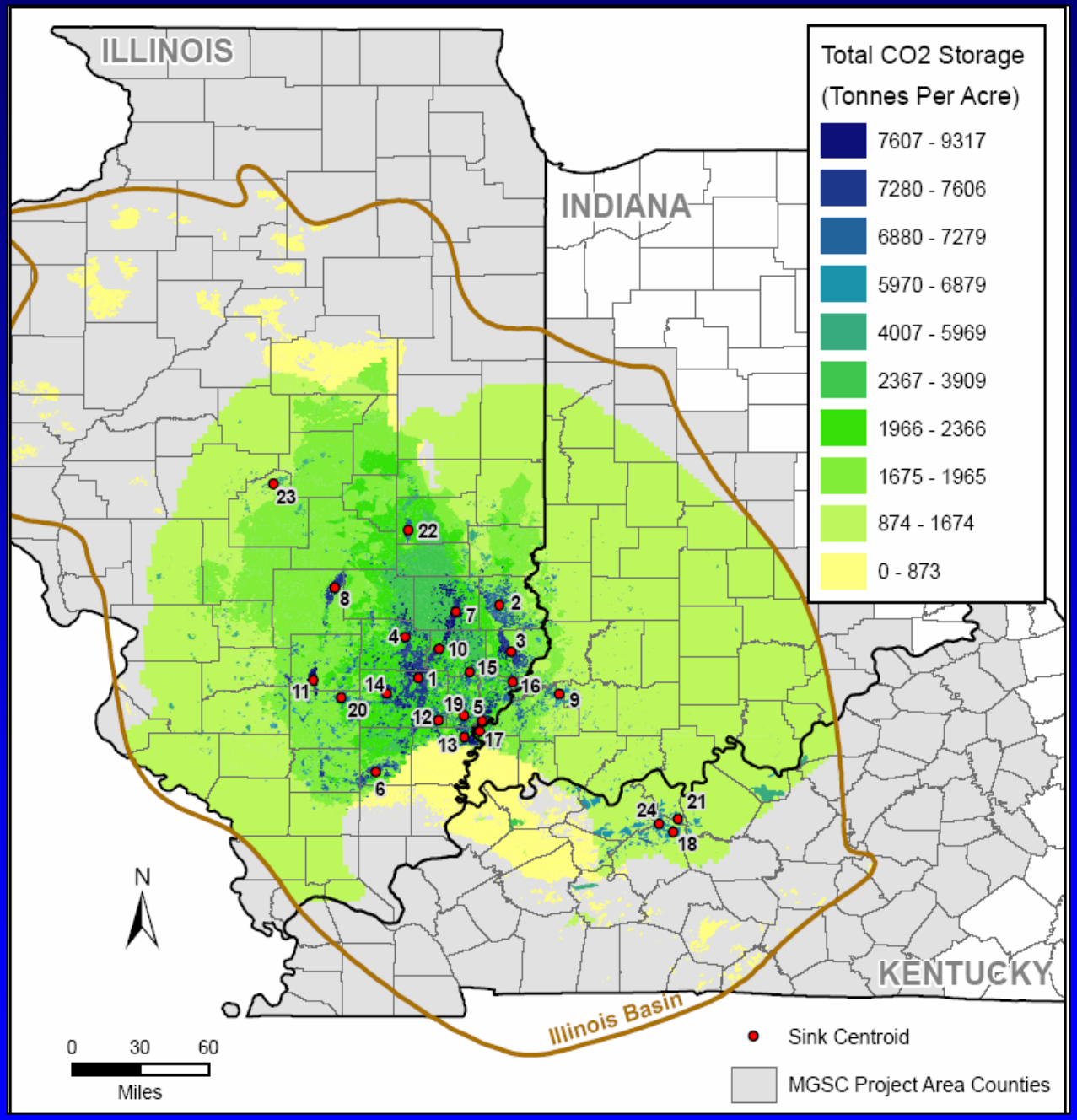
Electric Generators Annual CO_2 Emissions



Source: US DOE Energy Information Administration 2002; US EPA Acid Rain 2002, EGRID 2000.

Locations of 122 Power Plants and Largest 24 Sinks



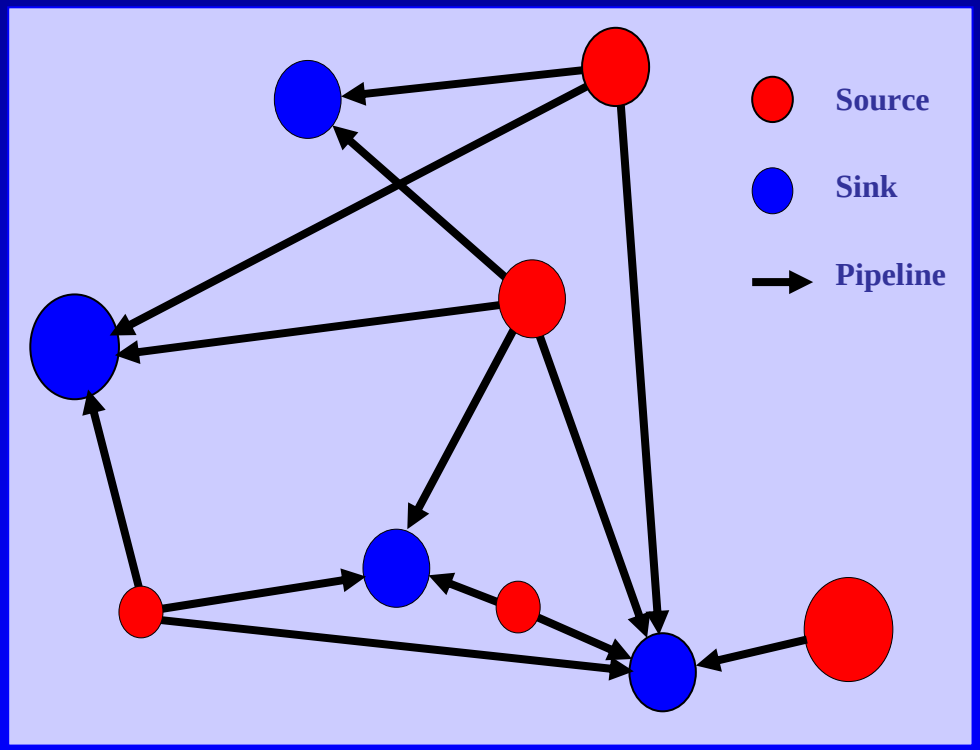


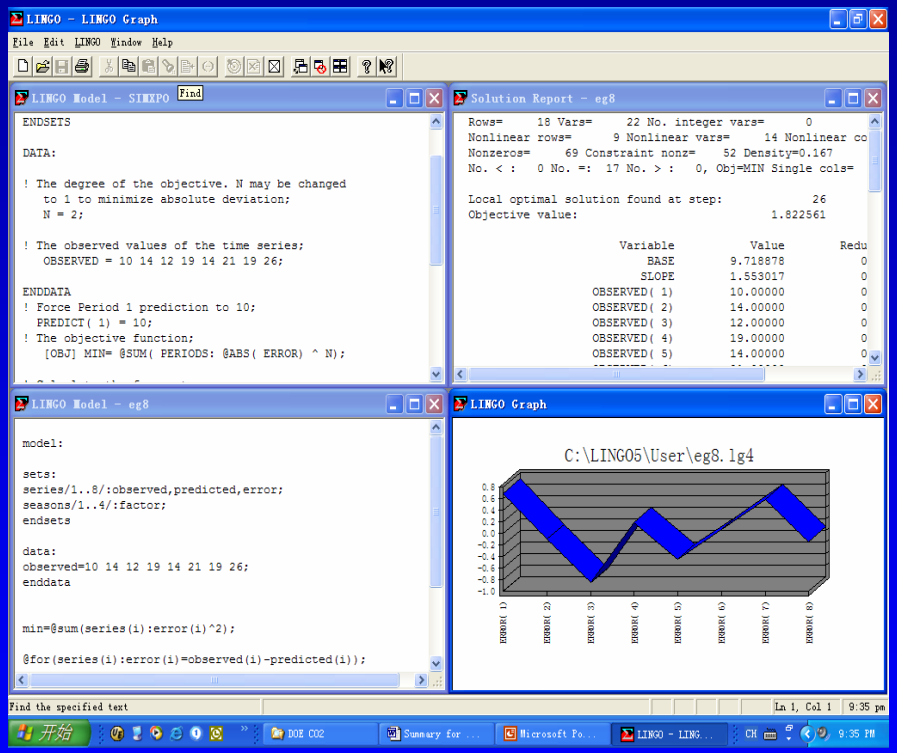
Potential Geological Storage Sinks

Capacity (Mmt) for 24 largest sinks defined by oil field structure:

- *EOR: 268*
- *ECBM:282*
- *Saline aquifer: 4,121*
- *Total: 4,671*

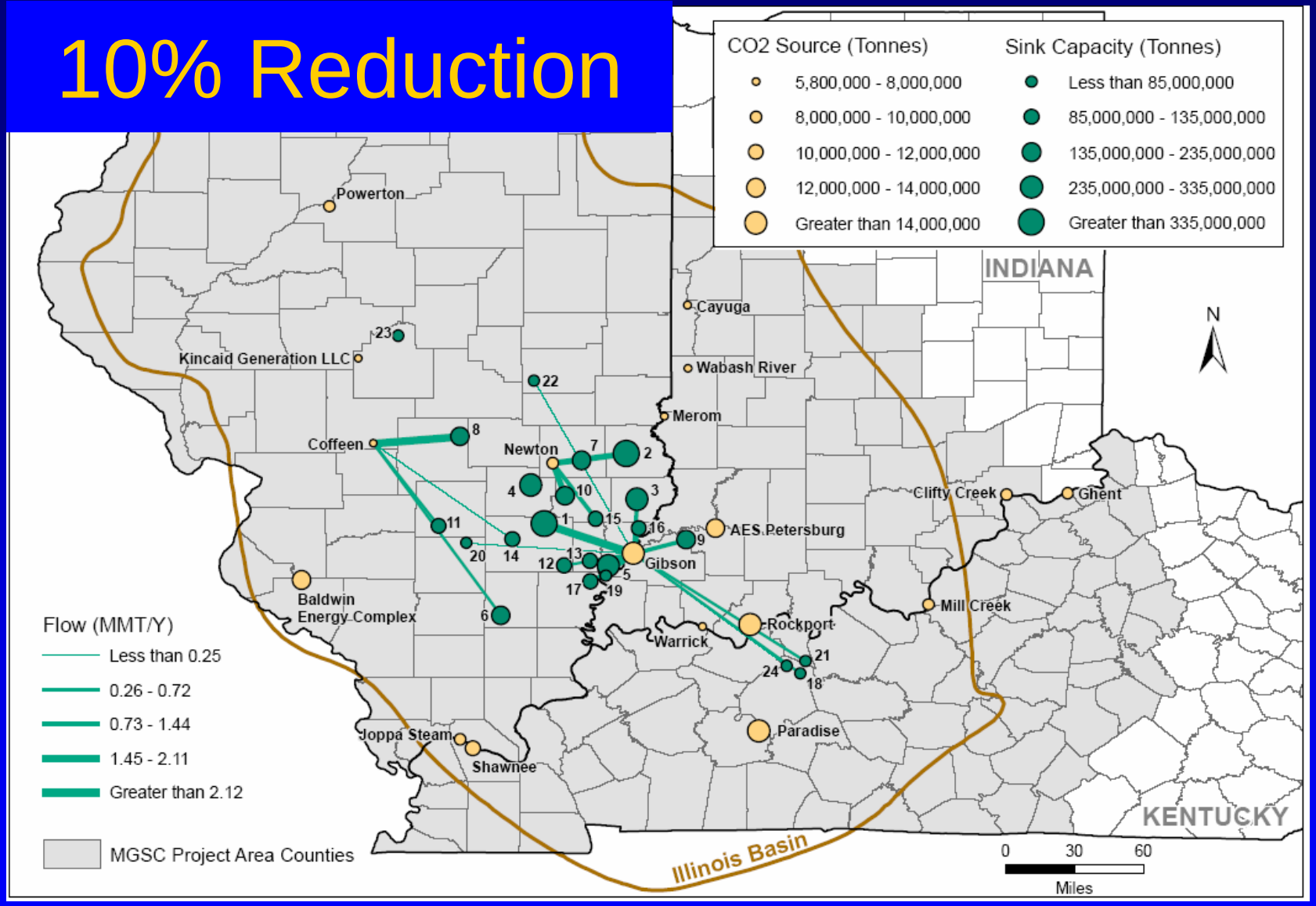
Sequestration Source-Sink Optimization





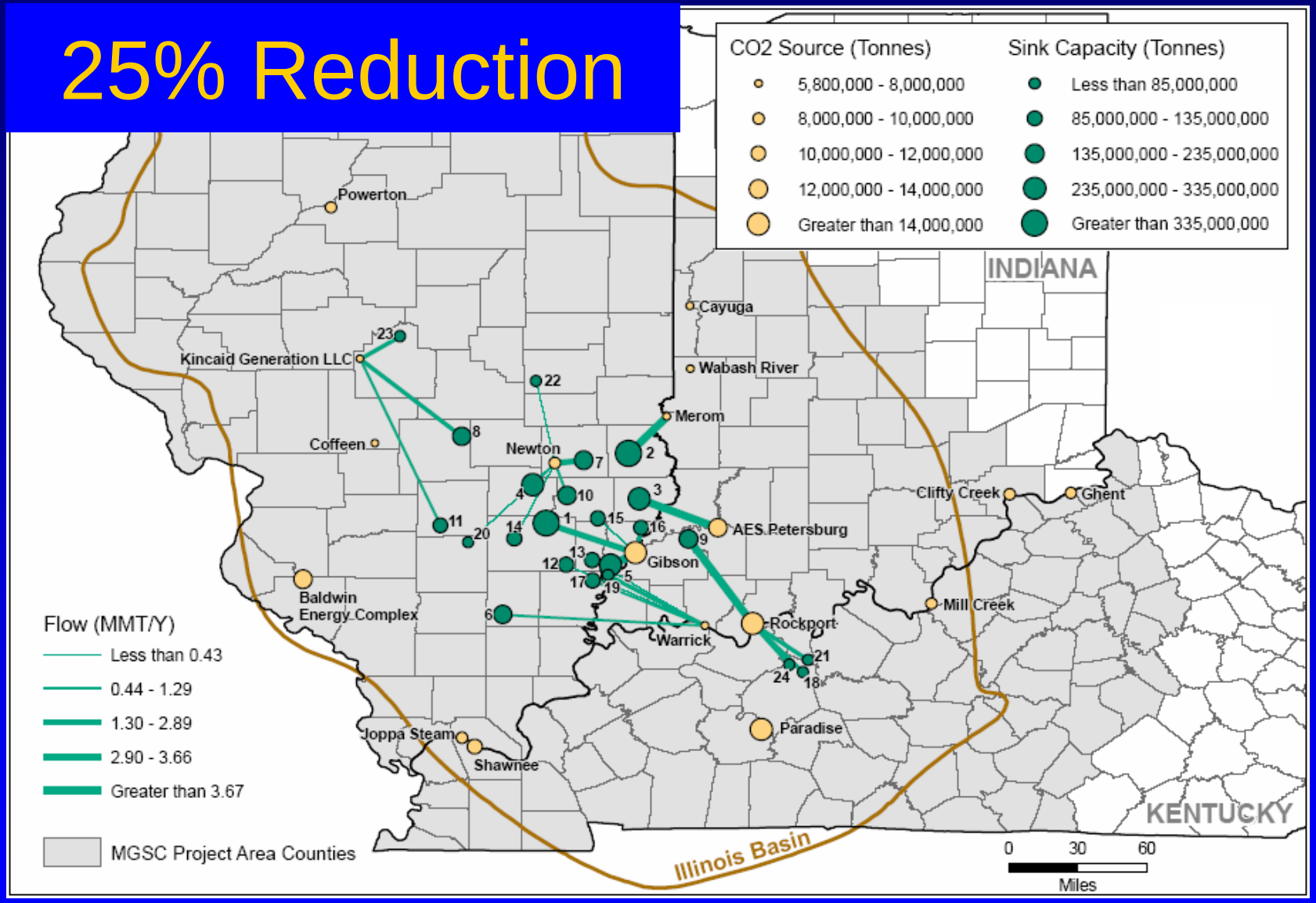
LINGO: Nonlinear optimization tool

10% Reduction



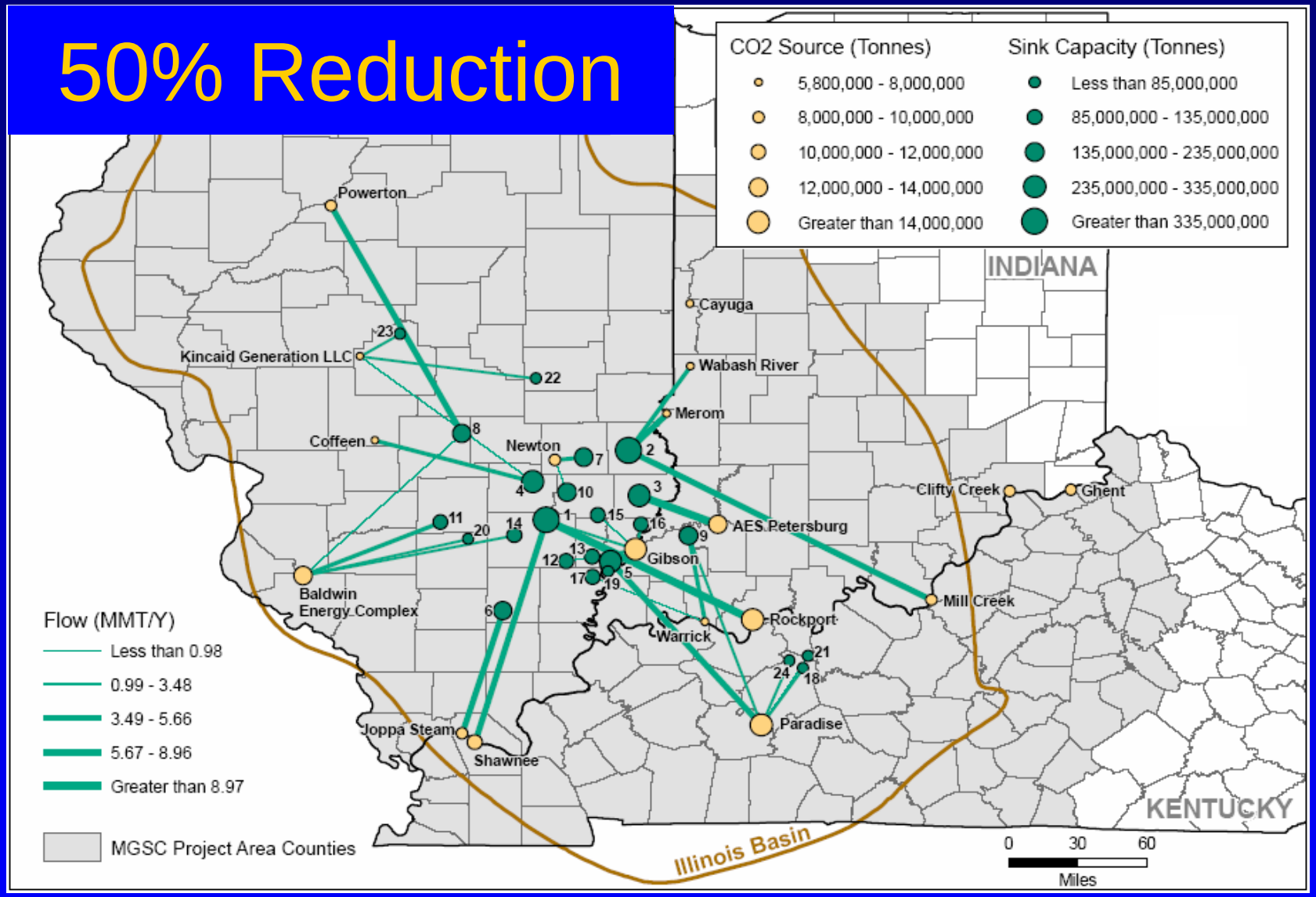
- *3 power plants, 27 Mmt/y CO_2 reduction; 1,634 Mw loss*
- *17% of storage capacity including all EOR and ECBM*
- *Average pipeline distance 22.61 miles*

25% Reduction



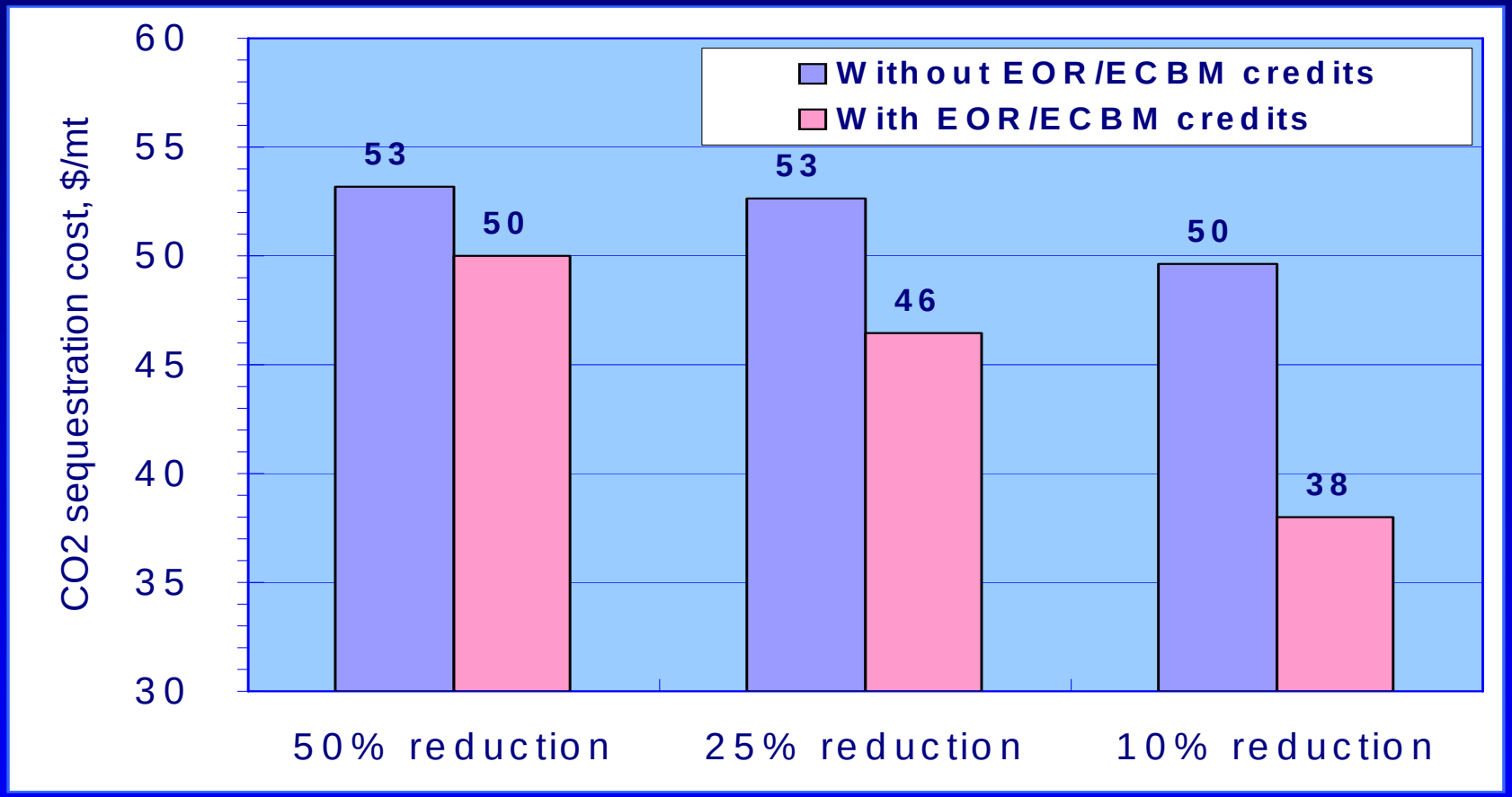
- *7 power plants, 64 Mmt/y CO_2 reduction; 3,873 Mw loss*
- *41% of storage capacity including all EOR and ECBM*
- *Average pipeline distance 26.68 miles*

50% Reduction



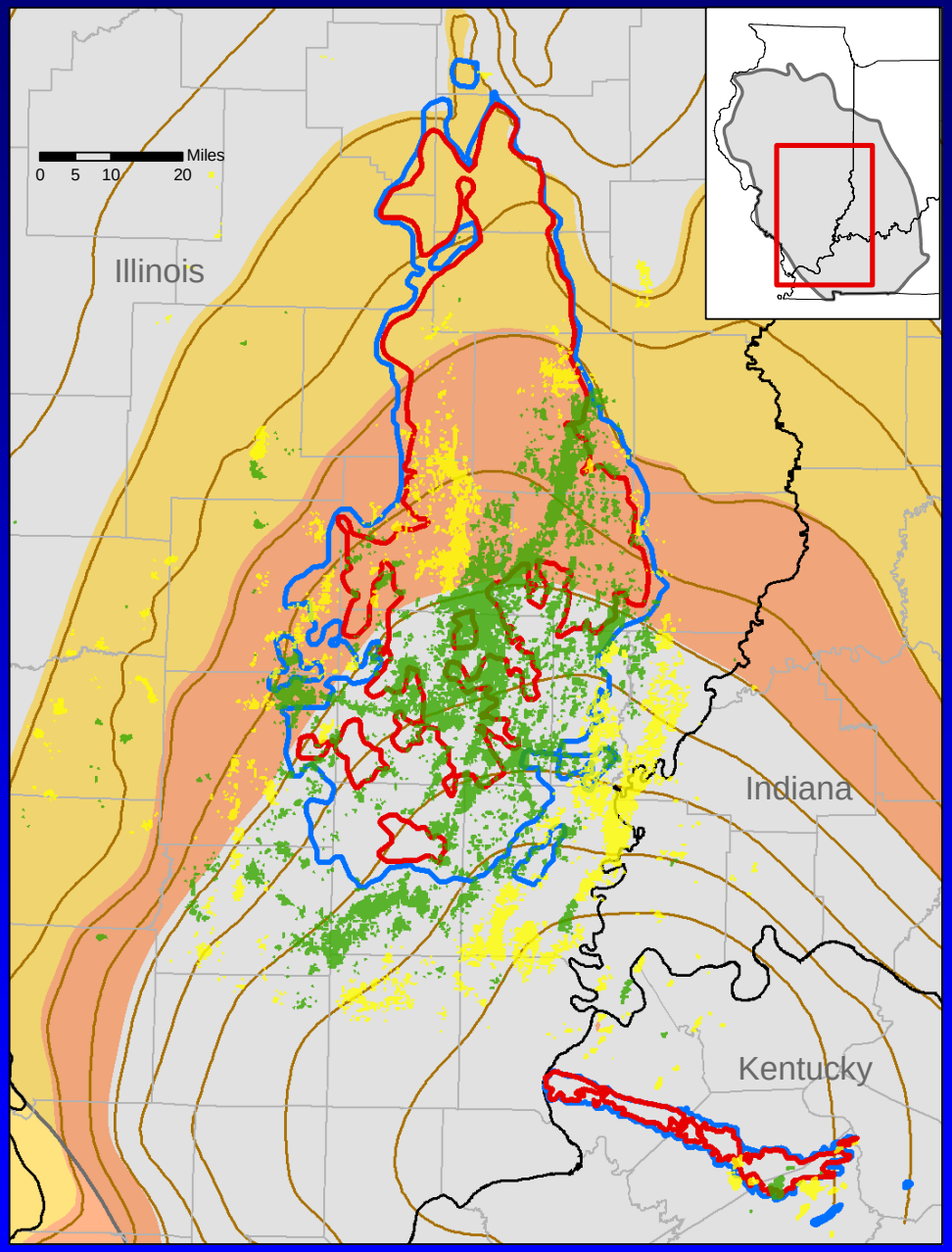
- ***15 power plants, 128 Mmt/y CO_2 reduction; 7,746 loss***
- ***82% of storage capacity including all EOR and ECBM***
- ***Average pipeline distance 57.37 miles***

CO_2 Sequestration Cost



- CO2 storage in EOR and ECBM fields are economically preferred regardless of their locations in the Basin
- 82% capacity used at 24 structural oil field sites in 30 years at 50% control

SE Illinois-SW Indiana-W Kentucky Fairway Emerges



Oil Fields EOR Class

- Predominately Miscible
- Near-Miscible

Coal Depth

- Herrin greater than 1000 feet
- Springfield greater than 1000 feet

Mt. Simon elevation (msl)

- -6,000 to -8,000 feet
- -8,000 to -10,000 feet
- 1000 foot Contours

MGSC: Seeking Optimal Sinks

- High CO_2 storage capacity
- High CO_2 injection rate
- Storage mechanism assessment

- Recommended sites at conclusion of Phase I:
  - Deep basin coal fairway
  - Miscible oil trend
  - Near to immiscible oil trend
  - Saline reservoirs in deep, closed structures
  - Saline reservoirs on regional dip

Transition to Phase II

- 33 oils sampled and characterized at potential EOR sites; 1 MMP for inject/soak/produce test
- Outreach increasing; W.Texas to Illinois Basin “producer dialogue” on CO_2 EOR on November 15
- Ameren’s 3D seismic of Mt. Simon gas storage field to be reviewed, along with operator 3D seismic
- Field test site portfolio remains open
- New Albany Shale (Devonian) to be studied in detail as both sink and seal (Kentucky Geological Survey)
- Monitoring, mitigation, and verification (MMV) to be a major expansion of project effort

Midwest Geological
Sequestration Consortium
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Oil Reservoirs and Coal Seams: CO_2 Storage, EOR, and ECBM

Scott M. Frailey

Illinois State Geological Survey

DOE NETL Review
October 12, 2005

Oil: CO_2 Storage Assessment

MGSC Project Team

B. Seyler, R. Knepp, S. Rittenhouse, J. Grube, C. Korose, D. Garner, B. Huff, S. Gustison, and D. Keefer ISGS

J. Rupp, IGS and B. Nuttall, KGS

Oil Reservoir Study Objectives

- Basin Wide Assessment:
  - Oil Sequestered CO_2 Volume (O-SCV)
  - CO_2 Enhanced Oil Recovery (C-EOR)
  - CO_2 EOR geographic distribution

Method to Estimate CSV and EOR

- *CO_2 Oil Recovery Factor* (E_R)

$$E_R = \frac{N_{pEOR}}{N}$$

- *CO_2 Storage Factor* (E_S)

$$E_S = \frac{G_{injCO2}}{N}$$

Storage Factor includes all CO_2 storage mechanisms: Free phase mobile and immobile, and dissolution in oil and water.

- Multiplicative fractions of the Original Oil In Place (N) in the Basin to find CSV and EOR

Approaches to Estimate E_R and E_S

- Geological and Reservoir Modeling
  - Based on Illinois Basin geologic description, reservoir pressure and temperature, and fluid properties of generalized Basin crude oil.
  - Computational only
- West Texas Rules-of-Thumb
  - Based on actual production and injection
  - Generalization of field experience

Geological and Reservoir Modeling

- Landmark software (Geographix, VIP) and Isatis
- Geologic Models
  - Structure and isopach: Deterministic
  - Porosity and permeability: Statistical
- Nine fields studied to develop generic geologic models for most prolific oil producing formations:
  - Aux Vases
  - St. Genevieve
  - Cypress
- Reservoir models: Miscible & Immiscible pressure; continuous and WAG CO_2 injection

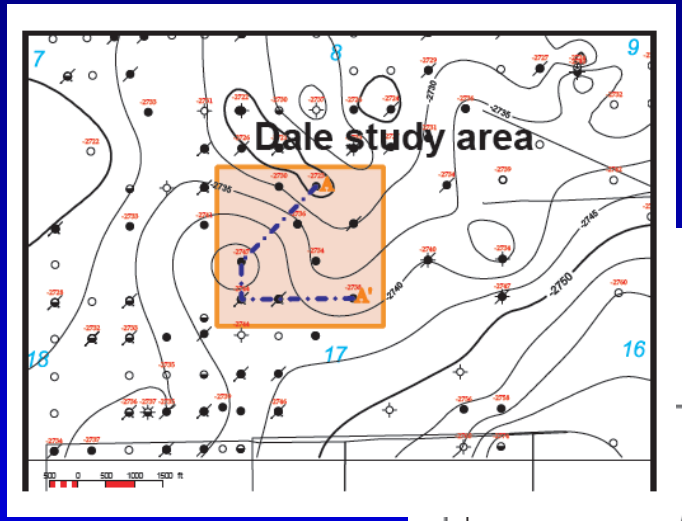
Geologic Modeling

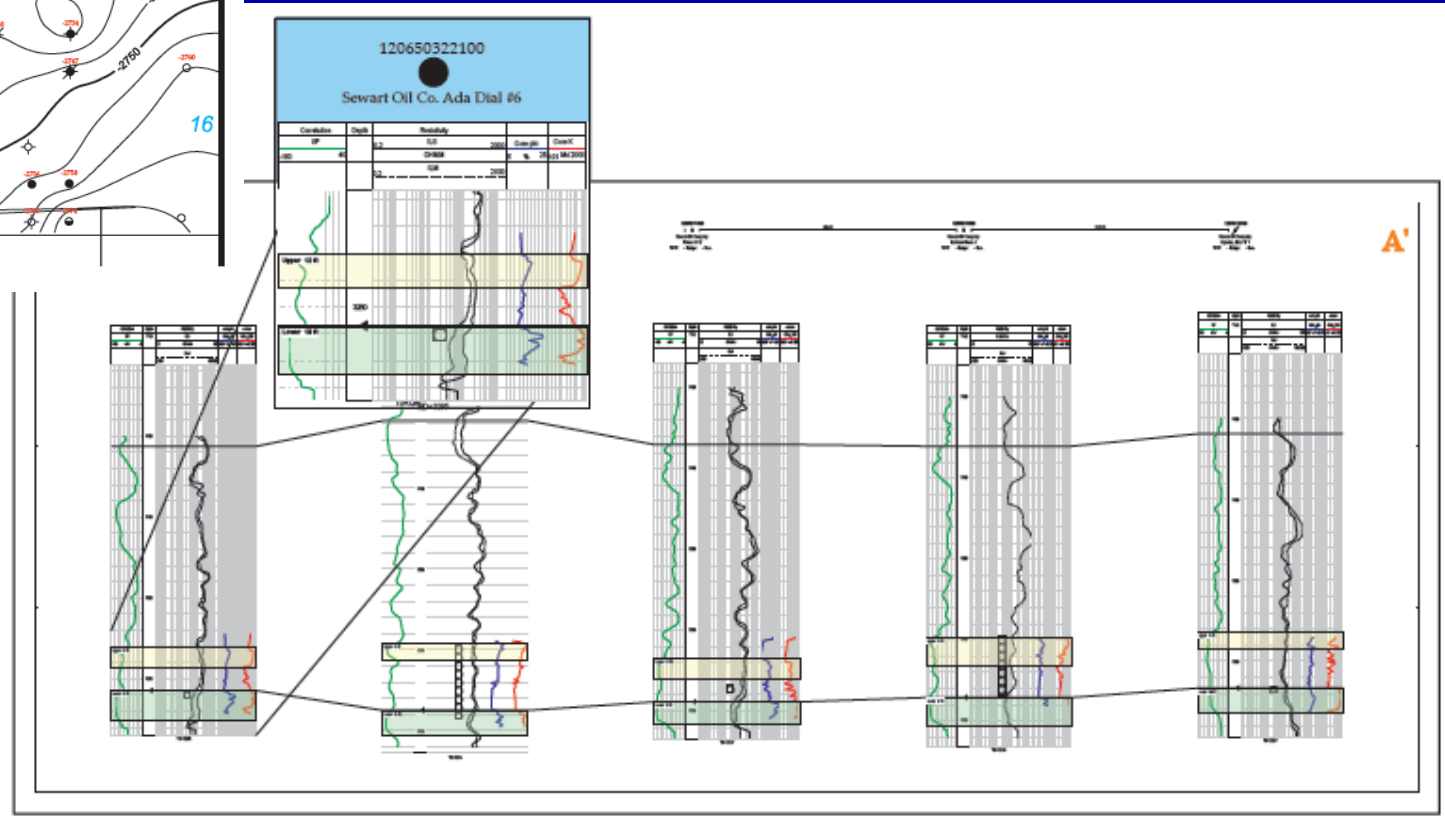
- Nine study areas
  - Dale, Lawrence (Griggs), Iola, Johnsonville, Mill Shoals, Olney, Sailor Springs, Clay City (Wakefield) and Zeigler
  - Aux Vases, Cypress and Ste. Genevieve geologic formations
    - Approximate number of wells studied >1000
    - Total number of cored wells = 120
    - Total number of core points >2000
    - Total surface acreage = 12,000
    - Total number of flow zones = 20

Geologic Modeling

- Example St Genevieve (Dale) Study Area
  - Number of wells = 9
  - Number of core points = 257
  - Acres = 108.4
  - Flow zones = 2
  - Maps = top of structure, isopach
  - Cross-Section

Deterministic Modeling

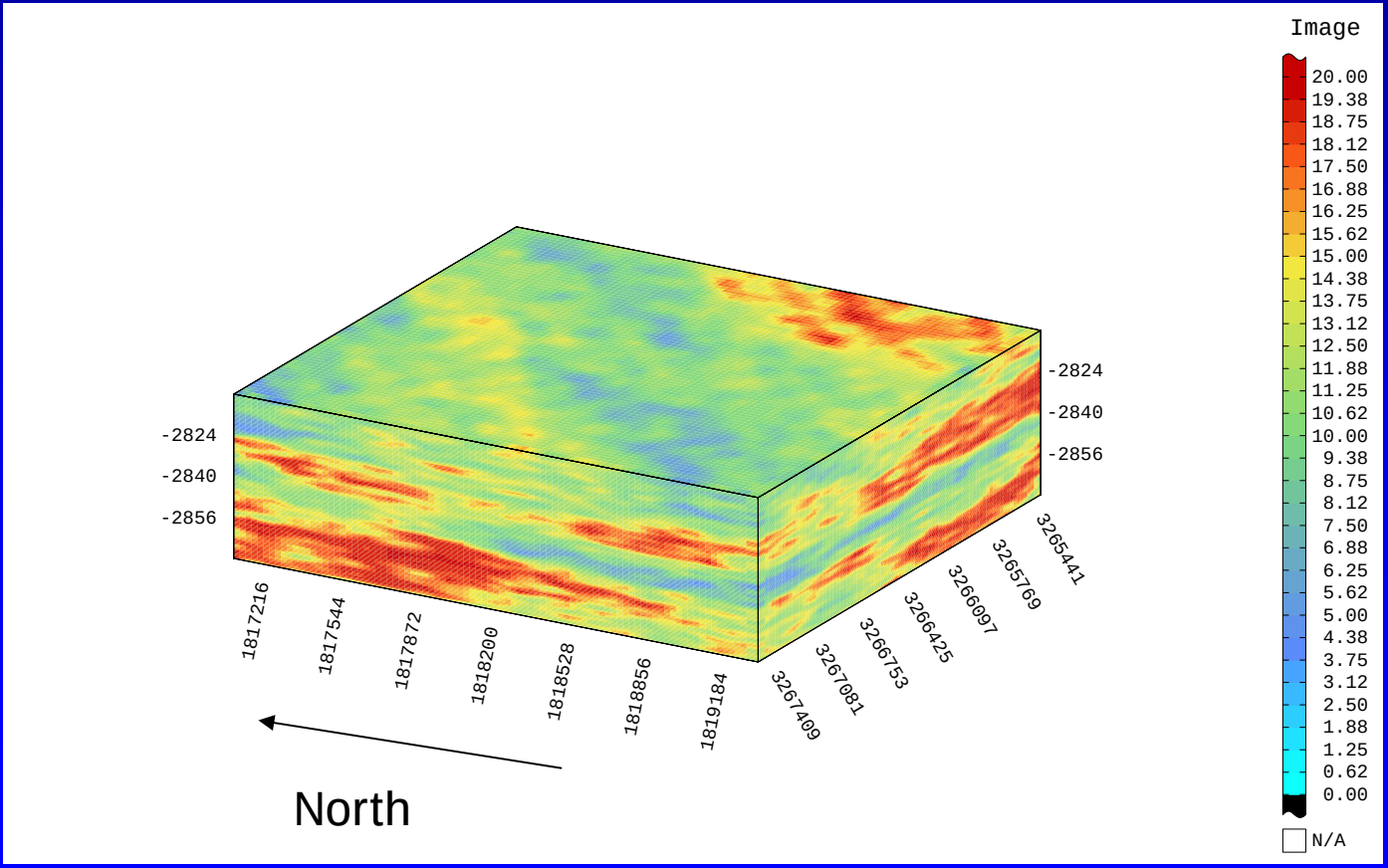




Structural cross section A-A' (see location map) through study area in Dale field, Hamilton County, IL, showing cored wells used to build geostatistical models. Log suite includes SP (track I), resistivity (track II), porosity (track III) and $\log_{10}$ permeability (track IV). Two stacked high-porosity and -permeability oolitic shoals are represented by the intervals shaded yellow and green.

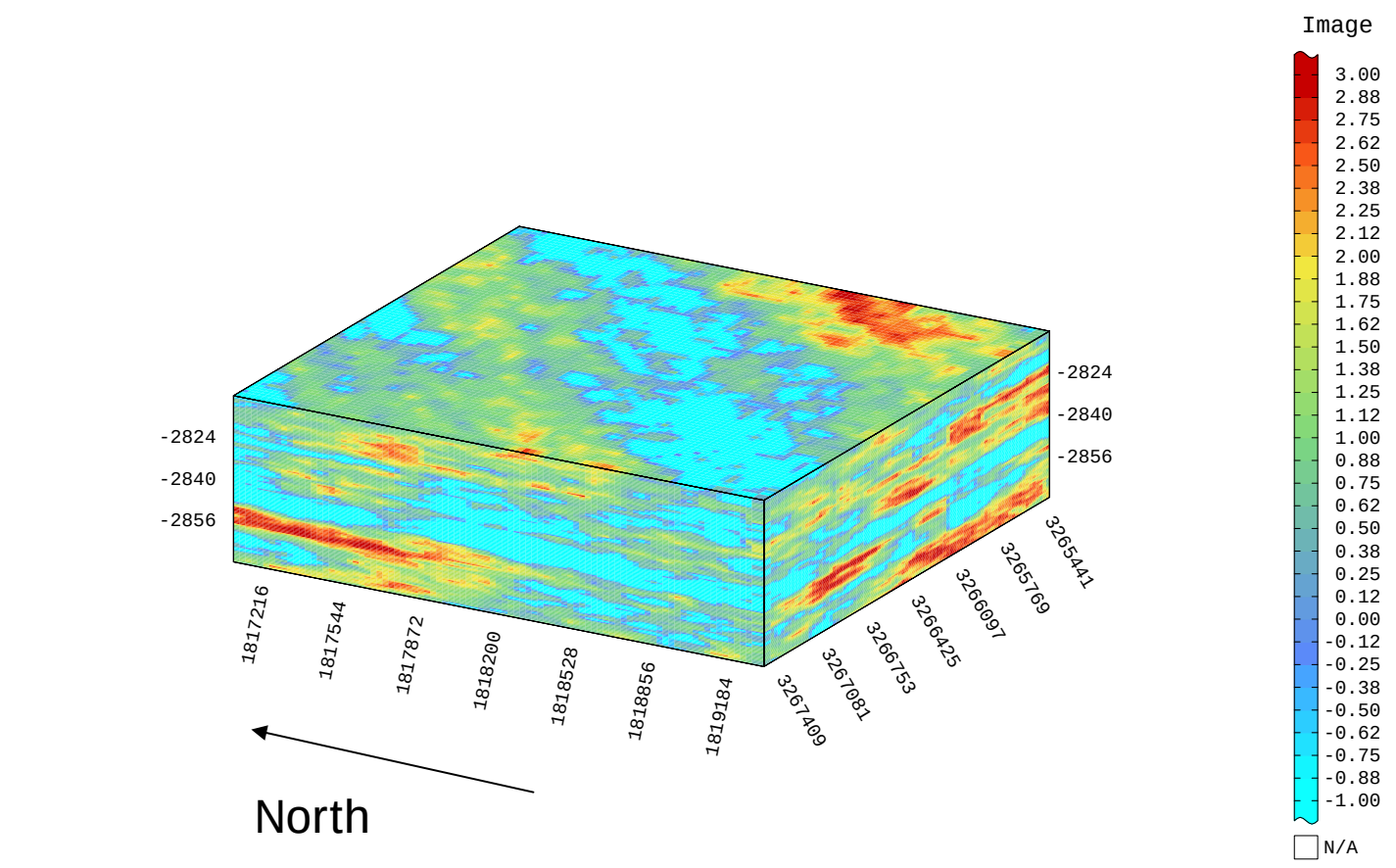
Geostatistical Modeling

- Percent porosity
  - Average porosity = 14.12

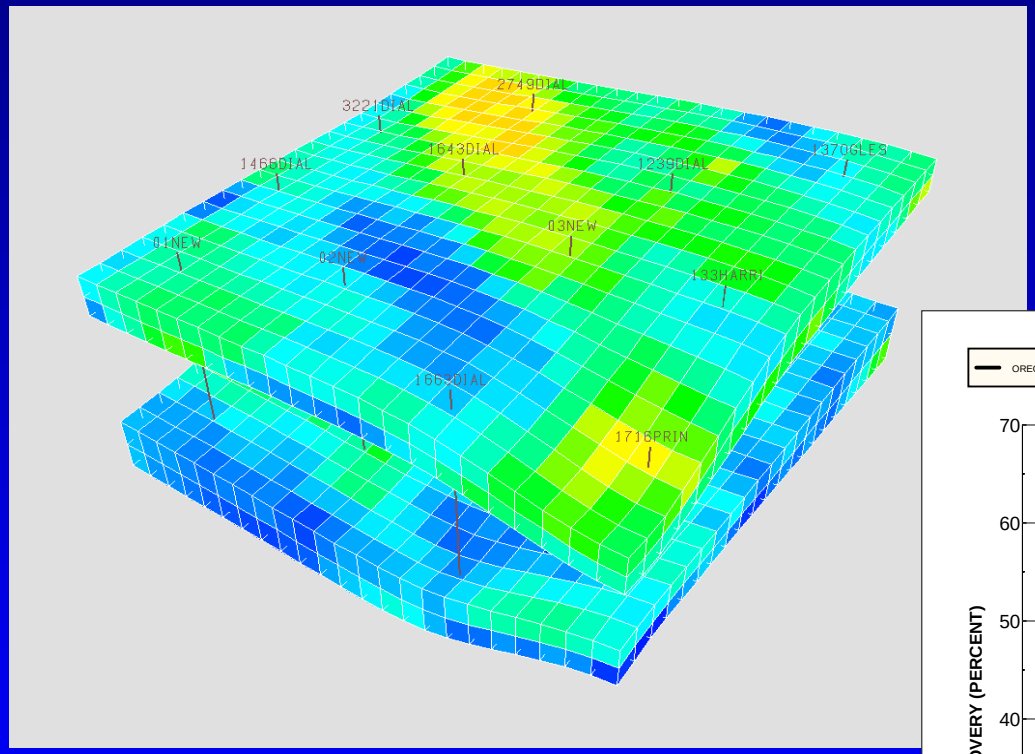


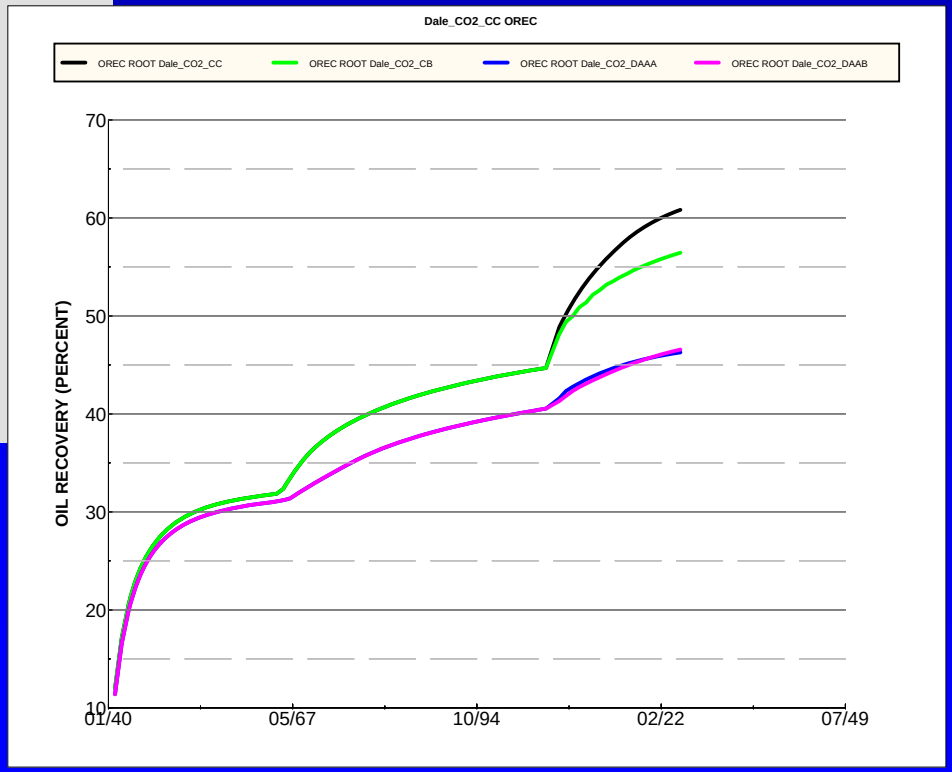
Geostatistical Modeling

- Log of horizontal permeability
  - Average permeability = 95 milliDarcies



Reservoir Modeling





West Texas Based Rules-of-Thumb

- CO_2 EOR, E_R
  - 10% of OOIP
  - 25% of primary plus secondary production
- CO_2 Storage Factor, E_S
  - CO_2 Net Utilization 5-10 Mscf/stb-produced (0.265 -0.530 tonnes/stb-produced), U_n
  - Net is cumulative injected CO_2 *less* the produced CO_2. Inference is the CO_2 "lost" to reservoir in order to produce 1 barrel of oil
  - $E_S = E_R U_n$ (0.0265-0.053 tonnes/stb-OOIP)

Oil Recovery and CO_2 Storage Factors via Modeling

Oil Recovery Factors

Zone	Imm	Misc
Cyp	*4.5-5.9*	*8.6-11*
A-V	*5.6-7.1*	*11-15*
St.G	*5.0-6.5*	*8.6-16*
W Tx	*4-10*	*8-16*

*Bbl of oil produced per bbl of **OOIP***

CO2 Net Utilization

Zone	Imm	Misc
Cyp	*1.7-3.1*	*4.6-9.0*
A-V	*1.5-3.3*	*4.6-8.8*
St.G	*1.4-5.4*	*4.6-9.2*
W Tx	*5-10*	

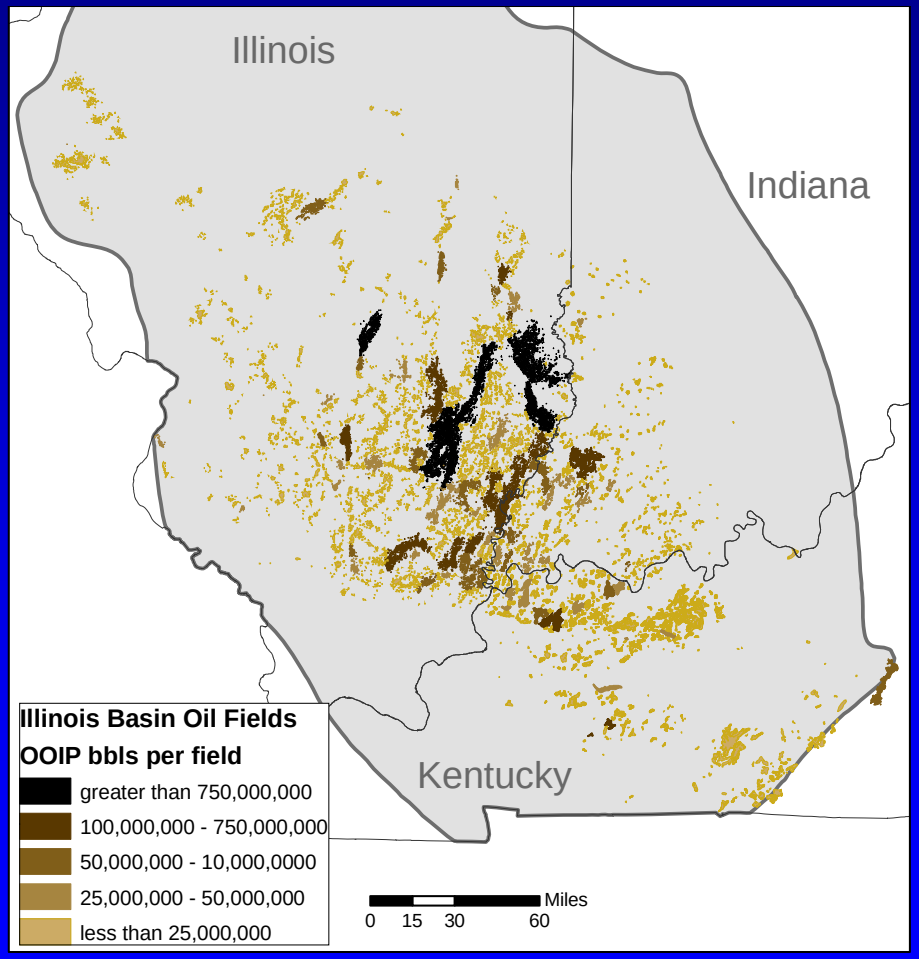
*Mscf of CO_2 stored per bbl oil **produced***

Applying E_R and E_S to the Basin

- OOIP by geologic formations
  - Cypress
  - Aux Vases
  - St. Genevieve
  - Other
- Miscibility condition
  - Immiscible
  - Near
  - Miscible

Original Oil In Place Map

OOIP MMstb	Number of Fields
>750	4
100-750	15
50-100	24
25-50	38
<25	>1000



14.1 Bstb ~ 1500 oil fields

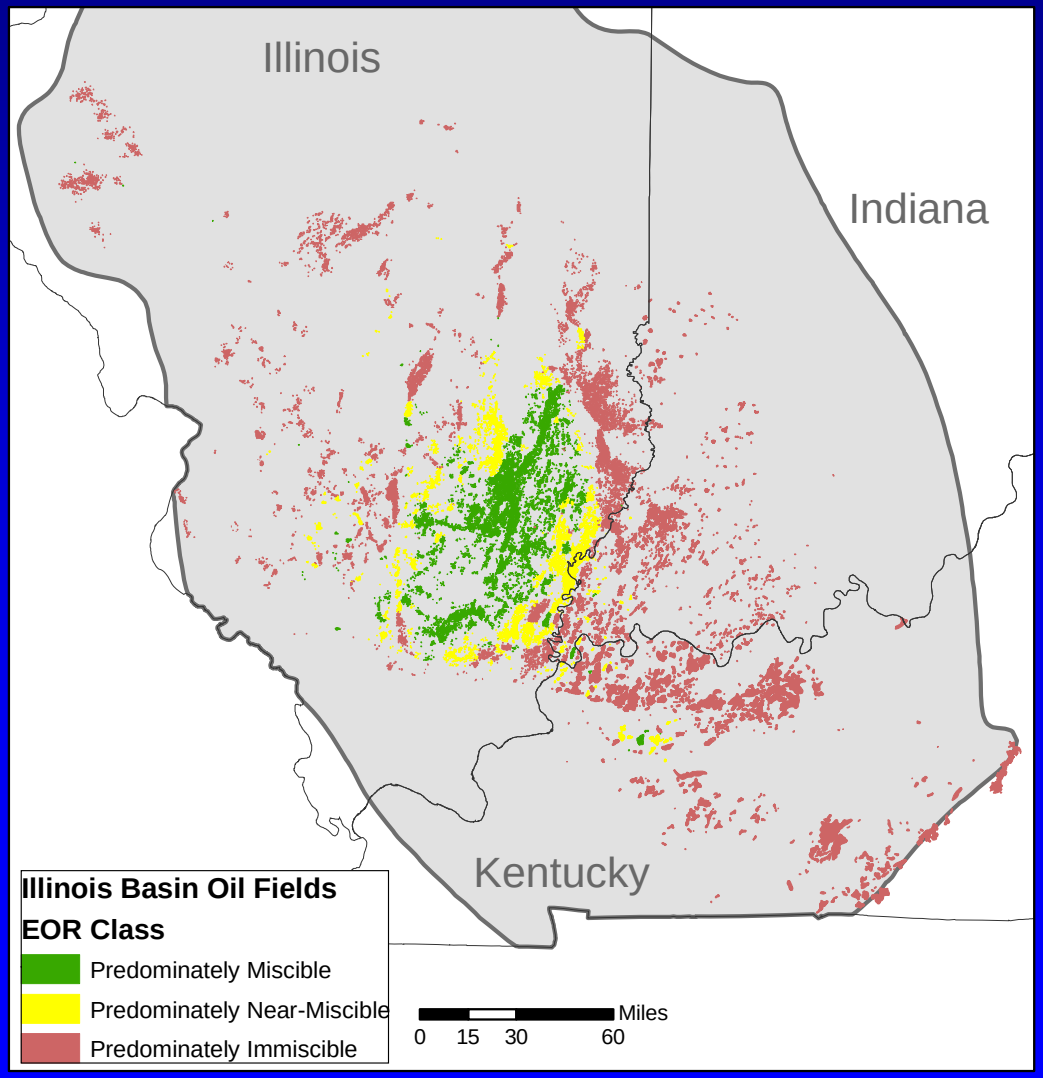
Miscible, Near Miscible and Immiscible Map

Classification based on anticipated pressure and temperature using gradients observed in the Basin

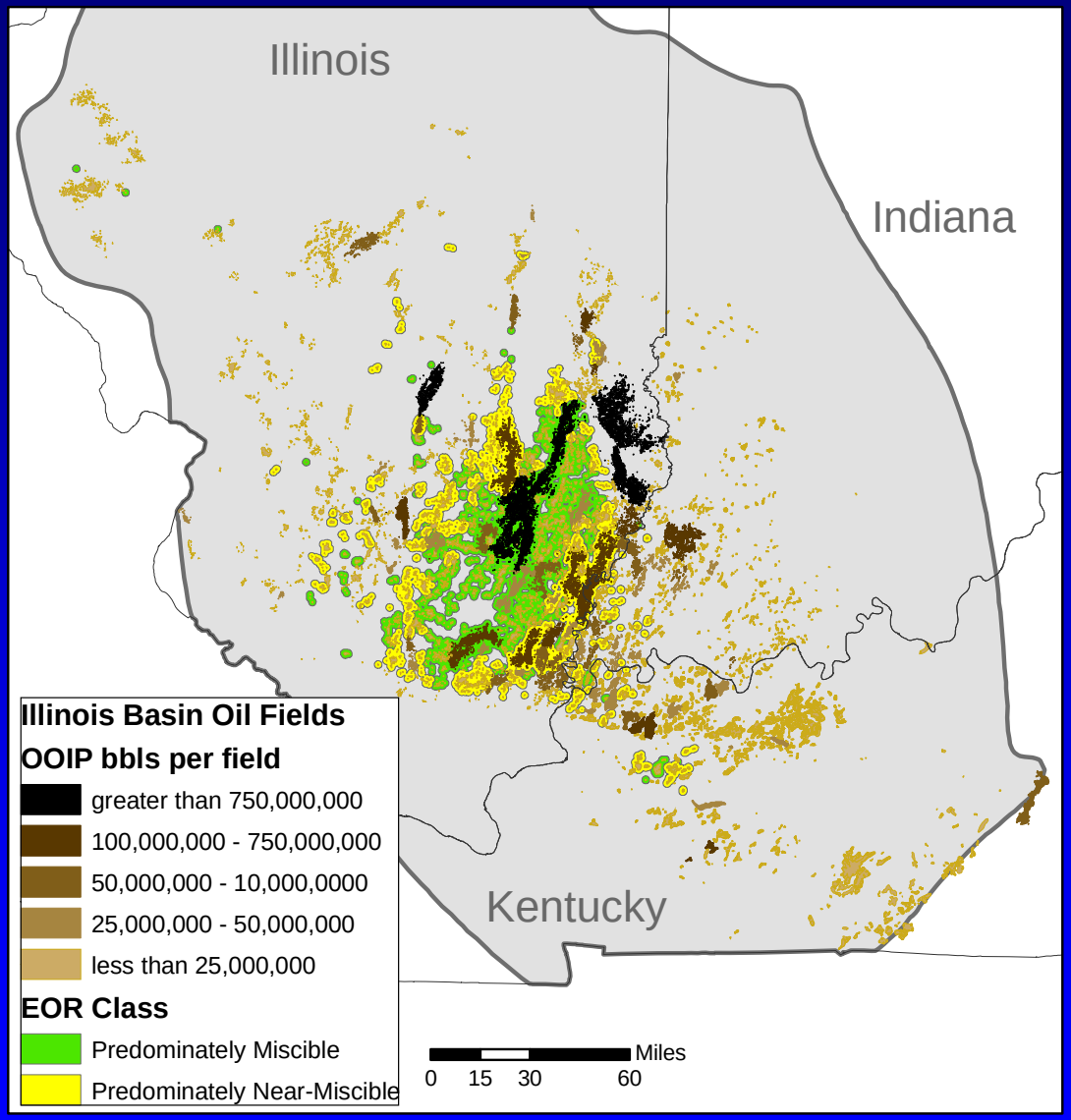
Field depth: bulk volume weighted by formation

Pressure: 0.433-1.0 psi/ft

Temperature: 1.0-1.2 F/100 ft

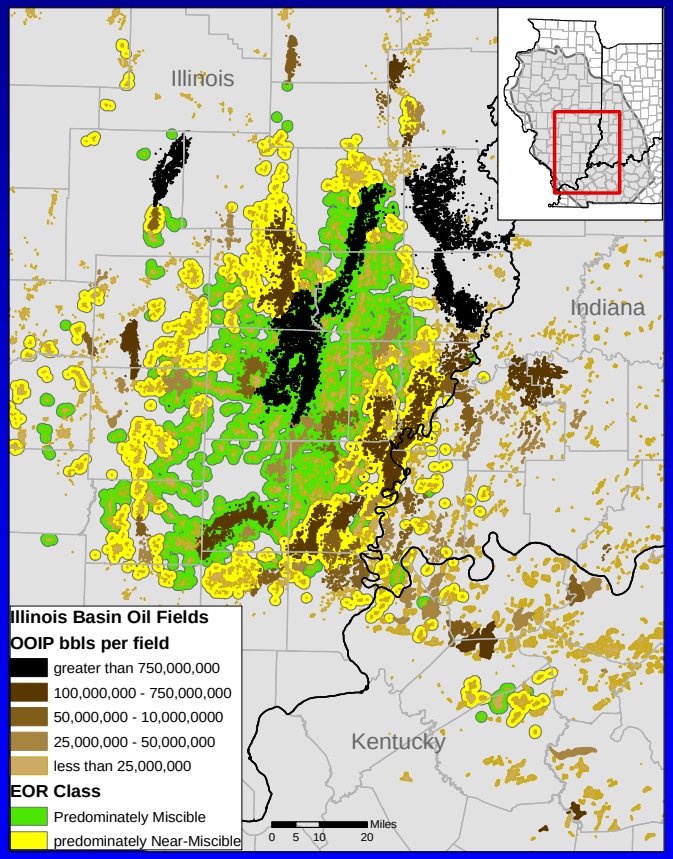


GIS Analysis: OOIP & Miscibility Map



Miscibility Condition	OOIP Bstb
Miscible	*2.1-2.5*
Near	*3.5-4.1*
Immiscible	*6.4-7.5*

CO_2 EOR and CO_2 SV Maps (Distribution)



Condition	CO_2 Mtonne	EOR Bstb
Miscible	*58-180*	*0.24-0.38*
Near	*53-153*	*0.28-0.40*
Immiscible	*29-110*	*0.34-0.49*
Total	*140-440*	*0.86-1.3*

Maps and tables for EOR and CSV based on geologic and reservoir modeling

Coal: CO_2 Storage Assessment

MGSC Project Team

J. Rupp, M. Mastalerz, and A. Drobniak IGS

C. Eble, KGS

T. Moore, C. Korose and A. Anderson, ISGS

S. Harpalani, SIU-C

Coal Bed Objectives

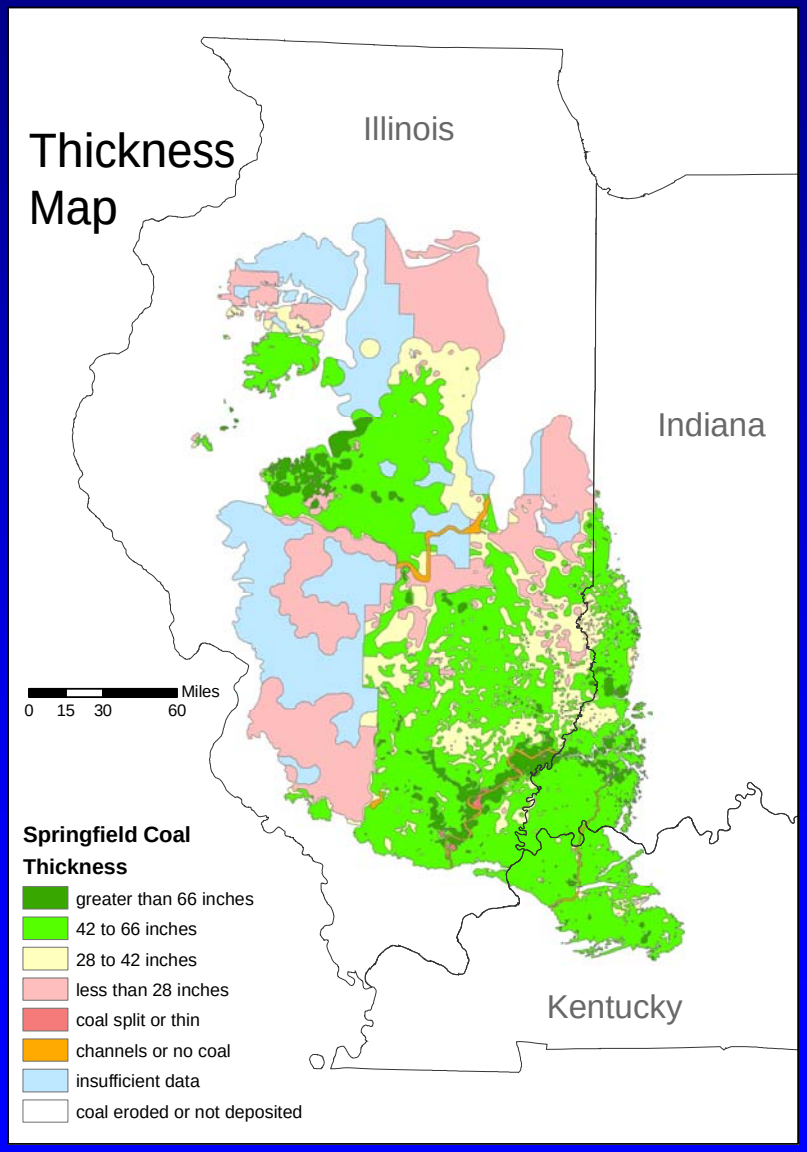
- Coal Characterization (Basin Specific)
- Coal Sequestered CO_2 Volume (C-SCV)
- CO_2 Enhanced Coalbed Methane (C-ECBM)
- Coal Geographical Distribution

Coal CO_2 Storage: Parameters Required

- Bulk volume: Area and thickness mapped
- Gas Content: constant or mapped
  - Ash map
  - Porosity (cleat), pressure and moisture
  - CO_2 adsorption (Langmuir isotherm)
- Storage and recovery factors via COMET modeling for low, best, and high estimates.

Area and Thickness

- Seven coal seams assessed
- Screening criteria: Less likely to be mined (LLTBM)
  - h>18”
  - 500-1000’: h<42”
  - > 1000’: All coal



Parameter Distribution

- Limited Data (quantity, spatial distribution)
  - Isotherms (V_L and P_L)
  - Degree of saturation
  - Moisture
  - Porosity
- Data analyzed and classified
  - Depth divisions: 500-900, 900-1200, >1200’
  - Low, Best and High estimates made

Example Data Distribution Best Estimate

	Depth, feet		
Parameter	500-900	900-1200	>1200
V_L, scf/ton	16	14	15
P_L, scf/ton	580		
Moisture %	10	10	8.7
P_i, psia	303	450	560
Porosity	0.03	0.02	0.01
Saturation*	0.52	0.43	0.47

*Degree of saturation: actual gas content divided by gas capacity via Isotherm

Example Storage and Recovery Factor: Best Estimate

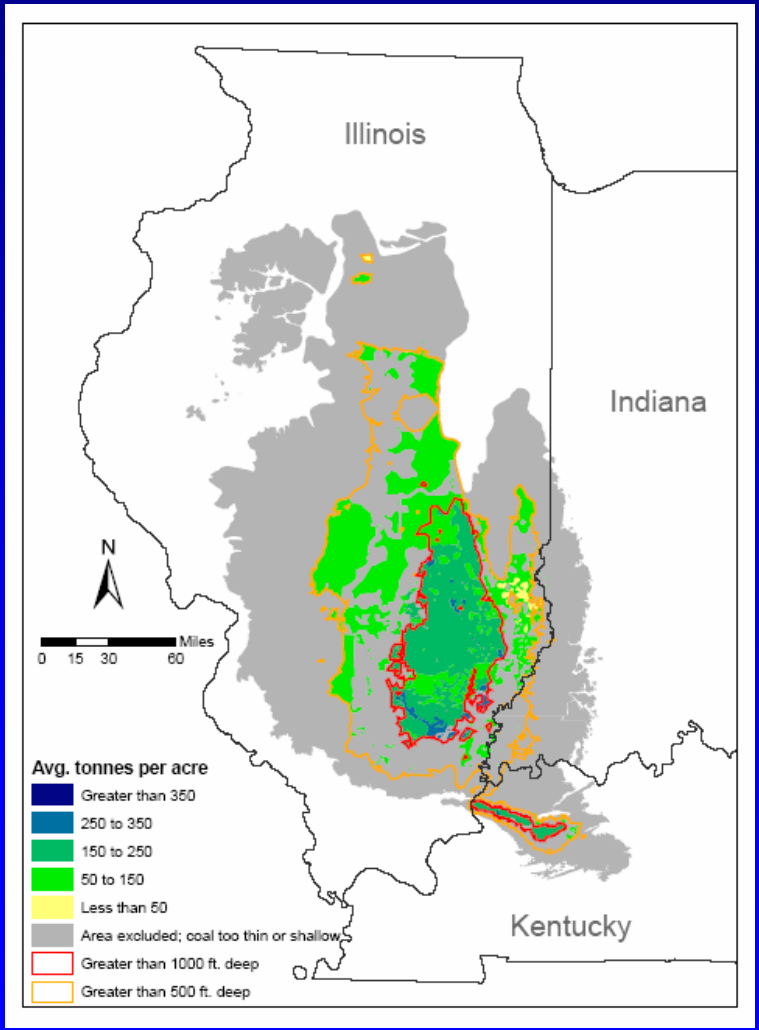
- SF: MSCF of CO_2 stored per MSCF of original CBM
- RF: fraction of CBM produced via CO_2
- SF and RF from COMET ECBM modeling

Depth	SF	RF
500-900	7.1 (6.1-8.6)	0.74 (0.66-0.89)
900-1200	8.2 (7.3-8.7)	0.70 (0.60-0.86)
>1200	7.1 (4.9-7.7)	0.78 (0.64-0.85)

10-30% E_V; 33% C1/CO_2 (Allison)

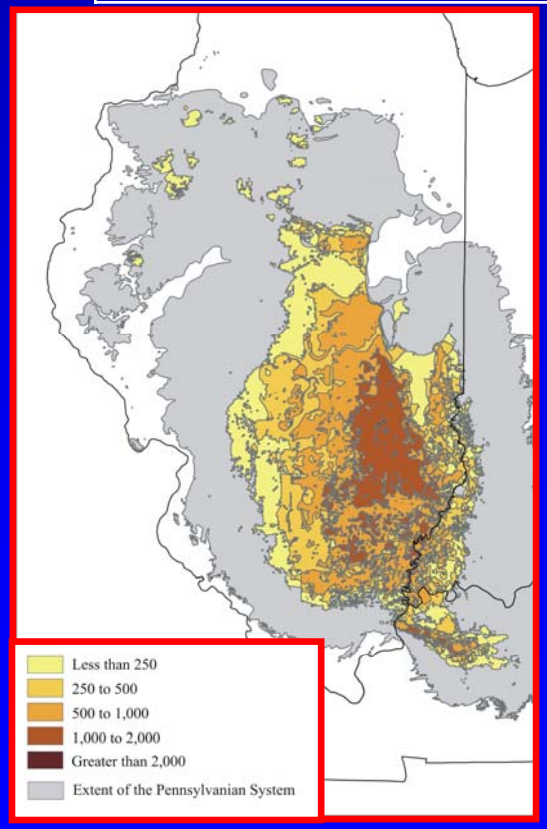
GIS Calculation of CO_2 Storage

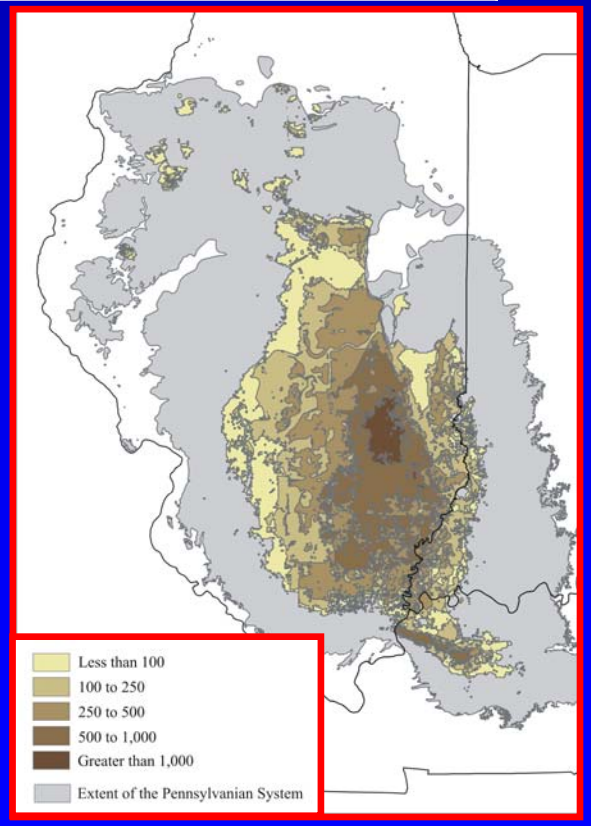
- Combine GIS layers of coal properties using C-SCV equation for each coal seam
- Sum C-SCV for all coal seams
- Contour map of C - SCV for Basin
- Similar approach for ECBM



Coal

Zone	CSCV Btonne	ECBM Tscf
Springfield	*0.72*	*1.3*
Colchester	*0.67*	*1.3*
Seelyville/Davis	*0.60*	*1.2*
Survant	*0.58*	*1.1*
Total	*3.6 (1.6-4.6)*	*6.7 (3.0-11)*





Oil Reservoirs and Coal Seams: CO_2 Storage, EOR, and ECBM

Scott M. Frailey

Illinois State Geological Survey

DOE NETL Review
October 12, 2005

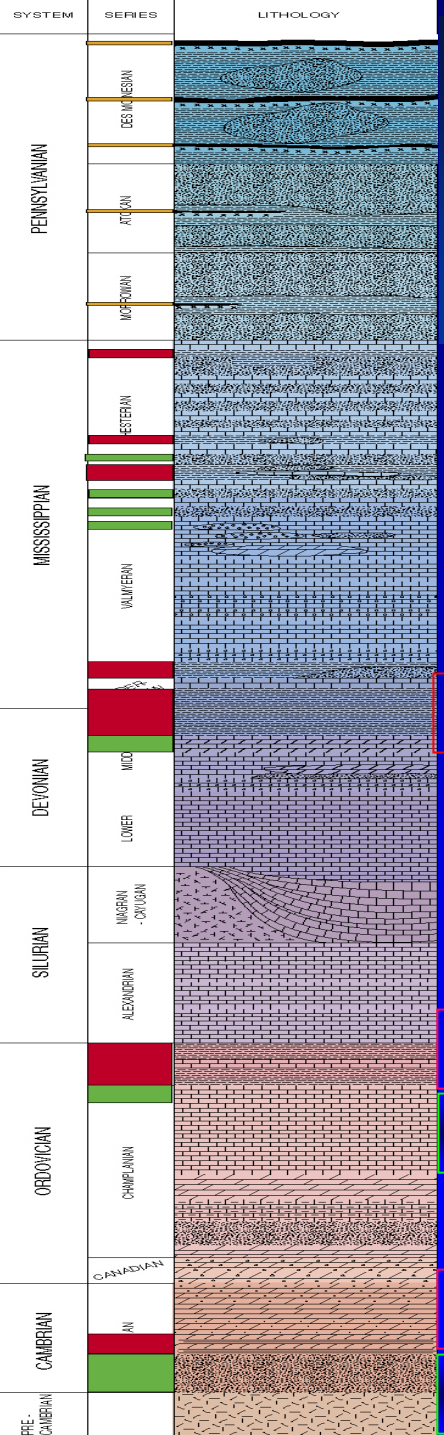
The Deep Geological Option: Saline Reservoirs

Hannes Leetaru (ISGS)
David Morse (ISGS)
Scott Frailey (ISGS)
James Drahovzal (KGS)
John McBride (BYU)
Don Keefer (ISGS)
Chris Korose (ISGS)
Sarah Rittenhouse (ISGS)
Robert Bauer (ISGS)
Edward Mehnert (ISGS)
Dennis Kolata (ISGS)
Steve Fisher (KGS)

Midwest Geological Sequestration Consortium

Pittsburgh, PA
October, 2005

Illinois Basin Stratigraphic Column Showing Seals and Sinks



New Albany (Seal)

Maquoketa (Seal)

St. Peter Sandstone (Sink)

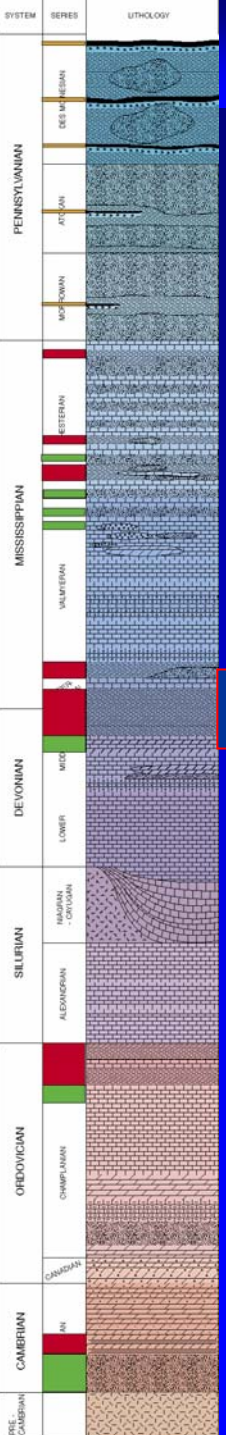
Eau Claire (Seal)

Mt. Simon (Sink)

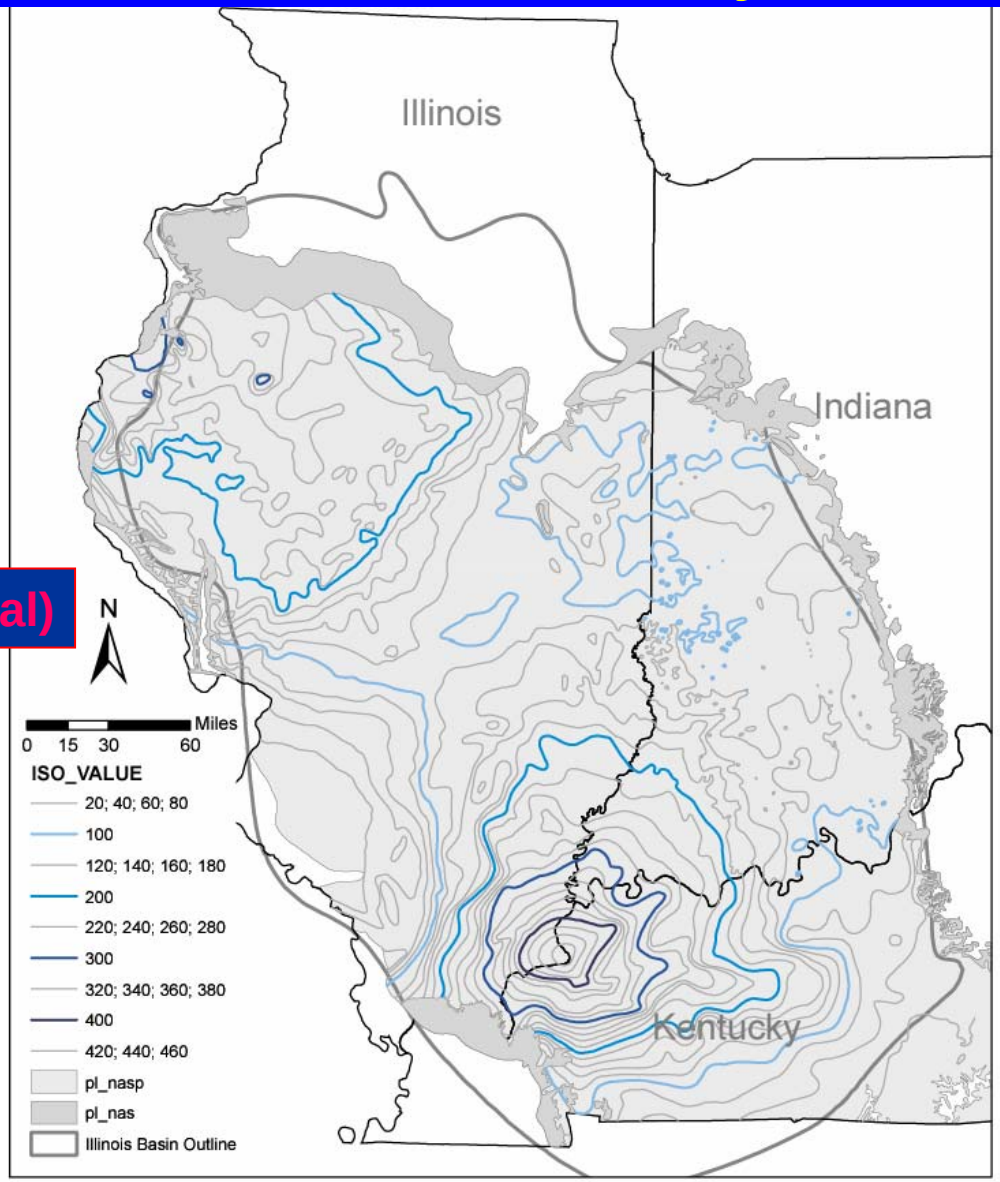
Mt. Simon is overlain by 3 thick impermeable shales and numerous thinner shale-rich strata

- Potential Seal
- Potential Sink
- Coal Bed Potential Sink and Seal

Thickness: New Albany Shale

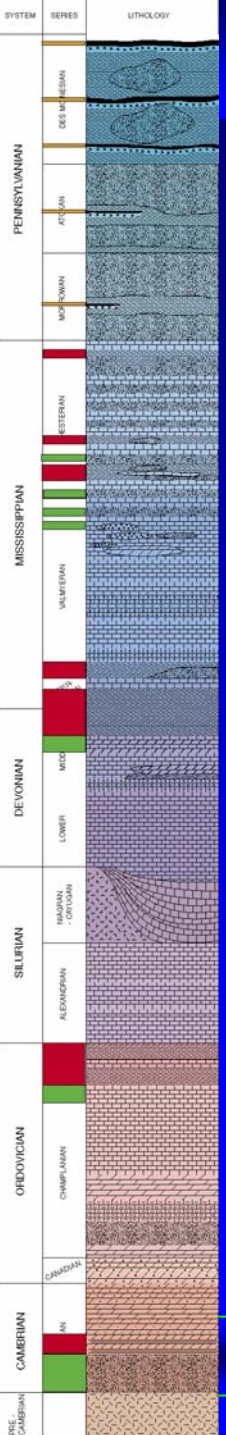


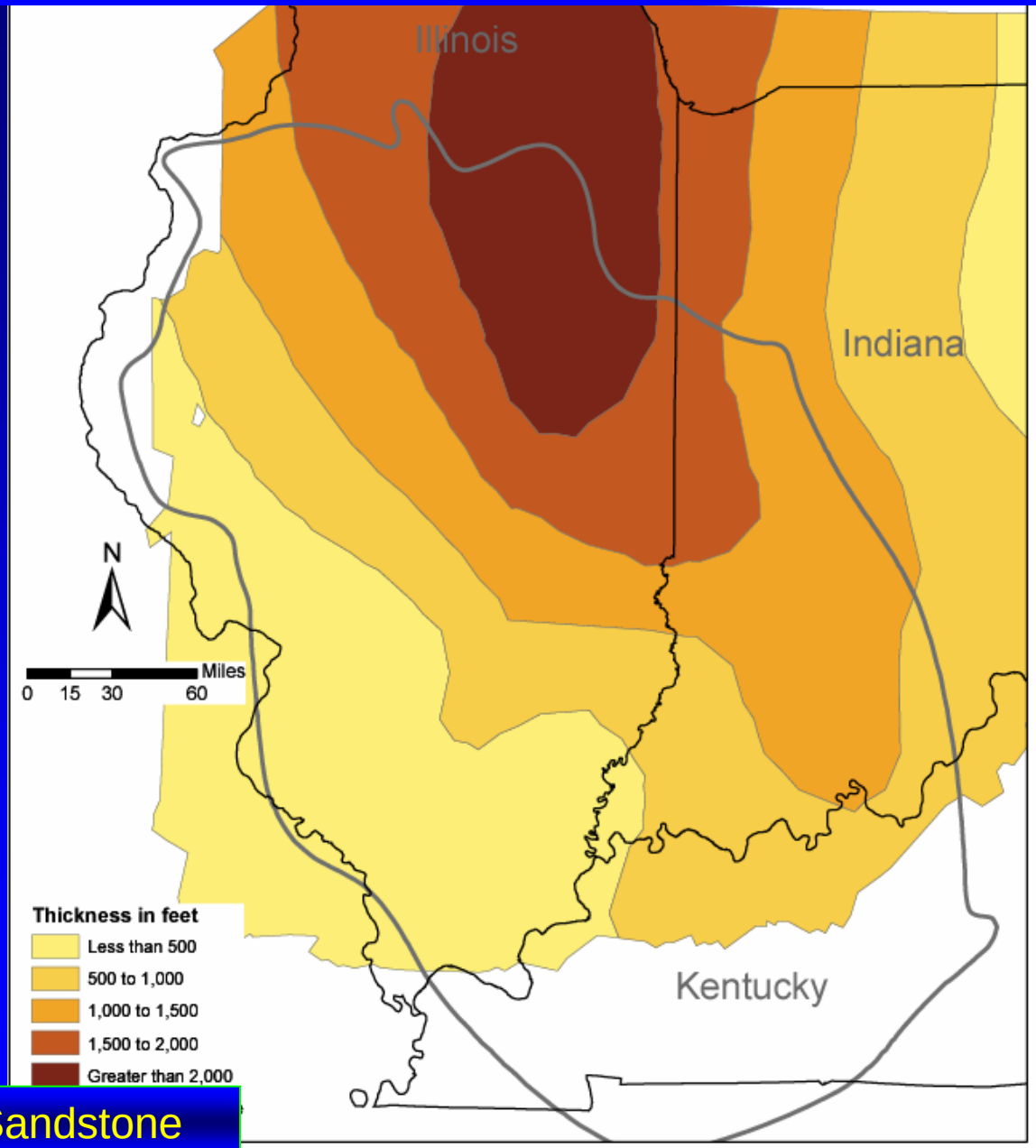
New Albany (Seal)



Isopach Thickness of the New Albany Shale (from GRI, IBC 6/2000)

Thickness of Mt. Simon Sandstone





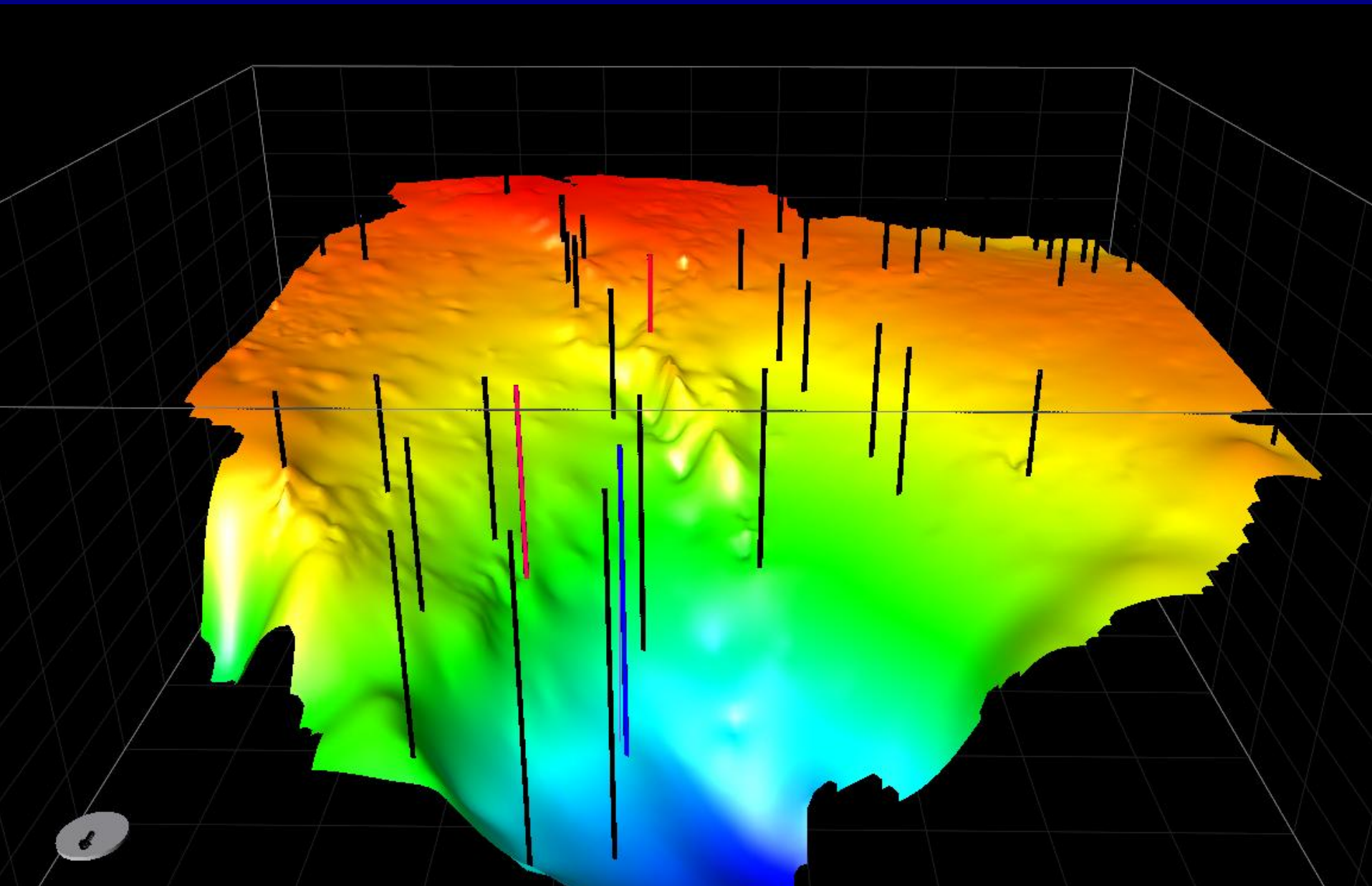
Mt. Simon Sandstone

Isopach Thickness of the Mt. Simon Sandstone, Regional

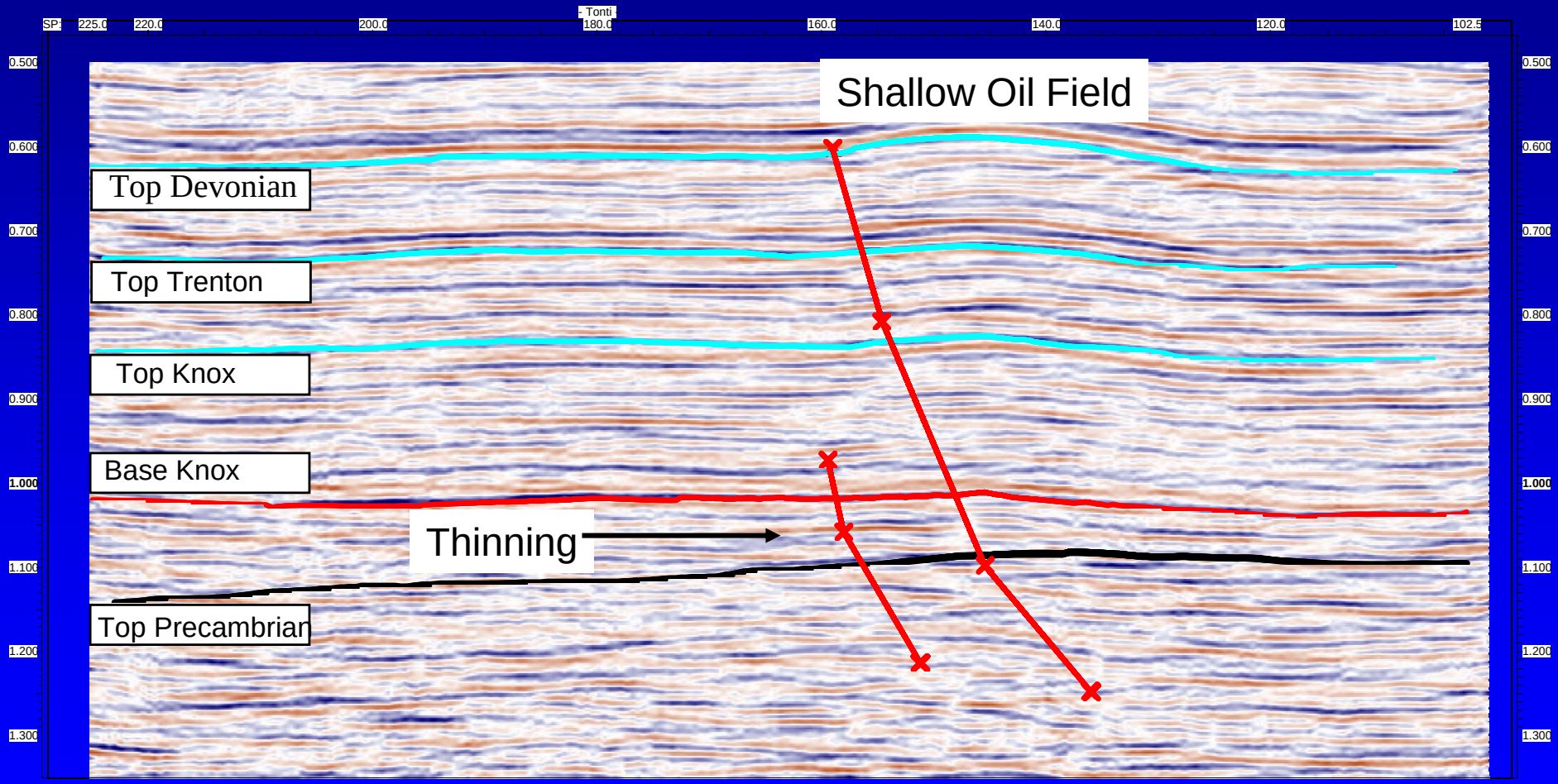
Geologic Uncertainty

- Lack of Well Control
  - Presence of Reservoir Sandstone
  - Reservoir Quality
  - Solubility of CO_2

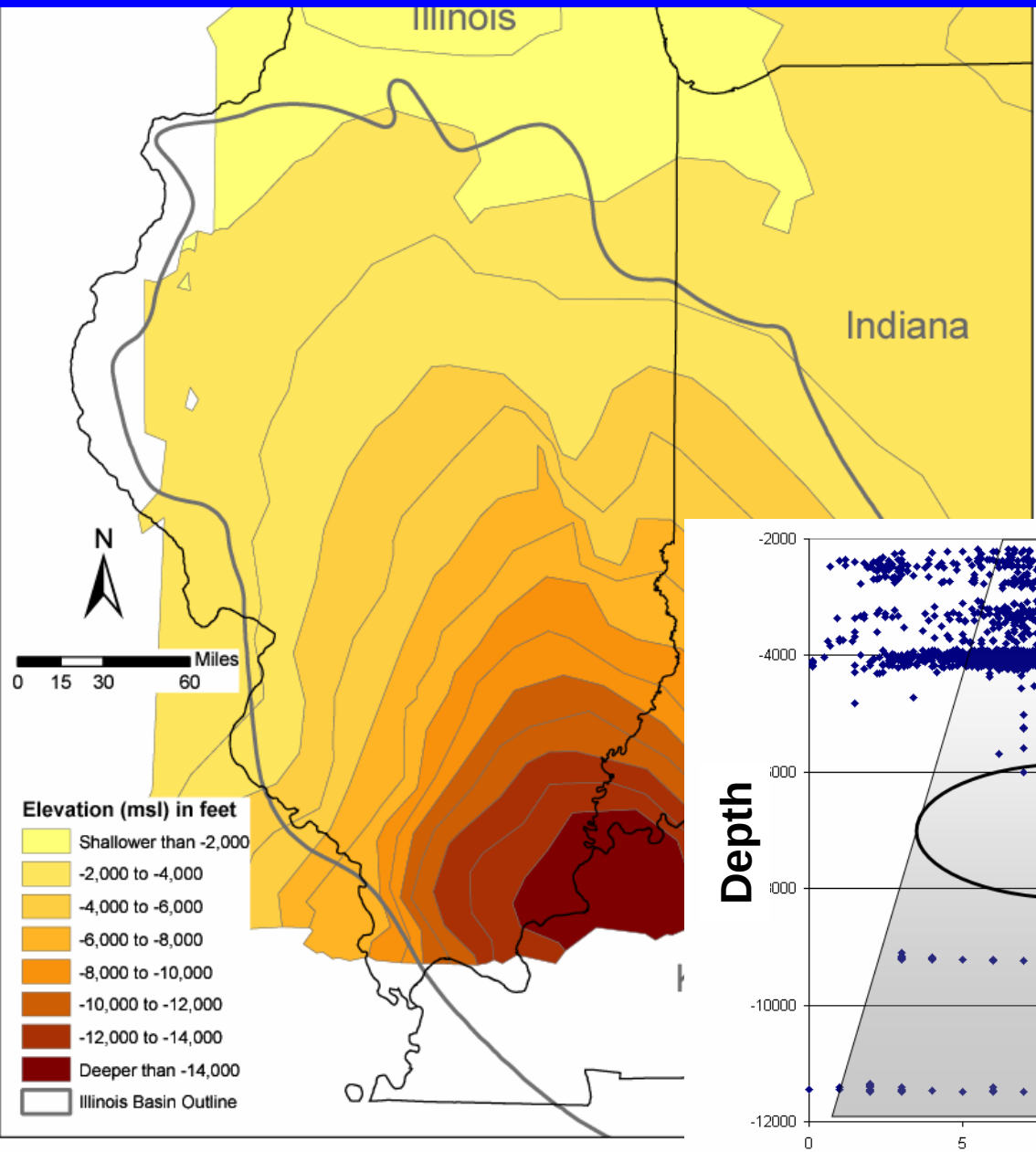
Model of Mt. Simon Structure



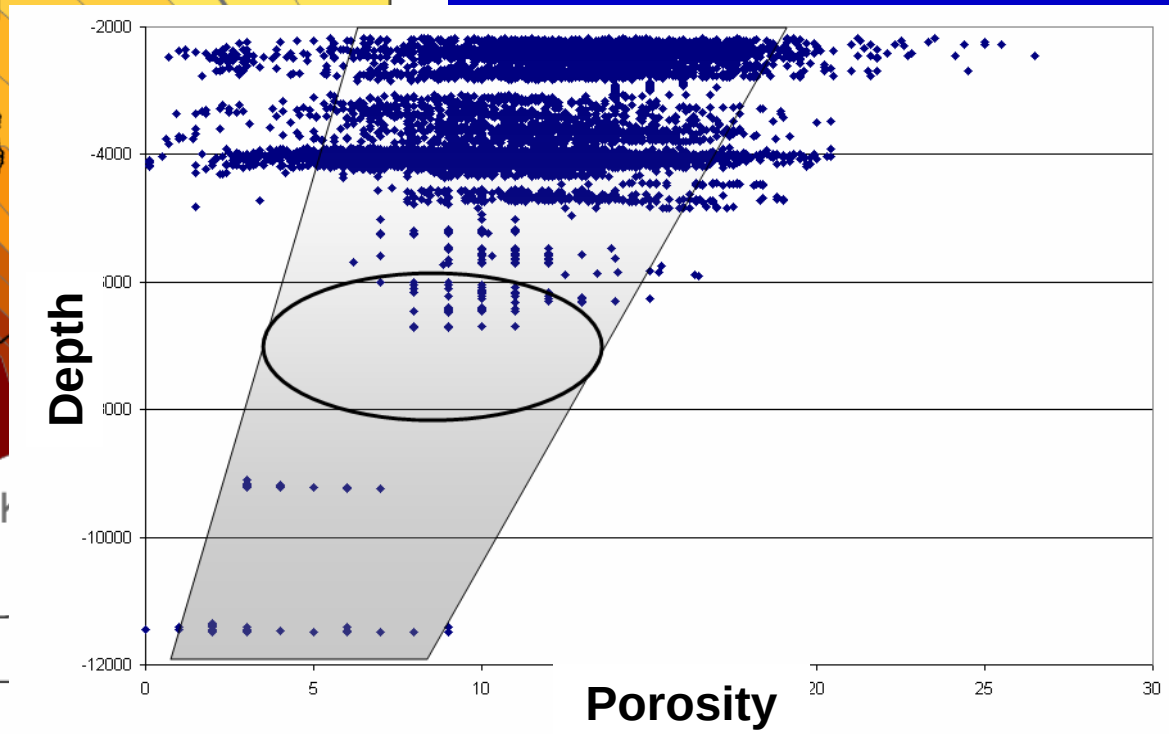
Reflection Seismic
Thin Areas May Lack Mt. Simon



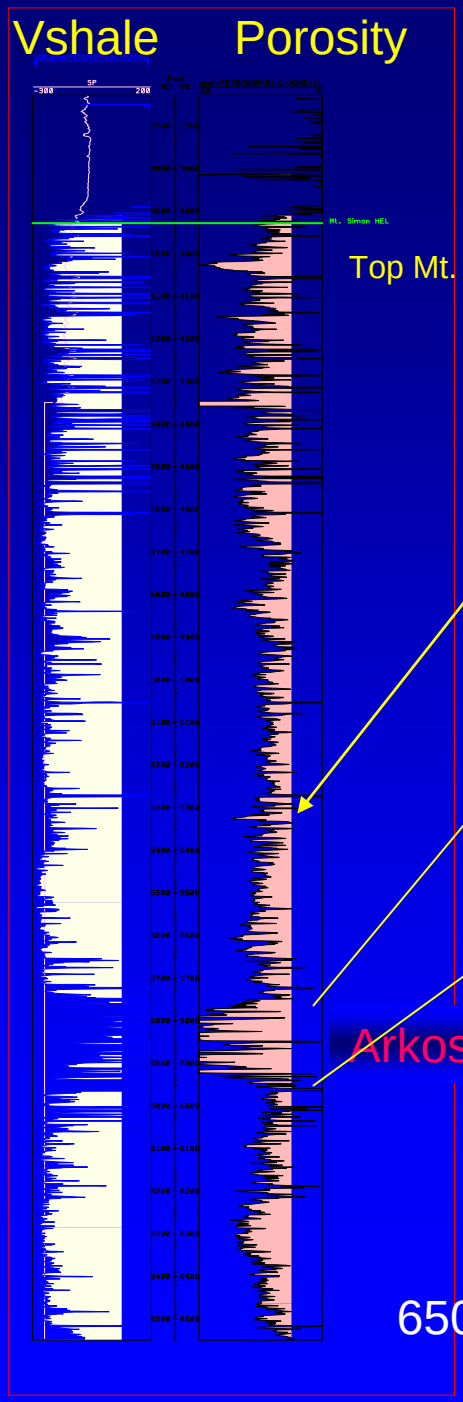
Structure: Top of Mt. Simon

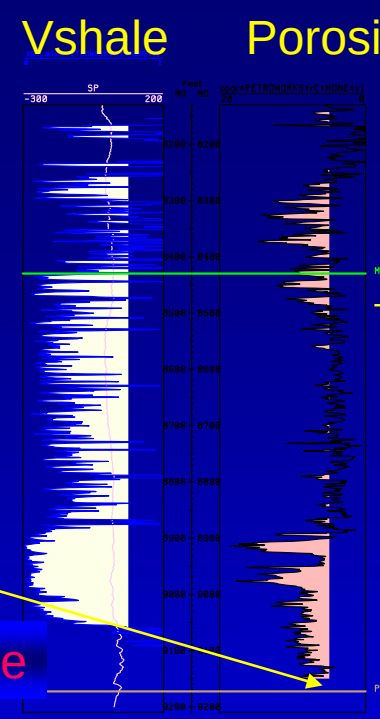


Mt. Simon ranges from -400 to a projected -16,000 feet below sea level



Elevation of the Mt. Simon Sandstone, Regional





5% cut off for porosity

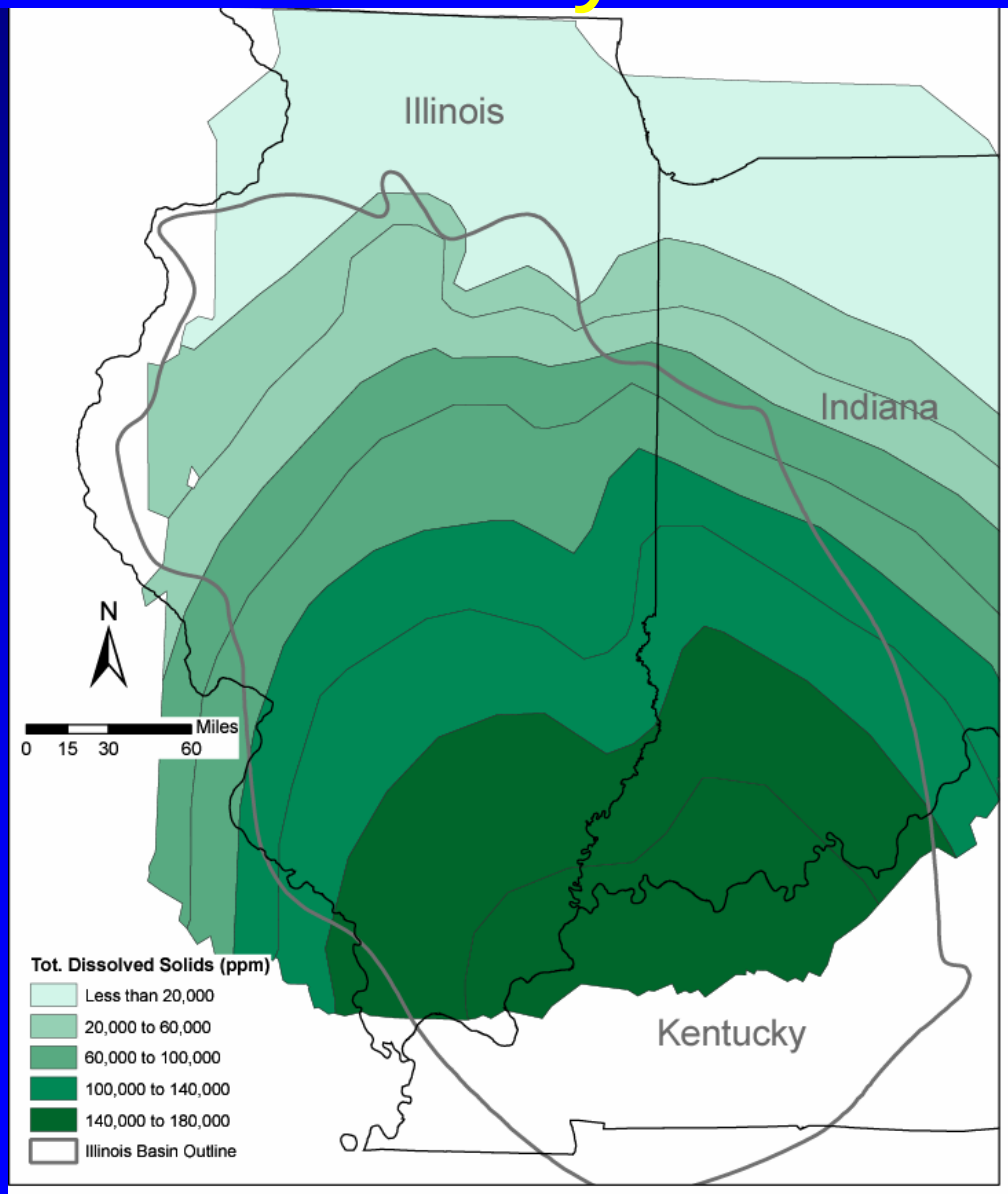
Arkose

20% Porosity
500 mD Permeability

Arkose

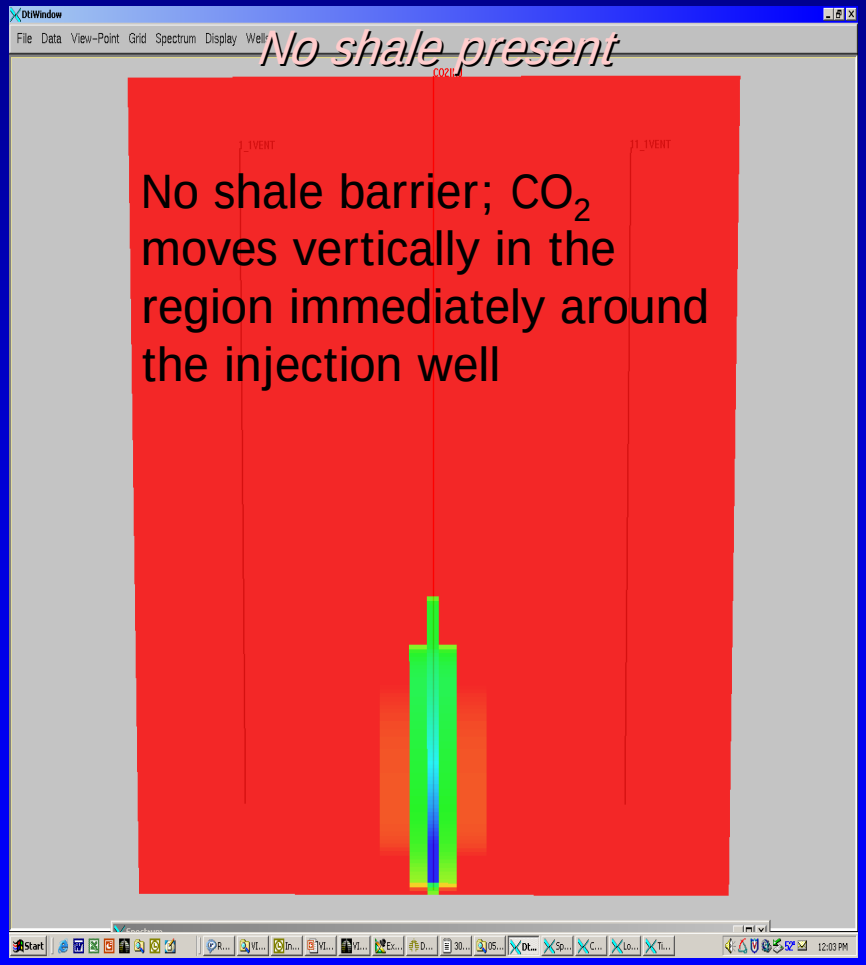
Distribution of Porosity in the Mt. Simon

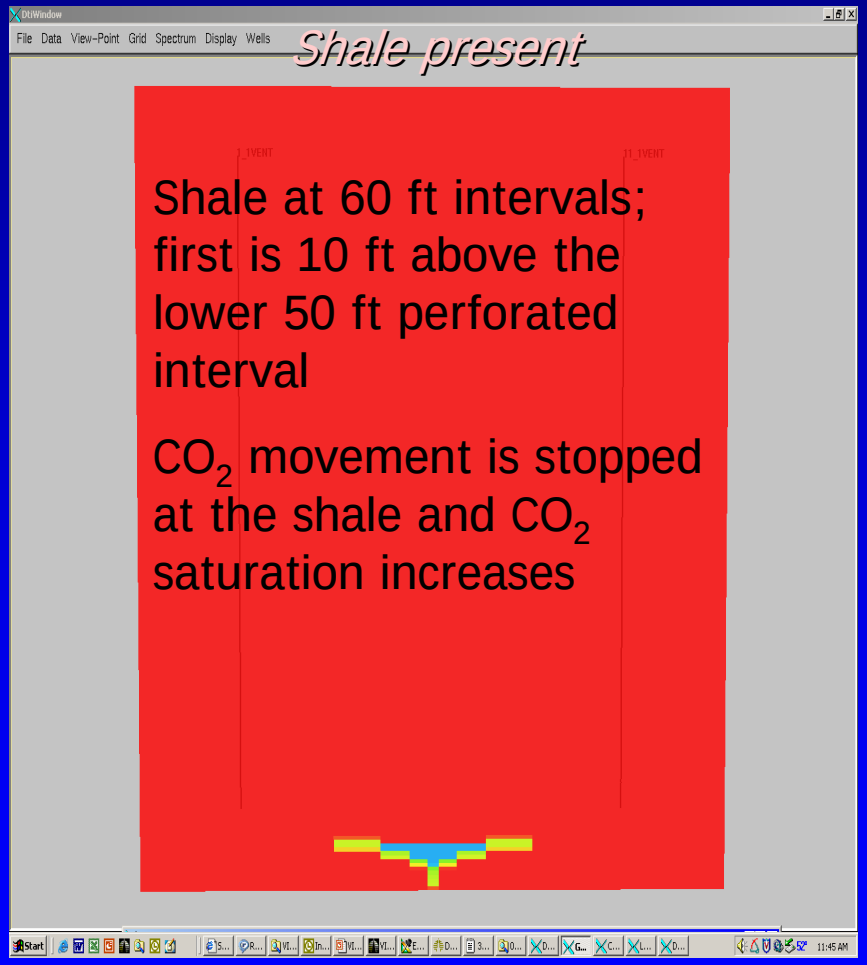
Salinity of Mt. Simon
Why Do We Care?



- Fresh Water Aquifers
- Solubility of CO_2 Decreases with Salinity

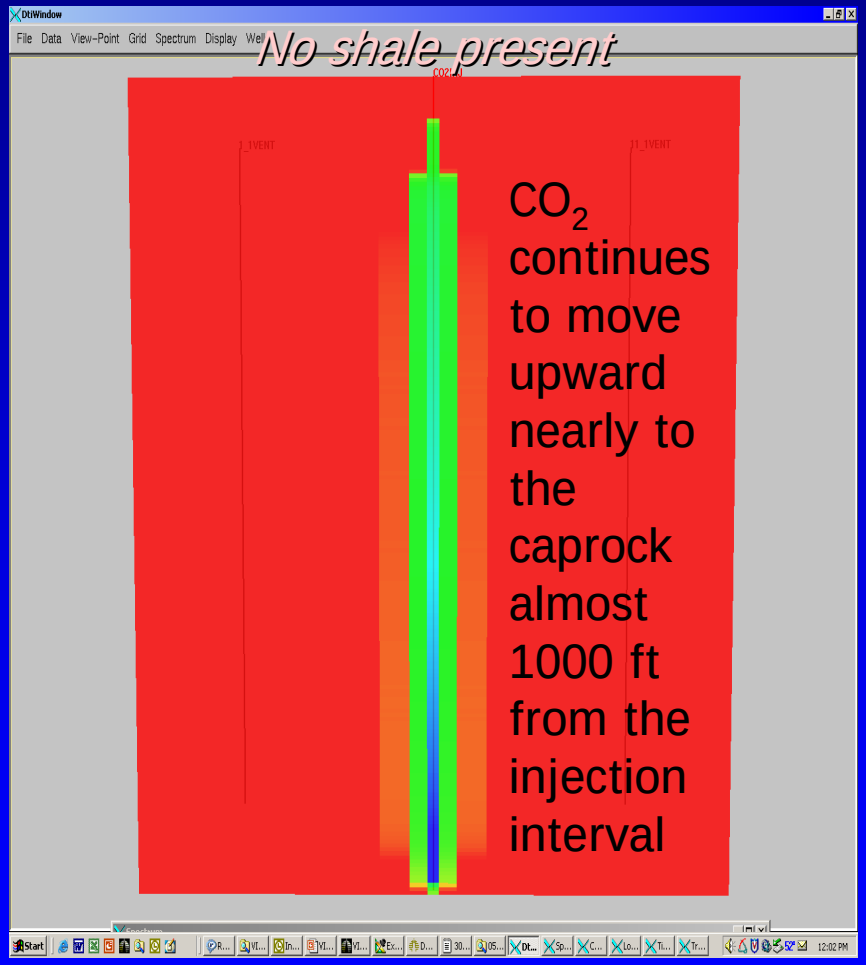
Impact of Vertical No-Flow Barriers

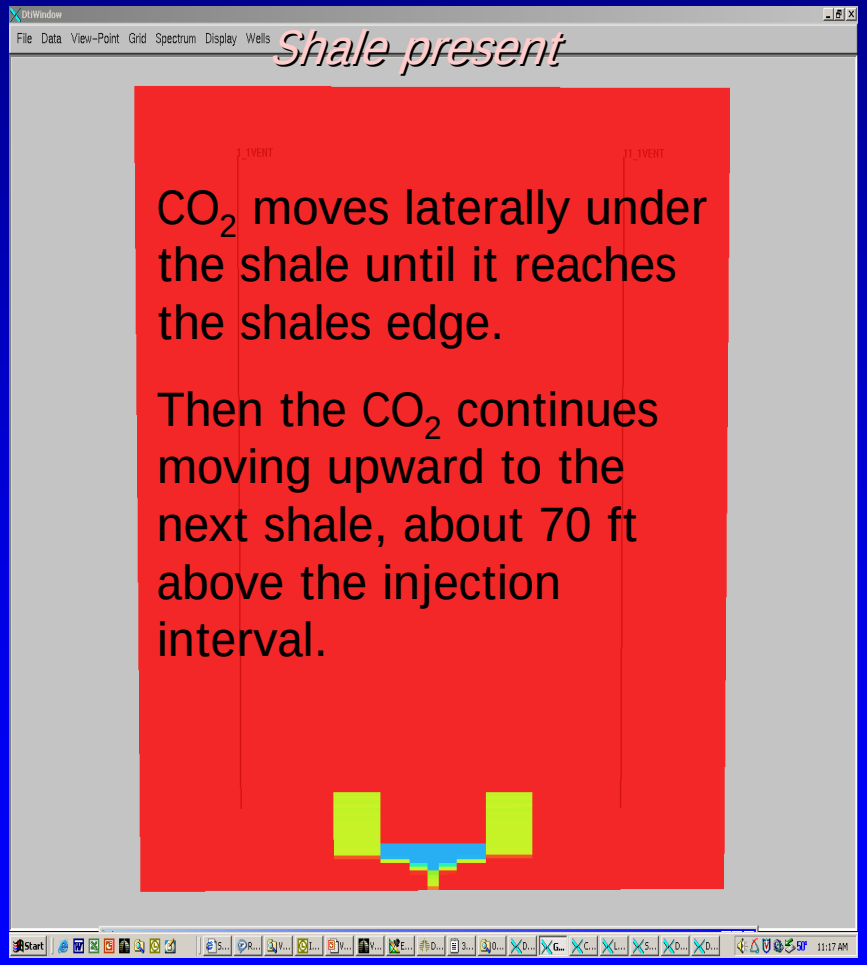




10 years injection

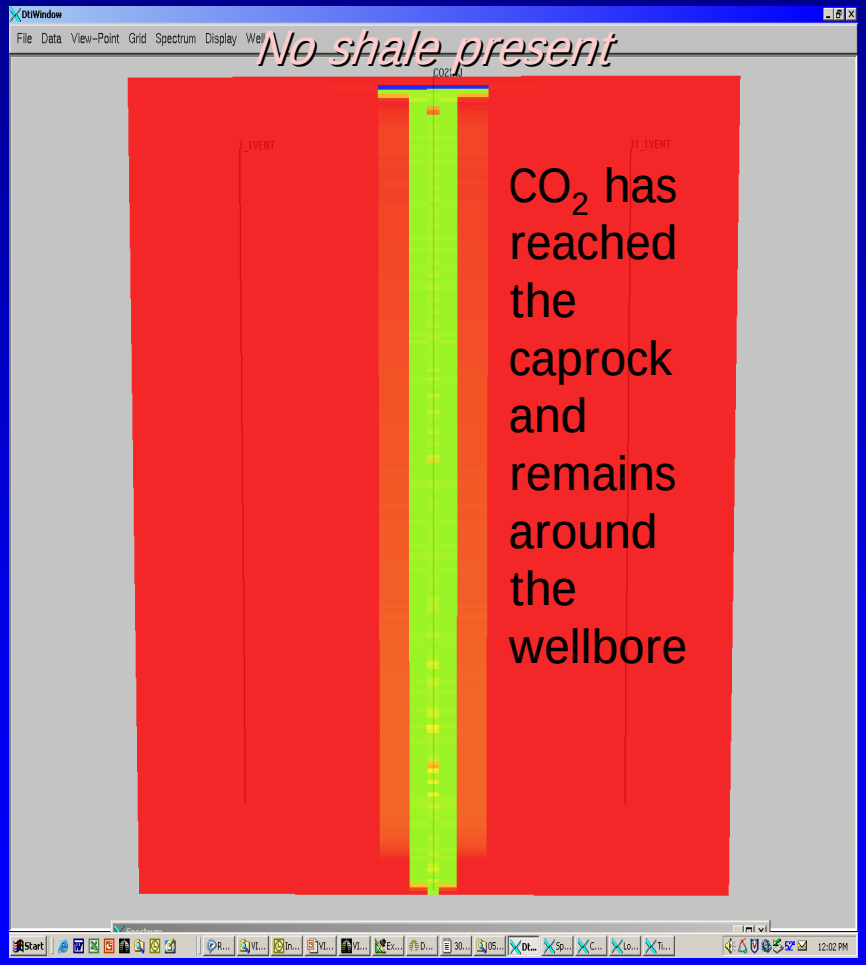
Impact of Vertical No-Flow Barriers

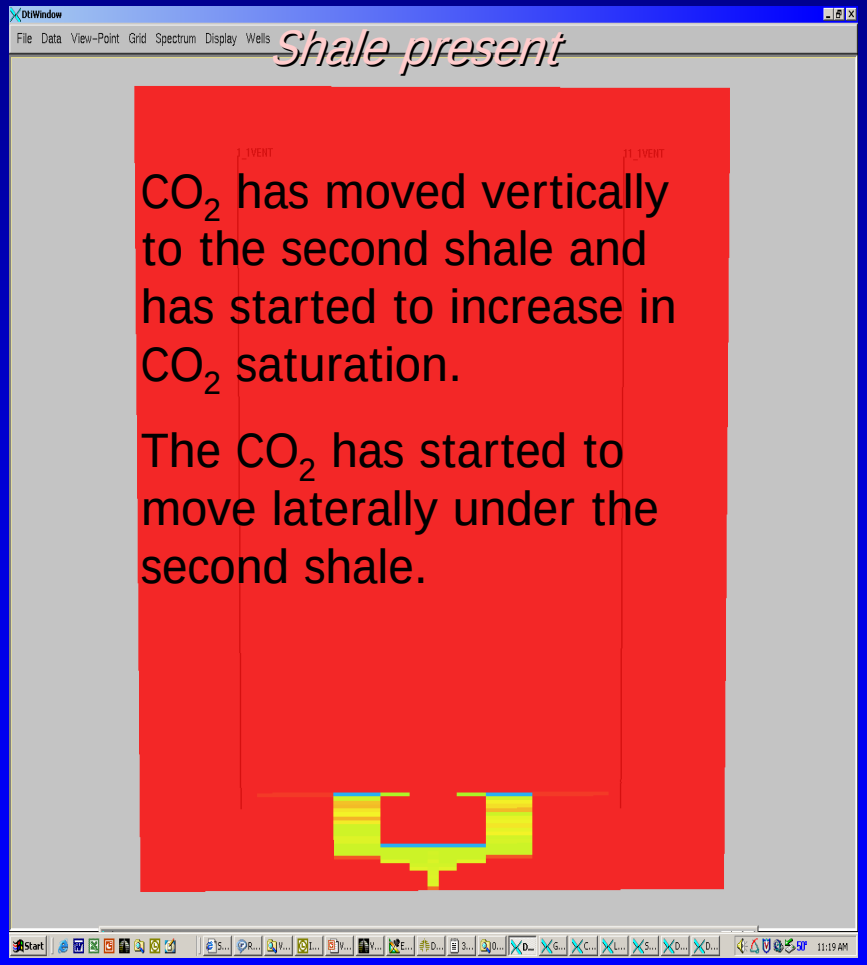




After 30 years injection

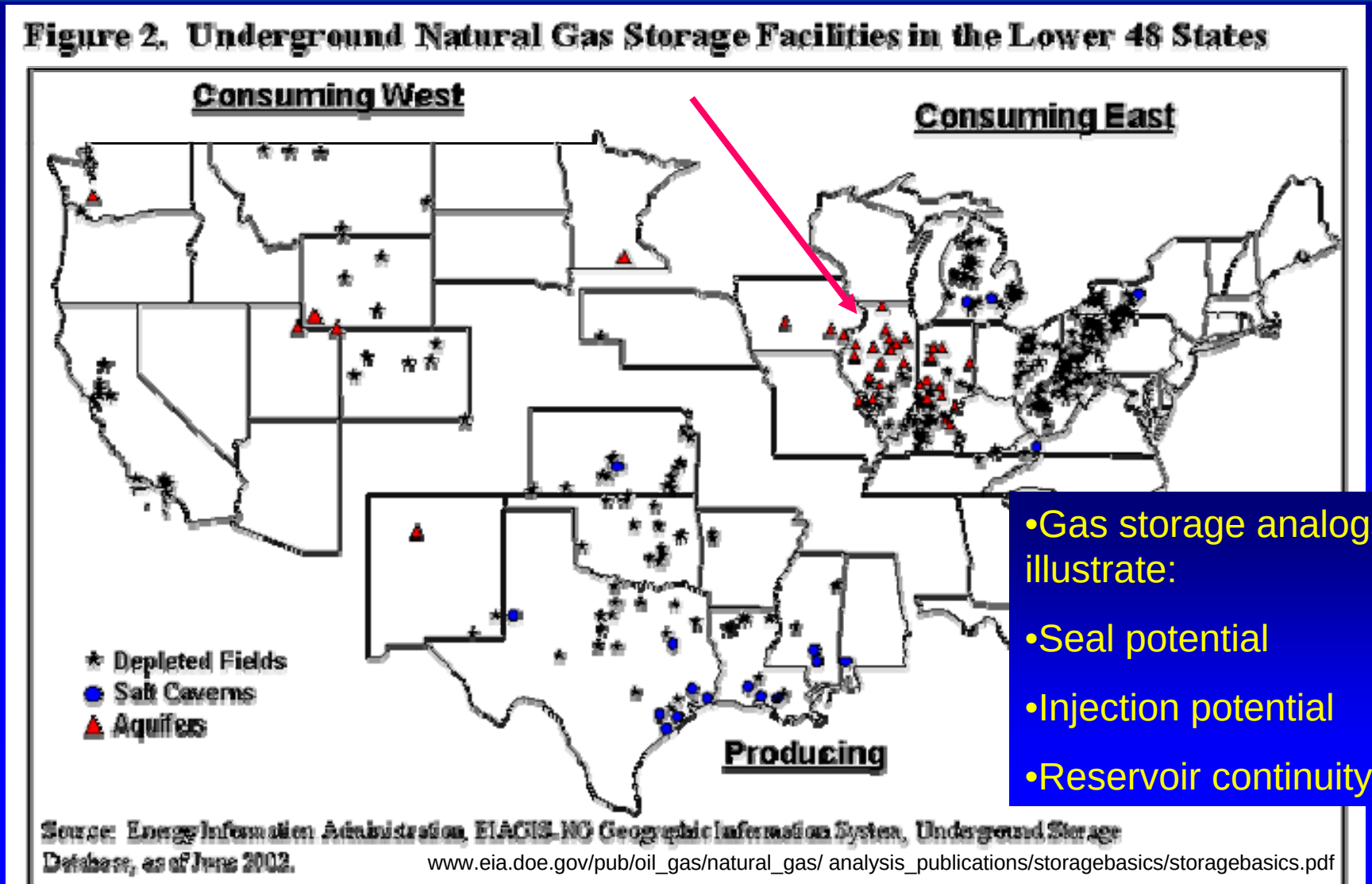
Impact of Vertical No-Flow Barriers





100 yrs shut-in following 30 years injection

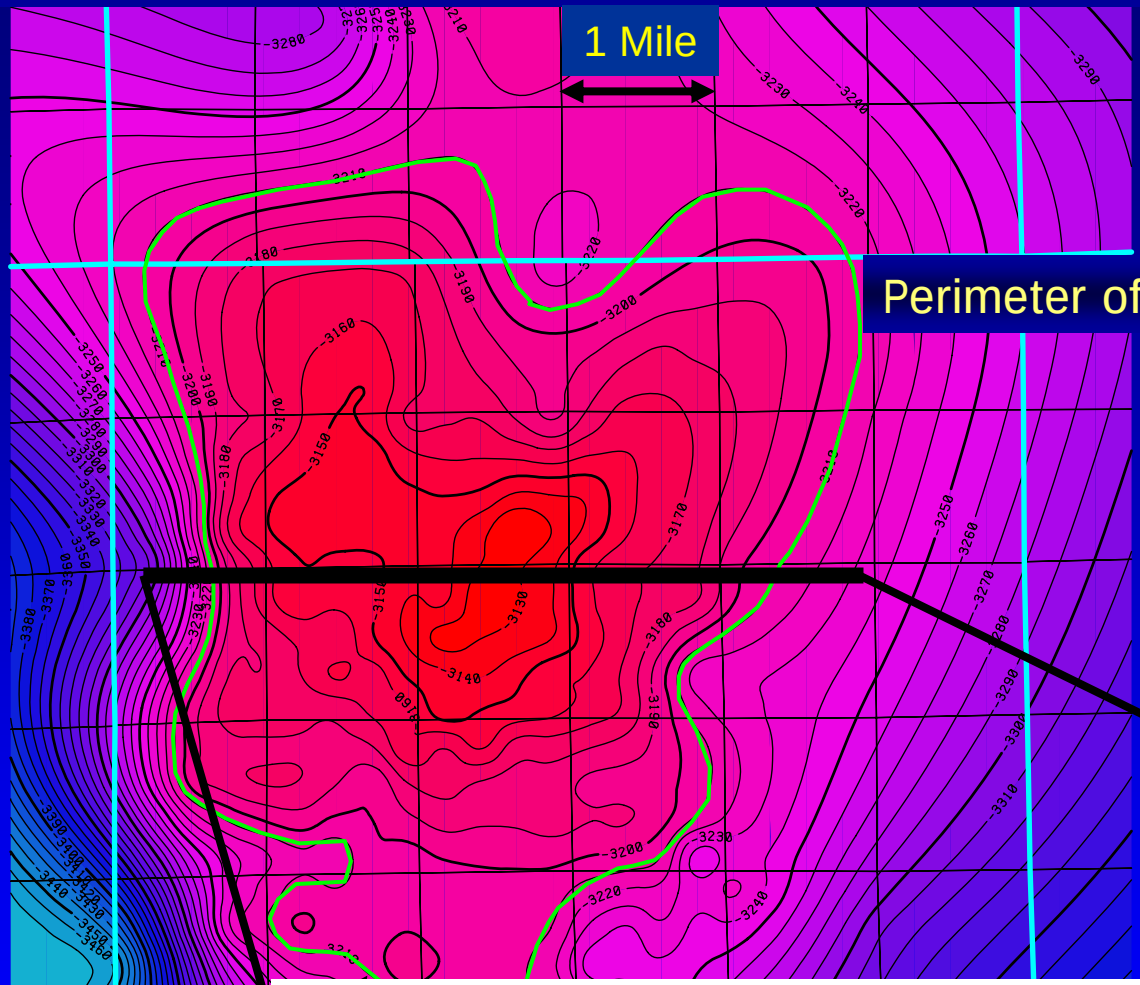
Illinois Basin has the Largest Concentration of Saline (Gas Storage) Reservoirs in the US



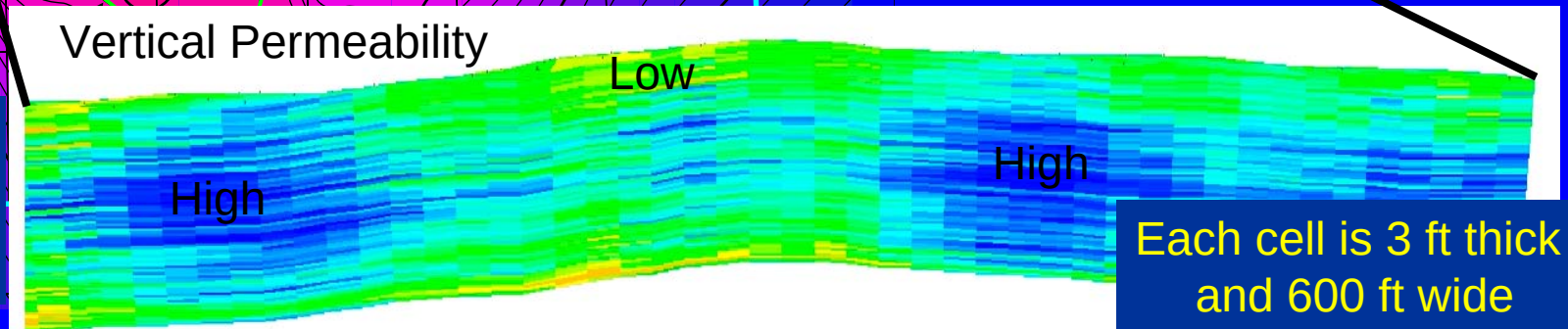
www.eia.doe.gov/pub/oil_gas/natural_gas/ analysis_publications/storagebasics/storagebasics.pdf

- Gas storage analogs illustrate:
- Seal potential
- Injection potential
- Reservoir continuity

Manlove Gas Storage Project

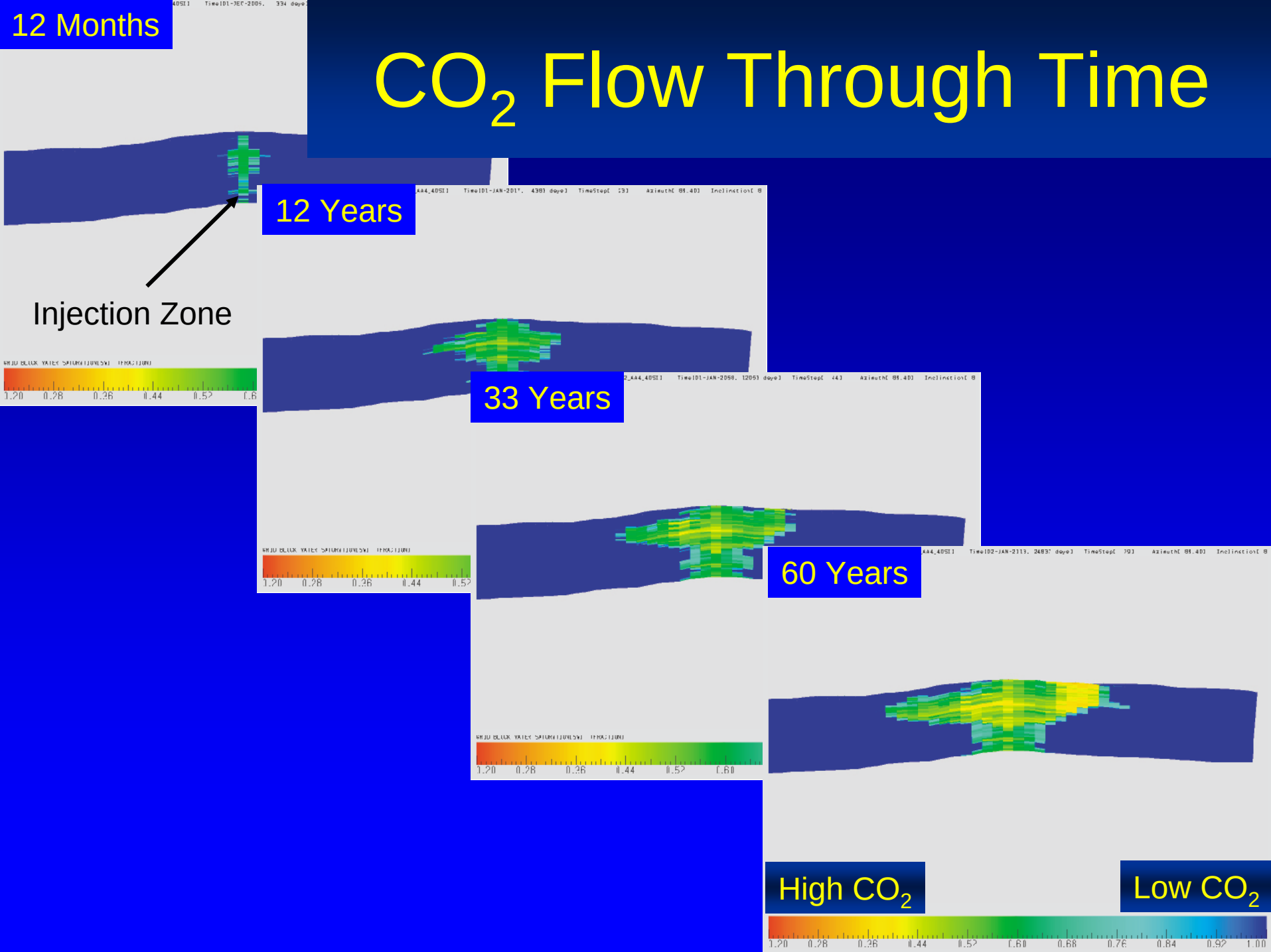


The Manlove Project has
90 feet of closure,
is 5 miles long and 4 miles wide

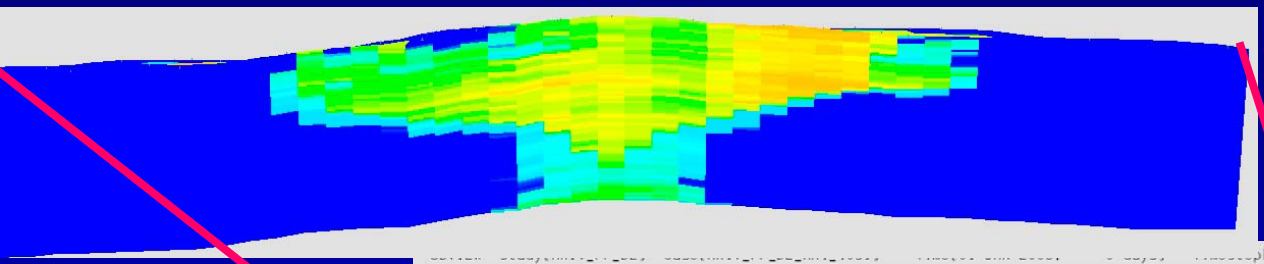


Each cell is 3 ft thick
and 600 ft wide

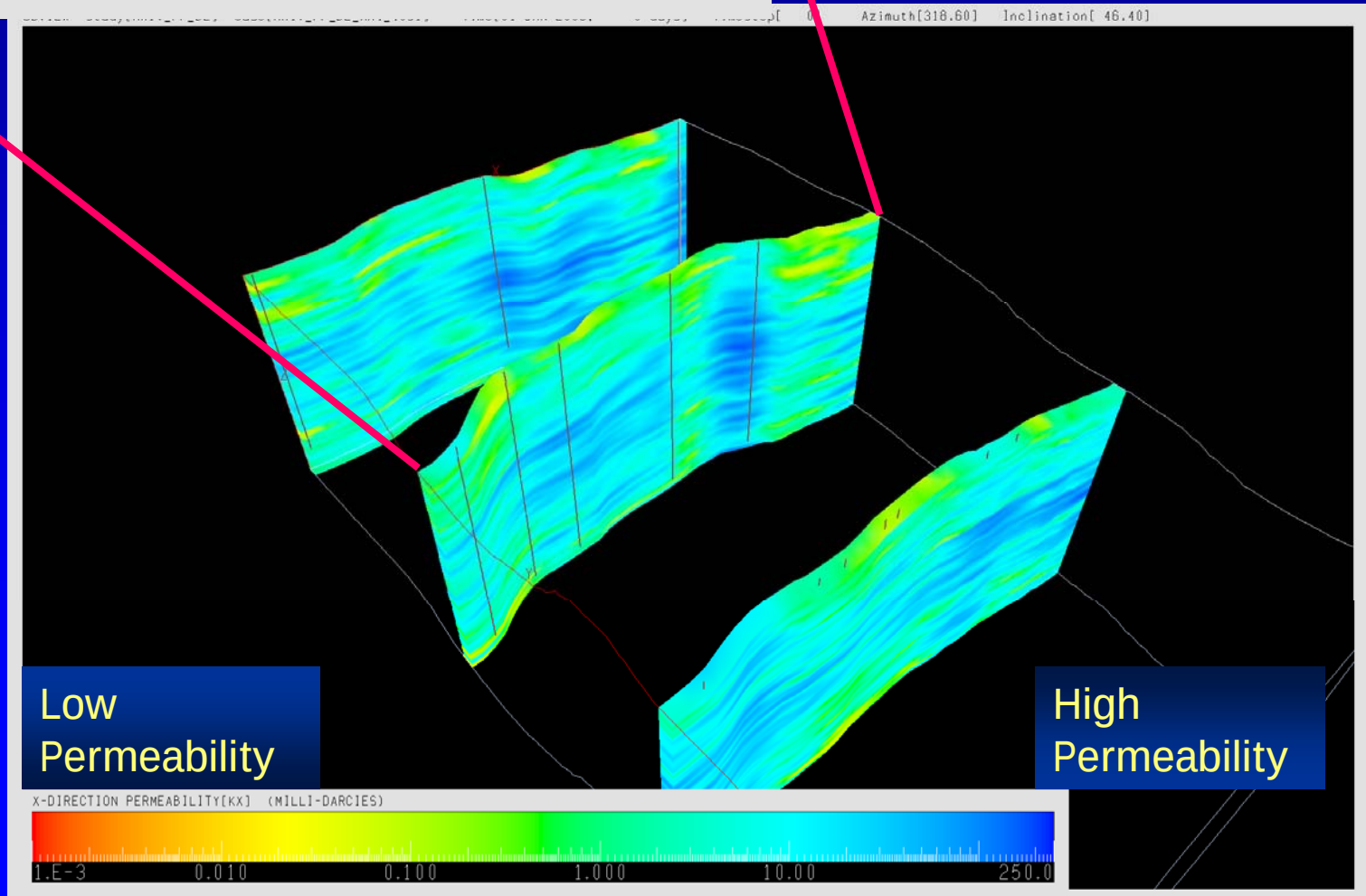
CO_2 Flow Through Time



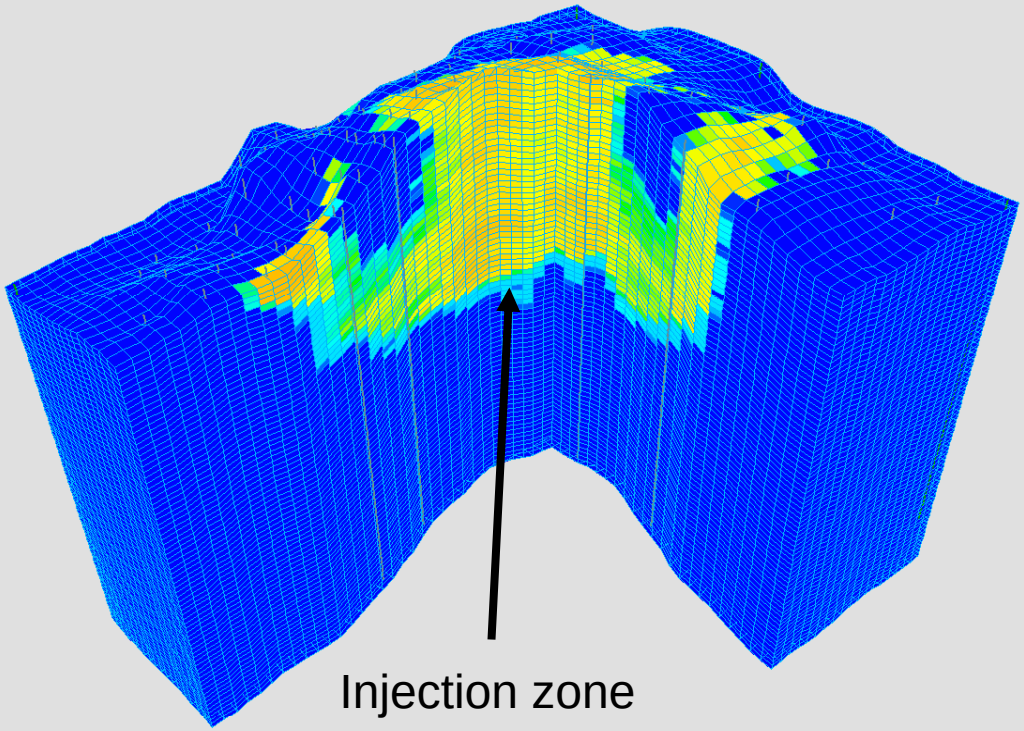
Mt. Simon After 120 years



80 years of injection
40 years shut-in

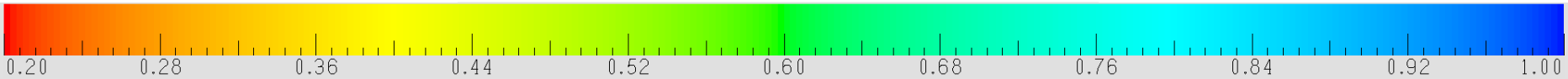


Mt. Simon After 120 years



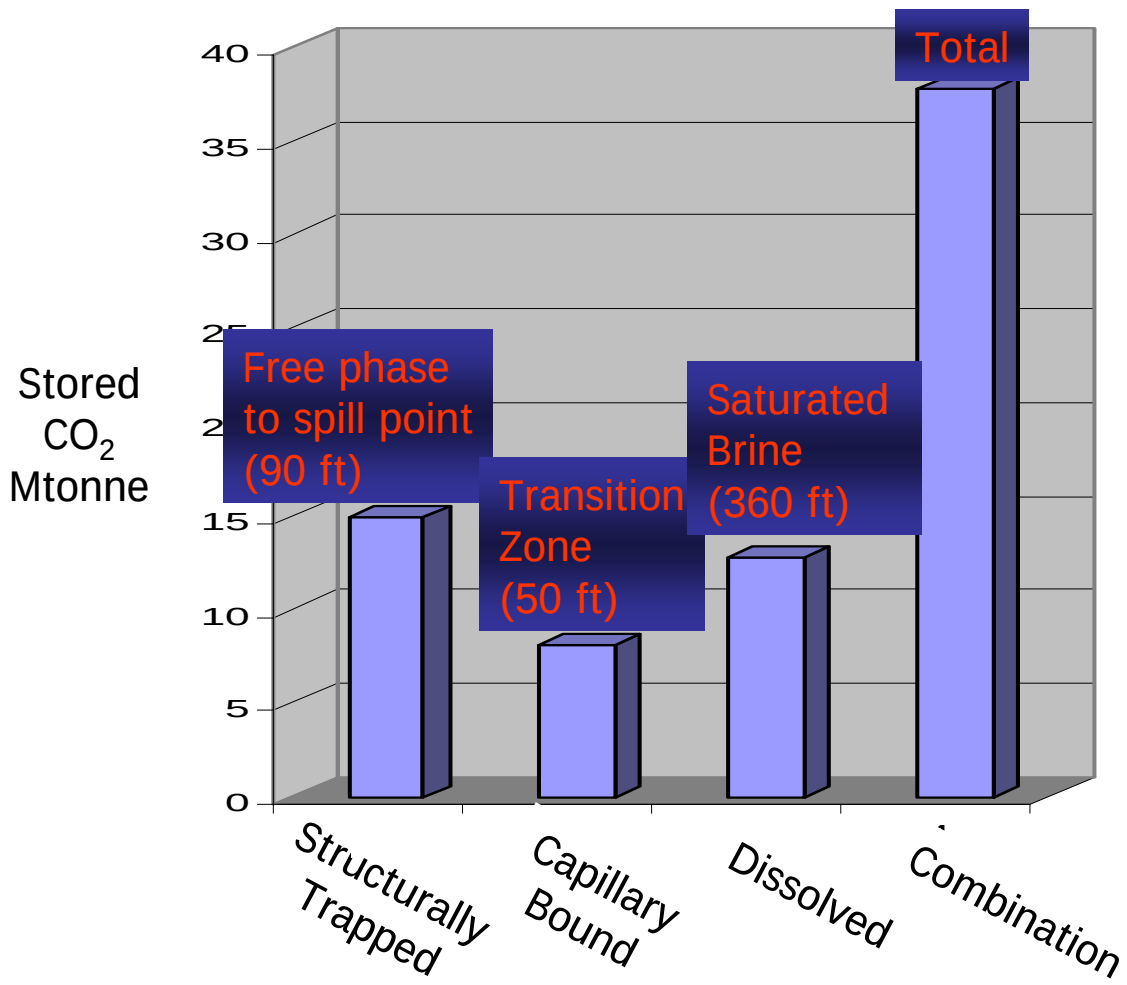
High CO_2 Concentration

Low CO_2 Concentration



How Much CO_2 Can Be Sequestered in Saline Reservoirs?

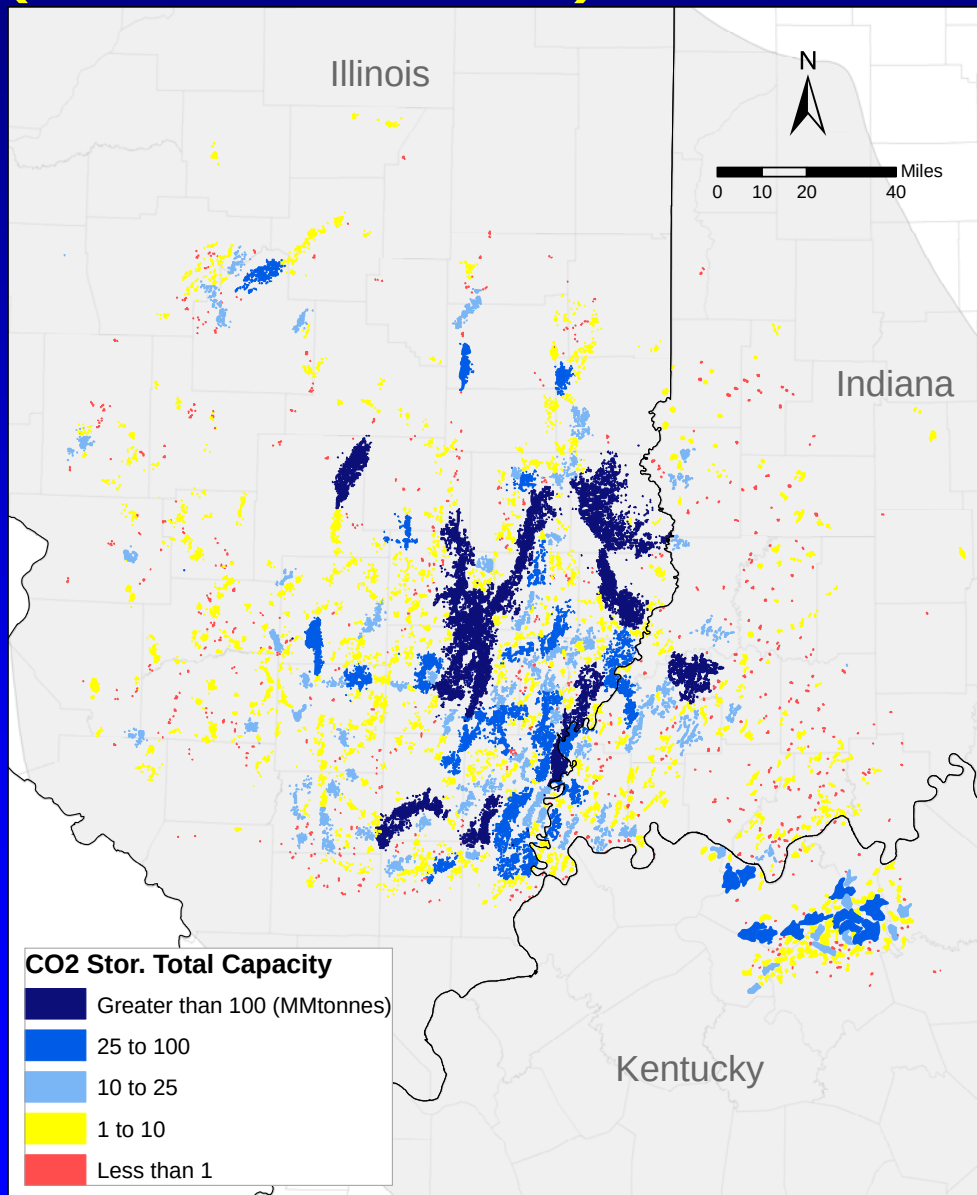
Underground Gas Storage Analog



A Manlove analog should hold up to 36 Mtonnes of CO_2

CO_2 Storage: Saline Water Bearing Formations (Structure Only)

- Mt. Simon: 5.9 Btonne
  - Mobile, free phase
    2,800 Mtonne
  - Immobile, free phase
    1,200 Mtonne
  - Dissolved phase
    1,900 Mtonne
- St. Peter: 1.9 Btonne
  - Mobile, free phase
- Dissolution (no structure) deeper than 4000 ft
  - 30-35 Btonne
- MIDCARB (no depth cutoff)
  - 65-80 Btonne



Midwest Geological
Sequestration Consortium
www.sequestration.org