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# Project Results from Simulation Framework for Regional Geologic $CO_2$ Storage Infrastructure along Arches Province of Midwest United States

**DOE Award No. DE-FE0001034**
**Ohio Dept. of Dev. Grant CDO/D-10-03**

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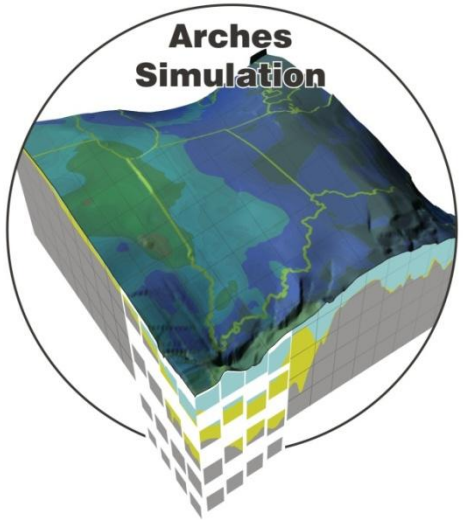

# Presentation Outline

1. Technical Status
2. Background ($CO_2$ Sources, Geologic Setting)
3. Injection Well history
4. Geocellular Model Development
5. Geological Data (Geological dataset, Geostatistics)
6. Geocellular porosity/permeability model development
7. Pipeline Routing Analysis
8. Scoping Level Simulations
9. Basin Scale Model Simulations
10. Other Simulations (Eau Claire Caprock Sims, Geomechanical Sims, Validation, Monitoring Analysis)
11. Summary Findings

# Arches Province Simulation Project

- *Simulation Framework for Regional Geologic $CO_2$ Storage Infrastructure along Arches Province of Midwestern United States* project selected by DOE/NETL under FOA23 program on carbon storage monitoring, risk, and simulation (NETL PM = Andrea Dunn).
- Three year project through October 2009 - September 2012.
- Project team includes Battelle, Indiana Geological Survey, Kentucky Geological Survey, Ohio Geological Survey, and Western Michigan University/Michigan Geological Survey. Cost share provided by Ohio Department of Development Grant Agreement CDO/D-10-03.

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# Benefit to the CCUS Program

- Carbon Storage Program goals being addressed.
  - Support industries' ability to predict $CO_2$ storage capacity in the Mount Simon Sandstone in the Arches Province of the midwestern U.S.
  - Demonstrate storage security in Mount Simon in Arches Province.
- Project benefits statement.
  - The work is focused on simulating large-scale $CO_2$ storage along the Arches Province geologic structure in an area of the country with a dense concentration of large $CO_2$ sources.
  - Address technical and infrastructure questions related to simulation methods, monitoring, and risk assessment.
  - Simulate $CO_2$ transport, injection field arrangements, injection operational parameters, storage capacity, and storage security for the Arches Province.

# Project Overview: Goals and Objectives

- The objective of this project is to develop a simulation framework for the Arches Province of the Midwest United States through:

    1. Development of a geologic model and
    2. Advanced reservoir simulations of large-scale $CO_2$ storage along the province.

- Project results are intended to define the infrastructure necessary to implement large-scale $CO_2$ storage along the province.

# Statement of Work and Status

- Part of DOE/NETL program on Monitoring, Simulation, and Risk Assessment for $CO_2$ Storage (DOE Award DE-FE0001034).
- Period of Performance: 3 years from 10/1/2009 to 9/30/2012
- All technical tasks have been completed, final reporting in progress.

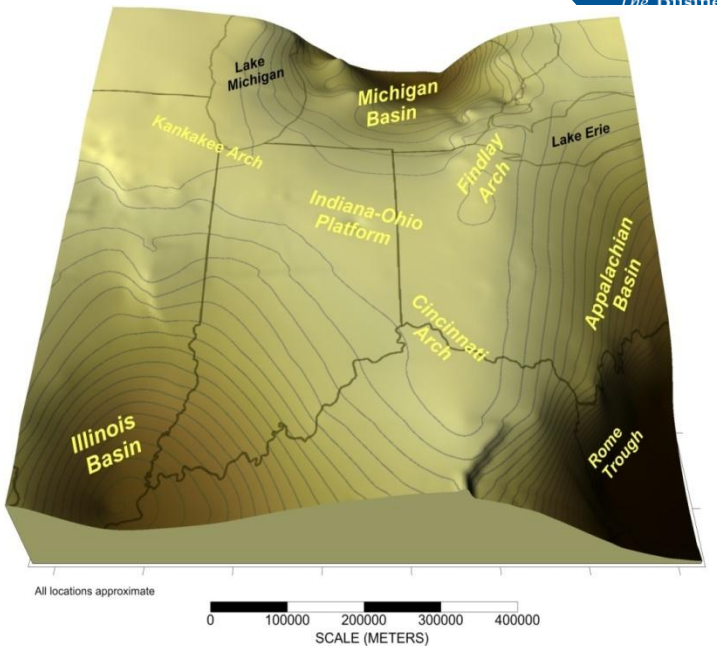
| Task | Percent Complete | Completion Date |
|---|---|---|
| 1.0 Project Management Planning & Reporting | LOE | 12/30/2012 |
| 2.0 Compilation of Geologic, Hydraulic, and data on Mt. Simon | 100 | 6/30/2010 |
| 3.0 Development of Model Framework and Parameters | 100 | 6/30/2011 |
| 4.0 Preliminary variable density flow model simulations | 100 | 9/23/2011 |
| 5.0 Multi-phase model runs of regional storage scenarios | 100 | 3/30/2012 |
| 6.0 Implications for Regional Storage Feasibility | 100 | 6/30/2012 |
| 7.0 Reporting and Tech. Transfer | 40 | 12/30/2012 |
| | | |

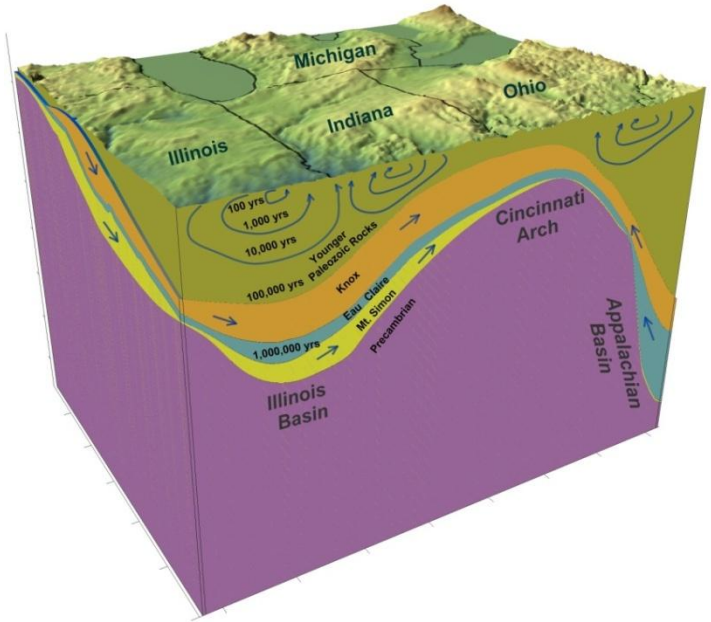
# Accomplishments to Date

- Compiled ~40 years of Class I injection data for project area.
- Revised Mount Simon southern boundary distribution in Kentucky.
- Evaluated Mount Simon hydrostratigraphic units across study area.
- Developed 50,000,000 node geocellular model of Arches Province for geologic structure, porosity, and permeability for Eau Claire-Mt. Simon.
- Completed source-sink pipeline routing study for Arches Province.
- Completed scoping level 2D STOMP and variable density simulations to determine parameters for numerical model.
- Upscaled geocellular model into basin-scale numerical multi-phase STOMP simulations: 4-layer model contains 295,728 nodes, and the 19-layer model contains 1.5 million nodes.
- Completed multi-phase, basin-scale numerical simulations in STOMP of regional injection fields with total injection of 70-140 MMT $CO_2$/yr.
- Completed regional scenarios on model validation to East Bend $CO_2$ injection, caprock simulations, geomechanical simulation, and monitoring analysis.

# Study Area

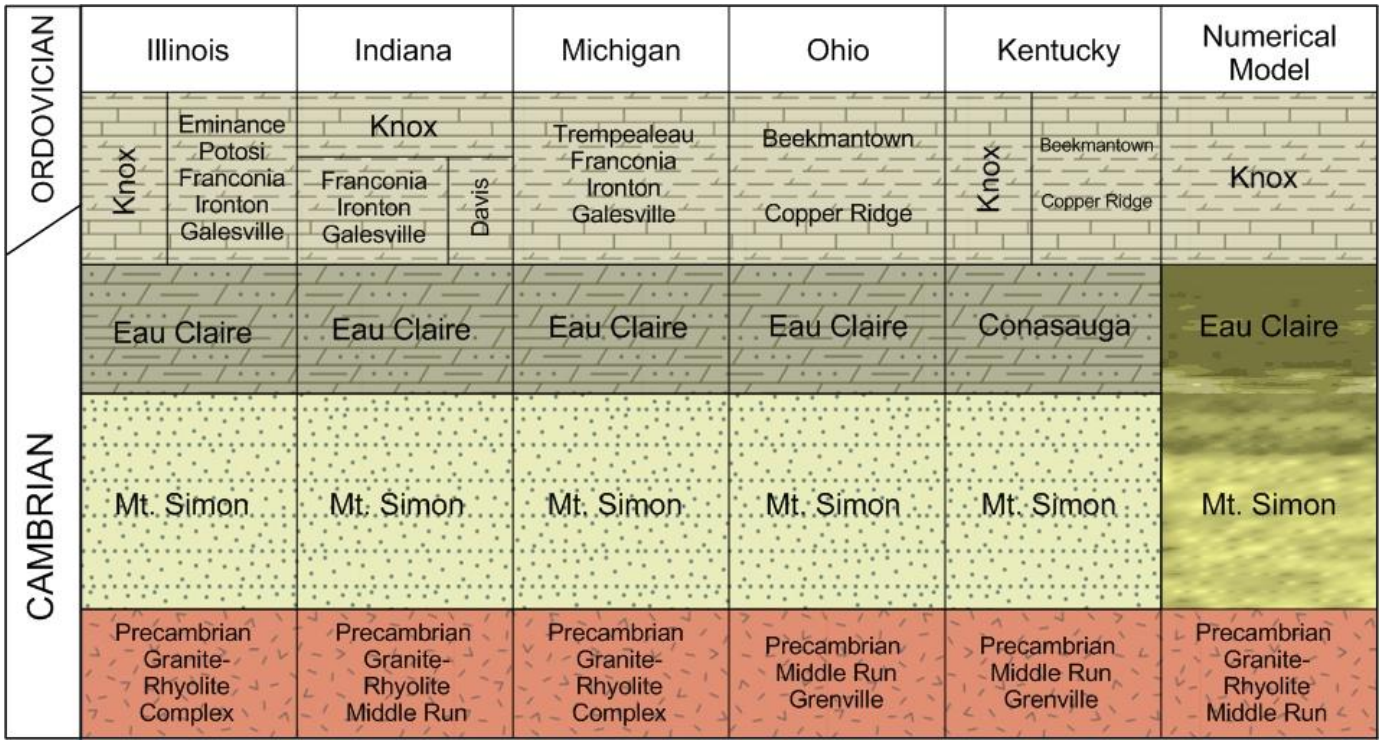
- Arches Province is an informal area present between the Appalachian, Illinois, and Michigan sedimentary Basins.
- The province includes portions of Indiana, Illinois, Kentucky, Michigan, and Ohio.
- Mount Simon Sandstone is the main storage formation in the province based on pressure and temperature conditions.
- There is a history of wastewater injection operations in Mount Simon in the region dating back to 1970s.



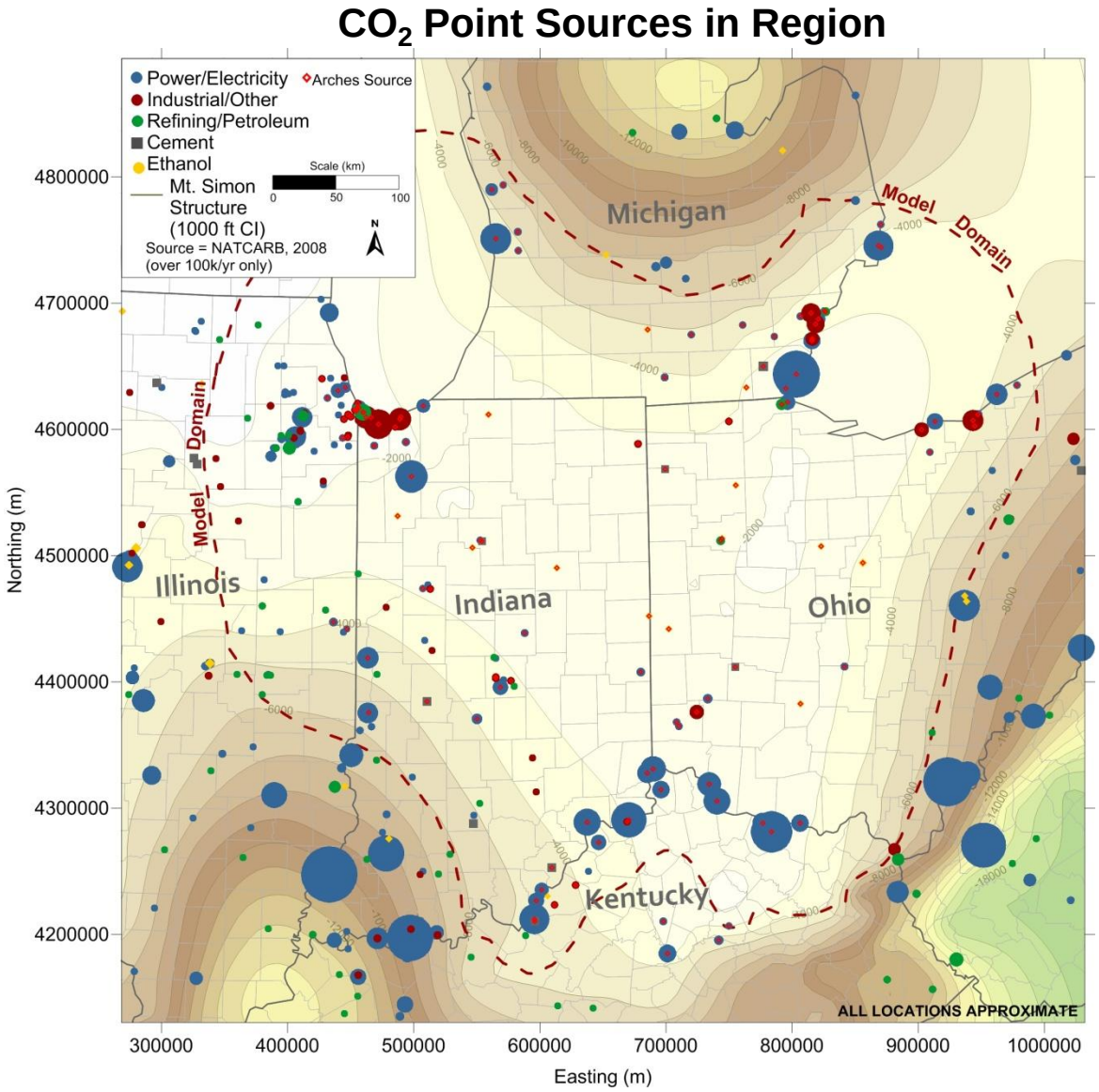
# Injection Site Geological Data

- Mount Simon is Cambrian-age sandstone formation.
- Eau Claire Formation is the caprock, and the Knox group is present above the Eau Claire.
- Numerical model designed to address variability in rock units.



# $CO_2$ Sources in Arches Province

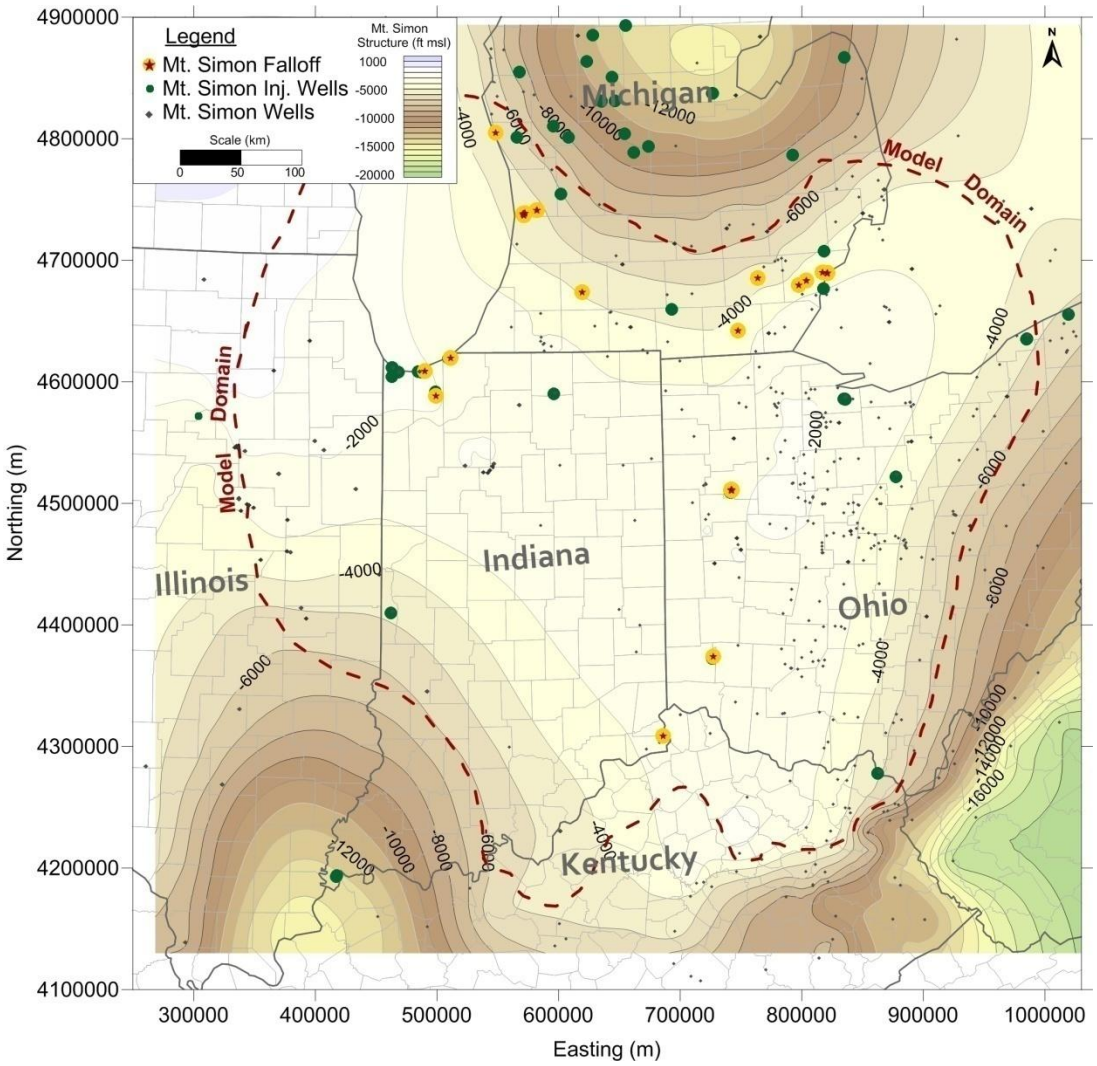
- There are 53 point sources with emissions over 1 million metric tons per yr which have total emissions of ~262 million metric tons $CO_2$ /yr.
- To reduce greenhouse gas emissions in the Arches Province by 25 to 50%, $CO_2$ storage projects with total storage rates of ~70 to ~140 million metric tons $CO_2$/yr would be necessary.



# Deep Well Injection in Arches Province

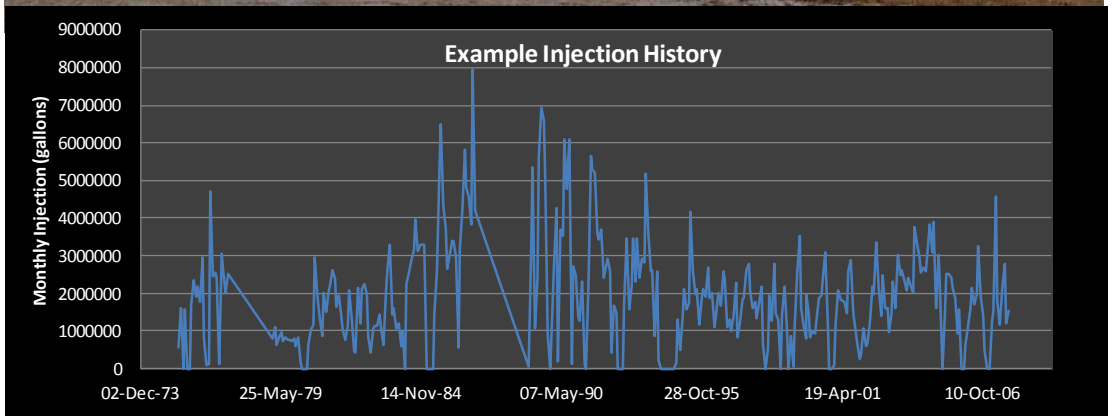
- Over 30 Class I Mount Simon injection wells are present in the Arches Province.
- Class I wells provide a valuable data set for calibration.
- Falloff reservoir test data obtained from 31 Mt. Simon injection wells (note: many sites have multiple wells).
- Data was used for development of numerical model and validation.

**Mount Simon Injection Wells in Region**



# Injection Well History

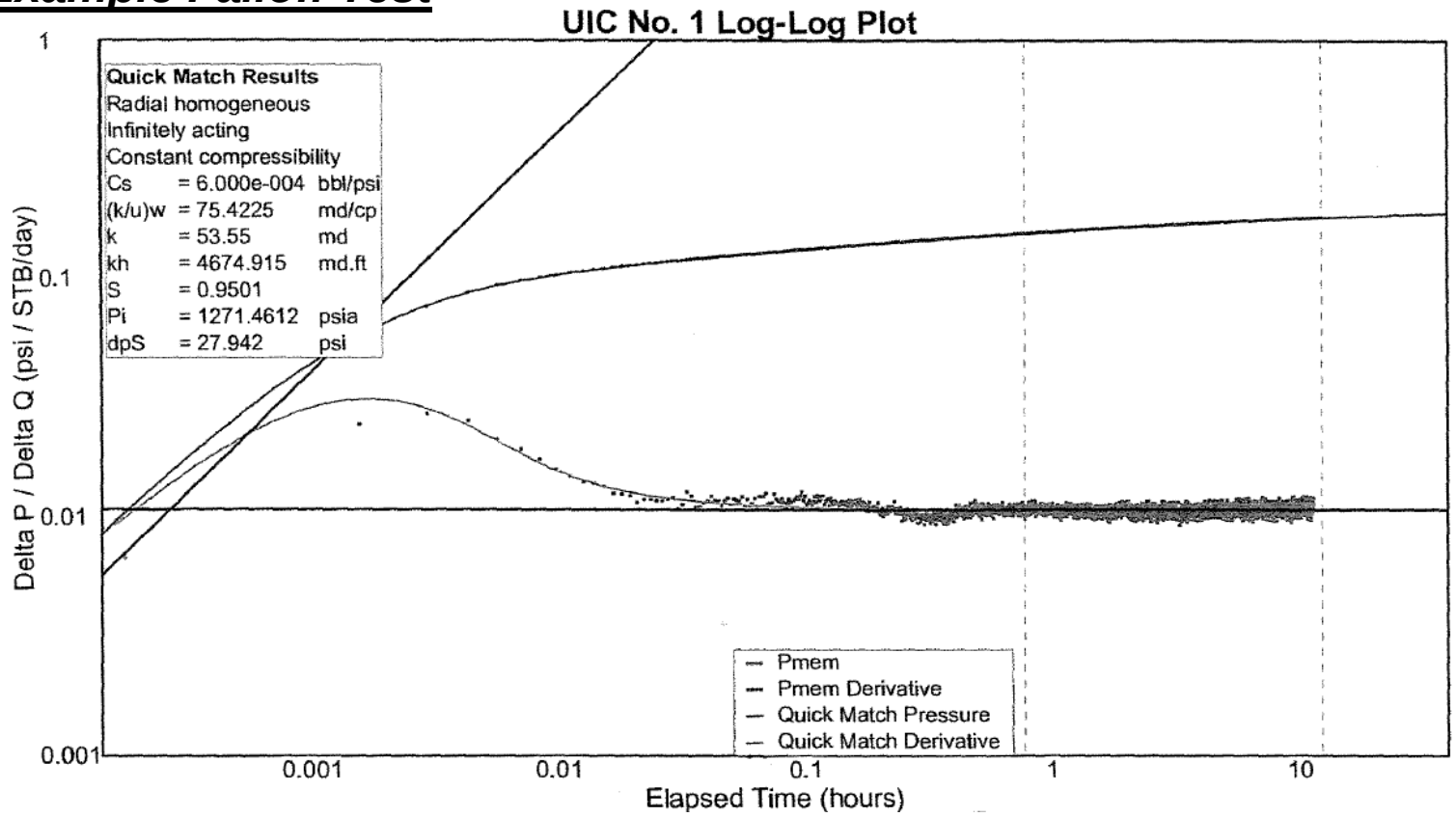
- Data was obtained from EPA UIC programs for 31 injection wells.
- Records indicate total Mount Simon injection of more than 18 billion gallons in the Arches Province over the past ~40 years.
- Equivalent to ~50 million metric tons $CO_2$.
- Injection rates generally range from 50-300 gallons/minute.



# Injection Site Operational Data

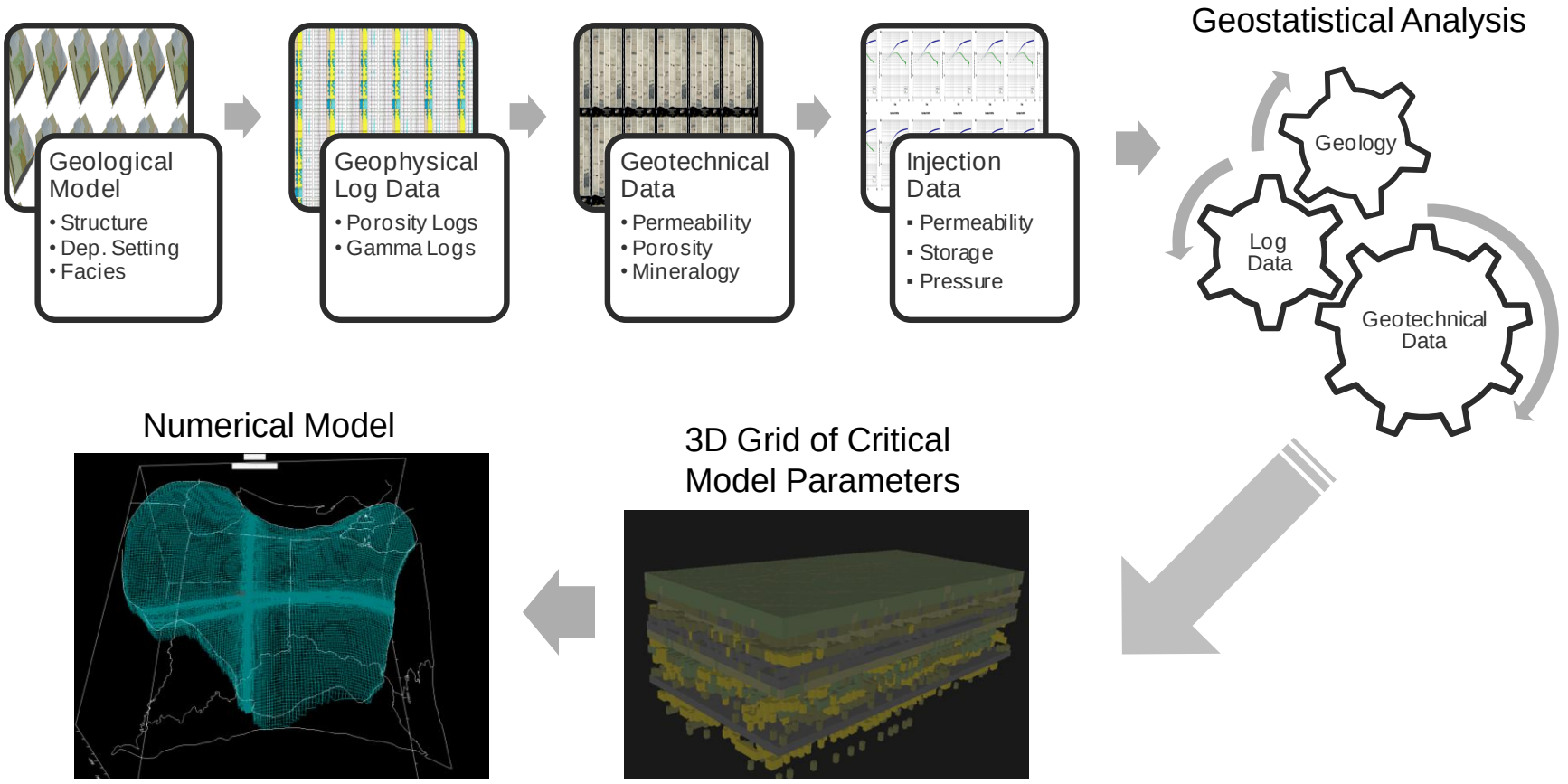
- Falloff tests provide key reservoir properties: transmissivity, permeability, storage, and static reservoir pressure.

***Example Falloff Test***



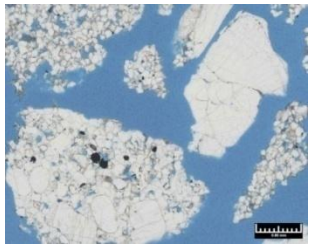
# Geocellular Model Development

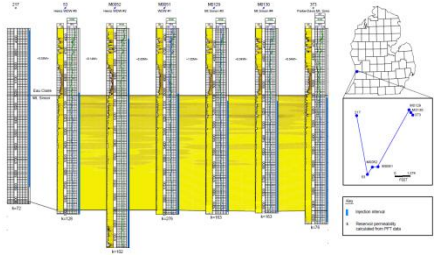
- Data integration process was developed to assign model parameters and integrate operational, geotechnical, geophysical, and geological information.

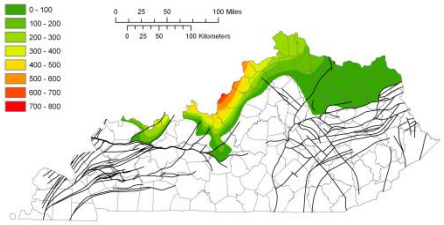


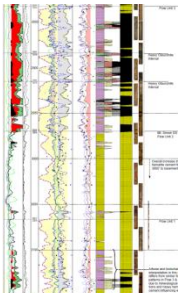
# Geocellular Model

- Geophysical well logs, rock samples, drilling logs, geotechnical test results, and reservoir tests were evaluated for a 500,000 km$^2$ study area centered on the Arches Province:
  - Geophysical well logs from 496 wells,
  - Approximately 4,000 rock core test results in Eau Claire or Mount Simon intervals,
  - 105 additional permeability and porosity tests on Mount Simon/Eau Claire rock samples,
  - Completion of geomechanical tests on 11 rock samples,
  - 16 mercury injection capillary pressure tests on rock samples,
  - 10 other advanced saturation tests on rock core samples,
  - Deep well injection operational data from 48 wells in the study area,
  - Pressure fall-off reservoir test data from 31 wells,
  - Compilation and analysis of a total of 960,000 porosity data from geophysical logs,
  - 8 regional geologic cross sections across study area.







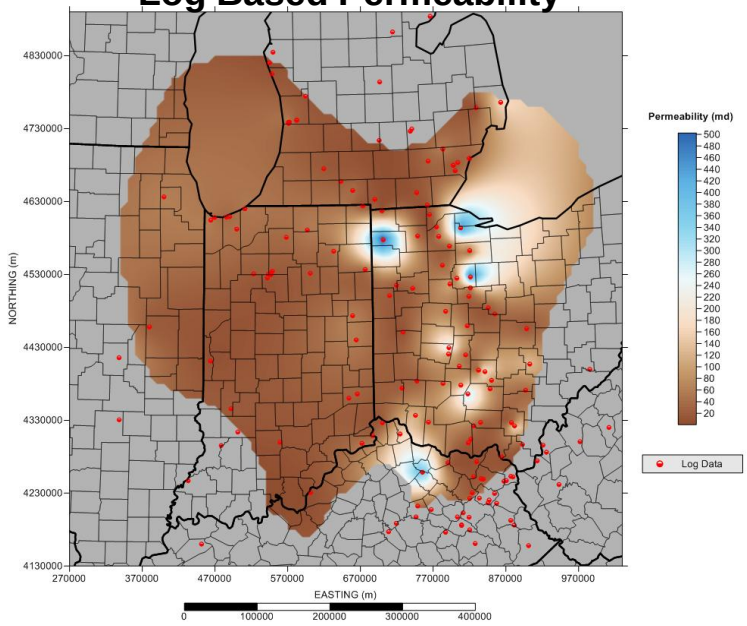



# Geocellular Permeability Model

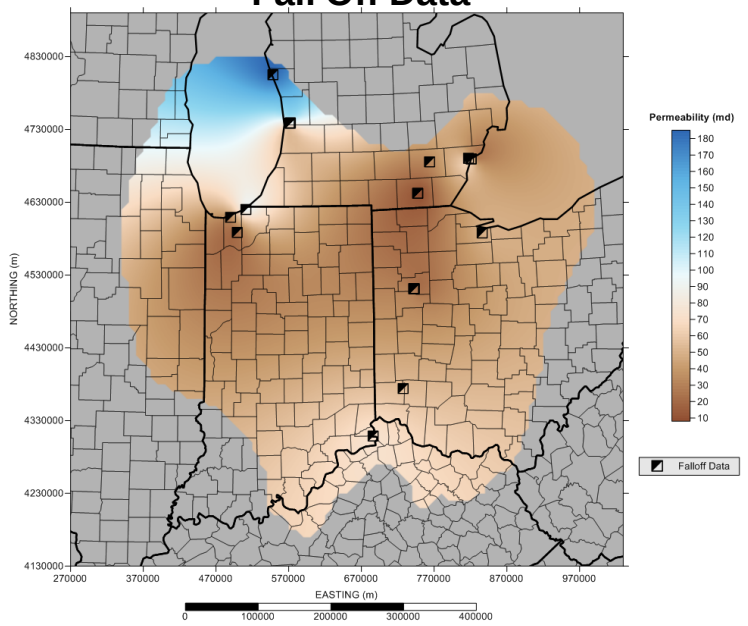
- Porosity-Permeability transform was used to estimate Mount Simon permeability after Medina et al (2011) $k = 0.7583 * e^{0.283 * \phi}$.
- Correction factor was applied to normalize permeability to pressure fall-off test data at injection well sites.

| Date Type | Number of Wells | Average Permeability Value (mD) |
|---|---|---|
| Pressure Falloff | 21 | 61.9 |
| Log Porosity | 172 | 49.5 |
| Corrected Permeability | 137 | 69.1 |

**Log Based Permeability**

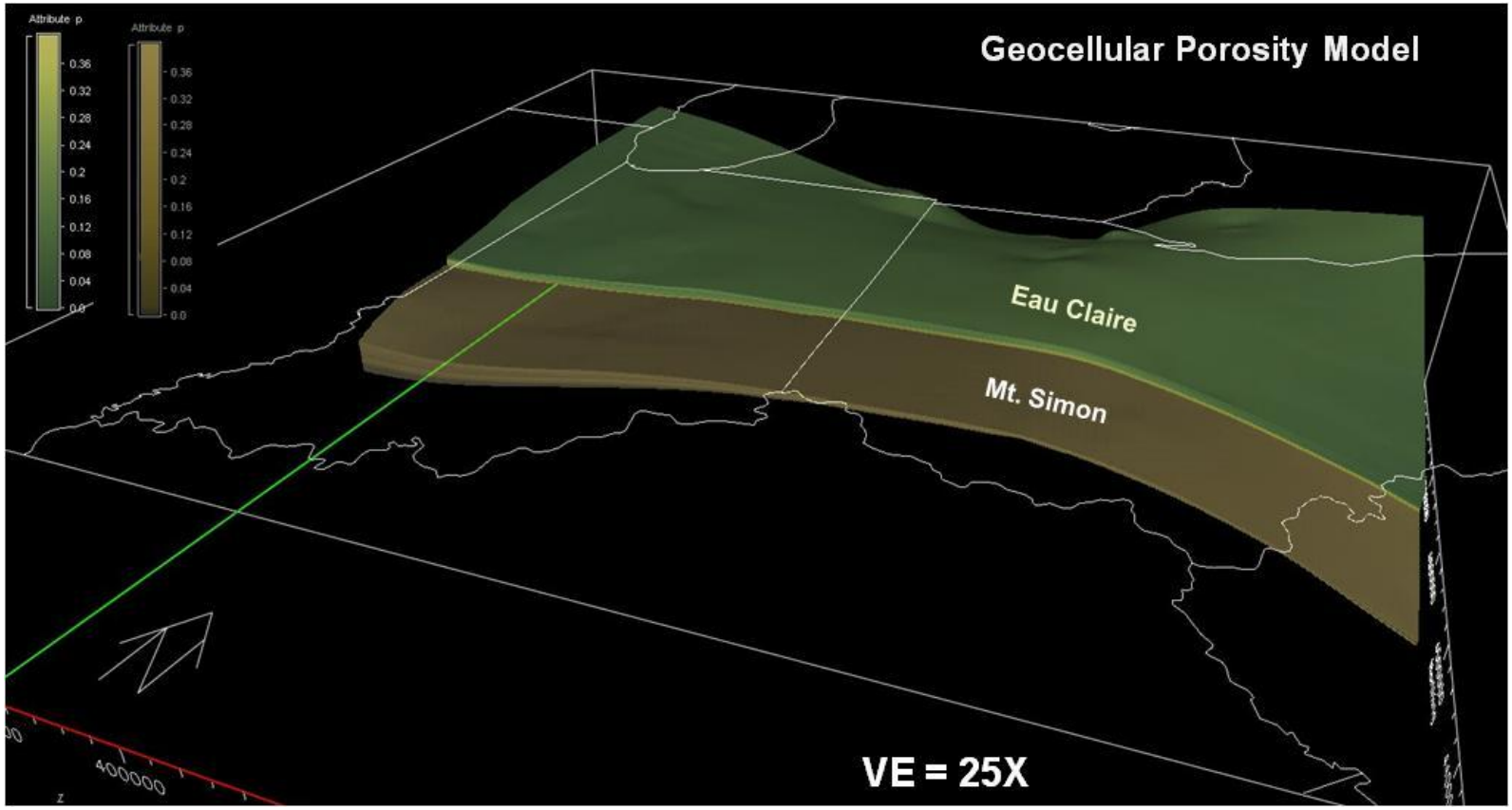



**Fall Off Data**



# Geocellular Model Development

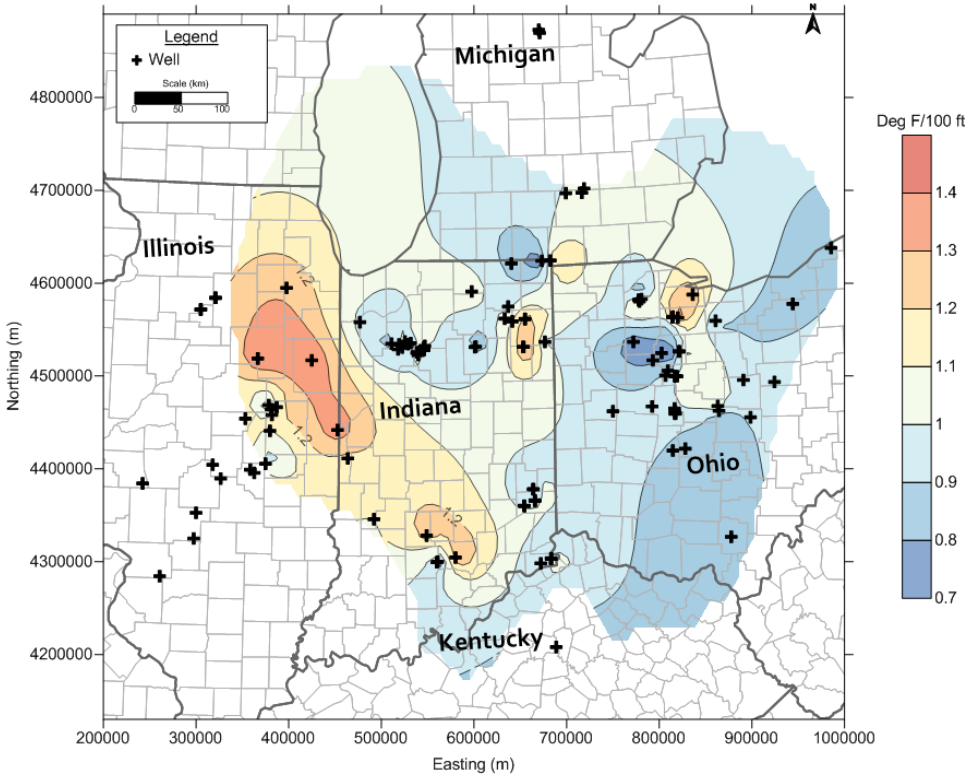
- Final geocellular model includes ~50 million cells for porosity and permeability for Mount Simon-Eau Claire.
- Resolution = 5000 m x 5000 m x 2 m.
- Geostatistics suggests porosity trends are difficult to correlate >40-50 km.



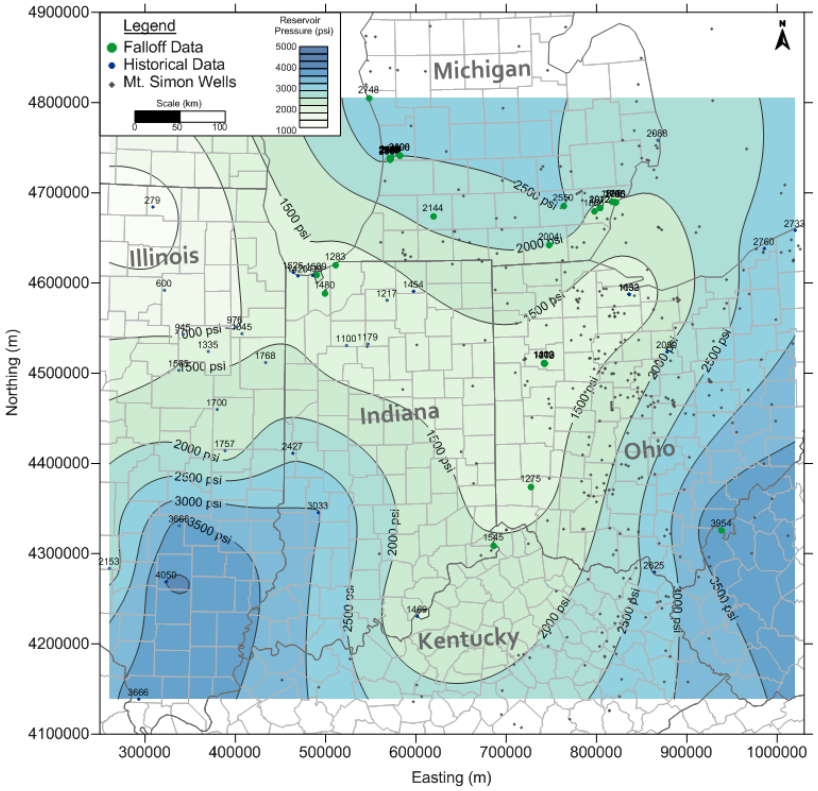
# Geocellular Model: Initial Conditions

- Mount Simon initial conditions reflect reservoir pressure, temperature, and salinity.
- Based on data from well logs and reservoir tests.

**Temperature Gradient**



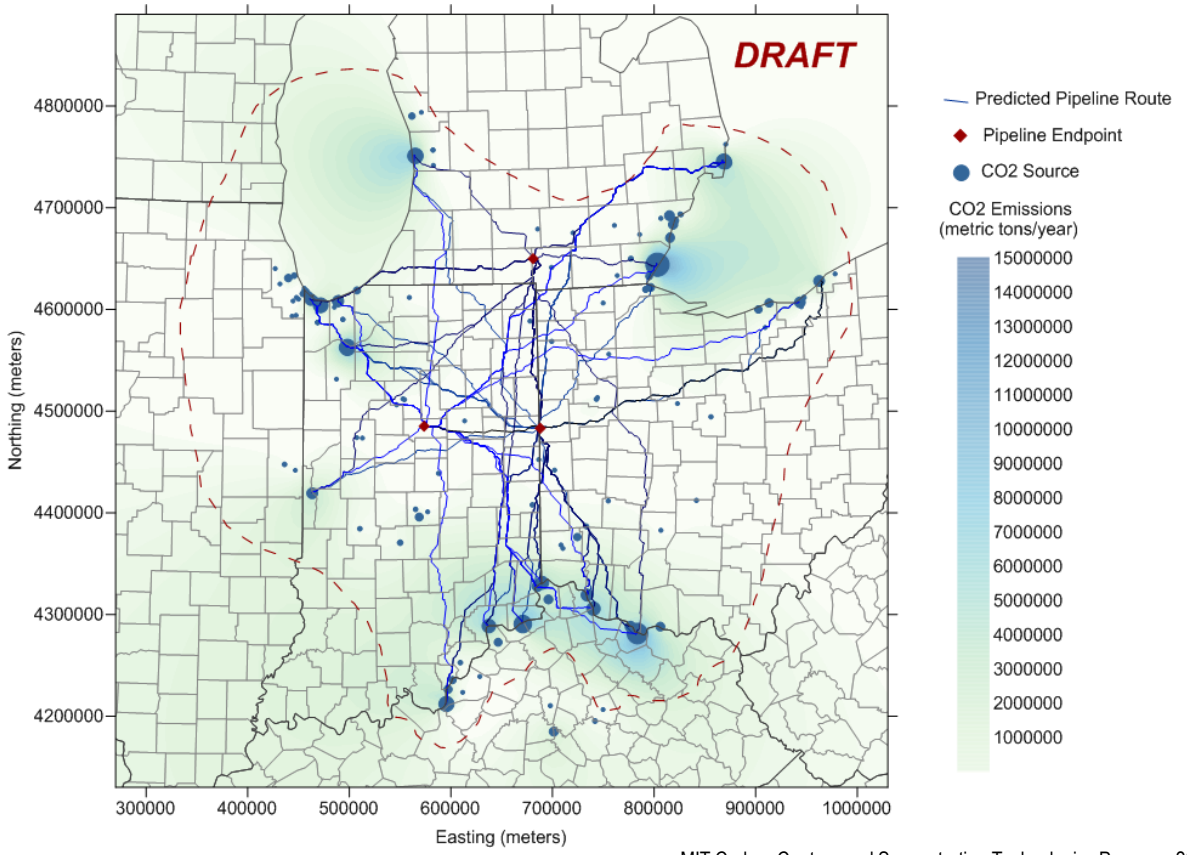

**Mt. Simon Reservoir Pressure**



# Pipeline Routing Analysis

- Pipeline routing analysis was completed using MIT GIS module (2009) to determine central corridors where pipeline routes intersect or blend together. These locations may be practical potential regional storage fields.

**Pipeline Routing Analysis**

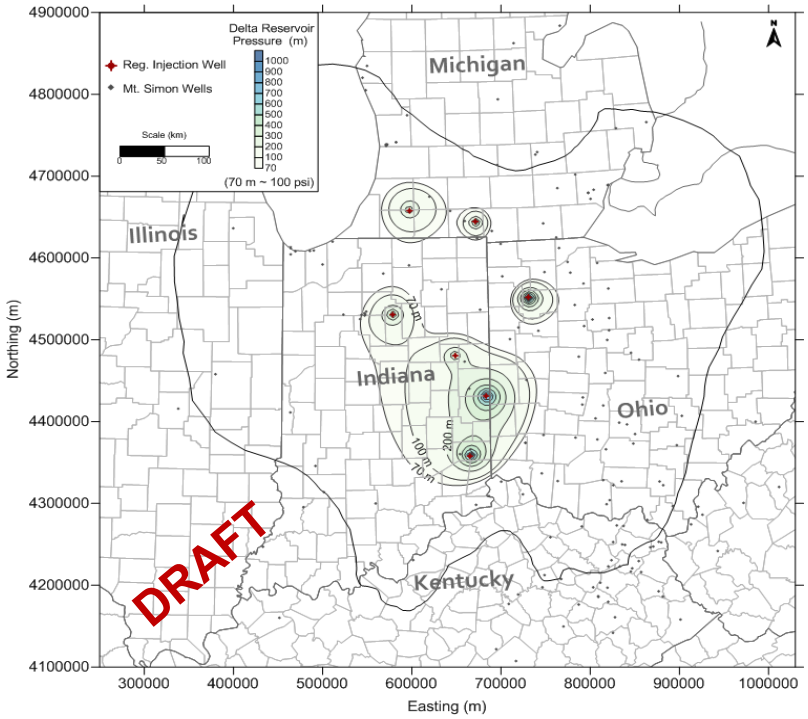



MIT Carbon Capture and Sequestration Technologies Program. 2009. Carbon Management GIS: CO2 Pipeline Transport Cost Estimation. Report for NETL, DOE Contract: Contract DE-FC26-02NT41622.

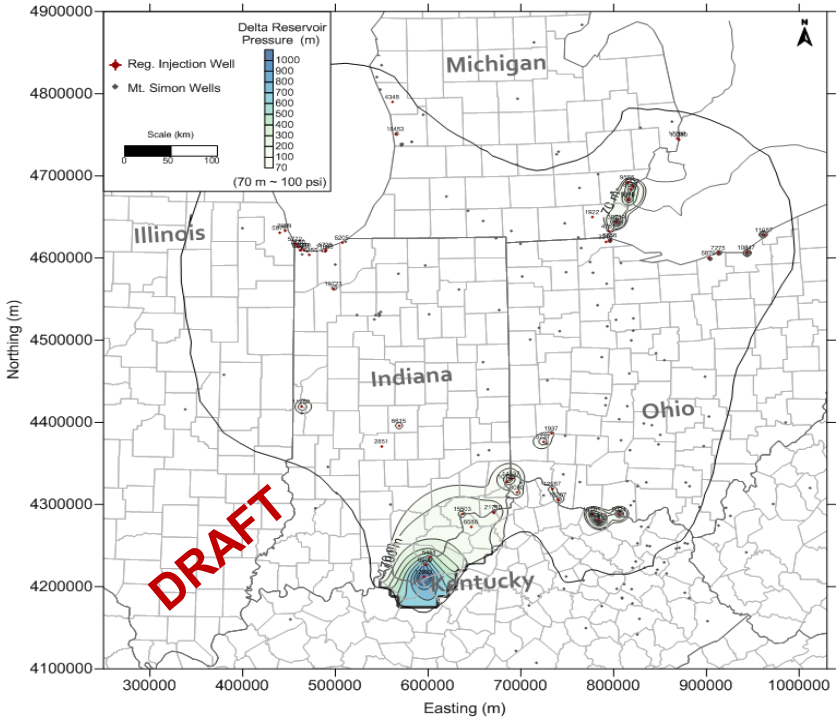
# Preliminary Variable Density, Single Phase Flow Simulations

- Fully 3D model developed in SEAWAT based on geocellular model. The single-phase simulations simulate brine flow and variable density effects, not $CO_2$. However, the models allow rapid numerical solutions, and many different model iterations were evaluated to determine a suitable model setup.

Regional Storage Field 21 Mt/yr total



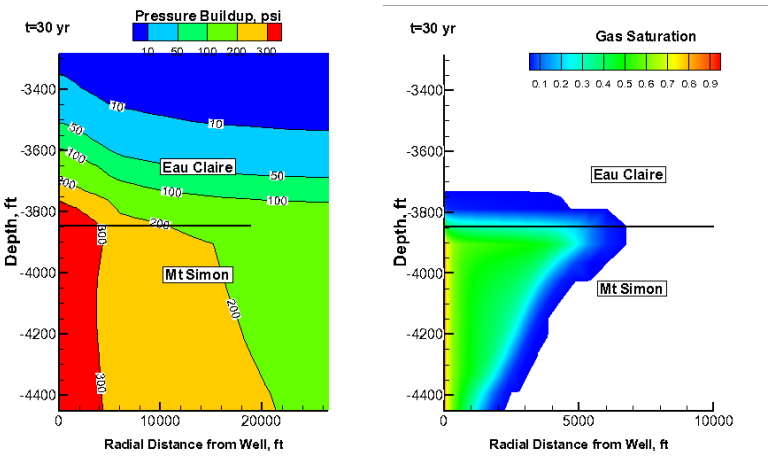

On-site Injection 25.6 Mt/yr total

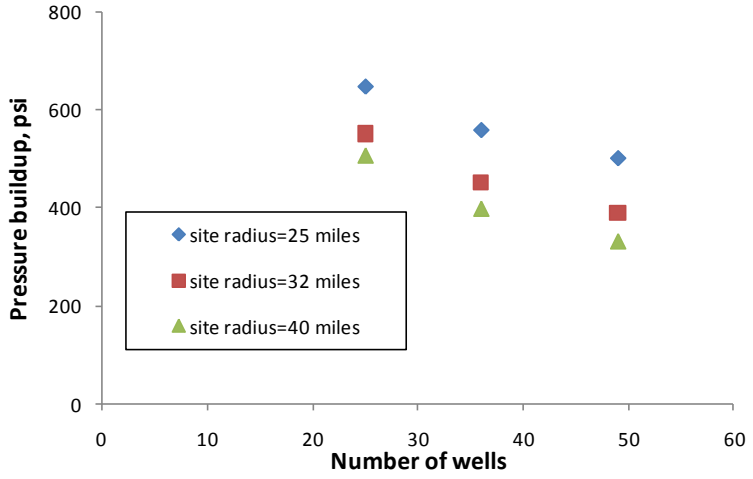


# Regional Storage Field Scoping Simulations

- Scoping level simulations were completed to evaluate storage field arrangements in terms of well spacing, site radius between fields, and reasonable injection rates.
- Simulations were completed with STOMP-$CO_2$ multi-phase numerical code in 2D radial mode for locations identified in pipeline routing study.
- Results indicate injection fields spaced 25-40 miles apart may prevent pressure buildup and $CO_2$ front interference. Arrays of 9-50 wells may be required in fields.

**2D STOMP Model Results**



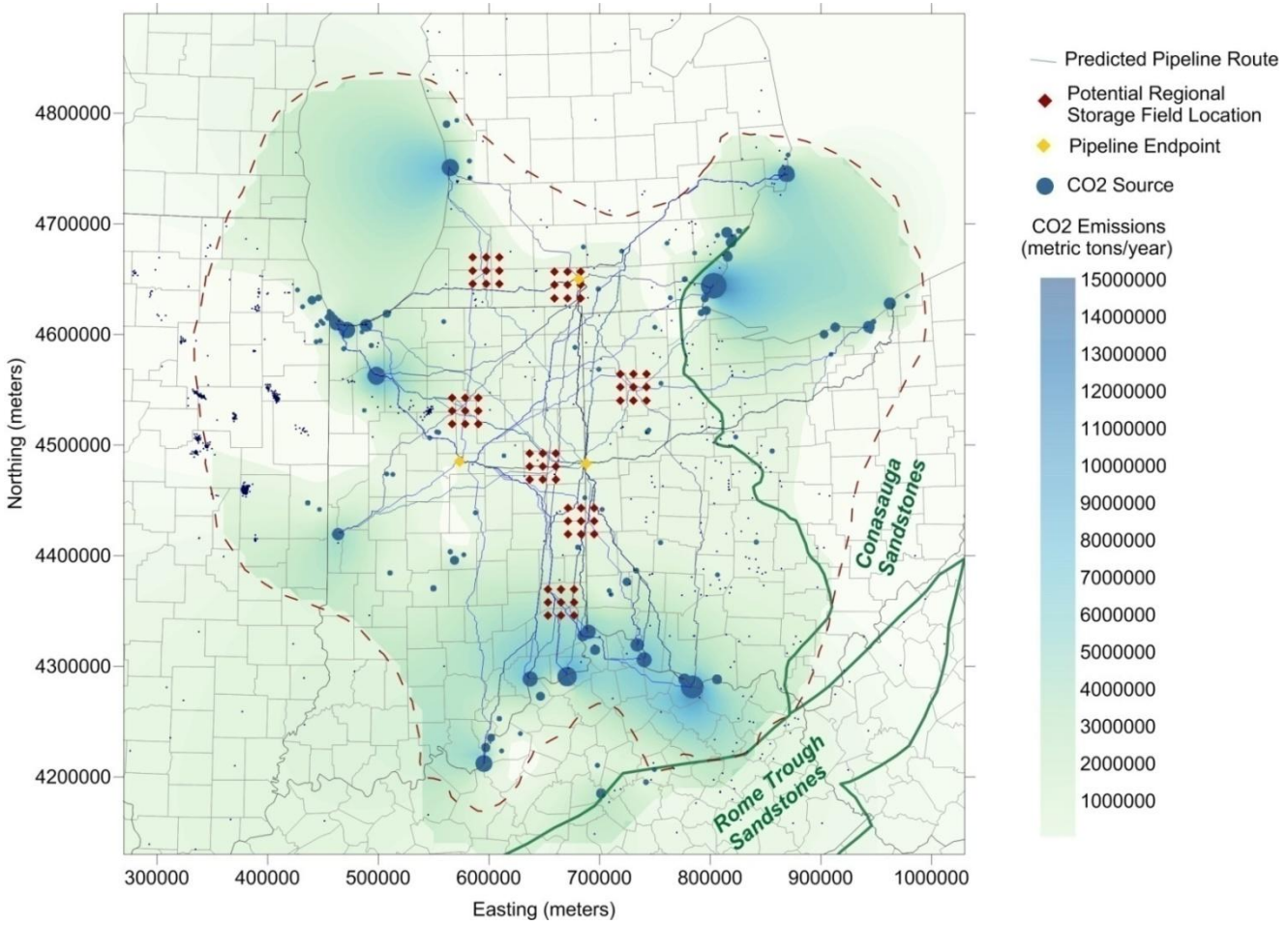




| Site radius (miles) | | 25 | 32 | 40 | |
|---|---|---|---|---|---|
| | | | | | |
| array | # of wells | Storage Radius (m) | | | q (MMT/yr |
| 7 x 7 | 49 | 5782 | 7401 | 9251 | 0.68 |
| 6 x 6 | 36 | 6746 | 8635 | 10793 | 0.93 |
| 5 x 5 | 25 | 8095 | 10362 | 12952 | 1.33 |

# Infrastructure Analysis

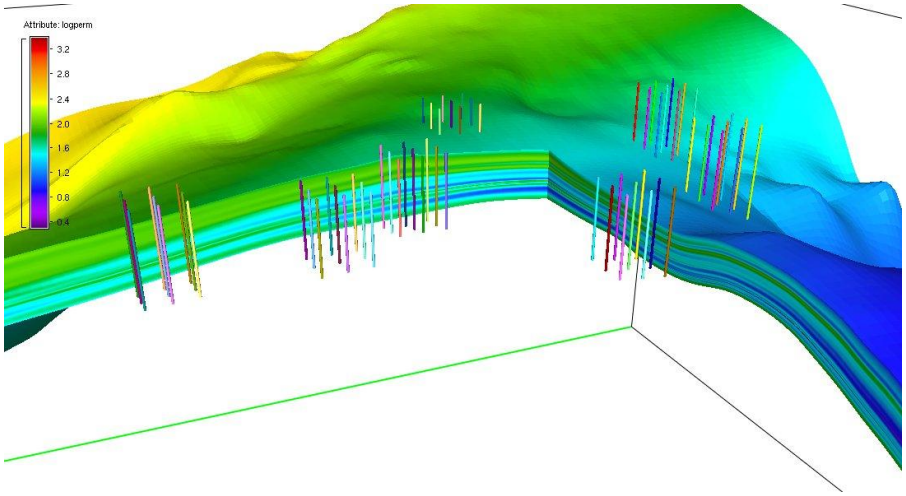
- Results of scoping simulations combined with pipeline routing study to input potential storage field locations.

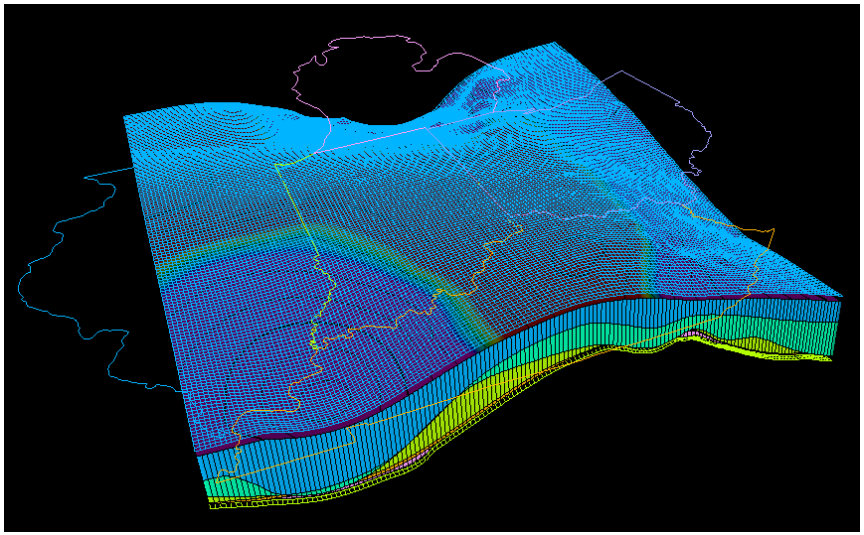
**Conceptual Regional Injection Field Scenario**



# Basin Scale Multi-phase Simulations

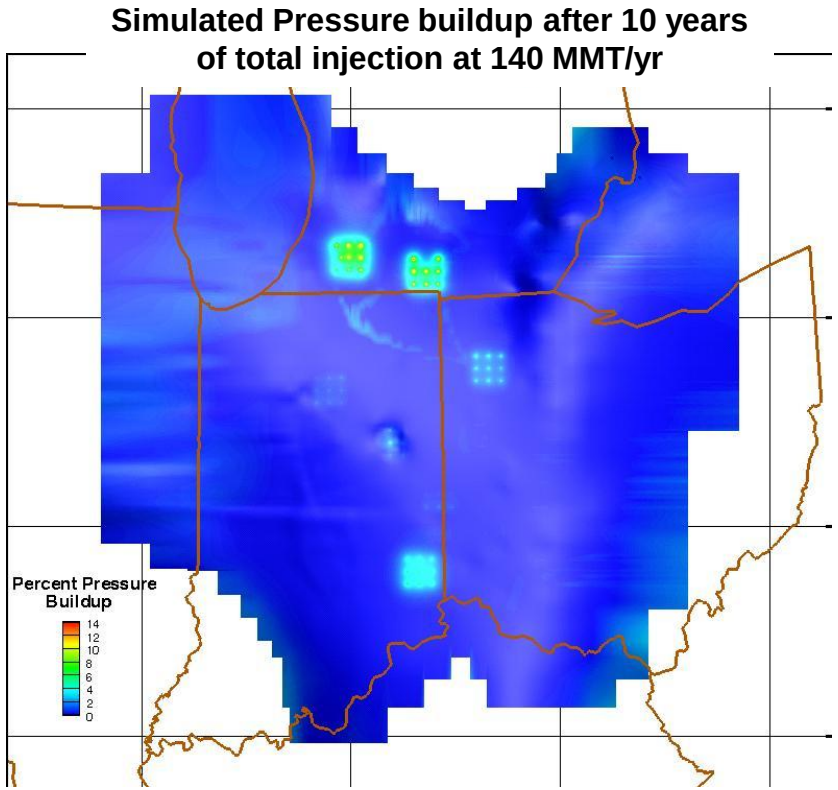
- Simulations were completed in STOMP (3D multi-phase simulator).
- 50 million-cell 3D geocellular model developed in EarthVision based on 2 m vertical resolution and 5000 m horizontal resolution upscaled to 1.5 million node, 16 layer numerical simulation.



# Basin-Scale Simulation Results

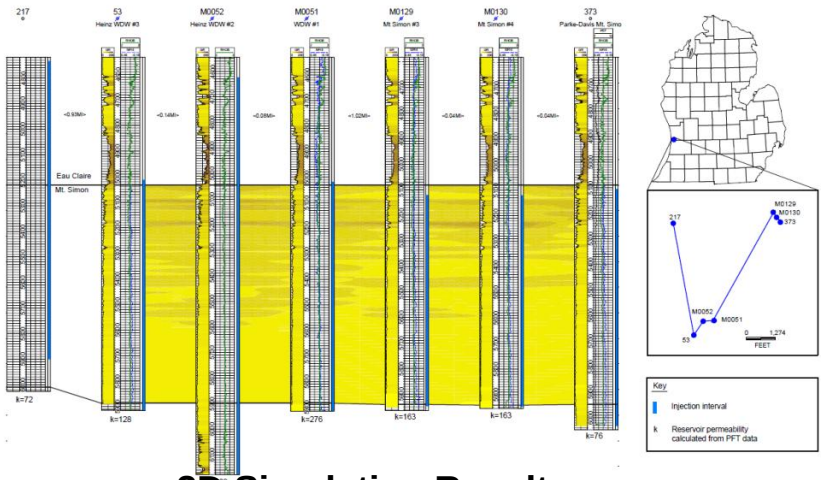
- Basin-scale simulations were run for total injection of 70-140 MMT/yr distributed across 63 wells in 7 fields.
- Results reflect variations in geology and hydraulic conditions. Some areas required different injection rates, pressure limits, and limitations of basin-scale models.



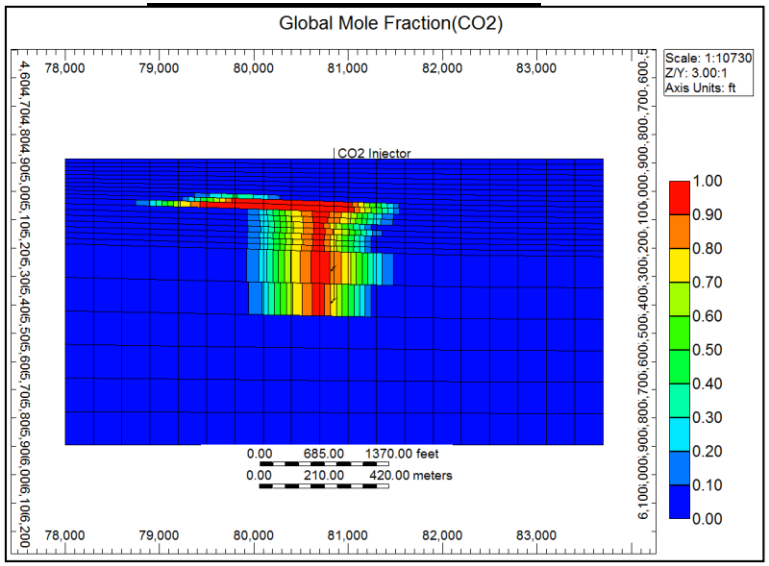
# Geomechanical Simulations

- Geomechanical simulation developed for Holland, MI area in CMG-GEM.
- Objective = examine potential for caprock fracture, injection pressure limits, geomechanical deformation, effect of injection dept and thickness in Mount Simon.
- Input based on Arches Sims geomechanical tests on Mount Simon and Eau Claire cores.
- Initial results reflect 1000 ft of permeable Mount Simon, which is unlikely to fracture.

**Mount Simon Cross Section in Holland Area**




**2D Simulation Results**



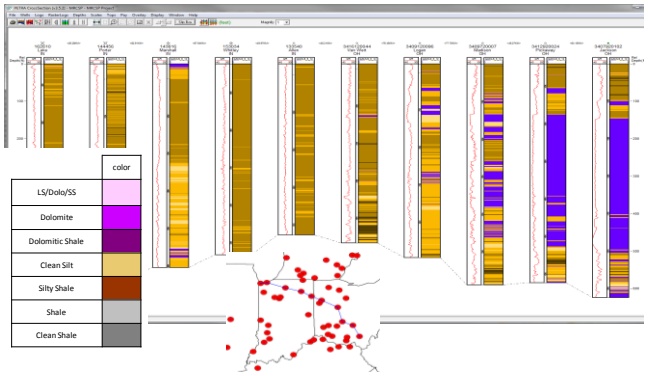
# Regional Storage Scenarios

- Caprock simulations- site specific simulations were completed for 2 locations with increased model resolution in the Eau Claire. Models were run for 1000 years. Results showed minimal upward migration of $CO_2$.

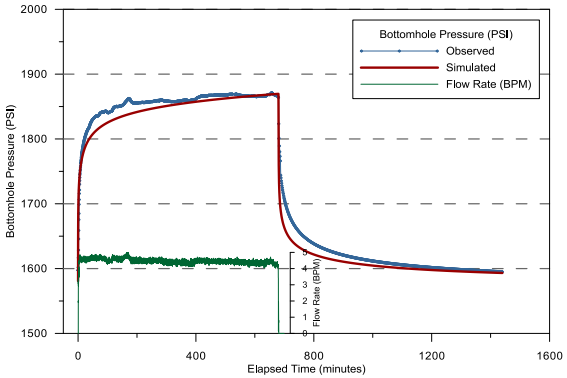
- Model Validation- a model validation exercise was completed by simulating $CO_2$ injection test completed at the MRCSP East Bend test site, Rabbit Hash, KY. Results showed a good match to field data.

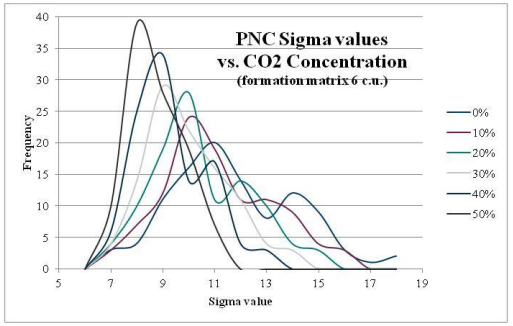
- Monitoring Analysis- simulation results were used in substitution analysis for pulsed neutron capture (PNC) saturation logs and sonic velocity data. Results better define monitoring feasibility.

**Eau Claire Cross Section**




**Model Validation**



# Summary Findings

- Class I injection wells have injected more than 18 billion gallons of fluid into the Mount Simon formation in the Arches Province over the past 40 years (equivalent to approximately 50 million metric tons $CO_2$).
- Multi-state collaboration aided in defining the distribution of the Mount Simon formation in more detail across the Arches Province. Trends were exhibited in maps of hydraulic and geotechnical parameters.
- The southern margin of the Mount Simon sandstone in Kentucky was adjusted where structures associated with the Rough Creek Graben and Rome Trough influence the southern limit of the sandstone, causing thinning or absence on structural highs.
- Large areas have little well control, so uncertainty remains in areas. Geostatistical variogram analysis indicates it is difficult to correlate porosity trends beyond approximately 40 km.
- Reservoir tests in injection wells indicate total permeability in the Mount Simon may be 1.4 X greater than indicated in the geocellular model.

# Summary Findings

- A series of scoping level and basin-scale numerical simulations were completed to better define infrastructure necessary to support large-scale $CO_2$ storage in the Arches Province.
- Basin scale simulations of large scale injection reflect variability in Mount Simon. Overall, they suggest that large scale injection may be achieved with proper field design, operation, siting, and monitoring.
- There are some advantages to on-site injection because injection wells would be distributed throughout a large area; however, areas with concentrated sources along Great Lakes coast and Ohio River may not support large injection rates.
- A pipeline routing analysis shows that there are central corridors for a pipeline distribution system from sources to sink areas.

# Summary Findings

- Simulations better define potential well fields, well field arrangement, and operational parameters for large-scale injection in the Arches Province.
- Multiple well fields with 9-40 wells in each field may aid minimizing pressure buildup and $CO_2$ saturation front interference.
- Well fields may require 50-60 km separation. Individual wells in each field may require 3-10 km spacing to prevent operational interference.
- Simulations with more detailed model layers for the Eau Claire caprock show minimal upward migration into the caprock.

- *Final technical report is under preparation with more detail on the project.*

# Thank You.

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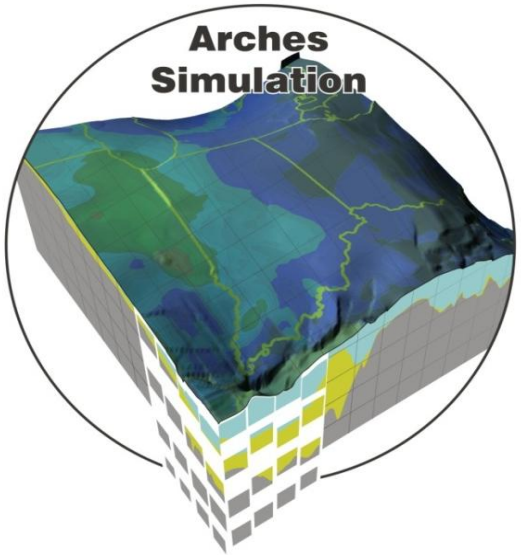
Ohio Department of Development

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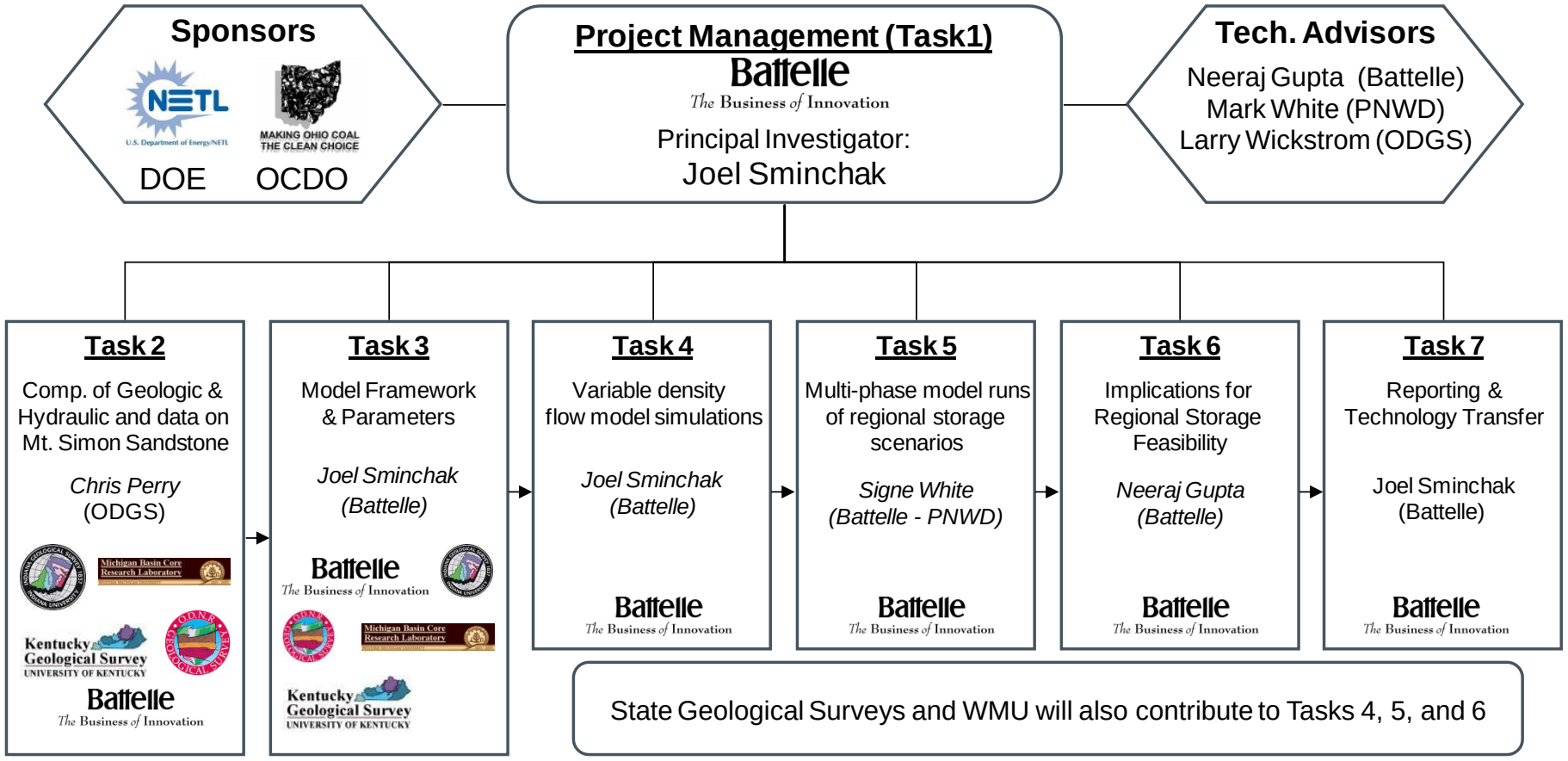
UNIVERSITY OF KENTUCKY

Michigan Basin Core Research Laboratory

Pacific Northwest

# Appendix Slides

# Organization Chart



# Gantt Chart

| Task | Milestone | FY2010 | | | | FY2011 | | | | FY2012 | | | | Planned Start Date | Planned End Date | Actual Start Date | Actual End Date | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q 1 | Q 2 | Q 3 | Q 4 | | | | | |
| Project Status | | | | | | | | | | | | | | 9/30/2009 | 9/30/2012 | 9/30/2009 | --- | |
| 1 | Revised Project Management Plan | X | | | | | | | | | | | | 9/30/2009 | 10/23/2009 | 9/30/2009 | 12/03/2009 | PMP submitted 12/3/2009 |
| 2 | Geologic data Compilation | | | X | | | | | | | | | | 9/30/2009 | 6/30/2010 | 9/30/2009 | 7/1/2010 | Data Compilation Report submitted 7/1/2010 |
| 2 | Mapping and GIS of Mt. Simon | | | | X | | | | | | | | | 1/30/2010 | 9/30/2010 | 1/30/2010 | 9/23/2010 | Geological Model completed 9/23/2010 |
| 3 | Development of Conceptual Model | | | | | | | X | | | | | | 3/1/2010 | 6/30/2011 | 3/1/2010 | 6/30/2011 | Conceptual Model completed 6/30/2011 |
| 4 | Variable-Density Flow Modeling | | | | | | | | X | | | | | 10/1/2010 | 9/30/2011 | 10/1/2010 | 9/30/2011 | Variable Density Flow Modeling completed 9/23/2011 |
| 5 | Multiphase Simulations | | | | | | | | | | X | | | 3/1/2011 | 3/30/2012 | 4/1/2011 | 3/30/2012 | Basin-scale multi-phase model completed 3/30/12 |
| 6 | Regional Storage Simulations | | | | | | | | | | | X | | 7/1/2011 | 6/30/2012 | 6/1/2011 | 6/26/2012 | Team meeting held on June 26, 2012 |
| 7 | Final Technical Report | | | | | | | | | | | | X | 10/1/2011 | 9/30/2012 | 3/1/2012 | --- | |

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