Resource Assessment Methods for CO_2 Storage in Geologic Formations

Carbon Storage R&D Project Review Meeting

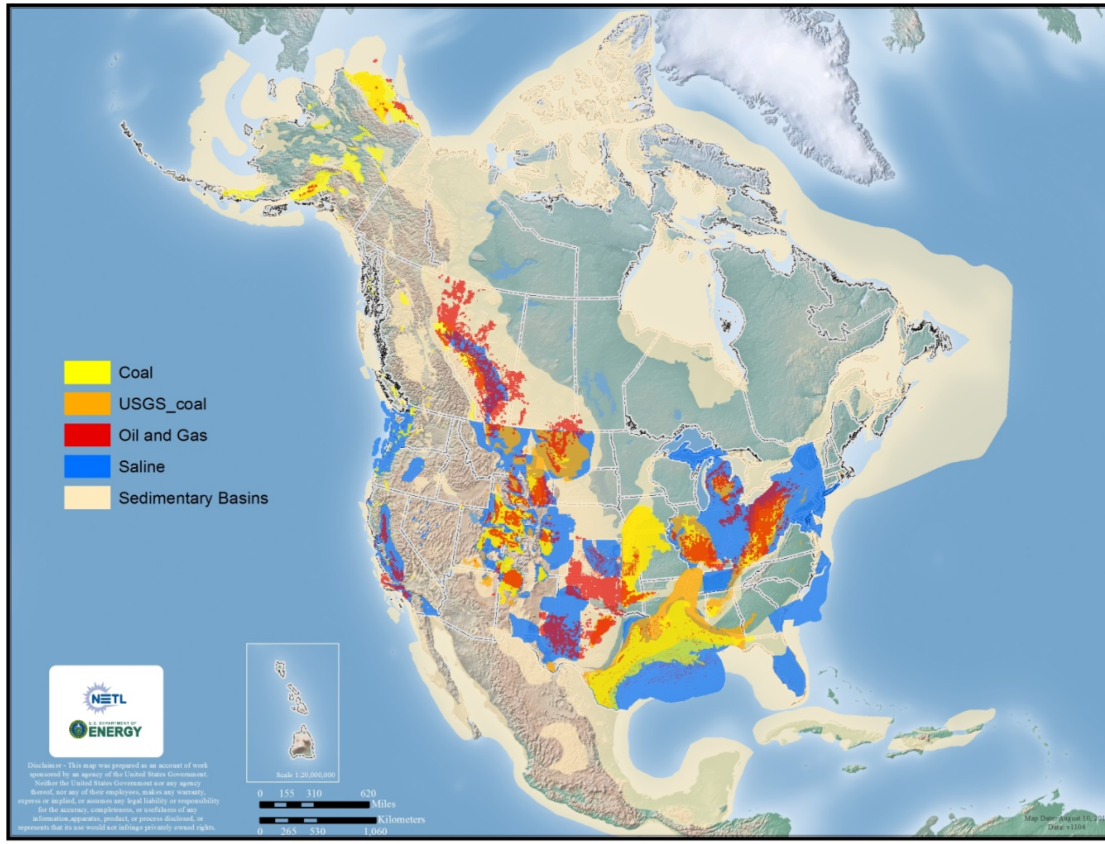
Developing the Technologies and Infrastructure for CCS

U.S. Department of Energy

Fossil Energy and National Energy Technology Laboratory

August 20-22, 2013

Sheraton Station Square, Pittsburgh, Pennsylvania

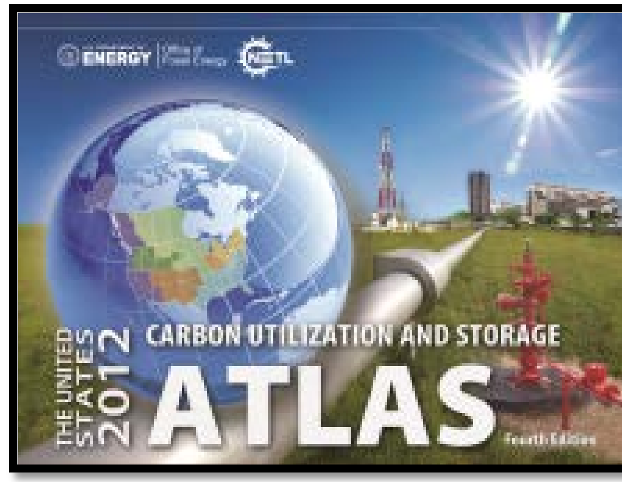


- **Presenter: Angela Goodman**
- **Team:** Angela Goodman, Grant Bromhal, Brian Strazisar, Traci Rodosta, Kelly Rose, Dan Soeder, Bob Dilmore, Isis Fukai, Jen Bauer, Corinne Disenhof, and George Guthrie
- United States Department of Energy, National Energy Technology Laboratory

Prospective Storage Resource for CO_2 storage reservoirs in the United States and Canada at the *regional and national scale at the Exploration Phase*.

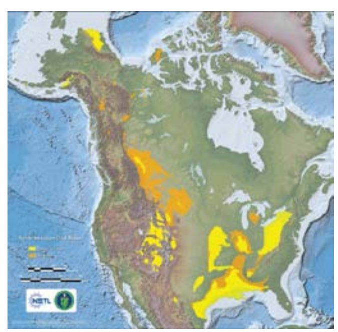
Program Goal: *Support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.*

- Based on **physically** accessible pore volume without consideration of **regulatory** or **economic** constraints.
- broad **energy-related** government policy and business decisions

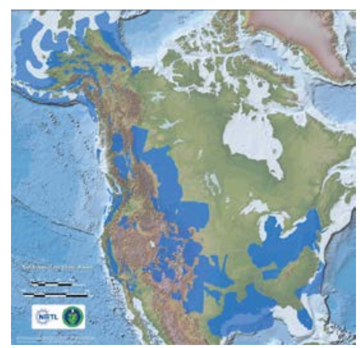


Oil and Gas Fields

Saline Formations



Unmineable Coal Seams



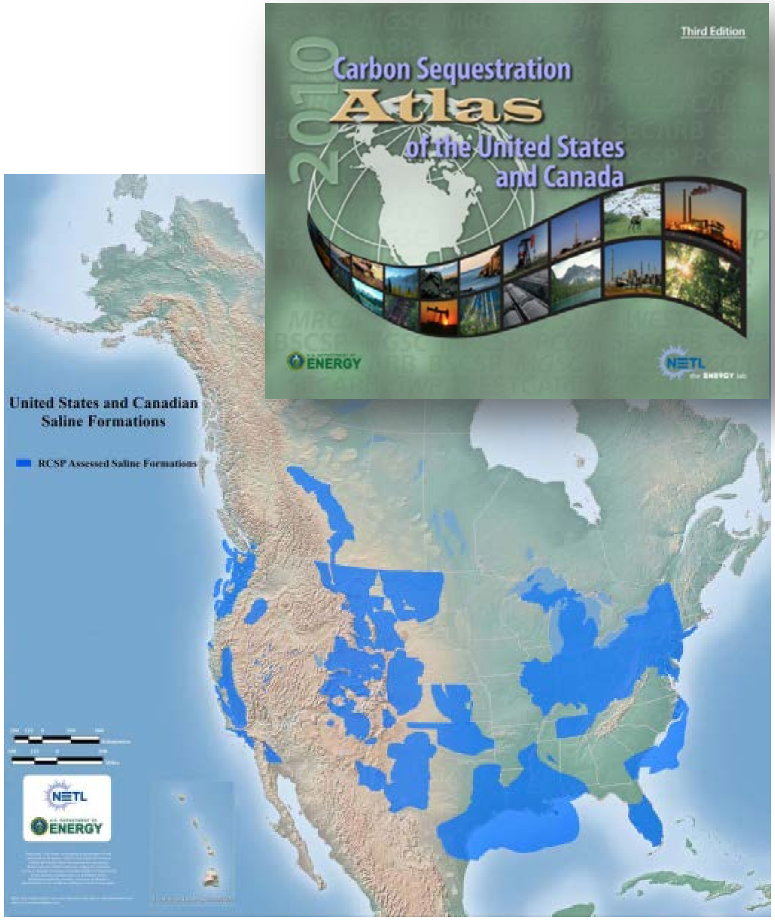
Basalt Formations

Organic-Rich Shale

DOE/NETL Estimates of CO_2 Storage Potential
National, Regional, Basin, and Formation Scale

- Assess storage potential and Identify regions for CCUS technologies to reduce CO_2 emissions

- High degree of uncertainty:
  - **simplifying assumptions**
  - **deficiency or absence of data**
  - **natural heterogeneity of geologic formations**
  - **undefined rock properties**
  - **scale of assessment**
  - **Inconsistent terminology**



- Site characterization will allow for the refinement of high-level CO_2 storage resource estimates and development of CO_2 storage capacities.

Prospective CO_2 Resource Storage Method

- **Volumetric approach**: *geologic properties & storage efficiency*

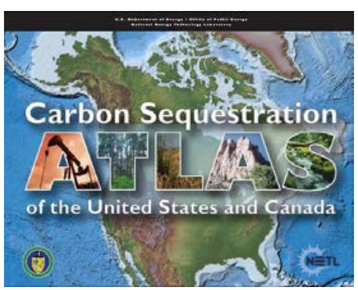
Geologic Formation	Mass Resource Estimate	Storage Efficiency
(1) Saline	$G_{CO2} = A_t\, h_g\, \phi_{tot}\, \rho\, E_{saline}$	$E_{saline} = E_{An/At}\, E_{hn/hg}\, E_{\phi e/\phi tot}\, E_v\, E_d$
(2) Oil and Gas	*(in progress)*	*(in progress)*
(3) Coalseams	$G_{CO2} = A_t\, h_g\, C_s\, \rho\, E_{coal}$	$E_{coal} = E_{An/At}\, E_{hn/hg}\, E_A\, E_L\, E_g\, E_d$
(4) Shale	*(in progress)*	*(in progress)*

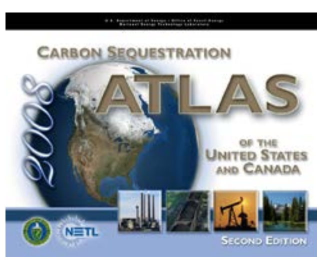
total pore volume — fluid properties — efficiency

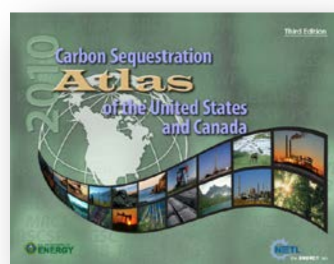
% of volume that is amenable to CO_2 sequestration — effective CO_2 plume shape — accessible pore volume

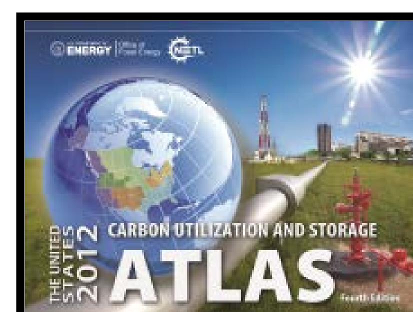
Distributed by:

- Hard-copy: CCUS Atlas of the United States and Canada
- Peer-reviewed Journal: Int. J. Greenhouse Gas Control 5 (2011) 952-965
- Web-served geographic information system: NATCARB









Atlas I - March 2007 --- Atlas II - November 2008 --- Atlas III - November 2010 --- Atlas IV – November 2012

Stochastic Treatment of Storage Efficiency

A **fraction of the total** volume of the formation that will effectively store CO_2

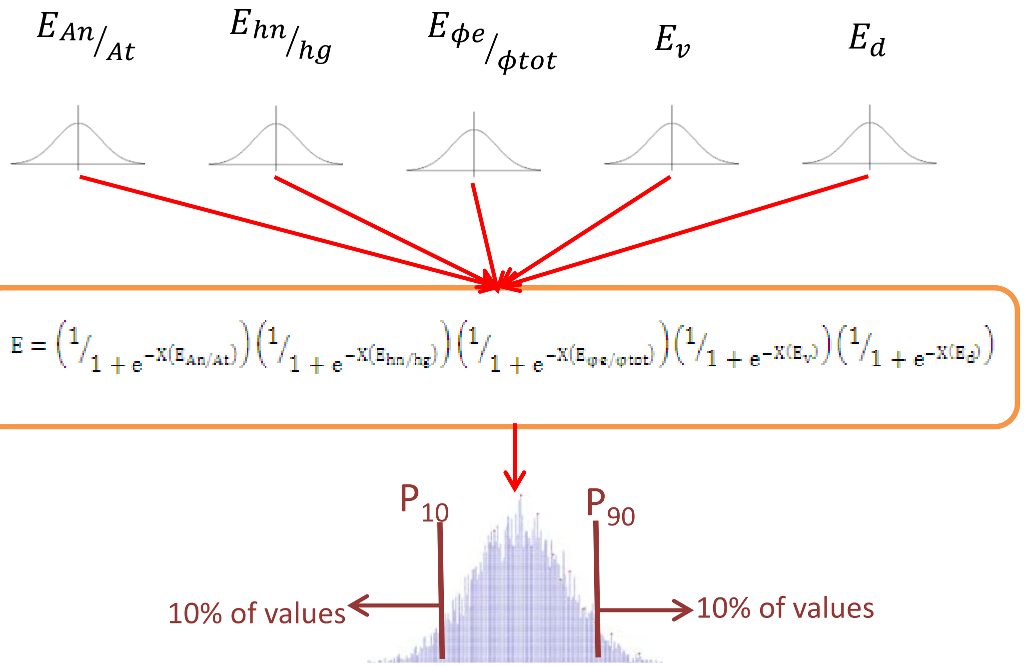
Represents **variability** in geologic parameters used to calculate G_{CO_2}

E_{saline}

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

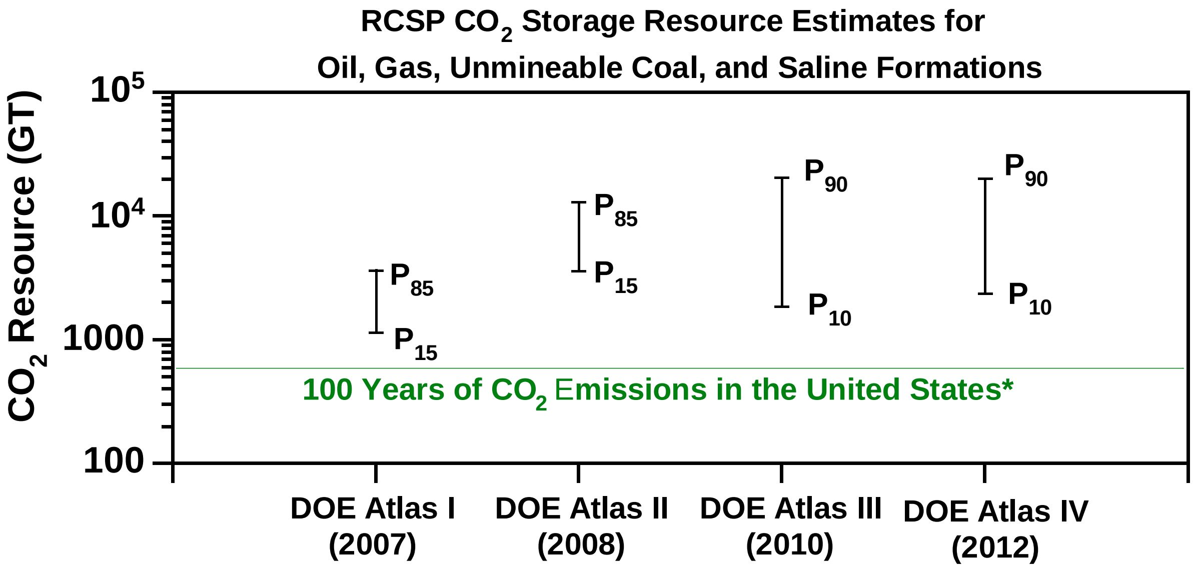
Saline Formation Efficiency Factors		
Lithology	**P_{10}**	**P_{90}**
Clastics	0.51%	5.4%
Dolomite	0.64%	5.5%
Limestone	0.40%	4.1%

Log Odds Method applied with *Monte Carlo* sampling



Source: Goodman, A., Hakala, A., Bromhal, G., Deel, D., Rodosta, T., Frailey, S., Small, M., Allen, D., Romanov, V., Fazio, J., Huerta, N., McIntyre, D., Kutchko, B.,and Guthrie, G. "U.S. DOE methodology for the development of geologic storage potential for carbon dioxide at the national and regional scale. International Journal of Greenhouse Gas Control (2011)

Progression of Carbon Storage Resource Estimates



*based on 2011 annual US energy-related CO_2 emissions U.S. EIA, 2012 (5.5 Gt)

	DOE Atlas I (2007)	DOE Atlas II (2008)	DOE Atlas III (2010)	DOE Atlas IV (2012)
National Assessment	✓	✓	✓	✓
Peer-Reviewed			✓	✓
Probabilistic Assessment			✓	✓
Geological Based	✓	✓	✓	✓
Excludes Fresh Water	✓	✓	✓	✓
Detailed Method			✓	✓
Lithology Dependent Efficiency			✓	✓
Saline	✓	✓	✓	✓
Enhanced Oil and Gas	✓	✓	✓	✓
Unmineable Coal Seams	✓	✓	✓	✓
Shale				
Regulatory, Legal, Economics				
Site Specific				

Development of CO_2 Storage Methods since 2005

- *Approach*
- *CO_2 Storage Terminology and Classification*
- *Storage Efficiency and Mechanism*

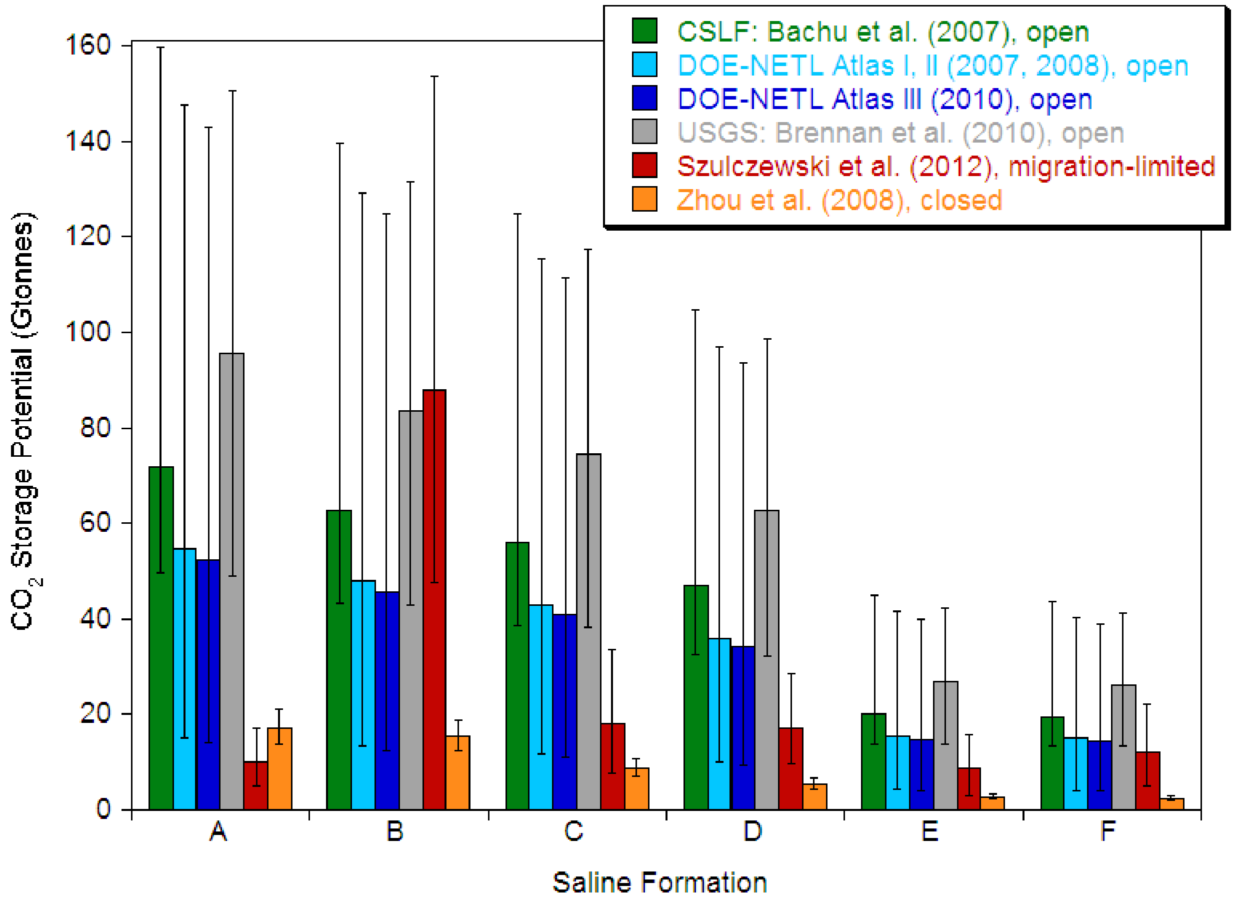
Method	Year	Volumetric Approach	Boundary	Terminology	Trapping Mechanism	Efficiency
CSLF	2007	✓	open	Effective Capacity	Structural and Stratigraphic	Field[a]
US-DOE	2007, 2008	✓	open	Prospective Storage Resource	Structural and Hydrodynamic	Generic[b]
US-DOE	2010, 2012	✓	open	Prospective Storage Resource	Structural and Hydrodynamic	Lithology[c]
USGS	2010, 2013	✓	open	Technically Assessable Storage Resource	Buoyant and Residual	Permeability[d]
Szulc. et al.	2012	✓	open and closed	Migration-Limited and Pressure-Limited Capacity	Residual and Solubility	Formation Specific[e]
Zhou et al.	2008	✓	closed	Storage Capacity	Compressibility	Compressibility[f]

[a]To be determined through field work or numerical simulation. [b]Uniform value for all formations. [c]Based on formation lithology.
[d]Based on rock permeability class. [e]Based on geologic properties of formation. [f]Based on formation pressure and compressibility constraints.

How do CO_2 storage estimates compare for different methodologies?

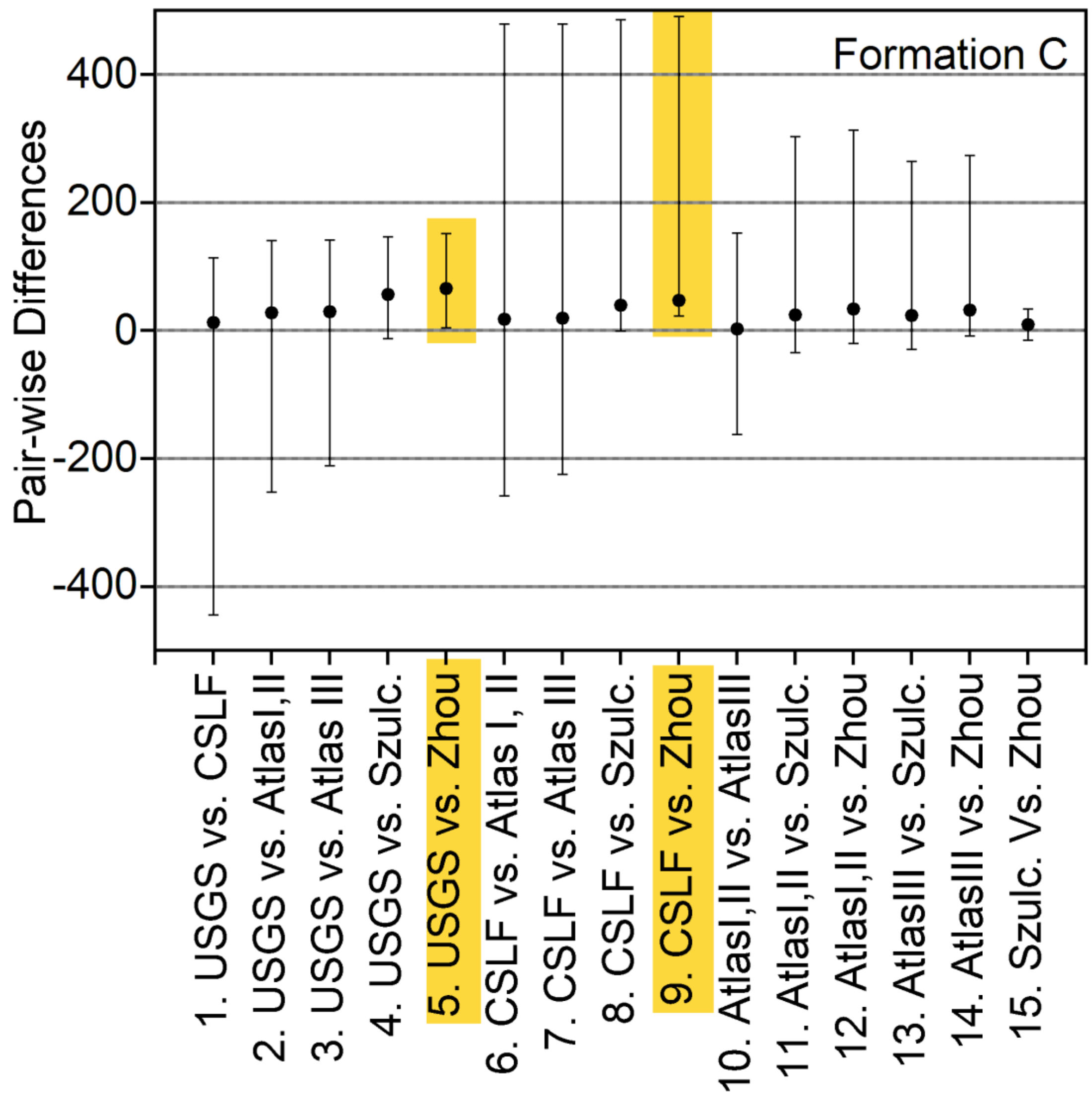
Does **method choice** significantly impact storage resource estimates?

- Compared methodologies using the **same input data** to assess significant differences between the various methodologies.
  - **6 methods** to **13 saline formation** data sets.



Are Storage Estimates Statistically Different?

- Assessments of CO_2 storage potential made at the prospective level can be treated as giving comparable results relative to our typical knowledge of the relevant geologic input values when assessing CO_2 storage potential



Statistical Comparison of Storage Estimates

- In some cases, open-boundary methodologies are statistically different when compared to the closed-boundary methodology.

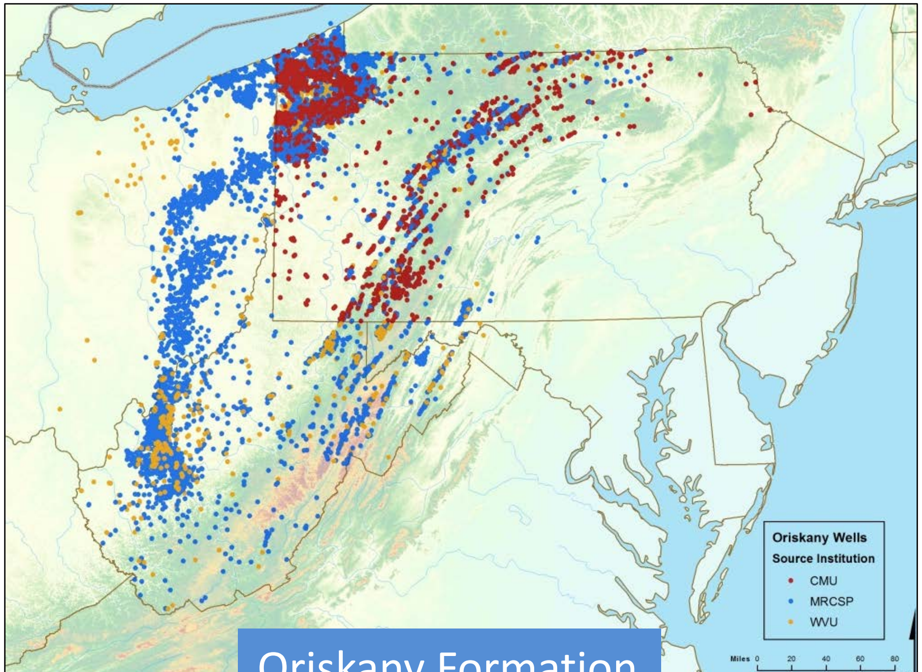
- In almost all cases, the open-boundary methodologies are not statistically different at the 95% confidence level.

	Formation												
Pair-wise Differences	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**
USGS - CSLF	■	■	■	■	■	■	■	■	■	■	■	■	■
USGS - AtlasI,II	■	■	■	■	■	■	■	■	■	■	■	■	■
USGS - AtlasIII,IV	■	■	■	■	■	■	■	■	■	■	■	■	■
USGS - Szulc.	□	■	■	■	■	■	■	■	■	■	■	■	■
USGS - Zhou	■	■	□	□	□	□	■	□	■	■	■	■	■
CSLF - AtlasI,II	■	■	■	■	■	■	■	■	■	■	■	■	■
CSLF - AtlasIII,IV	■	■	■	■	■	■	■	■	■	■	■	■	■
CSLF - Szulc.	□	□	■	□	■	■	■	■	■	■	■	■	■
CSLF - Zhou	□	■	□	□	□	□	■	□	□	■	□	□	□
AtlasI,II - AtlasIII,IV	■	■	■	■	■	■	■	■	■	■	■	■	■
AtlasI,II - Szulc.	■	■	■	■	■	■	■	■	■	■	■	■	■
AtlasI,II - Zhou	■	■	■	■	■	■	■	■	■	■	■	■	■
AtlasIII,IV - Szulc.	■	■	■	■	■	■	■	■	■	■	■	■	■
AtlasIII,IV - Zhou	■	■	■	■	■	■	■	■	■	■	■	■	■
Szulc. - Zhou	■	■	■	■	■	■	■	□	■	■	■	■	□

***white boxes represent statistical differences**

- **Uncertainty in the underlying parameters has a much greater impact on overall estimates of CO_2 storage resource than the choice of methodology does**

Data Driven CO_2 Storage Resource Estimates



Oriskany Formation

Identify patterns and trends within datasets:

- Spatial trends and patterns, identify correlations and relationships amongst parameters that could be used to calculate or interpolate missing values
- Look for spatial autocorrelation, point patterns, nearest neighbor distances, etc.

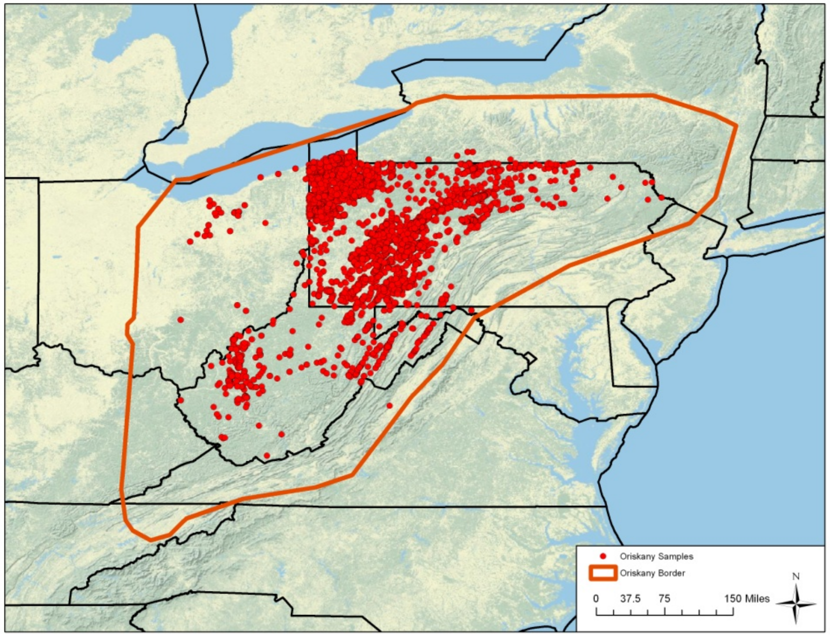
<u>Geostatistical Approach in Support of Storage & Risk Assessments</u>

Compiled data for target formation:

- Structural & Stratigraphic Depths
- Gross Thickness, Net Thickness
- Area, Volume, Porosity, Permeability
- Pressure, Pressure Gradient
- Temperature, Temp. Gradient
- Salinity, Total Dissolved Solids Brine Composition/chemistry
- Brittleness, Fault & Fracture Density
- Wellbore penetrations (X,Y,Z)
- Water Saturation, Gas Composition

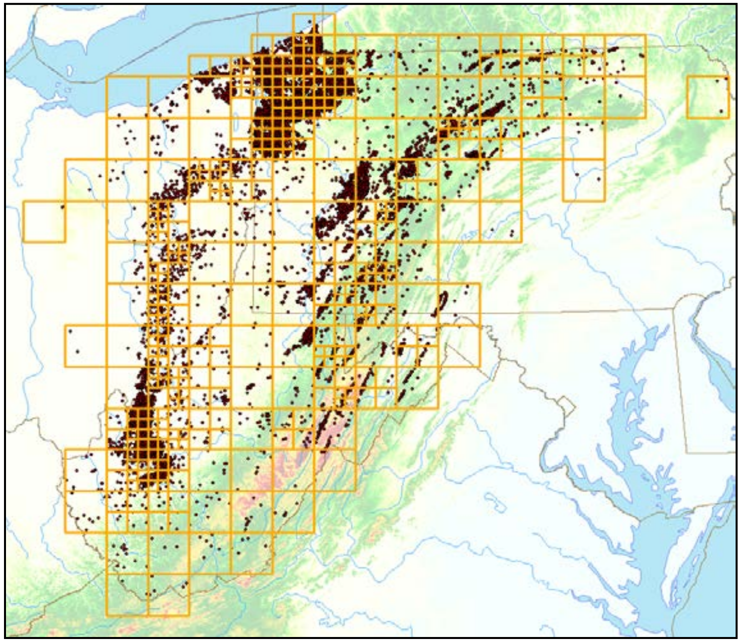
Data Driven Approach

Formation Outline



- **Quick**, screening calculation of CO_2 storage resource
- Applied when geologic subsurface data are **sparse**
- Based on **outline** of formation and average geologic properties of formations

Gridded Formation



- **Data driven** subsurface guide for spatial analysis and resolution to estimate CO_2 storage for each **grid block**
- Applied when geologic subsurface data is readily available
- Help inform **technology development, risk evaluation, and knowledge gaps**

Data Driven CO_2 Storage Resource Estimates

Outline $G_{CO2} = A_t \, h_g \, \phi_{tot} \, \rho \, E_{saline}$ $\quad E_{saline} = E_{An/At} \, E_{hn/hg} \, E_{\phi e/\phi tot} \, E_v \, E_d$

Applied average reservoir parameters and general efficiency to formation outline

Gridded $\sum_{grid} G_{CO2} = A(LW) \, h_g \, \phi_{tot} \, \rho \, E_{saline}$ $\quad E_{saline} = E_{hn/hg} \, E_{\phi e/\phi tot} \, E_v \, E_d$

Applied well log derived reservoir parameters and modified efficiency for each grid block

IEA, 2009/13. Development of Storage Coefficients for CO2 Storage in Deep Saline Formations, IEA Green house Gas R&D Programme (IEA GHG) October.

Gorecki, C.D., Sorensen, J.A., Bremer, J.M., Knudsen, D.J., Smith, S.A., Steadman, E.N., Harju, J.A., 2009. Development of storage coefficients for determining the effective CO2 storage resource in deep saline formations, Society of Petroleum Engineers International Conference on CO2 Capture, Storage, and Utilization. PE 126444-MS-P., San Diego, California.

Term	Symbol	P_{10}/P_{90} Values by Lithology			Description
		Clastics	Dolomite	Limestone	
Geologic terms used to define the entire basin or region pore volume					
Net-to-Total Area	$E_{An/At}$	0.2/0.8	0.2/0.8	0.2/0.8	Fraction of total basin or region area with a suitable formation.
Net-to-Gross Thickness	$E_{hn/hg}$	0.21/0.76*	0.17/0.68*	0.13/0.62*	Fraction of total geologic unit that meets minimum porosity and permeability requirements for injection.
Effective-to-Total Porosity	$E_{\phi e/\phi tot}$	0.64/0.77*	0.53/0.71*	0.64/0.75*	Fraction of total porosity that is effective, i.e., interconnected.
Displacement terms used to define the pore volume immediately surrounding a single well CO_2 injector.					
Volumetric Displacement Efficiency	E_V	0.16/0.39*	0.26/0.43*	0.33/0.57*	Combined fraction of immediate volume surrounding an injection well that can be contacted by CO_2 and fraction of net thickness that is contacted by CO_2 as a consequence of the density difference between CO_2 and in-situ water.
Microscopic Displacement Efficiency	E_d	0.35/0.76*	0.57/0.64*	0.27/0.42*	Fraction of pore space unavailable due to immobile *in-situ* fluids.

*Values from IEA (2009)/Gorecki (2009)

Basin/Regional Terms

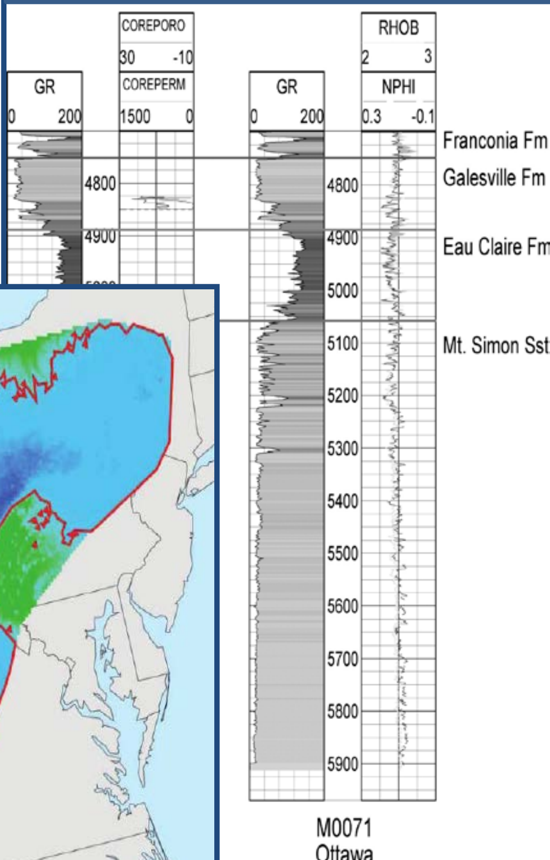
What fraction of basin can you use?

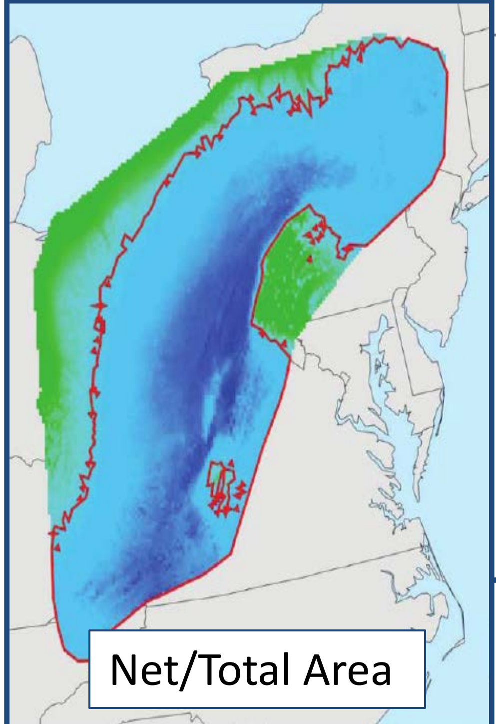
– **Net/Gross Area:** Fraction of basin area with suitable formation

– **Net/Gross Thickness:** Fraction of basin meeting minimum porosity/permeability

– **Effective/Total Porosity:** Fraction of total pore space that is interconnected

Net/Gross Thickness

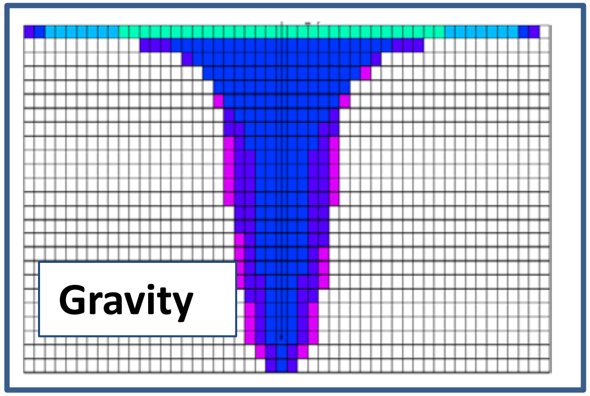


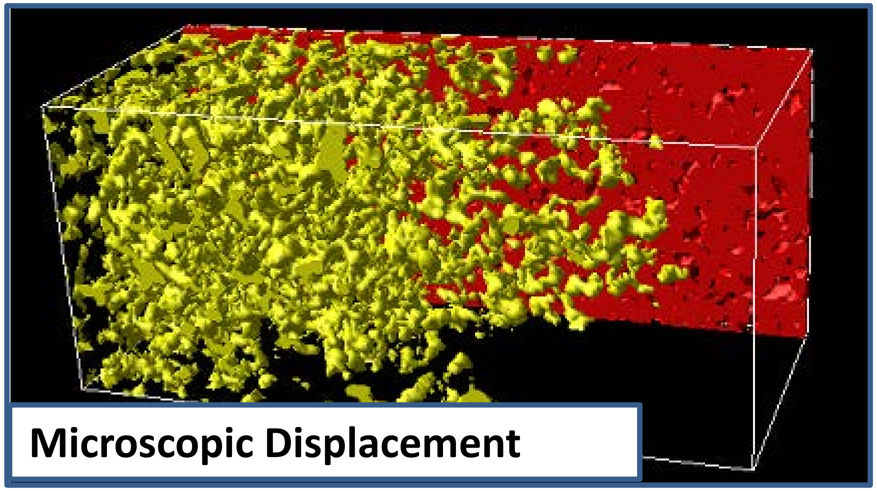


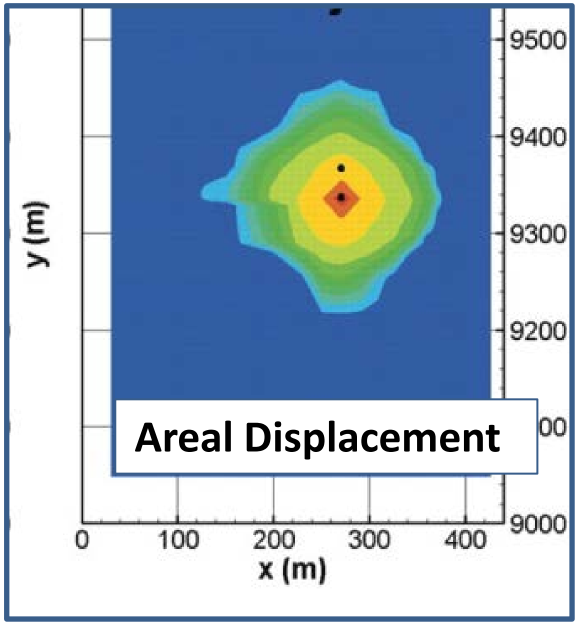
Net/Total Area

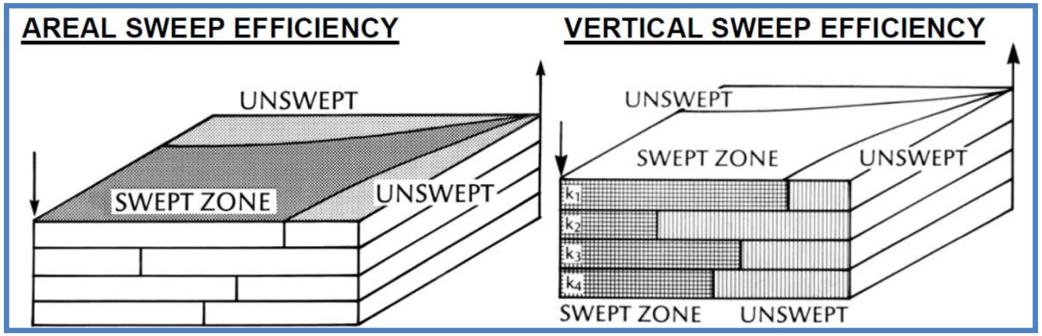
Displacement Terms

- Areal displacement
- Vertical displacement
- Gravity displacement
- Microscopic displacement



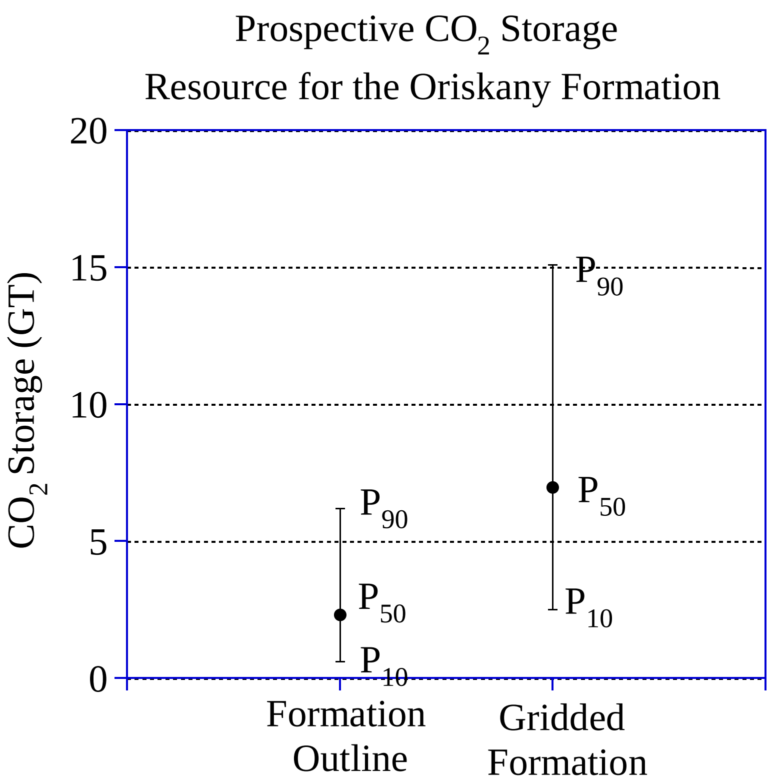


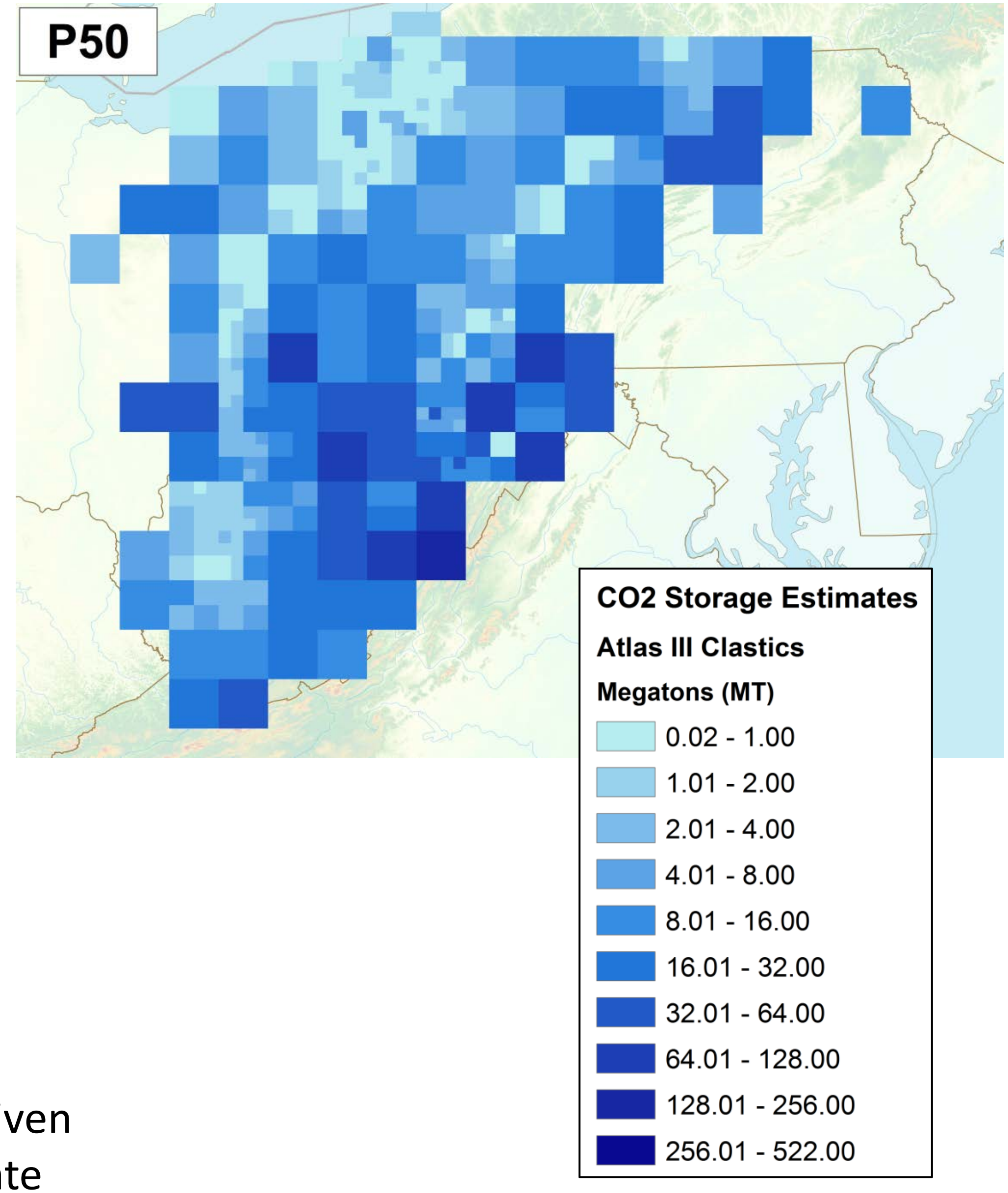




Source: Doughty, Christine. "Modeling Supercritical Carbon Dioxide Injection in Heterogeneous Porous Media." *Vadose Zone Journal* 3:837-847 (2004) © 2004 Soil Science Society of America. Earth Sciences Division, LBNL, 1 Cyclotron Rd., MS 90-1116, Berkeley, CA 94720, USA . Corresponding author (cadoughty@lbl.gov)

Data Driven CO_2 Storage Estimates





Quick Estimate

Data Driven Estimate

Data Driven CO_2 Storage Estimates
Key Observations

Formation Outline:

- General efficiency factors are applied if there is not adequate subsurface data to populate a grid approach

Gridded Formation:

- Use of multiple data points helps drive identification of key spatial trends
  - Areas of high to low potential storage capacity within a given formation/basin

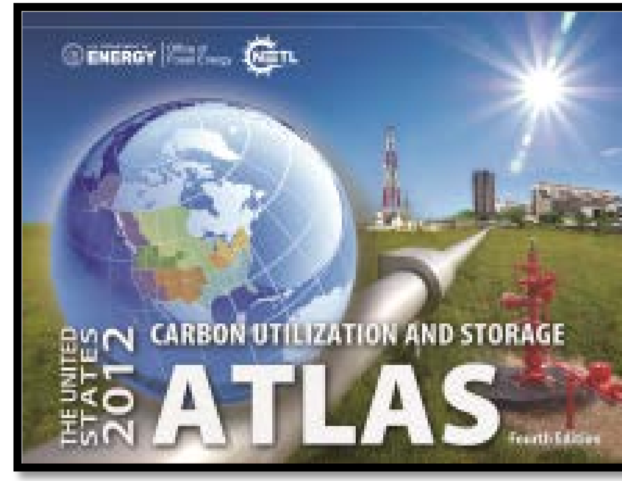
Oriskany Formation:

- *Gridded Approach* using in situ, wellbore data appears to provide higher storage estimates than using the *Formation Outline*
  - in situ data it will help constrain and improve estimates which should drive estimates up for some areas and down for others.

Data Driven Approach:

- To refine storage estimates, enough geologic data must be available to reduce or eliminate the dependency on efficiency factors

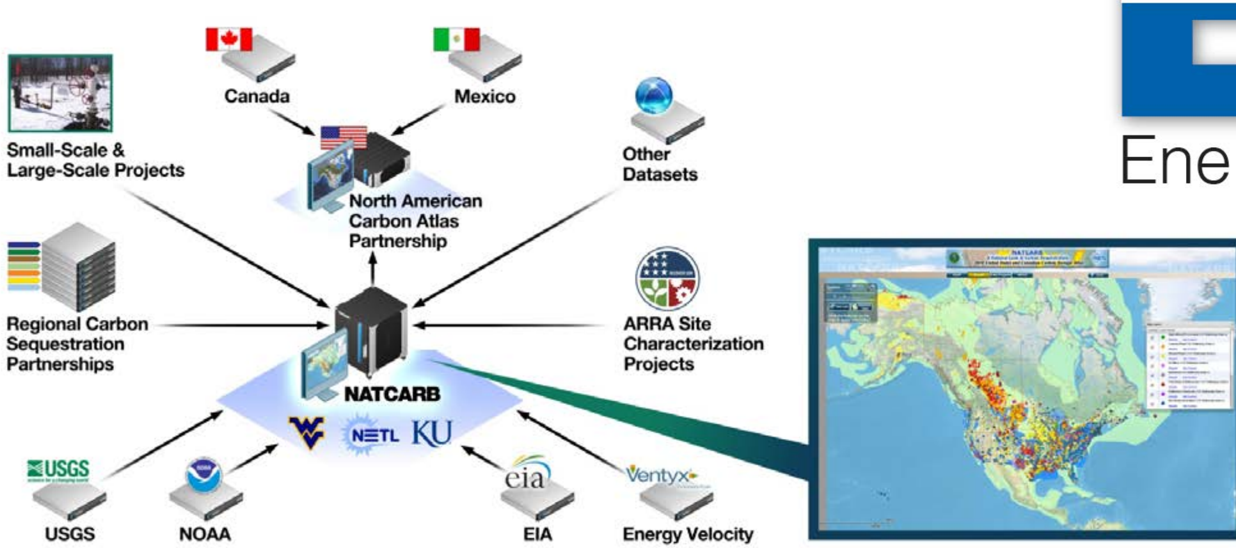
Summary

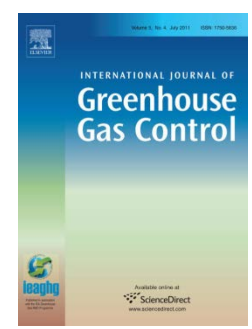


- High-level assessments of potential CO_2 storage reservoirs in the United States and Canada at the regional and national scale.
- Geologic formations:
  - oil and gas reservoirs
  - saline formations
  - unmineable coal seams
  - basalt formations
  - organic-rich shale basins
- Based on physically accessible pore volume without consideration of regulatory or economic constraints.
- Used for broad energy-related government policy and business decisions

http://www.natcarbviewer.org/

EDX
Energy Data eXchange





International Journal of Greenhouse Gas Control **5**: 952–965.

Organization Chart

- Describe project team, organization, and participants.
- **Team:** Angela Goodman, Grant Bromhal, Brian Strazisar, Traci Rodosta, Kelly Rose, Dan Soeder, Bob Dilmore, Isis Fukai, Jen Bauer, Corinne Disenhof, and George Guthrie United States Department of Energy, National Energy Technology Laboratory

- **Task 4.0 – Resource Assessments and Geospatial Resources**
- Method to use available geospatial data to assess storage resource to ±30% accuracy for a variety of storage scenarios (saline aquifers, oil/gas reservoirs, fractured shales, coal seams).
- Continuous improvement of the NATCARB database/website, EDX database/website, and future editions of the Carbon Storage Atlas.

Gantt Chart

- **Carbon Storage**
- **Field Work Proposal (FWP)**
- **Car Stor_FY14**

August 12, 2013

- **Task 4.0 Resource Assessments and Geospatial Resources**
- ***Sub-subtask 4.1.3 Methodology for Assessment of Saline Systems(Goodman & Rose, NETL)***
- Milestone Q3: Review and decide if existing ARRA projects have sufficient data quality and quantity to apply “Variable Grid” Storage methodology.
- **Deliverable Q1: Draft of Feature Page for Atlas V for “Variable Grid” data processing procedure. 2013**

Bibliography

Olga H. Popova, Mitchell Small, Sean T. McCoy, Andrew C. Thomas, Bobak Karimi, Angela Goodman, and Kristin M. Carter "Comparative Analysis of Carbon Dioxide Strorage Resource Assessments Methodologies" **Environmental Geosciences** 19, 3, 105-124, 2012

Goodman, A; Hakala, A; Bromhal, G; Deel, D; Rodosta, T; Frailey, S; Small, M; Allen, D; Romanov, V; Fazio, J; Huerta, N; McIntyre, D; Kutchko, B; Guthrie, G "US DOE methodology for the development of geologic storage potential for carbon dioxide at the national and regional scale" **International Journal of Greenhouse Gas Control** 5, 4, 952-965, 2011.

Goodman, A.; Bromhal, G.; Strazisar, B.; Rodosta, T.; Guthrie, G. *Comparison of Publicly Available Methods for Development of Geologic Storage Estimates for Carbon Dioxide in Saline Formations; NETL-TRS-1-2013;* ***NETL*** **Technical Report Series**; U.S. Department of Energy, National Energy Technology Laboratory: Morgantown, WV*, 2013; p 182.*