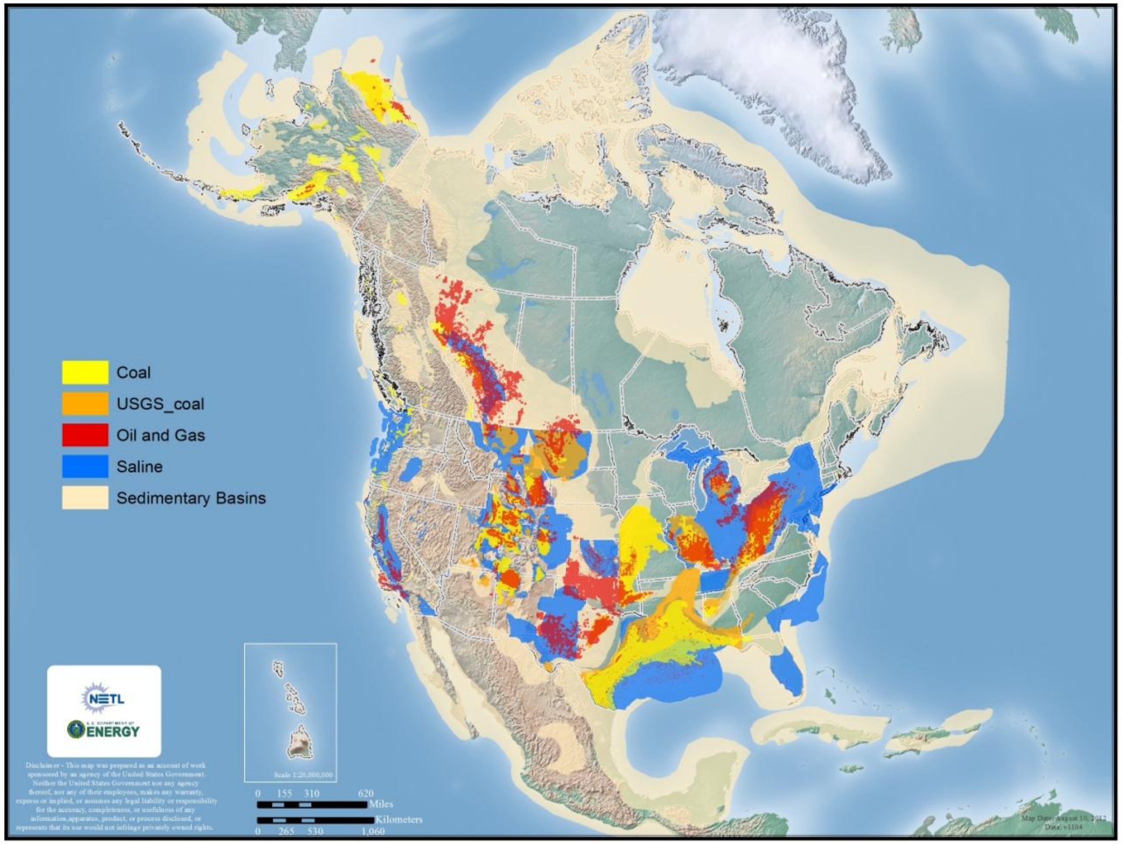
NATIONAL ENERGY TECHNOLOGY LABORATORY

Carbon Storage
R&D Project Review
Meeting Developing
the Technologies
and Building the
Infrastructure for
CCUS

August 21-23, 2012

Pittsburgh, PA



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Comparison of CO_2 Storage Resource Methodologies

Presenter: Angela Goodman

Team: *Angela Goodman, Grant Bromhal, Brian Strazisar, Traci Rodosta and George Guthrie*
United States Department of Energy, National Energy Technology Laboratory

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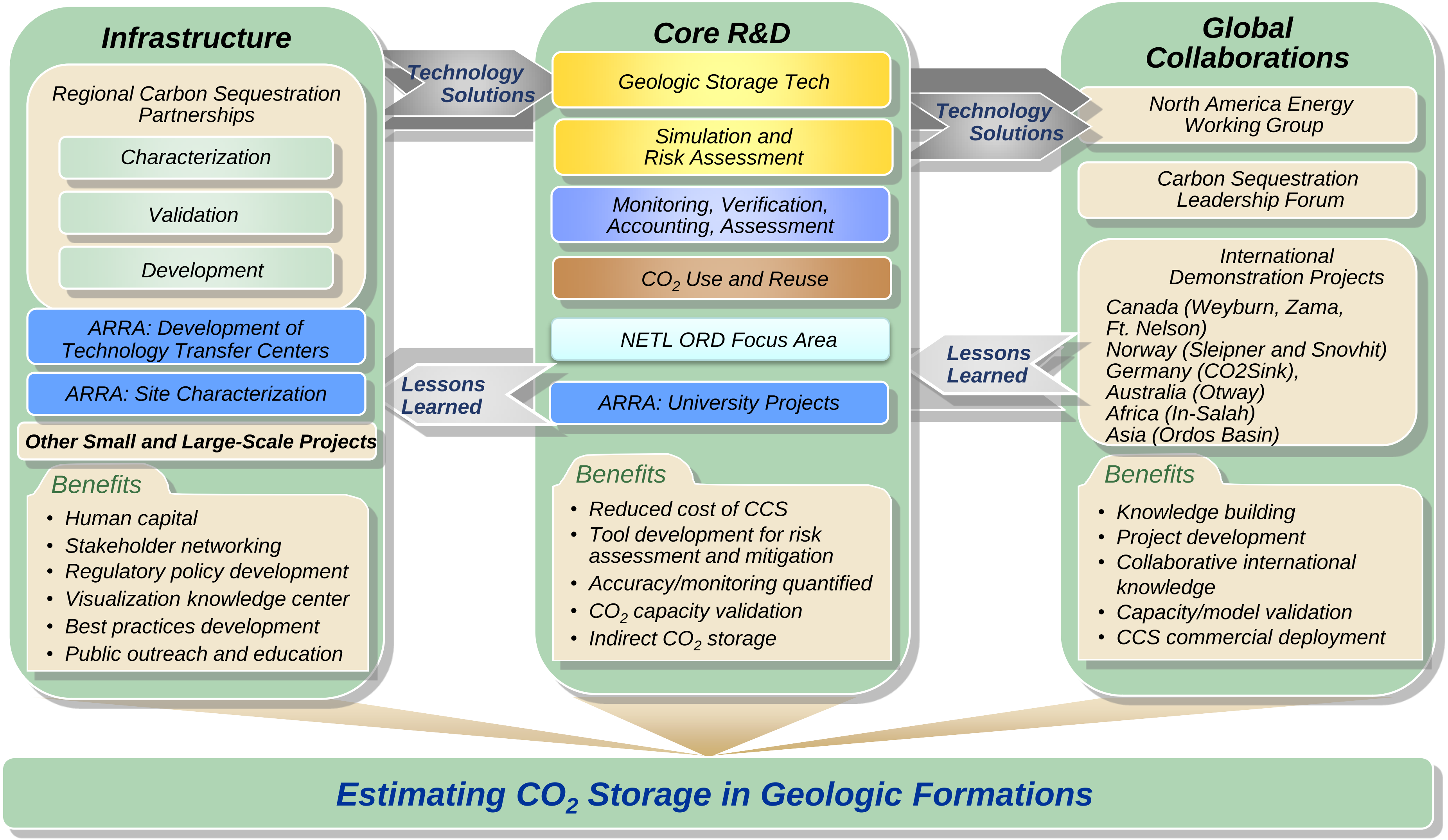
CARBON STORAGE PROGRAM *with ARRA Projects*



Infrastructure

Regional Carbon Sequestration Partnerships

- Characterization
- Validation
- Development

ARRA: Development of Technology Transfer Centers

ARRA: Site Characterization

Other Small and Large-Scale Projects

Benefits

- Human capital
- Stakeholder networking
- Regulatory policy development
- Visualization knowledge center
- Best practices development
- Public outreach and education

Core R&D

- Geologic Storage Tech
- Simulation and Risk Assessment
- Monitoring, Verification, Accounting, Assessment
- CO_2 Use and Reuse
- NETL ORD Focus Area
- ARRA: University Projects

Benefits

- Reduced cost of CCS
- Tool development for risk assessment and mitigation
- Accuracy/monitoring quantified
- CO_2 capacity validation
- Indirect CO_2 storage

Global Collaborations

North America Energy Working Group

Carbon Sequestration Leadership Forum

International Demonstration Projects

Canada (Weyburn, Zama, Ft. Nelson)
Norway (Sleipner and Snovhit)
Germany (CO2Sink),
Australia (Otway)
Africa (In-Salah)
Asia (Ordos Basin)

Benefits

- Knowledge building
- Project development
- Collaborative international knowledge
- Capacity/model validation
- CCS commercial deployment

Estimating CO_2 Storage in Geologic Formations

High-Level Estimates of CO_2 Storage Potential

National, Regional, Basin, and Formation Scale

- Assess potential for **CCUS technologies** to reduce CO_2 emissions
- Broad **energy-related government policy and business decisions**.
- Identify potential regions to successfully implement CCUS technologies
- 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.
- Until such detailed characterization can be documented, **dependable** high-level CO_2 storage estimates are essential to ensure **successful** widespread deployment of CCUS technologies

Existing CO_2 Storage Estimates

Intergovernmental Panel on Climate Change, 2005

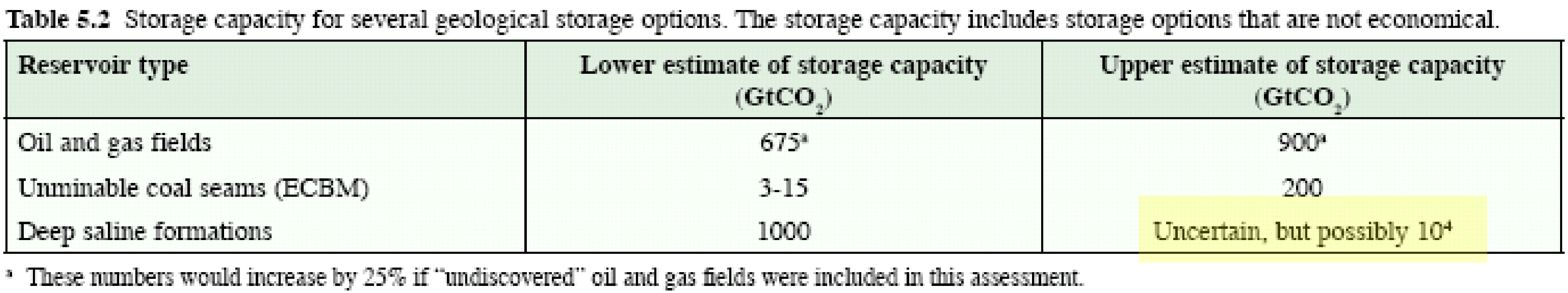
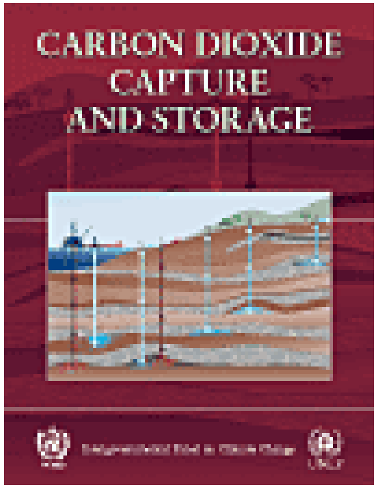


Table 5.2 Storage capacity for several geological storage options. The storage capacity includes storage options that are not economical.

Reservoir type	**Lower estimate of storage capacity ($GtCO_2$)**	**Upper estimate of storage capacity ($GtCO_2$)**
Oil and gas fields	675^a	900^a
Unminable coal seams (ECBM)	3-15	200
Deep saline formations	1000	Uncertain, but possibly 10^4

[a] These numbers would increase by 25% if "undiscovered" oil and gas fields were included in this assessment.



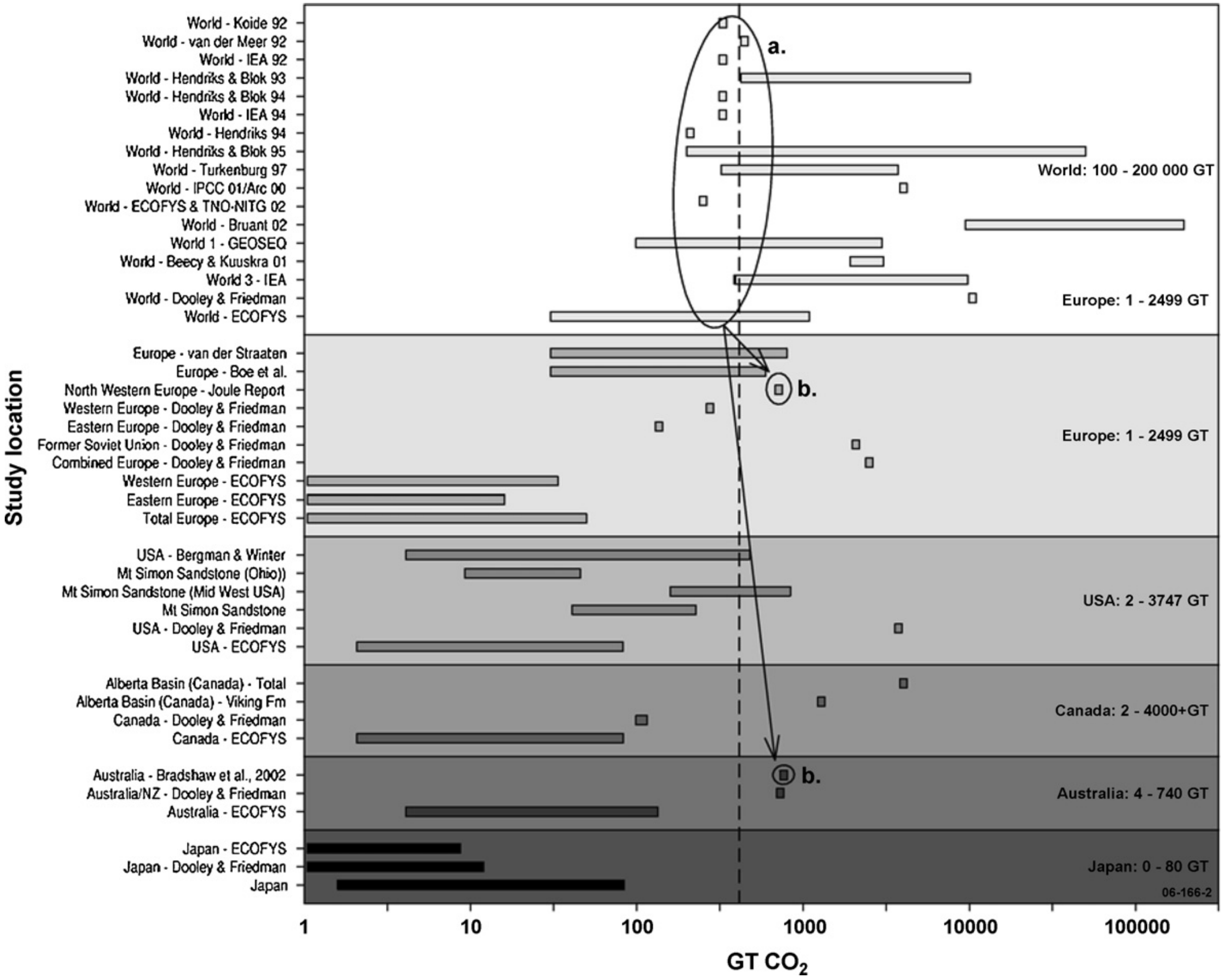
CARBON DIOXIDE CAPTURE AND STORAGE

Existing CO_2 Storage Estimates

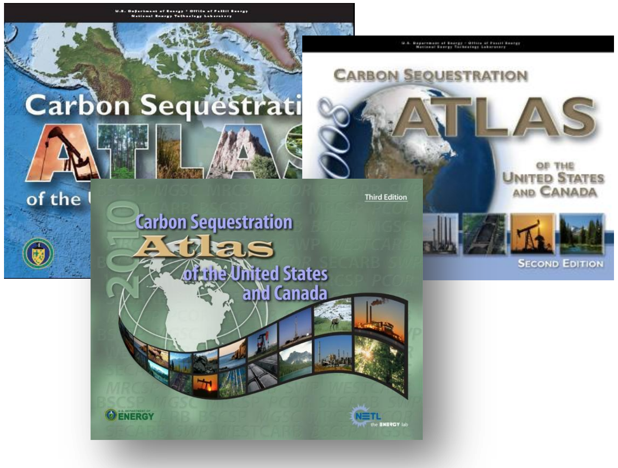
Inconsistent CO_2 Storage Estimates up to 2006

- Highly variable and contradictory

- Compiled in 2007 by Bradshaw et al. *IJGGC* (2007) 62-68 CO2 Storage Capacity Estimation: Issues and Development of Standards



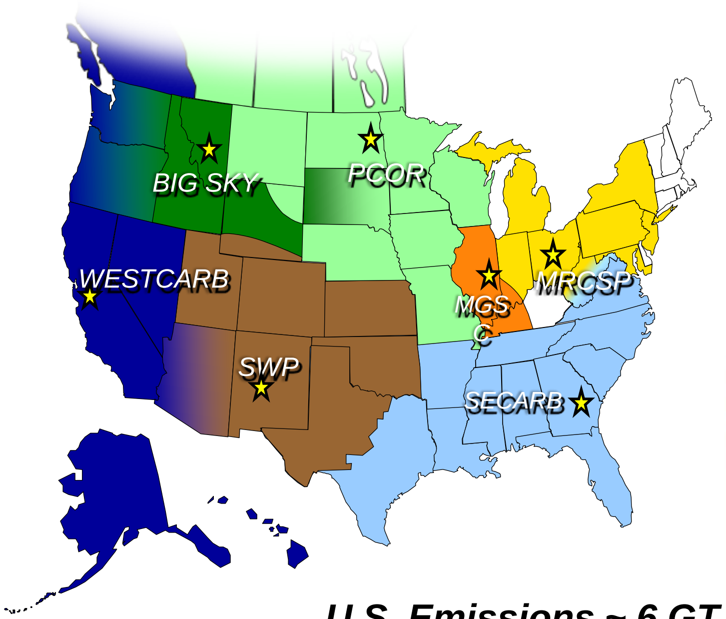
Examples of Recent CO_2 Storage Estimates (post 2007)



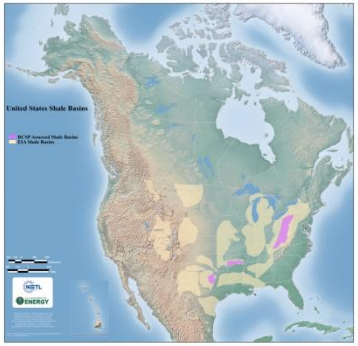
Atlas I - March 2007
Atlas II - November 2008
Atlas III - November 2010
Atlas IV – November 2012

Distributed by:

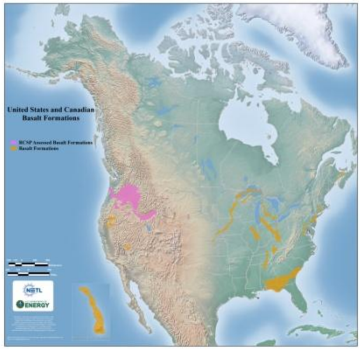
- Hard-copy: CCUS Atlas of the United States and Canada
- Peer-reviewed Journal: Int. J. Greenhouse Gas Control 5 (2011) 952-965
- Web-served geographic information system: NATCARB



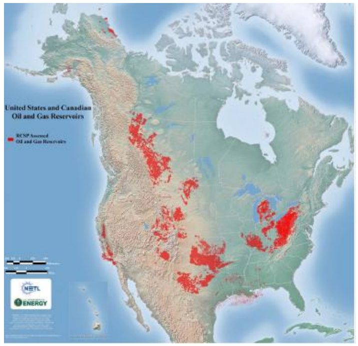
U.S. Emissions ~ 6 GT CO_2/yr (all sources)



Organic-Rich Shale



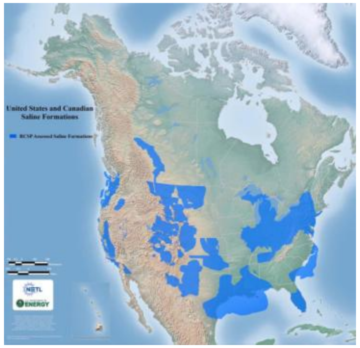
Basalt Formations



Oil and Gas Fields

143-155 GT CO_2

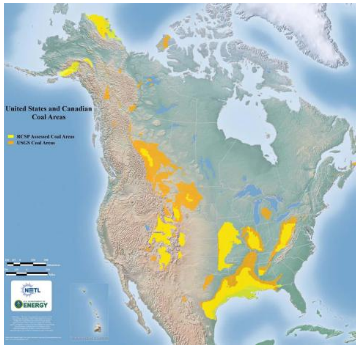
Storage Resource



Saline Formations

1,653 - 20,213 GT CO_2

Storage Resource



Unmineable Coal Seams

60-117 GT CO_2

Storage Resource

Examples of Recent CO_2 Storage Estimates (post 2007)

North American Carbon Atlas Partnership

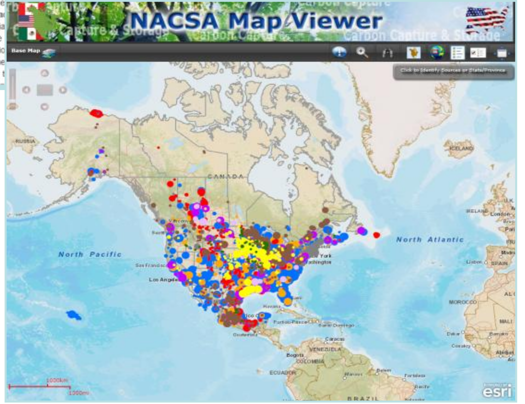
First coordinated effort between Canada, Mexico, and the United States to jointly publish a resource of data and information on CCS technologies, pressing issues, and current progress toward solutions

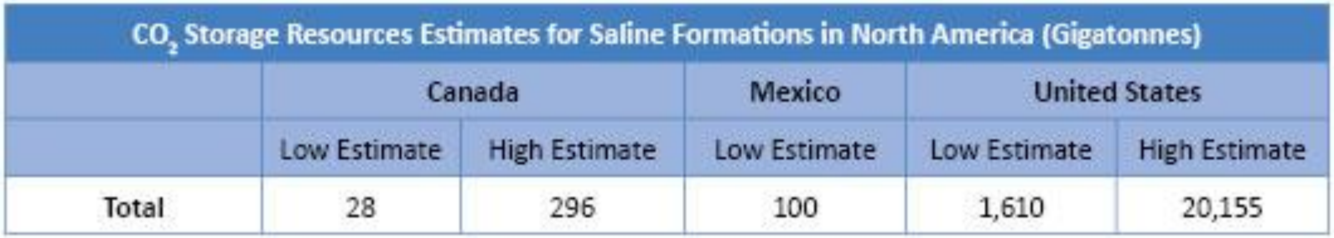
- **NACAP's Objective:**
  - Identify, gather, and ***share*** data of CO_2 sources and geologic storage potential
- **Development of this GIS-based CO_2 sources and storage database**
- **3 North American Products (April 2012):**
  - NACSA website (http://www.nacsap.org/) – online version of NACSA, links to resources (English, Spanish, and French)

About Us

Foreword

Natural Resources Canada, the Mexican Secretariat of Energy, and the U.S. Department of Energy are proud to release the North American Carbon Storage Atlas (NACSA). Production of this Atlas is the result of cooperation and coordination among carbon storage e





CO_2 Storage Resources Estimates for Saline Formations in North America (Gigatonnes)					
	Canada		Mexico	United States	
	Low Estimate	High Estimate	Low Estimate	Low Estimate	High Estimate
Total	28	296	100	1,610	20,155

Examples of Recent CO_2 Storage Estimates (post 2007)

- **Estimation of CO_2 Aquifer Storage Potential in Japan** *Takahashi et al. Energy Procedia 1 (2009) 2631-2638*

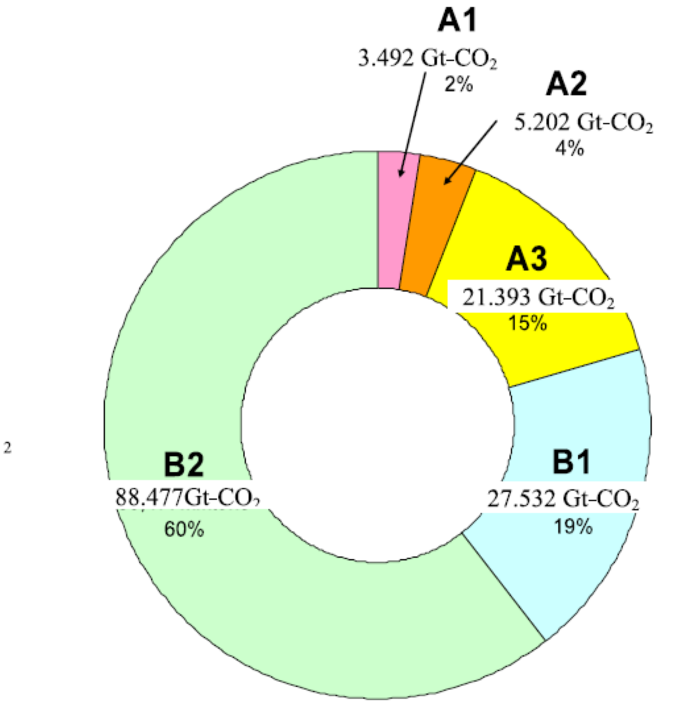


Figure-2 Comparison of estimated CO_2 storage capacity for each storage category in J

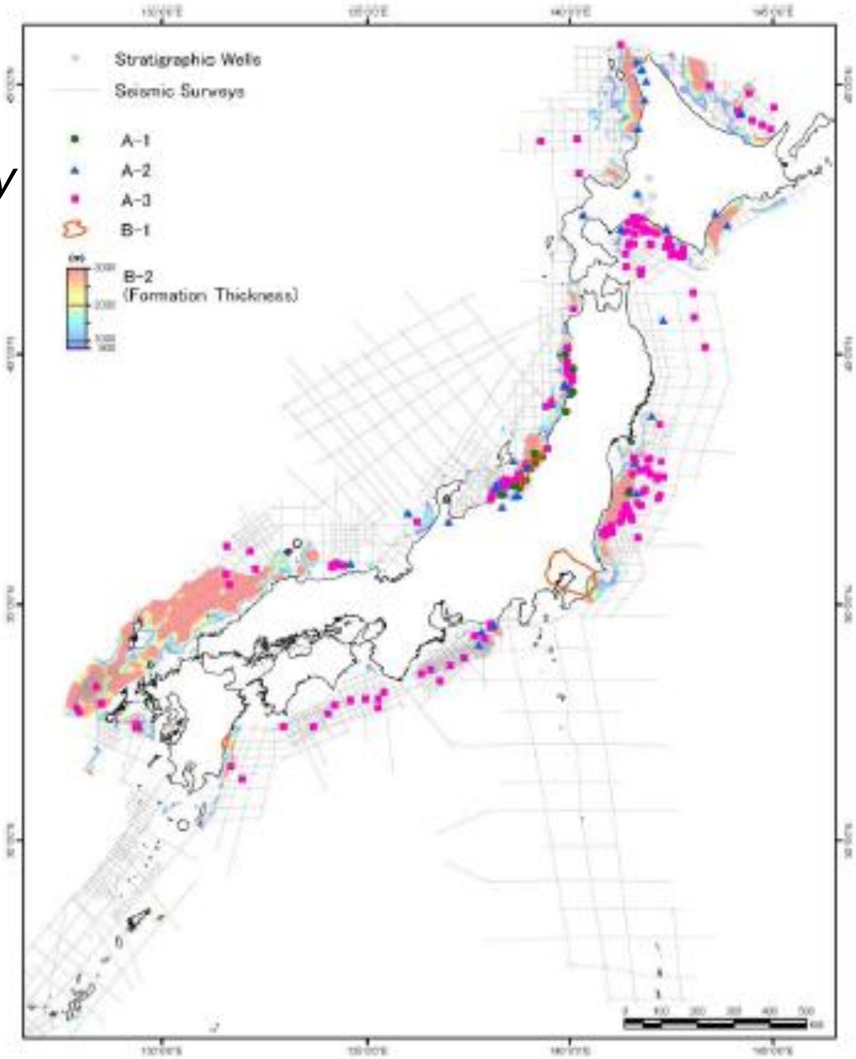


Figure3 Distribution map of CO_2 storage capacity for each storage category in Japan

Examples of Recent CO_2 Storage Estimates (post 2007)

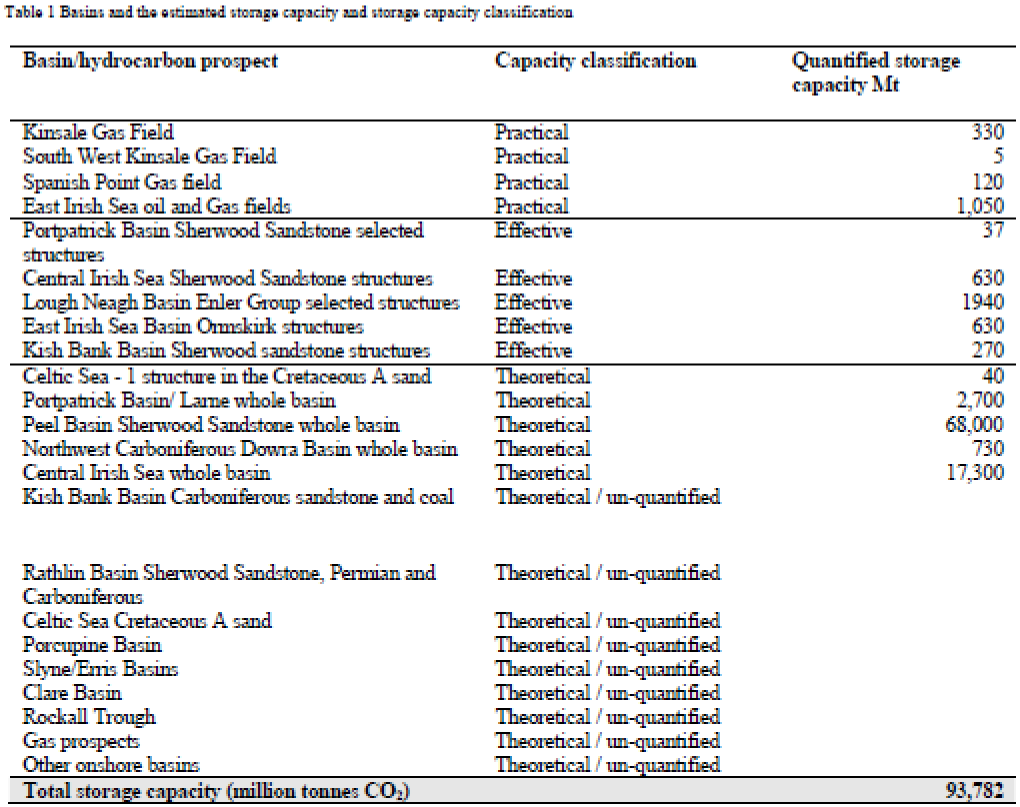


Table 1 Basins and the estimated storage capacity and storage capacity classification

Basin/hydrocarbon prospect	Capacity classification	Quantified storage capacity Mt
Kinsale Gas Field	Practical	330
South West Kinsale Gas Field	Practical	5
Spanish Point Gas field	Practical	120
East Irish Sea oil and Gas fields	Practical	1,050
Portpatrick Basin Sherwood Sandstone selected structures	Effective	37
Central Irish Sea Sherwood Sandstone structures	Effective	630
Lough Neagh Basin Enler Group selected structures	Effective	1940
East Irish Sea Basin Ormskirk structures	Effective	630
Kish Bank Basin Sherwood sandstone structures	Effective	270
Celtic Sea - 1 structure in the Cretaceous A sand	Theoretical	40
Portpatrick Basin/ Larne whole basin	Theoretical	2,700
Peel Basin Sherwood Sandstone whole basin	Theoretical	68,000
Northwest Carboniferous Dowra Basin whole basin	Theoretical	730
Central Irish Sea whole basin	Theoretical	17,300
Kish Bank Basin Carboniferous sandstone and coal	Theoretical / un-quantified	
Rathlin Basin Sherwood Sandstone, Permian and Carboniferous	Theoretical / un-quantified	
Celtic Sea Cretaceous A sand	Theoretical / un-quantified	
Porcupine Basin	Theoretical / un-quantified	
Slyne/Erris Basins	Theoretical / un-quantified	
Clare Basin	Theoretical / un-quantified	
Rockall Trough	Theoretical / un-quantified	
Gas prospects	Theoretical / un-quantified	
Other onshore basins	Theoretical / un-quantified	
Total storage capacity (million tonnes CO_2)		**93,782**

age sites

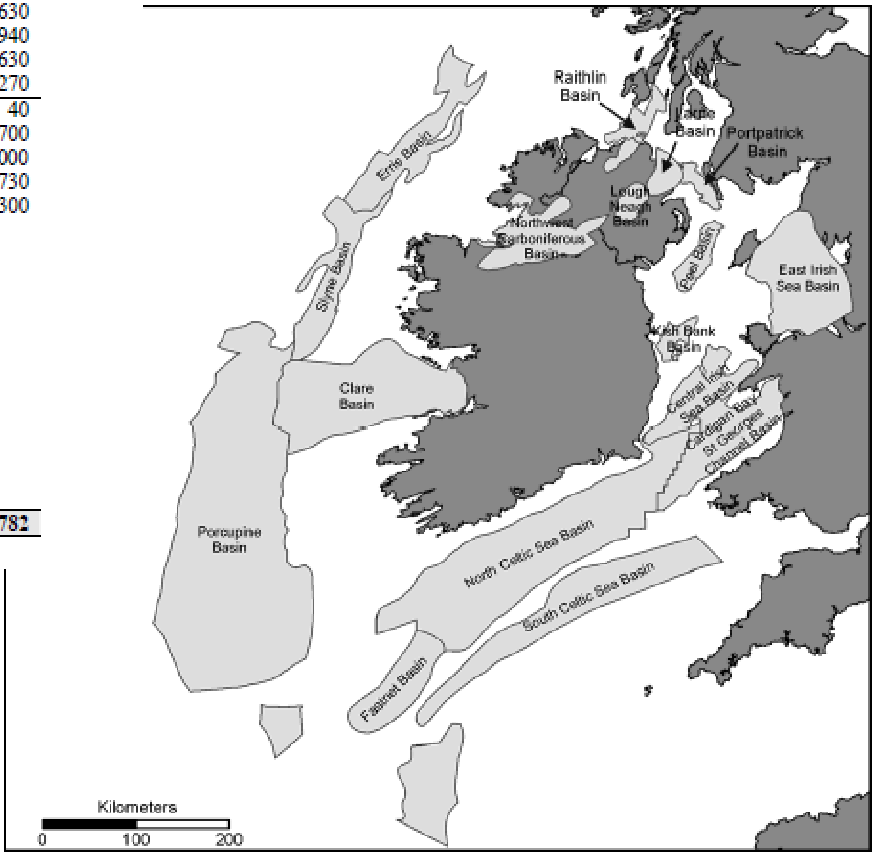


Figure 1 All-island Ireland sedimentary basins examined for this study

- **Assessment of potential for geological storage of carbon dioxide in Ireland and Northern Ireland** *Lewis et al. Energy Procedia 1 (2009) 2655-2622*

Examples of Recent CO_2 Storage Estimates (post 2007)

Table 1. CO_2 storage capacity in the Lower Cretaceous, Lower Jurassic and Lower Triassic aquifers and parameters used for calculation

Formation	Area [km^2]	Porosity [%]	Net gross ratio [%]	ρ_{CO2} [kg/m^3]	Storage capacity [Mt]
Lower Cretaceous	24,562.0	20.5	40	800	7,646.9
Lower Jurassic	70,106.0	17.3	60	700	43,825.7
Lower Triassic	112,036.0	9.7	70	600	26,494.1

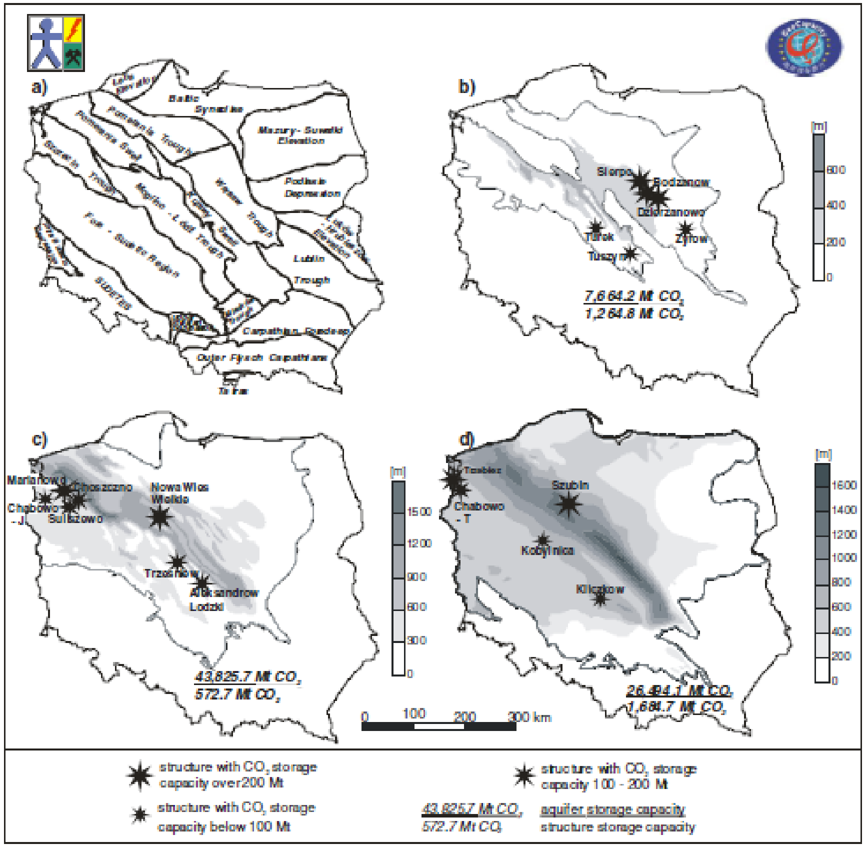


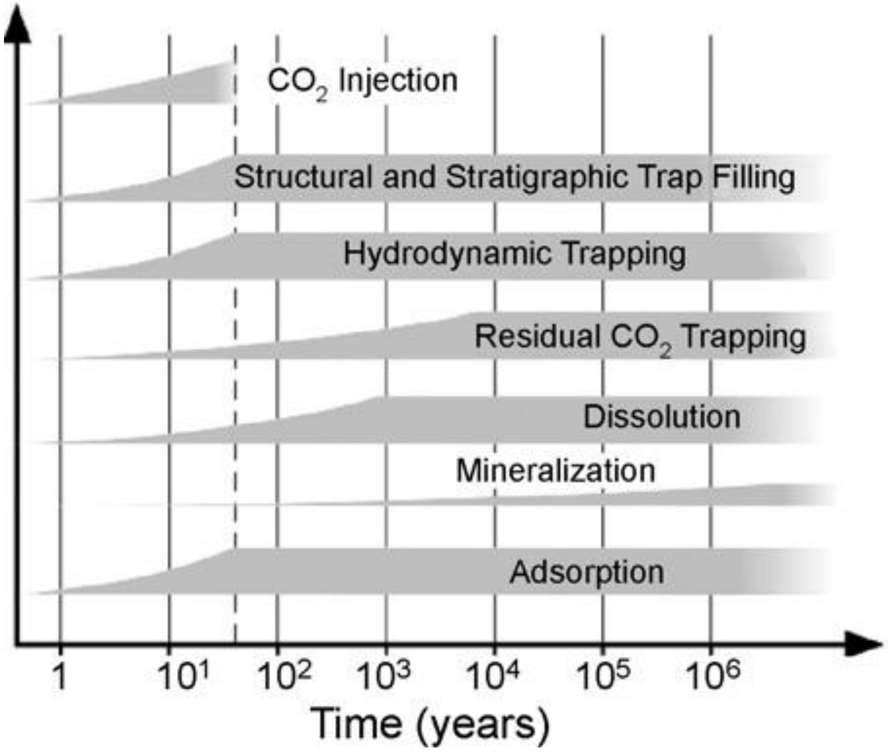
Fig. 1. Tectonical sketch of geological units in Poland (after Pożaryski [5]) (a) and thickness maps of the Lower Cretaceous (b), Lower Jurassic (c) and Lower Trissic aquifers (d) with geological structures selected to CO_2 storage

Deep aquifers and geological structures suitable for CO_2 storage

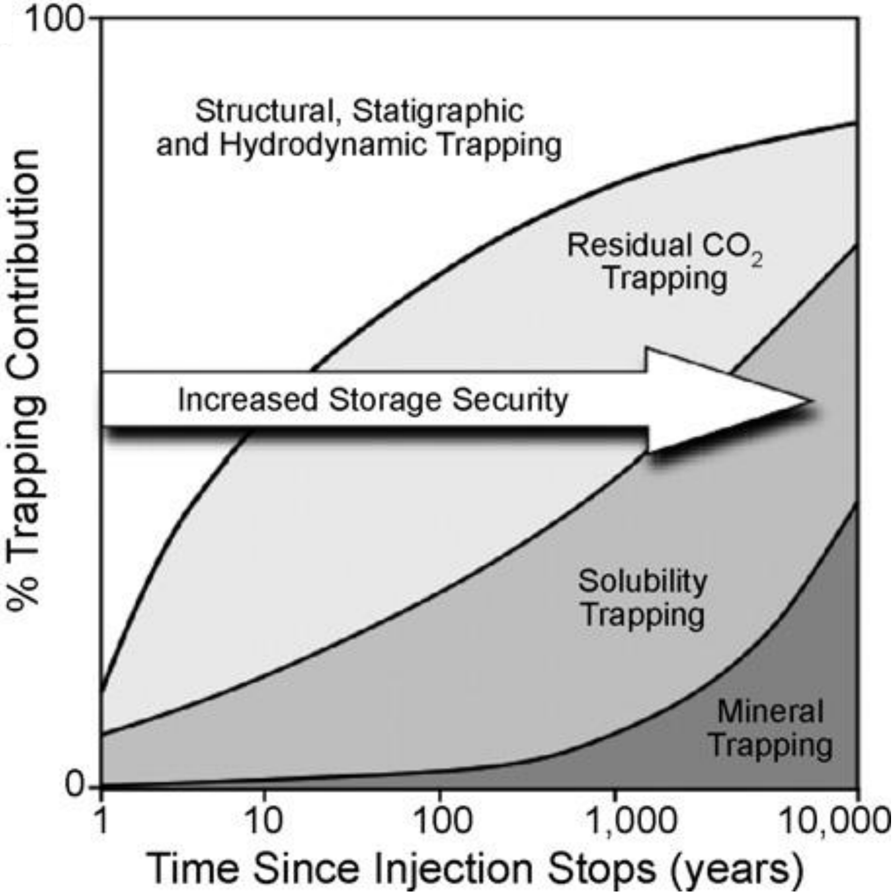
- CO_2 Storage Capacity of Deep Aquifers and Hydrocarbon Fields in Poland – EU GeoCapacity Project Results *Radoslaw et al. Energy Procedia 1 (2009) 2671-2677*

Time Dependency of Trapping Mechanisms Involved in CO_2 Geological Storage

Operating Time Frame



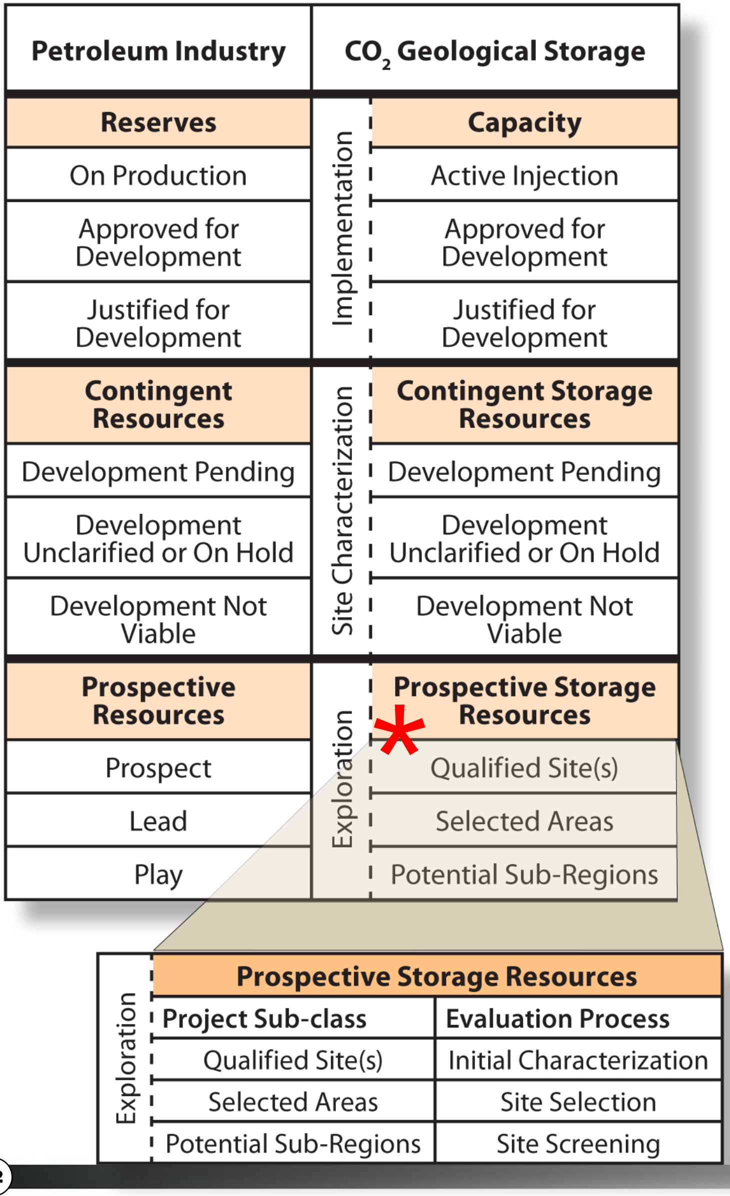
Storage Security



Bachu et al. Int. J. Greenhouse Gas Control 1 (2007) 430-443

CO_2 Storage Classification

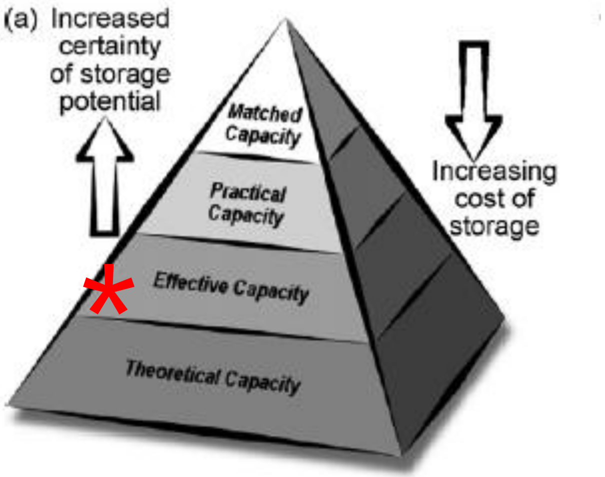
2010 DOE Storage Resource Estimates



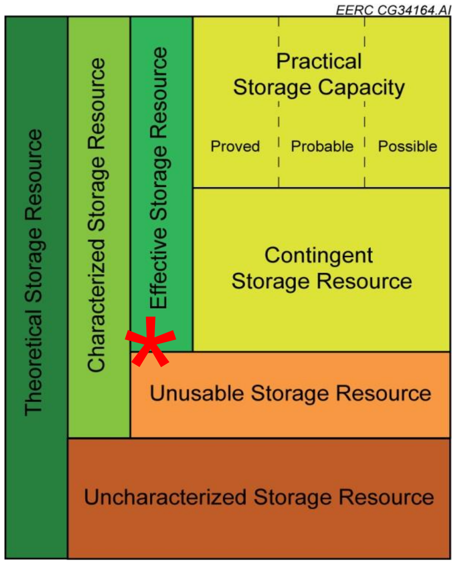
Petroleum Industry		CO_2 Geological Storage
Reserves	Implementation	**Capacity**
On Production		Active Injection
Approved for Development		Approved for Development
Justified for Development		Justified for Development
Contingent Resources	Site Characterization	**Contingent Storage Resources**
Development Pending		Development Pending
Development Unclarified or On Hold		Development Unclarified or On Hold
Development Not Viable		Development Not Viable
Prospective Resources	Exploration	**Prospective Storage Resources**
Prospect		Qualified Site(s)
Lead		Selected Areas
Play		Potential Sub-Regions

	Prospective Storage Resources	
Exploration	**Project Sub-class**	**Evaluation Process**
	Qualified Site(s)	Initial Characterization
	Selected Areas	Site Selection
	Potential Sub-Regions	Site Screening

CSLF Techno-Economic Resource Pyramid



IEA-GHG Storage Classification

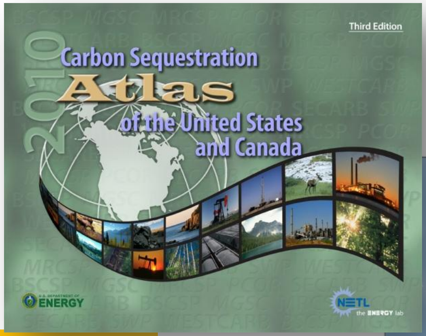


Comparison of CO_2 Storage Methodologies for Saline Formations

- ***2010 Atlas*** presents national scale CO_2 storage resource estimates of how much CO_2 can be stored in deep brine-filled formations
- How do other CO_2 storage estimates compare for **different methodologies**?
- **Trapping Mechanisms Considered?**
- **Scale**
  - Country?
  - Basin?
  - Regional?
  - Site Specific?

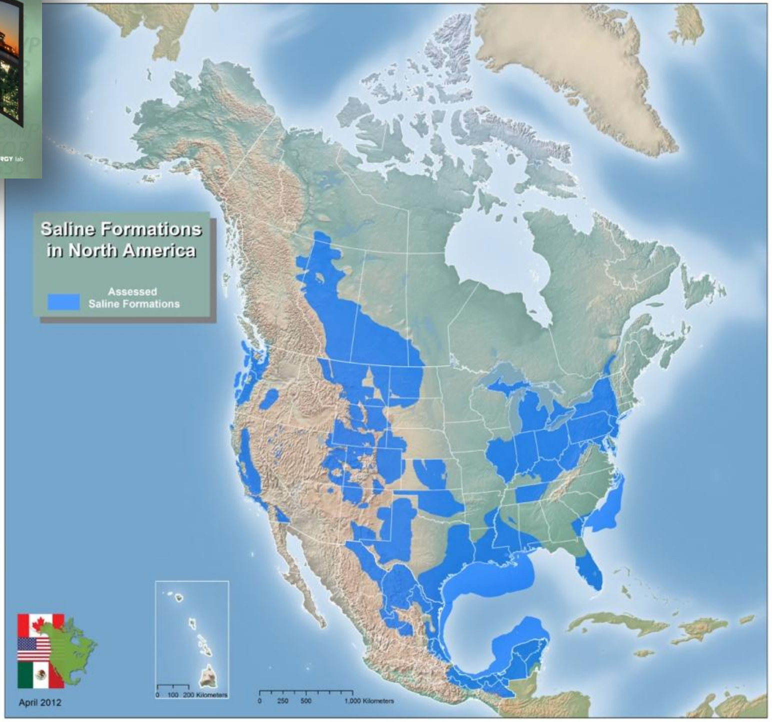
2010 CO2 Resource Estimates by Partnership

	Saline Formations	
	Low	**High**
	Billion Metric Tons of CO_2	Billion Metric Tons of CO_2
Big Sky	221	3,041
MGSC	12	160
MRCSP	46	183
PCOR	165	165
SECARB	908	12,527
SWP	219	3,013
WESTCARB	82	1,124
Total	1,653	20,213



Saline Formations

1,653 - 20,213 GT CO_2 Storage Resource



CO_2 Storage Methodologies for Open and Closed Systems

Open

CSLF: Bachu et al. 2007

- Carbon Sequestration Leadership Forum [2007, 2008]
- Methodology developed through the CSLF Technical Group Taskforce on CO_2 storage estimates is intended for external users

DOE-NETL Atlas I, II, III (2007, 2008, 2010)

- U.S. DOE / NETL [2007, 2008, 2010]
- Methodology developed by the DOE/NETL is intended for external users such as the Regional Carbon Sequestration Partnerships in high-level assessments of potential CO_2 storage reservoirs in the US and Canada.

USGS: Brennan et al. (2010)

- U.S. Geological Survey [2009, 2010]
- Methodology developed by the USGS is intended to be used by the USGS's geologists for assessments at scales ranging from regional to sub-basinal in which storage assessment units are defined on the basis of common geologic and hydrologic characteristics.

CGSS: Spencer et al. (2010)

- CO_2 Geological Storage Solutions [2010]
- Methodology developed for the 2009 Queensland CO_2 Geological Storage Atlas is intended for policy makers

Szulczewski et al. (2012)

- Lifetime of Carbon Capture and Storage as A Climate-Change Mitigation Technology [2009, 2012]
- Methodology to account for fluid dynamics and injection-rate constraints for CO_2 storage

Closed

Zhou et al. (2008)

- A Method for Quick Assessment of CO_2 Storage Capacity in Closed and Semi-closed Saline Formations [2008]
- Methodology for quick assessment of CO_2 storage in closed saline formation

CSLF Effective Storage Capacity

- Stems from the Technical Group Taskforce on CO_2 storage estimates led by the Carbon Sequestration Leadership Forum.
- Effective Storage Capacity, called previously ‘‘Realistic Capacity’’ represents a subset of the theoretical capacity and is obtained by applying a range of technical (geological and engineering) cut-off limits to a storage capacity assessment, including consideration of that part of theoretical storage capacity that can actually be physically accessed (structural and stratigraphic trapping). This estimate usually changes with the acquisition of new data and/or knowledge. ***Bachu et al. Int. J. Greenhouse Gas Control 1 (2007) 430-443***
- Open boundaries / formation scale

$$M_{CO2} = Ah\phi(1-S_{wirr})\rho_{CO2}C_c$$

IEA-GHG 2010 Saline Capacity Coefficients for the Formation Level

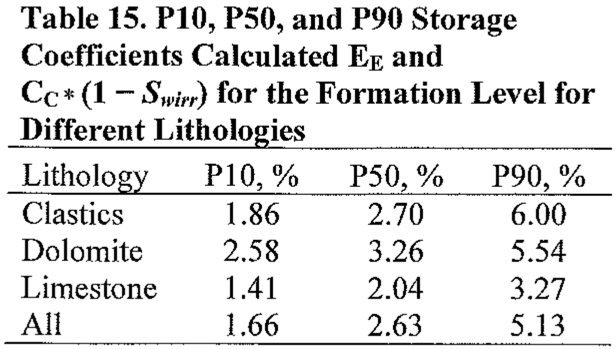


Table 15. P10, P50, and P90 Storage Coefficients Calculated E_E and $C_{C*}(1-S_{wirr})$ for the Formation Level for Different Lithologies

Lithology	P10, %	P50, %	P90, %
Clastics	1.86	2.70	6.00
Dolomite	2.58	3.26	5.54
Limestone	1.41	2.04	3.27
All	1.66	2.63	5.13

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.

EERC *Energy & Environmental Research Center*
EERC . . . The International Center for Applied Energy Technology®

U.S. DOE / NETL CO_2 Storage Resource Estimates

Volumetric Approach

- *Saline Formation CO_2 Storage Resource Estimates*

$$G_{CO2} = \underbrace{A_t\, h_g\, \phi_{tot}}_{\text{total pore volume}}\ \underbrace{\rho}_{\text{fluid properties}}\ \underbrace{E_{saline}}_{\text{efficiency}}$$

Parameter	**Units***	**Description**
G_{CO2}	M	Mass estimate of saline formation CO_2 storage resource.
A_t	L^2	Geographical area that defines the basin or region being assessed for CO_2 storage.
h_g	L	Gross thickness of saline formations for which CO_2 storage is assessed within the basin or region defined by A.
ϕ_{tot}	L^3/L^3	Total porosity in volume defined by the net thickness.
ρ	M/L^3	Density of CO_2 evaluated at pressure and temperature that represents storage conditions anticipated for a specific geologic unit averaged over h_g and A_t.
E_{saline}	L^3/L^3	CO_2 storage efficiency factor that reflects a fraction of the total pore volume that is filled by CO_2.

* L is length; M is mass

*Goodman, A., A. Hakala, et al. (2011). "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 **5**: 952–965.*

CO_2 Storage Resource Estimates

- Available pore volume of a given formation that is accessible to CO_2 injected through drilled and completed wellbores
- Only physical trapping of CO_2 is considered – structural and hydrodynamic trapping mechanisms
- Open boundaries / regional scale

ATLAS 2010 Saline Efficiency

Saline Formation Efficiency Factors For Geologic and Displacement Terms $E_{saline} = E_{An/At}\, E_{hn/hg}\, E_{\phi e/\phi tot}\, E_v\, E_d$			
Lithology	P_{10}	P_{50}	P_{90}
Clastics	0.51%	2.0%	5.4%
Dolomite	0.64%	2.2%	5.5%
Limestone	0.40%	1.5%	4.1%

CSLF and DOE-NETL Methodology

- Methods presented by CSLF (2007) and DOE (2007, 2008, 2010) are the same method (Gorecki et al., 2009)
- Any storage volume estimated with one method can be compared to the other, as long as the assumptions made are the same (Gorecki et al., 2009)

Gorecki, C.D., J.A. Sorensen, J.M. Bremer, S.C. Ayash, D.J. Knudsen, Y.I. Holubnyak, S.A. Smith, E.N. Steadman and J.A. Harju, 2009, Development of Storage Coefficients for Carbon Dioxide Storage in Deep Saline Formations, IEA Greenhouse Gas R&D Programme Technical Study 2009/13.

$$V_{CO_2,DOE_E} = A * h * \phi * E_E$$

$$V_{CO_2,CSLF_E} = A * h * \phi * \left(1 - S_{wirr}\right) * C_C$$

$$E_E = C_C * (1 - S_{wirr})$$

$$V_{CO_2,DOE_E} = V_{CO_2,CSLF_E}$$

USGS Technically Accessible Storage Resource Estimate

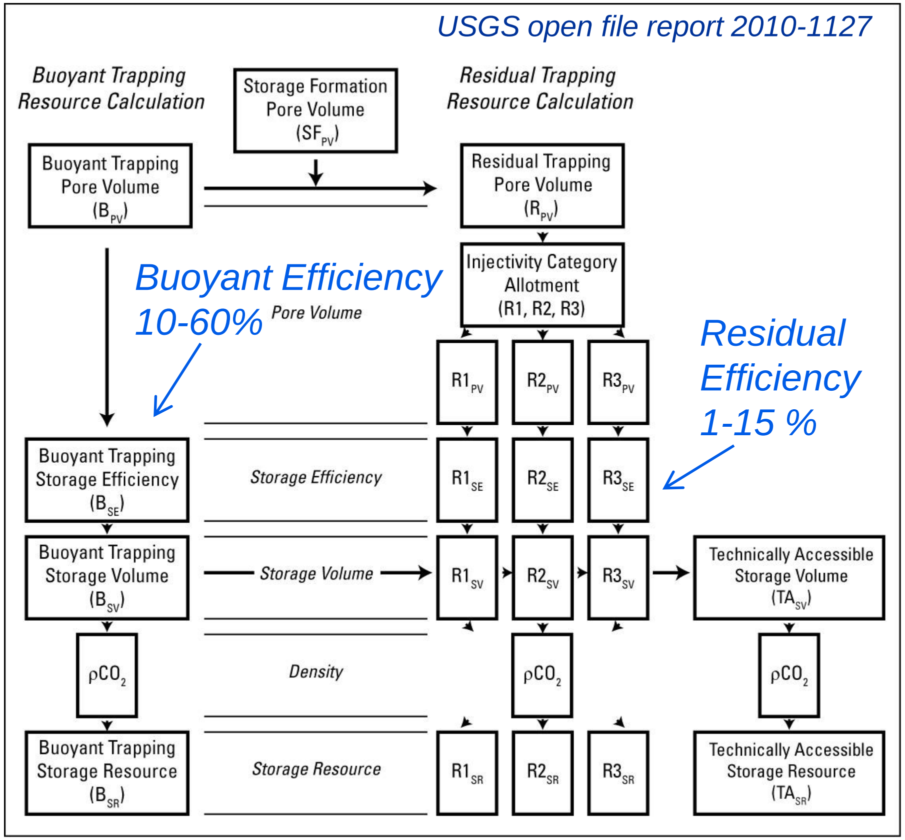
- Stems from 2007 Energy Independence and Security Act (Public Law 110-140)
- The technically accessible storage resource is defined as the mass of CO_2 that can be stored in the pore volume of the storage formation taking into account present-day geologic knowledge and engineering practice and experience.
- Open boundaries / regional to sub-basinal scale
- CO_2 storage is divided into buoyant and residual trapping with classes based on permeability

$$SF_{PV,\ USGS}=\underline{A_{SF}*T_{PI}*\phi_{PI}}$$

Buoyant Trapping

Residual Trapping

USGS open file report 2010-1127



Brennan, S. T., R. C. Burruss, et al. (2010). A Probabilistic Assessment Methodology for the Evaluation of Geologic Carbon Dioxide Storage, U.S. Geological Survey: 1-31 report 2010-1127.

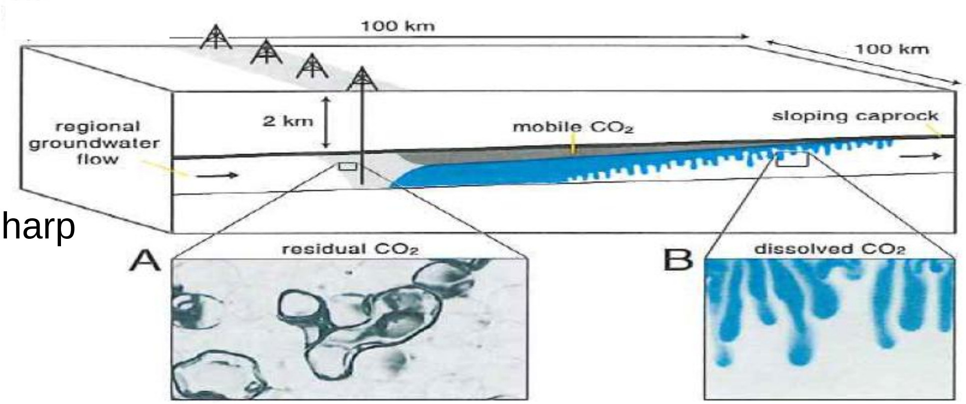
Injectivity Classification Section		Residual Trapping Efficiency			
Class 1	permeability greater than 1 Darcy	Efficiency	1	5	7
Class 2	permeability between 0.001 Darcy to 1 Darcy	Efficiency	1	7	15
Class 3	permeability less than 1 mDarcy	Efficiency	0	0	7

Szulczewski et al. (2012) Migration-limited Capacity

Lifetime of carbon capture and storage as a climate-change mitigation technology

- **Migration-limited Capacity**: injected volume in which the CO_2 plume will reach the boundary of the aquifer and become completely trapped by residual and solubility trapping
- **Pressure-limited Capacity:** limitations due to injection rate
- Methodology considers **residual trapping**, in which zones of CO_2 become immobilized by capillary forces and **solubility trapping**, in which CO_2 dissolves into the groundwater at the **basin scale / open and closed boundaries**

- $C_t = \rho_g L_T W H \phi (1-S_{wc)} 2/\varepsilon_t$



- The major assumptions in the model are:
- (1) the interface between the CO_2 and brine is sharp
- (2) capillary pressure effects are negligible
- (3) the flow is predominantly horizontal (Dupuit approximation)
- (4) CO_2 leakage through the caprock is negligible
- (5) the aquifer is homogeneous, isotropic, and incompressible
- (6) the fluids are incompressible and their properties are constant
- (7) during the dissolution of CO_2 into brine, the total fluid volume is conserved.

Szulczewski, M., C. W. MacMinn, et al. (2012). "Lifetime of carbon capture and storage as a climate-change mitigation technology." Proceedings of the National Academy of Sciences of the United States of America

Zhou et al. (2008)

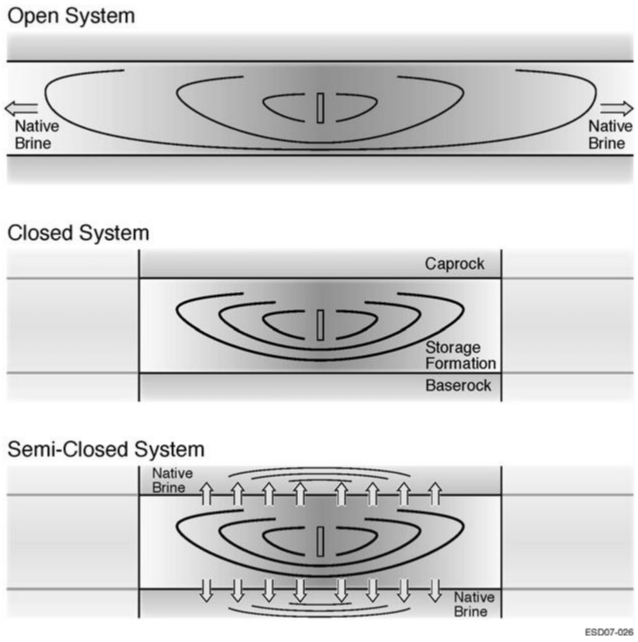
A method for quick assessment of CO_2 storage capacity in closed and semi-closed saline formations

- CO_2 injection into these systems will lead pressure buildup, because an additional volume of fluid needs to be stored
- Injected CO_2 displaces an equivalent volume of native brine, which may either (1) be stored in the expanded pore space due to compression of the rock, (2) be stored in the expanded pore space in the seals, and 3) ~~leakage of brine~~ **(closed boundaries)**
- Provide CO_2 storage estimates at early stages of site selection and characterization, when (1) quick assessments of multiple sites may be needed and (2) site characterization data is sparse

$$
\begin{aligned}
MCO_2(t_I) &= (B_p+B_w)\,\Delta p(t_I)\,\rho\,V_f \\
&= (B_p+B_w)\,\Delta p(t_I)\,\rho\,A\,b\,\phi
\end{aligned}
$$

- maximum storage capacity for a given sustainable pressure buildup, Δp_{max}. (*maximum pressure that the formation can sustain without geomechanical damage*)
- *Treated all parameters stochastically*

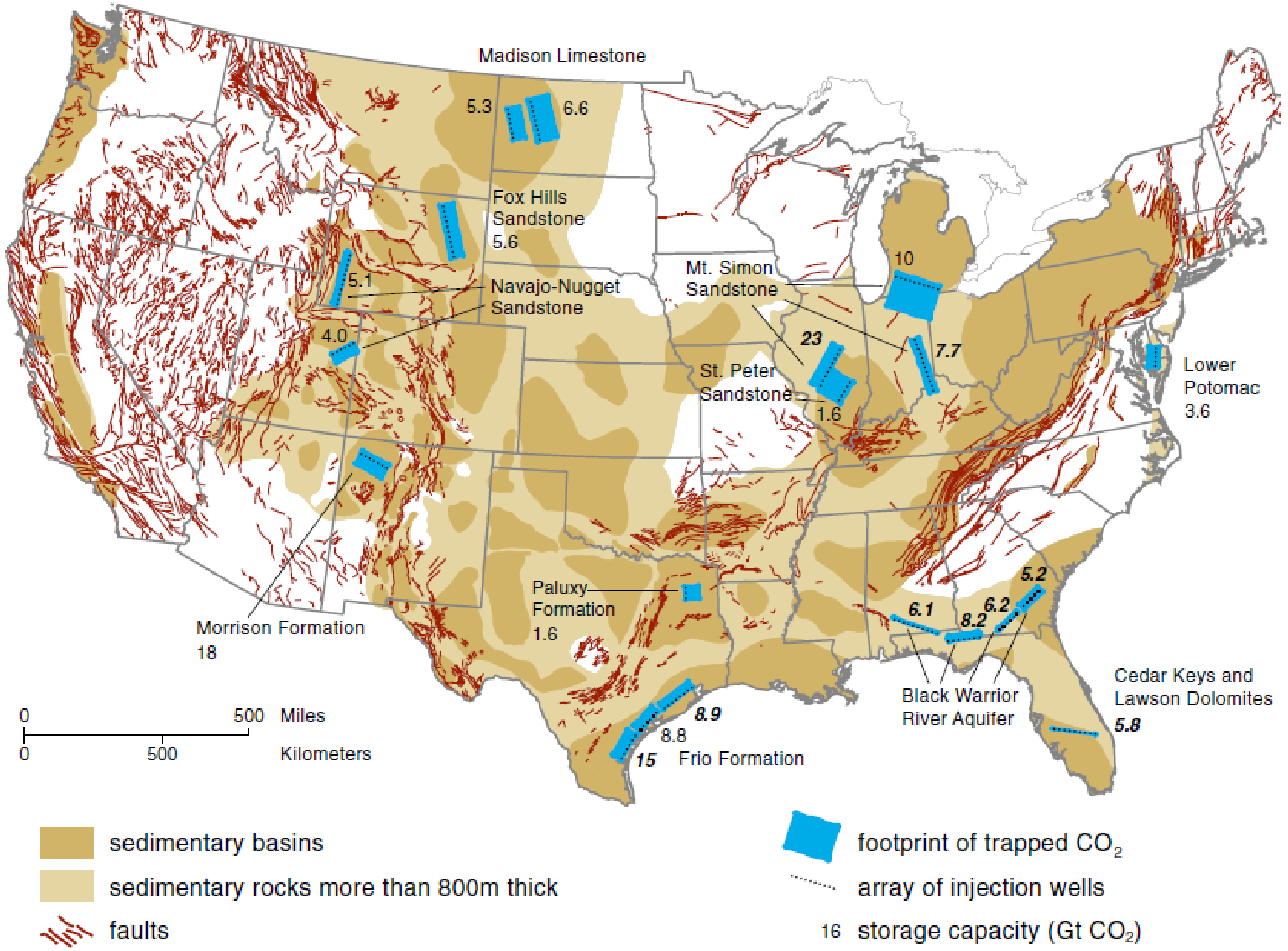
Zhou, Q., J. T. Birkholzer, et al. (2008). "A method for quick assessment of CO2 storage capacity in closed and semi-closed saline formation." International Journal of Greenhouse Gas Control ***2****: 626-639.*



Description of Saline Formation Data Set

10 U.S. Saline Formations characterized by Szulczewski et al. (2012)

Mt. Simon, Black Warrior River, Frio, Madison, Navajo-Nugget, Morrison, Potomac, Fox Hills, Paluxy, St. Peter



Criteria:

(i) The depth must exceed 800 m so that CO_2 is stored efficiently as a high-density, supercritical fluid;

(ii) the aquifer and caprock must be laterally continuous over long distances;

(iii) there must be very few faults that could serve as leakage pathways

Assumption:

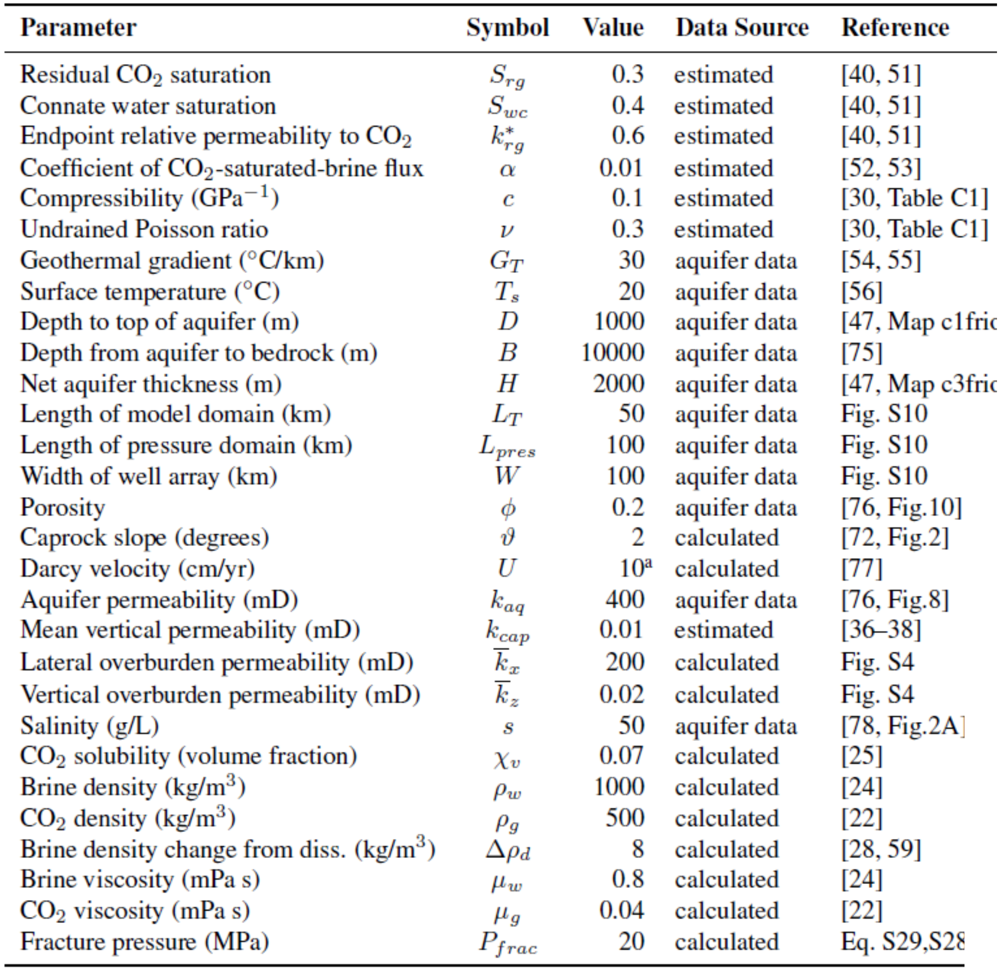
(i) cap rock is linear to ensure no structural trapping, (trapped at the top of an anticline or in a tilted fault block)

Lifetime of carbon capture and storage as a climate-change mitigation technology Michael L. Szulczewski, Christopher W. MacMinn, Howard J. Herzog, and Ruben Juanes *(2012). Proceedings of the National Academy of Sciences of the United States of America*

Saline Storage Formations

Example saline formation data set by Szulczewski et al. (2012)

Table S9: Parameters for Region a of the Frio Formation.



Parameter	Symbol	Value	Data Source	Reference
Residual CO_2 saturation	S_{rg}	0.3	estimated	[40, 51]
Connate water saturation	S_{wc}	0.4	estimated	[40, 51]
Endpoint relative permeability to CO_2	k^*_{rg}	0.6	estimated	[40, 51]
Coefficient of CO_2-saturated-brine flux	α	0.01	estimated	[52, 53]
Compressibility (GPa^{-1})	c	0.1	estimated	[30, Table C1]
Undrained Poisson ratio	ν	0.3	estimated	[30, Table C1]
Geothermal gradient (°C/km)	G_T	30	aquifer data	[54, 55]
Surface temperature (°C)	T_s	20	aquifer data	[56]
Depth to top of aquifer (m)	D	1000	aquifer data	[47, Map c1fric
Depth from aquifer to bedrock (m)	B	10000	aquifer data	[75]
Net aquifer thickness (m)	H	2000	aquifer data	[47, Map c3fric
Length of model domain (km)	L_T	50	aquifer data	Fig. S10
Length of pressure domain (km)	L_{pres}	100	aquifer data	Fig. S10
Width of well array (km)	W	100	aquifer data	Fig. S10
Porosity	ϕ	0.2	aquifer data	[76, Fig.10]
Caprock slope (degrees)	ϑ	2	calculated	[72, Fig.2]
Darcy velocity (cm/yr)	U	10^a	calculated	[77]
Aquifer permeability (mD)	k_{aq}	400	aquifer data	[76, Fig.8]
Mean vertical permeability (mD)	k_{cap}	0.01	estimated	[36–38]
Lateral overburden permeability (mD)	$\overline{k}_x$	200	calculated	Fig. S4
Vertical overburden permeability (mD)	$\overline{k}_z$	0.02	calculated	Fig. S4
Salinity (g/L)	s	50	aquifer data	[78, Fig.2A]
CO_2 solubility (volume fraction)	χ_v	0.07	calculated	[25]
Brine density (kg/m^3)	ρ_w	1000	calculated	[24]
CO_2 density (kg/m^3)	ρ_g	500	calculated	[22]
Brine density change from diss. (kg/m^3)	$\Delta\rho_d$	8	calculated	[28, 59]
Brine viscosity (mPa s)	μ_w	0.8	calculated	[24]
CO_2 viscosity (mPa s)	μ_g	0.04	calculated	[22]
Fracture pressure (MPa)	P_{frac}	20	calculated	Eq. S29,S28

[a] We set the Darcy velocity to 10 cm/yr based on reported ranges for the velocity [77] and
other deep saline aquifers.

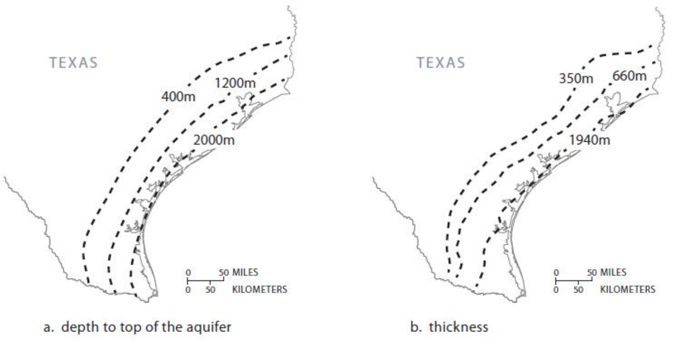


Figure S9: The Frio Formation is located on the east coast of Texas. It dips and thickens toward the coast. (a) Modified from [47, Map c1friog1]. (b) Modified from [47, Map c4friog].

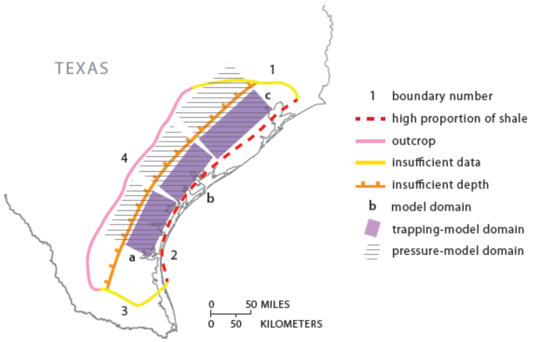
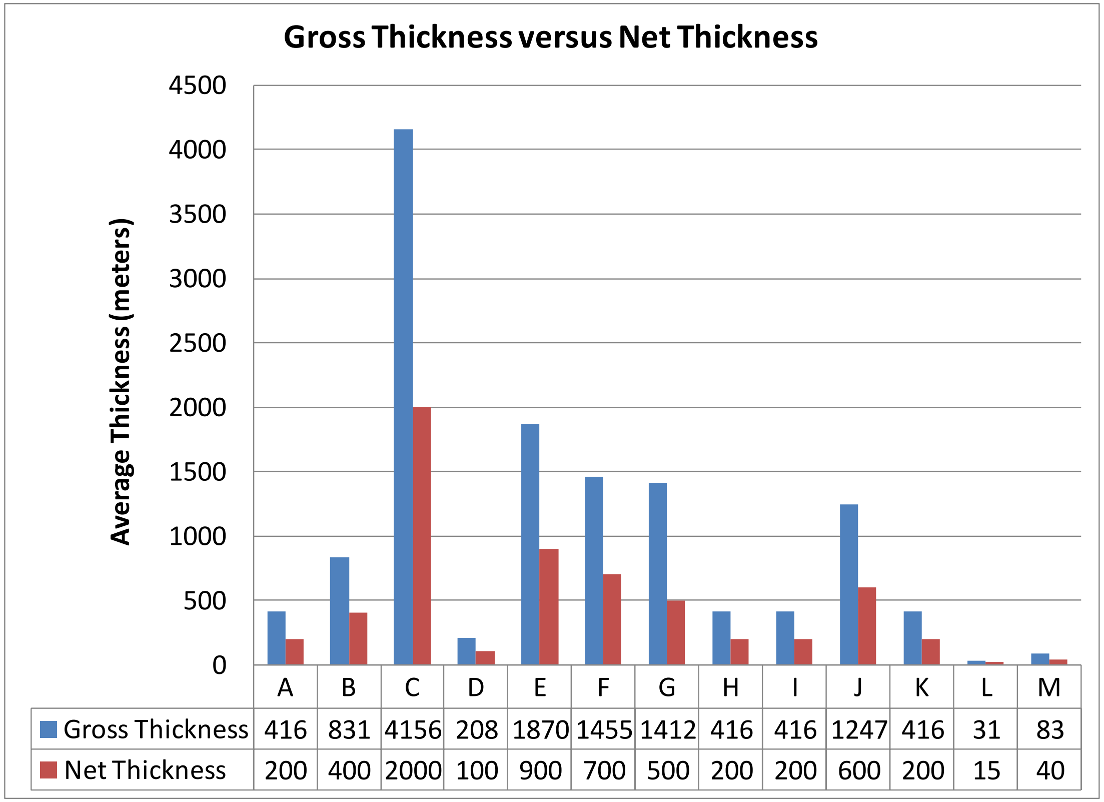


Figure S10: We identify four boundaries that constrain the portion of the Frio Formation that is suitable for sequestration. Boundaries 1 and 3 correspond to the edges of available depth and thickness maps [47]. Boundary 2 corresponds to where the proportion of shale in the formation becomes greater than 80% [47, Map 5frio]. Boundary 4 corresponds to outcrops [47]. Within these boundaries, we identify three regions in which to apply our models (Regions a, b, and c).

Comparison of CO_2 Storage Methodologies

- Used **select data and formations** from Szulczewski, 2012: **net aquifer thickness (H), length of trapping-model domain (L_T), width of well array (W), porosity (ϕ), CO_2 density (ρ_g), connate water saturation (S_{wc}), aquifer permeability (k_{aq}), surface temperature (T_s), temperature gradient (G_T), depth to the top of the aquifer (D), brine density ($\rho_{w,}$), and salinity (s)**.
- Estimated **gross thickness** by dividing the net thickness, by a net-to gross thickness efficiency term [0.48 for clastics, 0.41 for dolomite, and 0.35 for limestone formations]
- **Pore compressibility** set to range between $1x10^{-10}$ and $5x10^{-10}$ Pa^{-1}.
- **Brine compressibility** directly calculated as described by Battistelli et al. 1997.
- Excluded formations that were less than **10,000 ppm TDS**

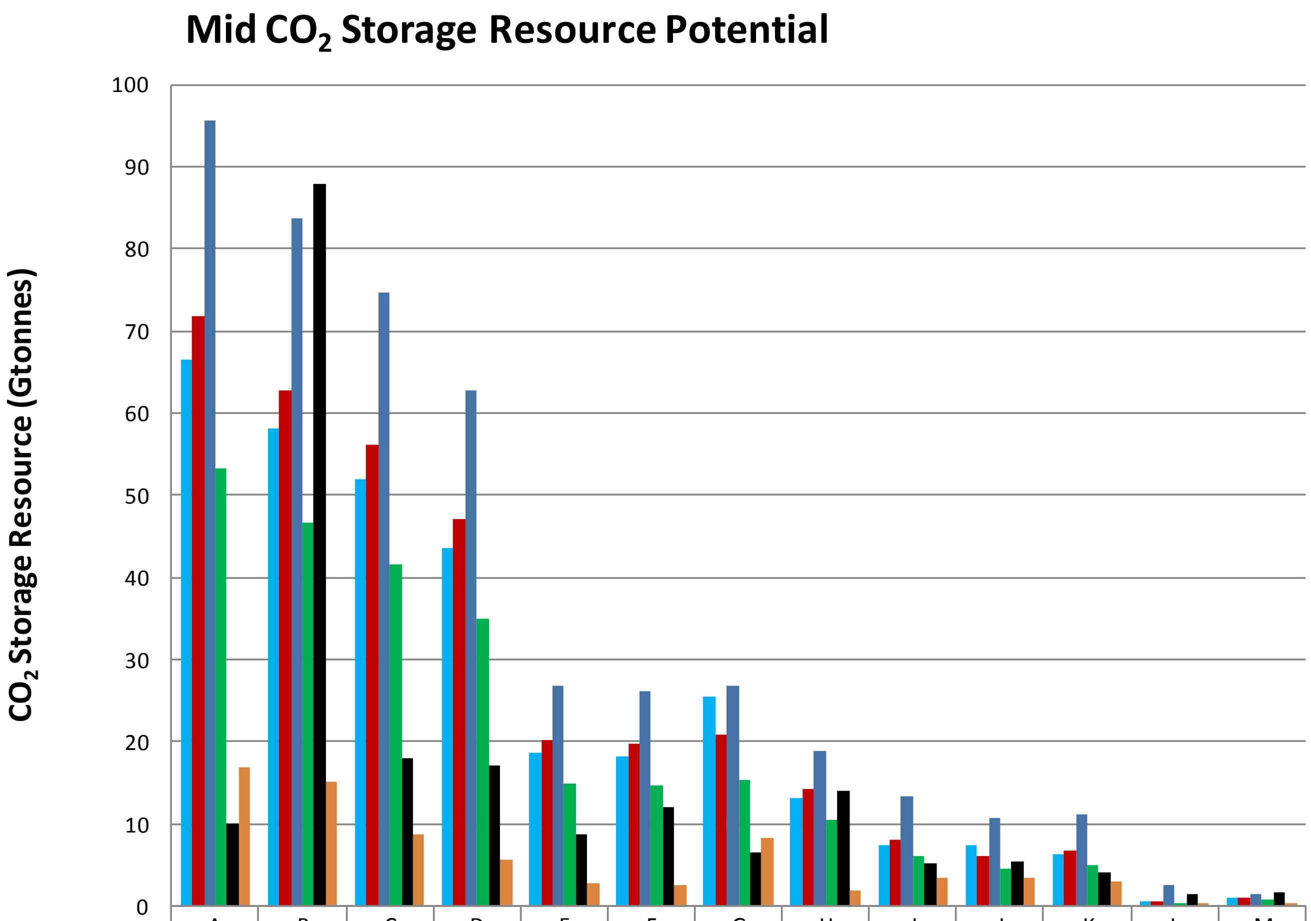


	A	B	C	D	E	F	G	H	I	J	K	L	M
🟦 Gross Thickness	416	831	4156	208	1870	1455	1412	416	416	1247	416	31	83
🟥 Net Thickness	200	400	2000	100	900	700	500	200	200	600	200	15	40

Comparison of CO_2 Storage Methodologies

- Apply **uniform input parameters** for each method
  - Consistently applied inputs for length, width, porosity, and CO_2 density
- **Gross or net thickness** was applied as prescribed by the methodology
- Each methodology required the use of a **specific efficiency**
  - gauges the fraction of the accessible pore volume that will be occupied by the injected CO_2.
  - based on **lithology** or **rock permeability** class
  - calculated for each **individual formation**
  - CO_2 **trapping mechanisms**
    - Structural [**not considered in data input model**] CSLF: Bachu et al. (2007), DOE-NETL Atlas I, II, III (2007, 2008, 2010), USGS: Brennan et al. (2010), Zhou et al. (2008)
    - Hydrodynamic (CSLF: Bachu et al. (2007), Zhou et al. (2008), DOE-NETL Atlas I, II, III (2007, 2008, 2010)
    - Residual (Szulczewski et al. (2012**)**, USGS: Brennan et al. (2010)
    - Solubility (Szulczewski et al. (2012)

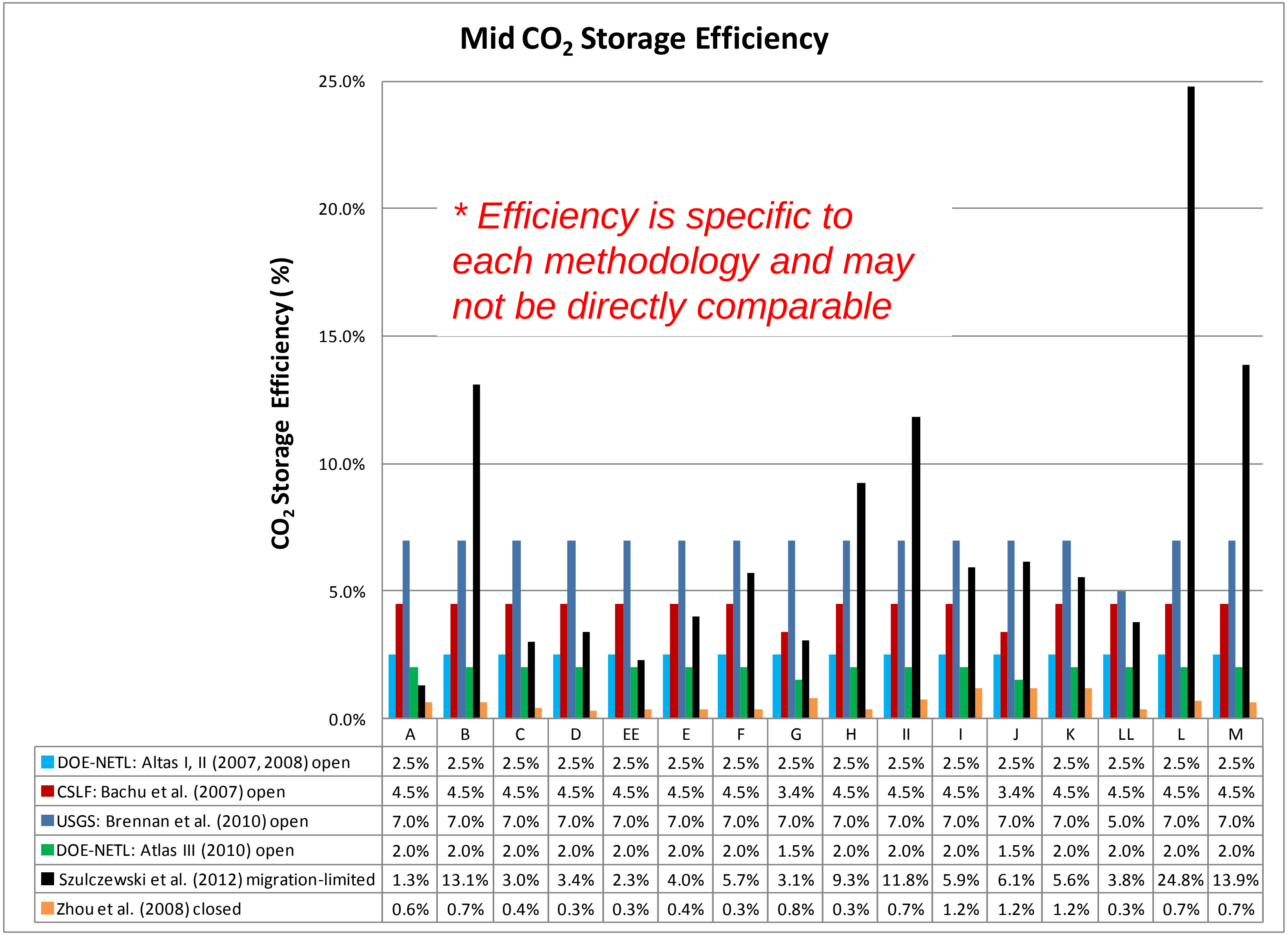
Comparison of CO_2 Storage Methodologies



Mid CO_2 Storage Resource Potential

	A	B	C	D	E	F	G	H	I	J	K	L	M
🟦 DOE-NETL: Altas I, II (2007, 2008) open	66.5	58.2	51.9	43.6	18.7	18.2	25.4	13.1	7.5	7.5	6.2	0.5	1.0
🟥 CSLF: Bachu et al. (2007) open	71.8	62.8	56.1	47.1	20.2	19.6	20.7	14.1	8.1	6.1	6.7	0.6	1.1
🟦 USGS: Brennan et al. (2010) open	95.6	83.6	74.7	62.7	26.9	26.1	26.9	18.8	13.3	10.7	11.1	2.6	1.4
🟩 DOE-NETL: Atlas III (2010) open	53.2	46.5	41.6	34.9	15.0	14.5	15.3	10.5	6.0	4.5	5.0	0.4	0.8
⬛ Szulczewski et al. (2012) migration-limited	10.0	88.0	18.0	17.0	8.6	12.0	6.6	14.0	5.1	5.3	4.0	1.5	1.6
🟧 Zhou et al. (2008) closed	16.9	15.1	8.7	5.5	2.8	2.5	8.3	1.8	3.5	3.5	3.0	0.1	0.3

Comparison of CO_2 Storage Methodologies



** Efficiency is specific to each methodology and may not be directly comparable*

	A	B	C	D	EE	E	F	G	H	II	I	J	K	LL	L	M
🟦 DOE-NETL: Altas I, II (2007, 2008) open	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
🟥 CSLF: Bachu et al. (2007) open	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	3.4%	4.5%	4.5%	4.5%	3.4%	4.5%	4.5%	4.5%	4.5%
🟦 USGS: Brennan et al. (2010) open	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	5.0%	7.0%	7.0%
🟩 DOE-NETL: Atlas III (2010) open	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	1.5%	2.0%	2.0%	2.0%	1.5%	2.0%	2.0%	2.0%	2.0%
⬛ Szulczewski et al. (2012) migration-limited	1.3%	13.1%	3.0%	3.4%	2.3%	4.0%	5.7%	3.1%	9.3%	11.8%	5.9%	6.1%	5.6%	3.8%	24.8%	13.9%
🟧 Zhou et al. (2008) closed	0.6%	0.7%	0.4%	0.3%	0.3%	0.4%	0.3%	0.8%	0.3%	0.7%	1.2%	1.2%	1.2%	0.3%	0.7%	0.7%

Comparison of CO_2 Storage Methodologies

General trends:

- All six methodologies fell within two standard deviations of the mean of an arithmetic averaging estimator for all 13 locations
- The method by Zhou et al. (2008), typically, reports the lowest estimates
- The method by USGS: Brennan et al. (2010), typically, reports the highest estimates
- In most cases, the migration-limited estimates by Szulczewski et al. (2012) are similar to the closed estimates provided by Zhou et al. (2008) (*Szulczweski et al (2012) pressure-limited estimates are directly comparable to Zhou et al. (2008)*)
- The estimates by DOE-NETL Atlas I, II, III (2007, 2008, 2010), CSLF: Bachu et al. (2007) fall between the estimates by USGS: Brennan et al. (2010) and Zhou et al. (2008) and are within one standard deviation of the mean of an arithmetic averaging estimator for all 13 locations.

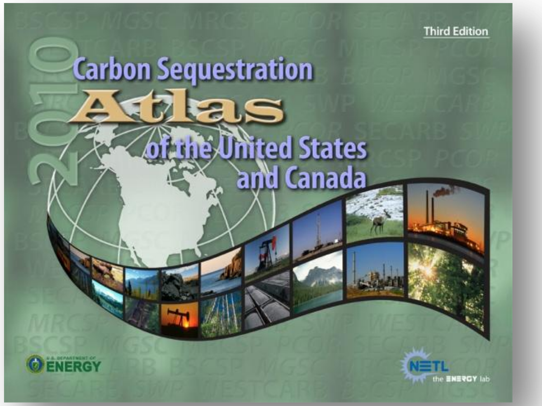
Summary:

- Applied several different resource estimation methodologies to uniform data set
- As is typical for these types of estimates currently for carbon storage in saline fields, the data sets were very sparse.
- Open system methodologies gave median results that were well within the uncertainty bounds of the others
    - high degree of confidence that the methodologies are reasonable and that the results can be used by decision-makers.
- Closed system estimates were consistently lower than those of the open system methodologies, but the estimated values from the closed system were also mostly well within the uncertainty bounds of the open system estimates.

Summary

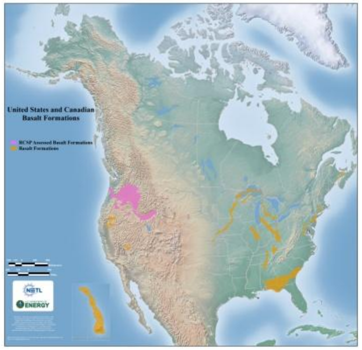
- High-level assessments of potential CO_2 storage reservoirs in the United States and Canada at the regional and national scale.
- Geologic formations:

  oil and gas reservoirs
  unmineable coal seams
  organic-rich shale basins
  saline formations
  basalt formations

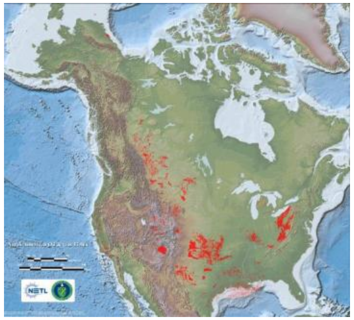


International Journal of Greenhouse Gas Control **5**: 952–965.

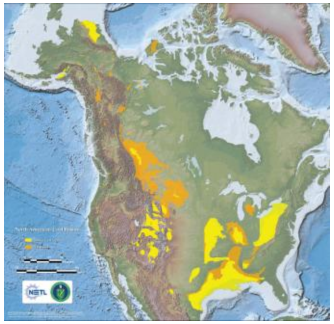
- Based on physically accessible pore volume without consideration of regulatory or economic constraints.
- Used for broad energy-related government policy and business decisions



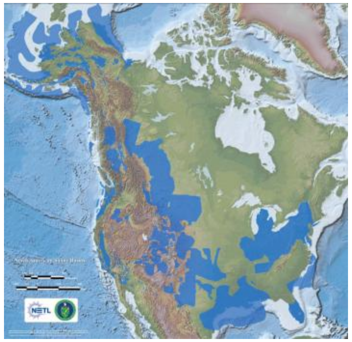
Oil and Gas Fields



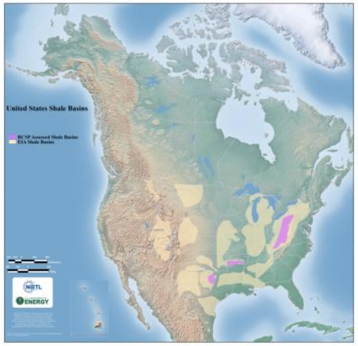
Saline Formations



Unmineable Coal Seams



Basalt Formations



Organic-Rich Shale

http://www.natcarbviewer.org/

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