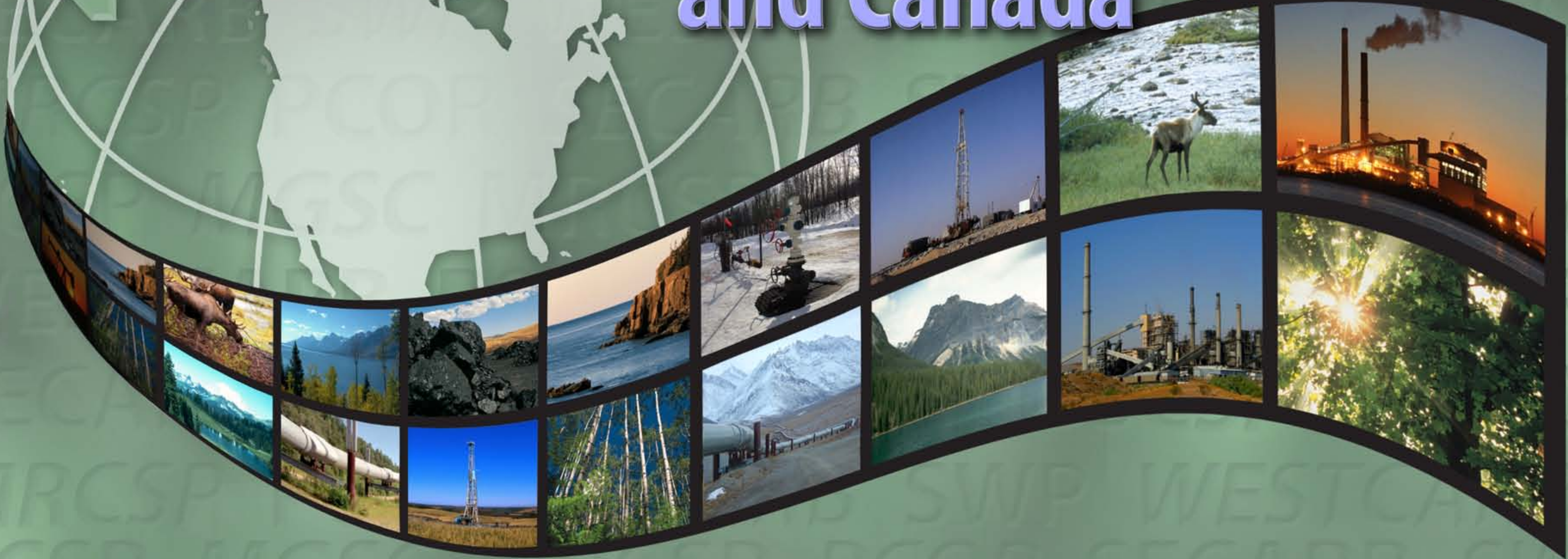
Third Edition

2010 Carbon Sequestration Atlas of the United States and Canada



U.S. DEPARTMENT OF ENERGY

NETL the ENERGY lab

Foreword

The U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL) is proud to release the third edition of the *Carbon Sequestration Atlas of the United States and Canada (Atlas III)*. Production of *Atlas III* is the result of collaboration among carbon storage experts from local, State, and Federal agencies, as well as industry and academia. *Atlas III* provides a coordinated update of carbon capture and storage (CCS) potential across most of the United States and portions of Canada. The primary purpose of *Atlas III* is to update the carbon dioxide (CO_2) storage potential for the United States and Canada, and to provide updated information on the Regional Carbon Sequestration Partnerships' (RCSPs) field activities. In addition, *Atlas III* outlines DOE's Carbon Sequestration Program, DOE's international CCS collaborations, worldwide CCS projects, and CCS regulatory issues; presents updated information on the location of CO_2 stationary source emissions and the locations and storage potential of various geologic storage sites; and further provides information about the commercialization opportunities for CCS technologies from each RCSP.

A key aspect of CCS deals with the amount of carbon storage potential available to effectively help reduce greenhouse gas emissions. As demonstrated in *Atlas III*, CCS holds great promise as part of a portfolio of technologies that enables the United States and the rest of the world to effectively address climate change while meeting the energy demands of an ever increasing global population. *Atlas III* includes the most current and best available estimates of potential CO_2 storage resource determined by a methodology applied consistently across all of the RCSPs. A CO_2 storage **resource** estimate is defined as the fraction of pore volume of porous and permeable sedimentary rocks available for CO_2 storage and accessible to injected CO_2 via drilled and completed wellbores. Carbon dioxide storage resource assessments do not include economic, chemical, or regulatory constraints; only physical constraints are applied to define the accessible part of the subsurface. Economic and regulatory constraints are included in geologic CO_2 **capacity** estimates. Under the most favorable economic and regulatory scenarios, 100 percent of the estimated CO_2 storage resource may be considered CO_2 capacity.

The data in *Atlas III* is current as of March 2010. It will be updated every 2 years as new data are acquired and methodologies for CO_2 storage estimates improve. Furthermore, it is expected that, through the ongoing work of the RCSPs, data quality and conceptual understanding of the CCS process will improve, resulting in more refined CO_2 storage resource estimates.

About Atlas III

The *Carbon Sequestration Atlas of the United States and Canada* contains three main sections: (1) Introduction; (2) National Perspectives; and (3) Regional Perspectives. The Introduction section contains an overview of CCS technologies, a summary of the DOE's Carbon Sequestration Program, a brief description of the RCSP Program, and information on the National Carbon Sequestration Database and Geographic Information System (NATCARB). The National Perspectives section provides maps showing the number, location, and magnitude of CO_2 stationary sources in the United States and portions of Canada, as well as the areal extent and estimated CO_2 storage resource available in geologic formations evaluated within the RCSP regions. The National Perspectives section also contains a summary of the methodologies and assumptions employed to calculate CO_2 emissions and the estimated CO_2 storage resource of various geologic formations. The Regional Perspectives section includes a detailed presentation of CO_2 stationary sources, CO_2 storage resource assessments, updates on field projects, and information on CCS public outreach for each RCSP.

Carbon dioxide storage resource estimates were derived from data collected by each RCSP. This data is representative of each RCSP region and necessary to estimate parameters, such as area (A), thickness (h), and porosity (ϕ). The data were compiled in NATCARB. National CO_2 emission maps and CO_2 storage resource maps covering the United States and parts of Canada were developed by NATCARB for *Atlas III* from the information provided by the RCSPs. Carbon dioxide emission maps show the location and magnitude of CO_2 stationary sources. The National CO_2 storage resource maps illustrate areas of potential CO_2 storage.

Carbon dioxide geologic storage information in Atlas III was developed to provide a high level overview of CO_2 geologic storage potential across the United States and parts of Canada. Areal extents of geologic formations and CO_2 resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCS project developers a starting point for further investigation of the extent to which geologic CO_2 storage is feasible. This information is not intended as a substitute for site-specific characterization, assessment and testing. Please refer to page 14 of *Atlas III* for additional information on this level of assessment.

DOE thanks the many individuals who contributed to *Atlas III*.

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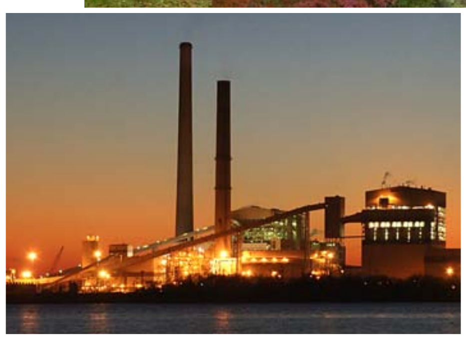



The Greenhouse Effect

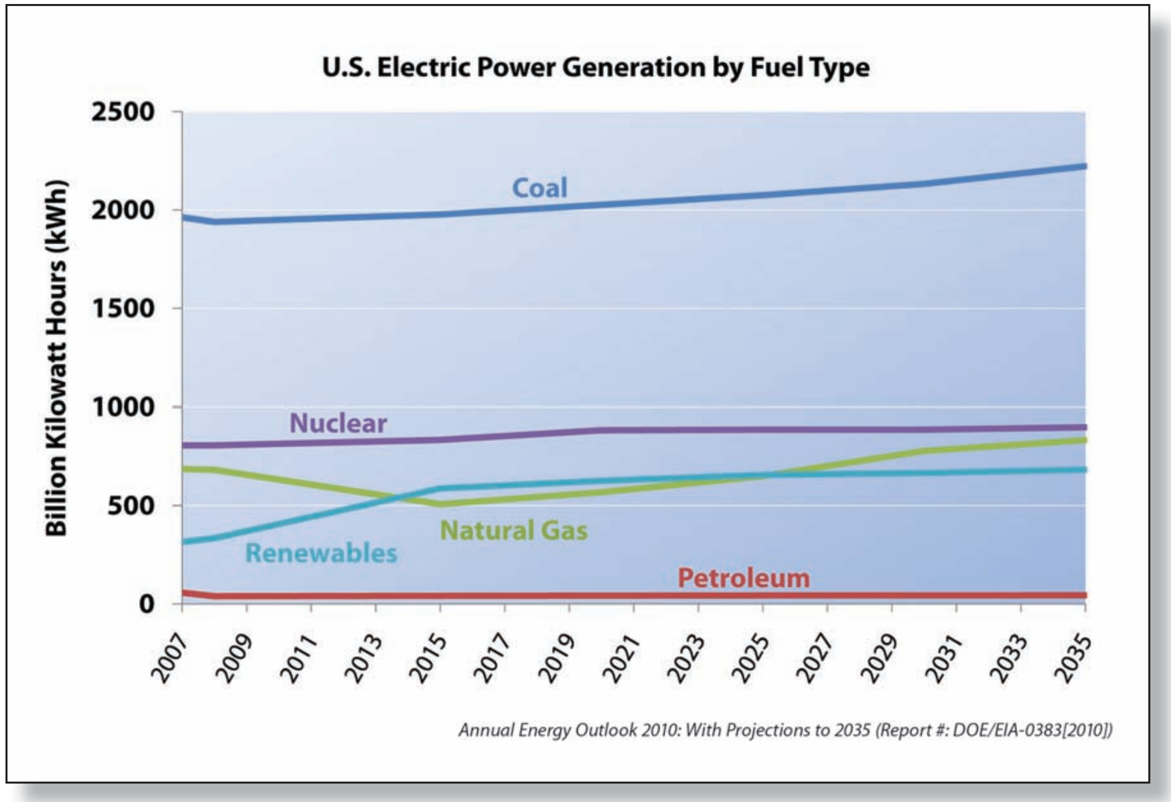
Greenhouse gases (GHGs) present in the atmosphere contribute to the greenhouse effect, which is the trapping of radiant heat from the sun in the Earth's atmosphere. One GHG of particular interest is carbon dioxide (CO_2) because it is one of the most prevalent GHGs. Carbon dioxide is a colorless, odorless, nonflammable gas that provides a basis for the sythesis of organic compounds essential for life. Atmospheric CO_2 originates from both natural and manmade sources. Natural sources of CO_2 include volcanic outgassing, the combustion and decay of organic matter, and respiration. Manmade, or anthropogenic, sources of CO_2 are primarily derived from the burning of various fossil fuels for power generation and transportation. However, industrial activities contribute to CO_2 emissions as well.

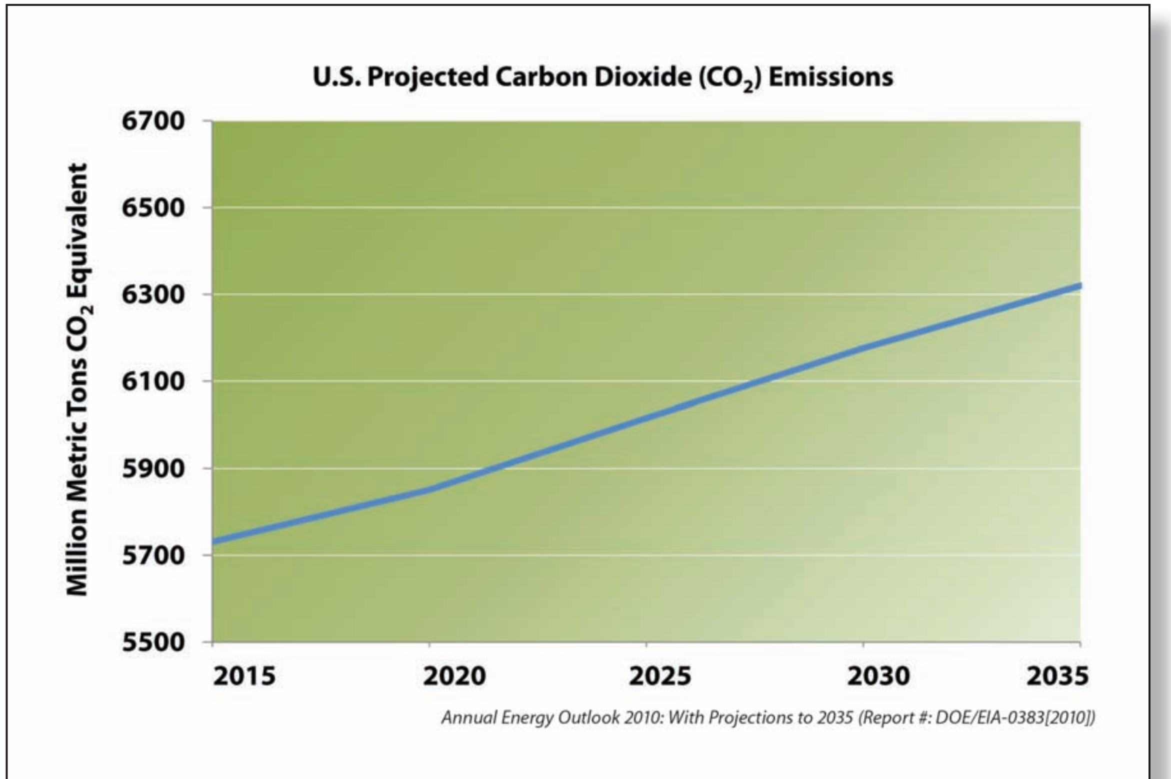
The greenhouse effect is a natural and important process in the Earth's atmosphere. However, GHG levels have significantly increased above pre-industrial level. According to the Energy Information Administration (EIA), annual global energy-related CO_2 emissions have reached 31 billion metric tons (34 billion tons). This increase in atmospheric GHGs is considered by many scientists to be a contributing factor to global climate change.

The United States is one of 192 countries that are signatories to the United Nations Framework Convention on Climate Change (UNFCCC). This treaty was approved in 1992 and calls for the stabilization of atmospheric GHGs at a level that could minimize impact on the world's climate. Conservation, renewable energy, and improvements in the efficiency of power plants, automobiles, and other energy consuming devices are all important steps which must be taken to mitigate GHG emissions. Carbon capture and storage (CCS) also promises to provide a significant reduction in GHG emissions. No single approach is sufficient to stabilize the concentration of GHGs in the atmosphere – especially when the growing global demand for energy and the associated potential increase in GHG emissions is considered. Technological approaches that are effective in reducing atmospheric GHG concentrations, while, at the same time, allowing economic growth and prosperity with its associated energy use, are needed.

CREDIT: NASA

CREDIT: NOAA/CMDR. JOHN BORTNIAK





A Technology Approach to Reduce Greenhouse Gas Emissions

The U.S. Department of Energy's (DOE's) Office of Fossil Energy's (FE) National Energy Technology Laboratory (NETL) manages a Carbon Sequestration Program focusing on the research and development (R&D) of CCS technologies with significant potential for reducing GHG emissions in order to mitigate global climate change. The Carbon Sequestration Program supports the UNFCCC goal to stabilize GHG emissions, as well as the President Obama's goal of bringing 5 to 10 commercial CCS demonstrations online by 2016 and reducing carbon emissions by 80 percent by 2050.

Power generation from from coal is one significant source of CO_2 emissions; therefore efforts to reduce these emissions is a critical R&D goal. The graph titled "U.S. Electric Power Generation by Fuel Type," shown at top left, displays the Annual Energy Outlook's 2010 predictions of growth in energy generation by various fuel types. Coal is predicted to continue to dominate U.S. power generation for the next 25 years.

The graph titled "U.S. Projected Carbon Dioxide (CO_2) Emissions," shown at bottom left, illustrates the projected increase in CO_2 emissions thoughout the United States over the next 25 years. Following AEO's 2010 assumptions, if no actions are taken, the United States will emit more than 6,300 million metric tons (6,930 million tons) of CO_2 by 2035, increasing 2007 emission levels by more than 10 percent. The United States can work toward reducing GHG emissions with the development and implementation of appropriate CCS technologies.

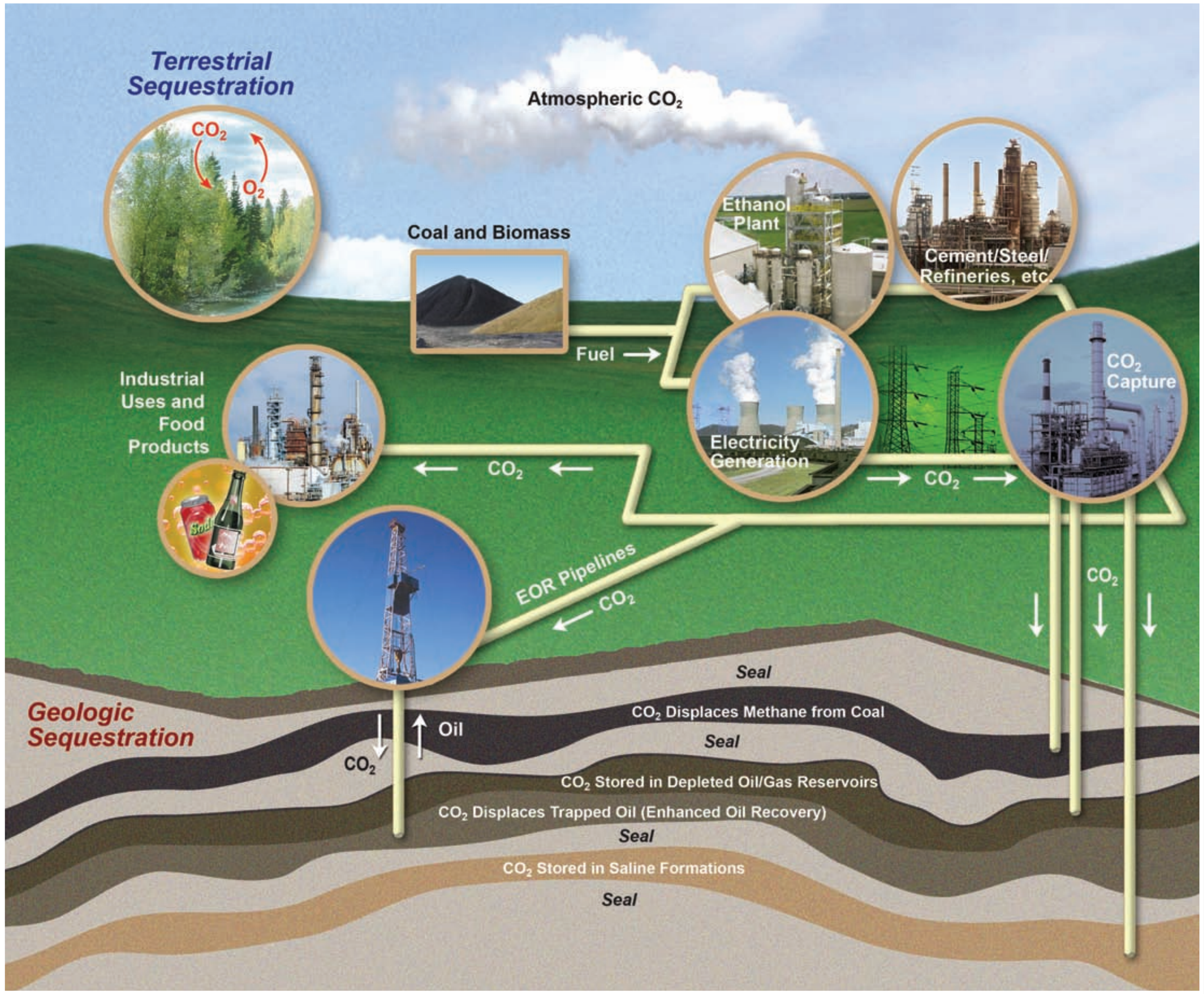
What is Carbon Sequestration?

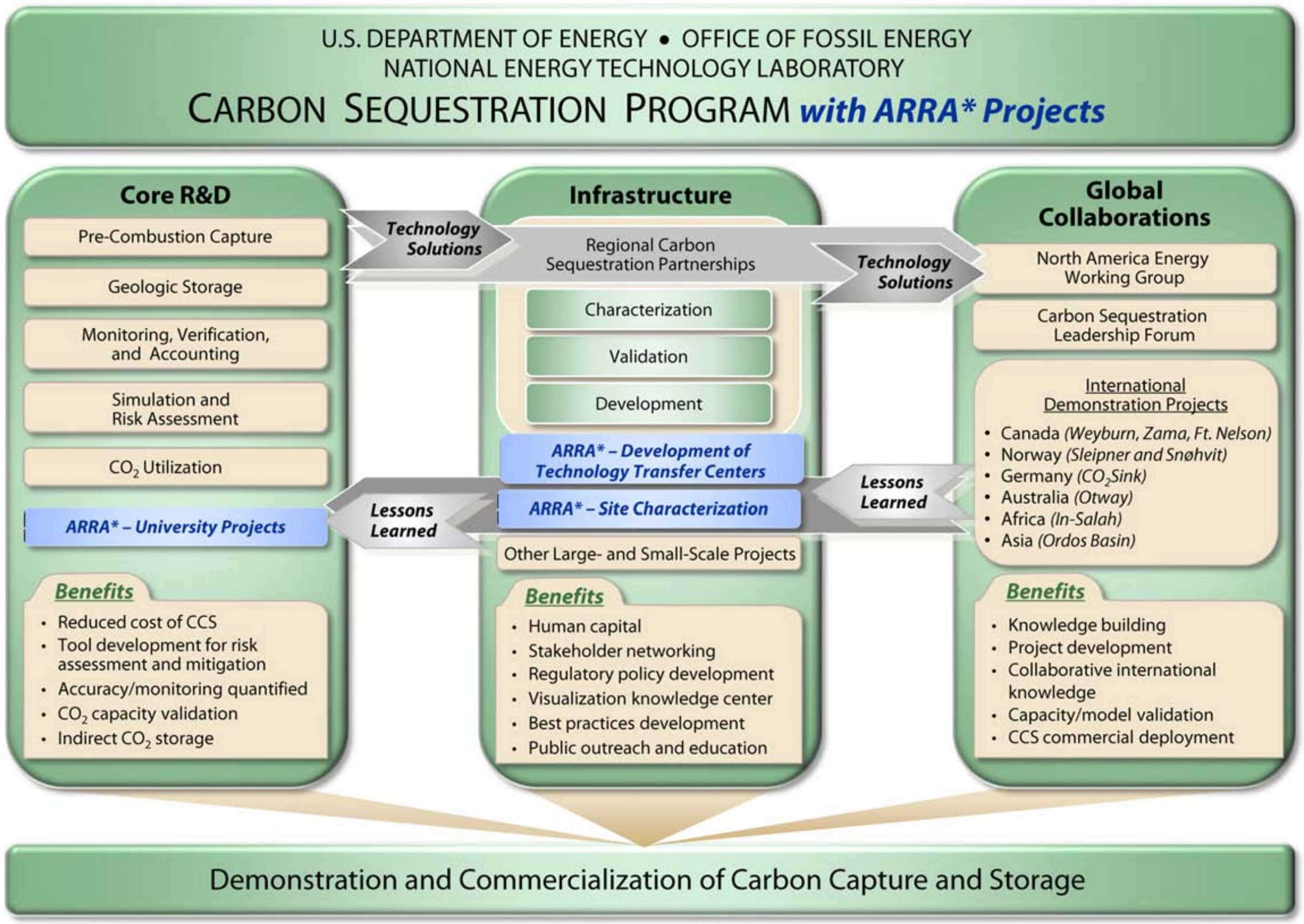
Carbon capture and storage (CCS) is the process of capturing and storing CO_2 that would otherwise accumulate in the atmosphere. DOE is investigating a variety of technology solutions for CCS including advanced capture techniques and CO_2 storage, or carbon sequestration, options. Geologic carbon storage involves the separation and capture of CO_2 at the point of emissions, the transportation of CO_2, and the storage of CO_2 in deep, underground geologic formations. Terrestrial carbon storage involves the net removal of CO_2 from the atmosphere by plants during photosynthesis and its fixation in vegetative biomass and soils.

Geologic storage is defined as the placement of CO_2 into a subsurface formation such that it will remain permanently stored. DOE is investigating five types of underground formations for geologic carbon storage, each with unique challenges and opportunities: (1) saline formations; (2) oil and gas reservoirs; (3) unmineable coal areas; (4) organic-rich shales; and (5) basalt formations.

It is projected that many new power plants and fuel processing facilities will be built in the coming decades. These new facilities, along with existing plants, which have the potential to be appropriately retrofitted, will create ample opportunities for deploying efficient and cost-effective CO_2 capture technologies. DOE's CO_2 capture efforts seek to cost-effectively capture CO_2 using various advanced technologies.

The CCS process includes monitoring, verification, and accounting (MVA) and risk assessment at the storage site. DOE's MVA efforts focus on the development and deployment of technologies that can provide an accurate accounting of stored CO_2 and a high level of confidence that the CO_2 will remain permanently stored. Effective application of these MVA technologies will ensure the safety of storage projects, and provide the basis for establishing carbon credit trading markets for stored CO_2 should these markets develop. Risk assessment research focuses on identifying and quantifying potential risks to humans and the environment associated with carbon sequestration, and helping to identify appropriate measures to ensure that these risks remain low.





* American Recovery and Reinvestment Act of 2009

DOE's Carbon Sequestration Program

DOE's Carbon Sequestration Program is comprised of three key elements for CCS technology development and research: (1) Core R&D; (2) Infrastructure; and (3) Global Collaborations. The Core R&D element consists of five focal areas for CCS technology development: (1) Pre-Combustion Capture, (2) Geologic Storage, (3) Monitoring, Verification, and Accounting, (4) Simulation and Risk Assessment, and (5) CO_2 Utilization. The Core R&D element is driven by technology needs and is accomplished through applied laboratory and pilot-scale research aimed at developing new technologies for GHG mitigation. The primary component of the Infrastructure element is the Regional Carbon Sequestration Partnerships, a government/academic/industry cooperative effort tasked with characterizing, testing, and developing guidelines for the most suitable technologies, regulations, and infrastructure for CCS in different regions of the United States and several provinces in Canada. The Core R&D and Infrastructure elements provide technology solutions that support the Global Collaborations element. DOE participates and transfers technology solutions to international efforts that promote CCS, such as the Carbon Sequestration Leadership Forum (CSLF), the North American Energy Working Group (NAEWG), and several international demonstration projects.

DOE's Carbon Sequestration Program is developing a portfolio of technologies addressing various aspects of CCS that will aid in the reduction of GHG emissions. The Carbon Sequestration Program Goal is to demonstrate safe, cost-effective, and long-term carbon mitigation, management, and storage by 2020. Reaching this goal requires an integrated R&D program that will advance fundamental CCS technologies and prepare them for commercial-scale development. The Program works in concert with several programs within FE that are developing and demonstrating technologies integral to coal-fired power generation and coal conversion with potential for carbon capture, including Innovations for Existing Plants, Fuels, Clean Coal Power Initiative, Advanced Integrated Gasification Combined Cycle, Fuel Cells, Advanced Turbines, and Advanced Research. Projects that meet the Program Goal will result in large-scale units that come online around 2020. In the long-term, the program is expected to significantly contribute to the reduction of GHG emissions.

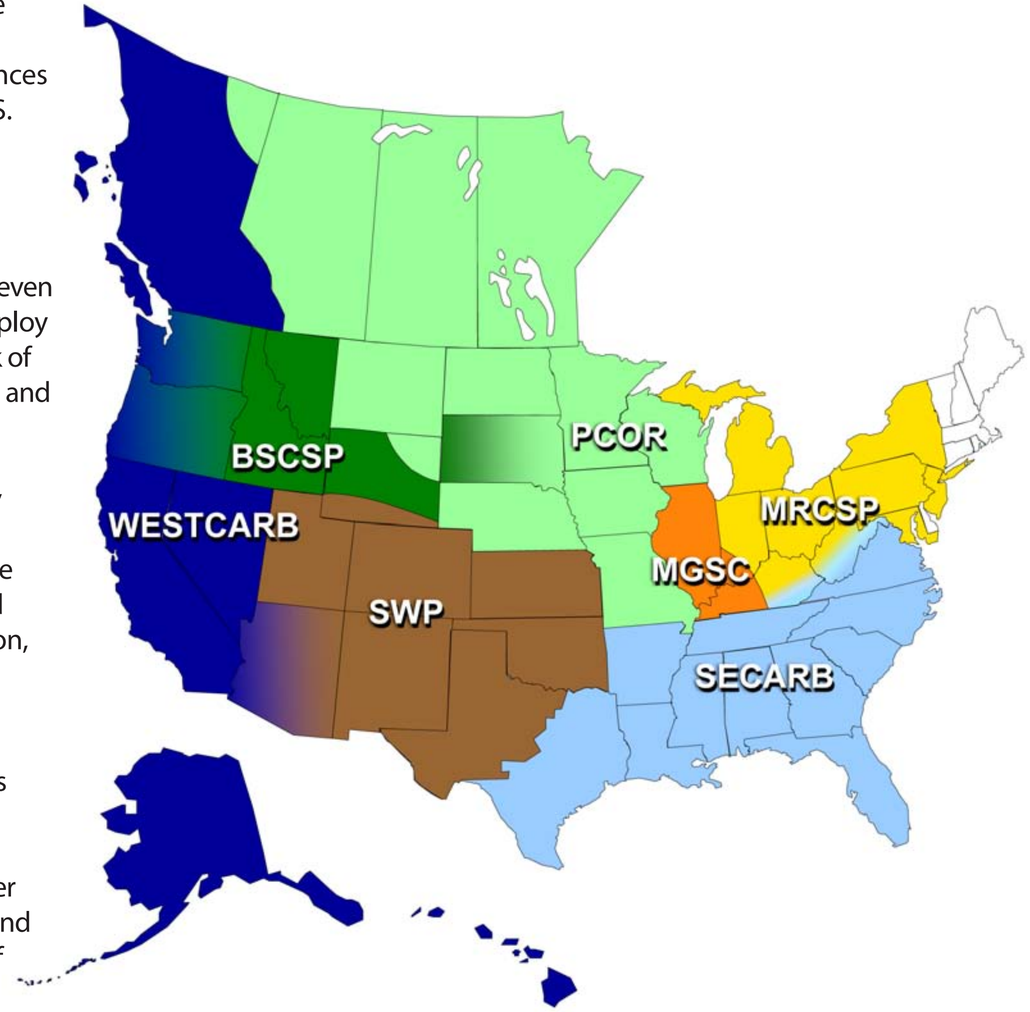
Regional Carbon Sequestration Partnerships

Initiated by DOE-FE, the Regional Carbon Sequestration Partnerships (RCSPs) (see map at right) are a public/private partnership tasked with developing guidelines and testing for the most suitable technologies, regulations, and infrastructure needs for CCS within seven different regions of the United States and Canada. Geographical differences in fossil fuel use and CO_2 storage potential across the United States and Canada dictate regional approaches to CCS. The seven RCSPs that form this network currently include more than 400 organizations, universities, and private companies, spanning 43 states, and 4 Canadian provinces.

The RCSPs' effort is being implemented in three phases: (1) Characterization Phase (2003–2005); (2) Validation Phase (2005–2011); and (3) Development Phase (2008–2018+). The Characterization Phase began in September 2003 with the seven RCSPs working to characterize storage potential and develop the necessary framework to validate and potentially deploy CCS technologies. At the end of the Characterization Phase, the RCSPs had succeeded in establishing a national network of companies and professionals working to support CCS deployments, creating a National Carbon Sequestration Database and Geographic Information System (NATCARB) and raising awareness and support for CCS as a GHG mitigation option.

The Validation Phase focuses on validating the most promising regional opportunities to deploy CCS technologies by building upon the accomplishments of the Characterization Phase. Two different CO_2 storage approaches are being pursued in this phase: geologic and terrestrial carbon storage. Efforts are being conducted to (1) validate and refine current reservoir simulations for CO_2 storage projects; (2) collect physical data to confirm CO_2 storage potential and injectivity estimates; (3) demonstrate the effectiveness of MVA technologies; (4) develop guidelines for well completion, operations, and abandonment; and (5) develop strategies to optimize the CO_2 storage potential of various geologic formations. The Validation Phase includes 20 geologic and 11 terrestrial CO_2 storage projects.

The Development Phase builds on the information generated in the Characterization and Validation Phases and involves the injection of 1 million tons or more of CO_2 by each RCSP into various regionally significant geologic formations. These large-volume injection tests are designed to demonstrate that CO_2 storage sites have the potential to store regional CO_2 emissions safely, permanently, and economically for hundreds of years. Development Phase projects will result in a better understanding of technical and non-technical aspects for commercial scale CCS projects, including regulatory, liability, and ownerships issues associated with these projects. These projects will provide a firm foundation for commercialization of large-scale CCS.



Regional Carbon Sequestration Partnership	Lead Organization	Member States/Provinces	Website
Big Sky Carbon Sequestration Partnership (BSCSP)	Montana State University	Western Montana, Idaho, South Dakota, Central Wyoming, Eastern Oregon and Washington, and adjacent areas in British Columbia and Alberta	http://www.bigskyco2.org/
Midwest Geological Sequestration Consortium (MGSC)	Illinois State Geological Survey	Illinois, Southwestern Indiana, and Western Kentucky	http://www.sequestration.org/
Midwest Regional Carbon Sequestration Partnership (MRCSP)	Battelle Memorial Institute	Eastern Indiana, Northeastern Kentucky, Maryland, Michigan, New Jersey, New York, Ohio, Pennsylvania, and Northwestern West Virginia	http://www.mrcsp.org/
Plains CO_2 Reduction (PCOR) Partnership	University of North Dakota, Energy and Environmental Research Center	Eastern Montana, Northeastern Wyoming, Nebraska, Eastern South Dakota, North Dakota, Minnesota, Wisconsin, Iowa, Missouri, Alberta, Saskatchewan, Manitoba, and Northeastern British Columbia	http://www.undeerc.org/PCOR/
Southeast Regional Carbon Sequestration Partnership (SECARB)	Southern States Energy Board	East Texas, Arkansas, Louisiana, Mississippi, Alabama, Tennessee, Florida, Georgia, South Carolina, North Carolina, Virginia, Kentucky, and Southeastern West Virginia	http://www.secarbon.org/
Southwest Regional Partnership on Carbon Sequestration (SWP)	New Mexico Institute of Mining and Technology	Western Texas, Oklahoma, Kansas, Colorado, Utah, and Eastern Arizona, New Mexico, and Southern Wyoming	http://www.southwestcarbonpartnership.org/
West Coast Regional Carbon Sequestration Partnership (WESTCARB)	California Energy Commission	Alaska, Western Arizona, Western British Columbia, California, Hawaii, Nevada, Western Oregon, and Western Washington	http://www.westcarb.org/

Regional Carbon Sequestration Partnerships

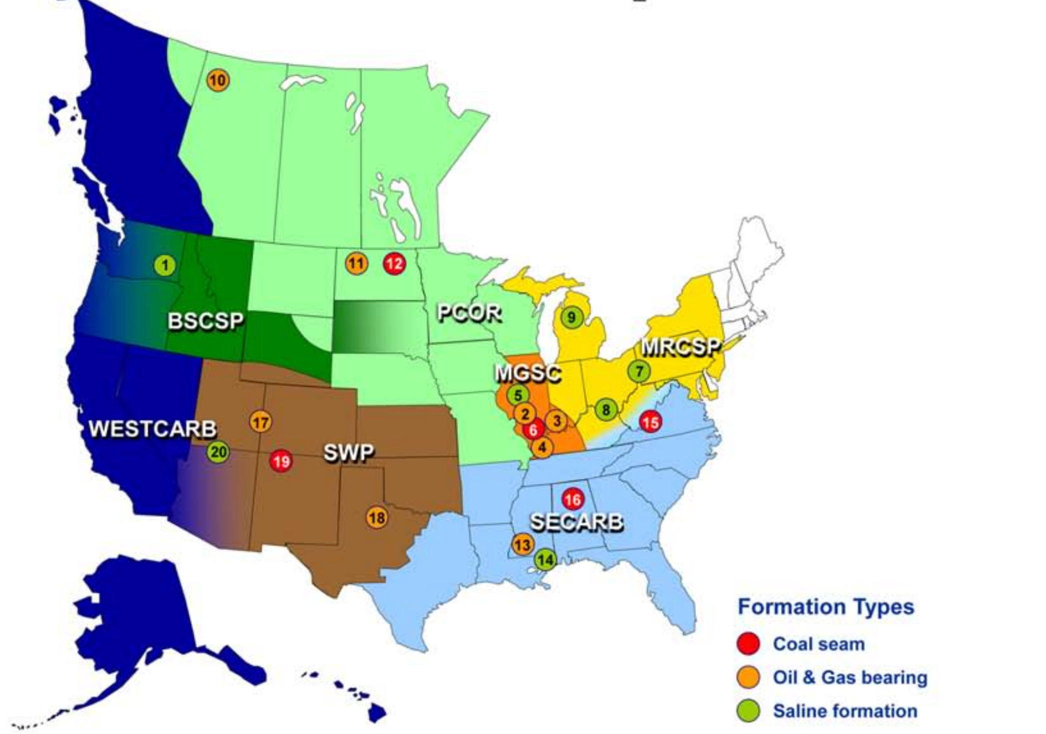
Validation Phase CO_2 Storage Projects

	Partnership	Geologic Province/ Location	Geologic: Total CO_2 Injection (metric tons CO_2)	Geologic: Approximate Depth (feet)	Terrestrial: Estimated CO_2 Storage Potential
1	Big Sky Carbon Sequestration Partnership	Columbia Basin	0	2,500 – 4,000	
A		North Central MT			60 Mt over 20 years
B		Eastern WY			30 Mt over 10 years
C		Region-wide			640–1,040 Mt over 80 years
2	MGSC	Illinois Basin–Loudon Field	< 39	1,550	
3		Illinois Basin–Mumford Hills Field	3,375	1,551	
4		Illinois Basin–Sugar Creek Field	6,500	1,548	
5		Illinois Basin*	*	7,200	
6		Illinois Basin	91	1,000	
7	MRCSP Midwest Regional Carbon Sequestration Partnership	Appalachian Basin	< 50	5,900 – 8,300	
8		Cincinnati Arch	1,000	3,200 – 3,500	
9		Michigan Basin	60,000	3,200 – 3,500	
D		Region-wide			25 Mt over 20 years
E		Region-wide			100 Mt over 20 years
F		Cambridge, MD			TBD
10	PCOR Partnership	Alberta Basin–Zama Field	25,400	4,900	
11		Williston Basin–Norhwest Field	400	8,050	
12		Williston Basin	80	1,100	
G		Great Plains wetlands complex (PPR)			14.4 Mt
13	SECARB Southeast Regional Carbon Sequestration Partnership	Gulf Coast–Cranfield	627,744	10,300–10,400	
14		Mississippi Coastal Plain	2,740	8,600	
15		Central Appalachian	907	1,600 – 2,300	
16		Black Warrior Basin	252	1,500 – 2,500	
17	SWP	Paradox Basin–Aneth Field	630,000	5,600 – 5,800	
18		Permian Basin–Sacroc Unit	86,000	5,800	
19		San Juan Basin	16,700	3,000	
H		Region-wide			TBD
I		San Juan Basin Coal Fairway (Navajo City, NM)			TBD
20	West Coast Regional Carbon Sequestration Partnership westcarb.org	Colorado Plateau	0	4,000	
J		Shasta County, CA			4,600 Mt over 80 years (CA)
K		Lake County, OR			900 Mt over 80 years (OR)

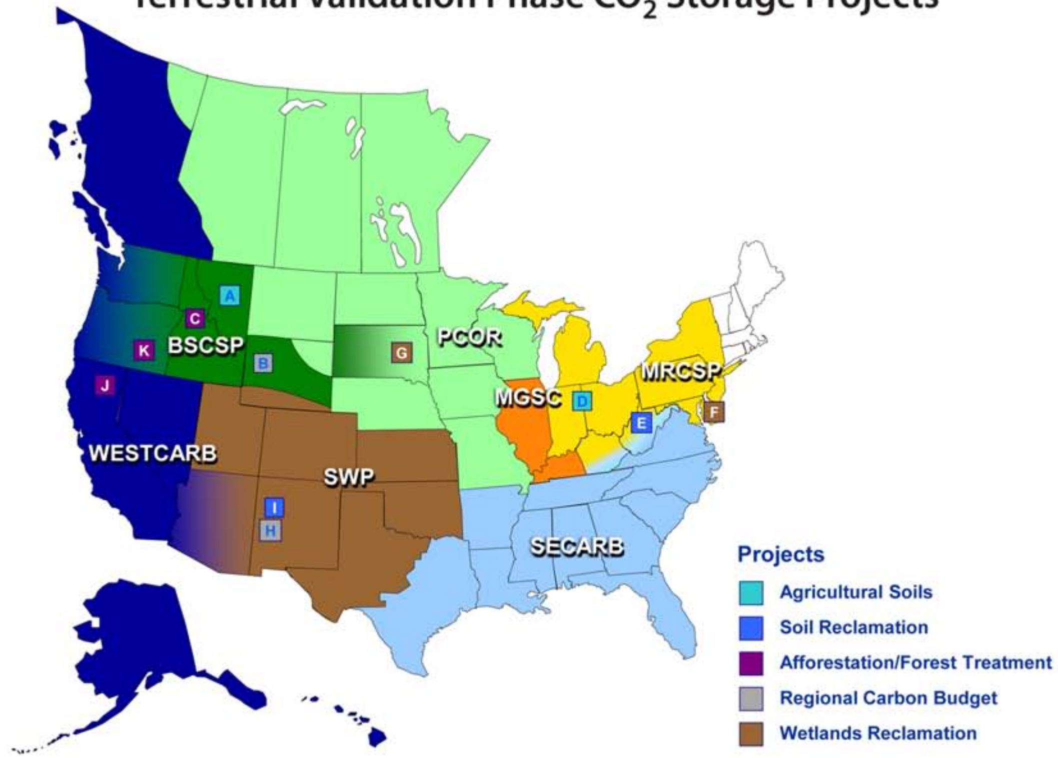
* Site was moved to Development Phase injection.

Information current as of June 2010

Geologic Validation Phase CO_2 Storage Projects



Terrestrial Validation Phase CO_2 Storage Projects



Regional Carbon Sequestration Partnerships

DOE's CCS Best Practices Manuals

The lessons learned during Validation Phase will result in a series of Best Practices Manuals (BPMs) that serve as the basis for the design and implementation of commercial CCS projects. These BPMs will provide recommended approaches for simulation and risk assessment; well construction, operations, and closure; terrestrial sequestration; MVA; public outreach and education; and site selection and characterization for future CCS commercial projects.

As of August 2010, FE's NETL has published three BPMs: (1) "Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations," (2) "Public Outreach and Education for Carbon Storage Projects," and (3) "Site Screening, Selection, and Characterization for Storage of CO_2 in Deep Geologic Formations."

NETL's "Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations" BPM provides an overview of MVA techniques that are currently in use or are being developed; summarizes DOE's MVA R&D program; and presents information that can be used by regulatory organizations, project developers, and national and State policymakers to ensure the safety and efficacy of carbon storage projects. NETL's "Public Outreach and Education for Carbon Storage Projects" BPM is intended to assist project developers in understanding and applying best outreach practices for siting and operating CO_2 storage projects. It provides practical, experience-based guidance on designing and conducting effective public outreach activities. The purpose of NETL's latest BPM, titled, "Site Screening, Selection, and Characterization for Storage of CO_2 in Deep Geologic Formations," is to establish a framework and methodology for proper site screening, selection, and initial characterization of geologic storage sites that: (1) provides stakeholders with a compilation of best practices for site screening, selection, and characterization; (2) communicates the experience gained through DOE's RCSP Program in the Characterization and Validation Phases; and, (3) develops a consistent, industry-standard framework, terminology, and set of guidelines for project-related storage capacity and risk estimates.

NETL's BPMs are available at: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/refshelf.html.

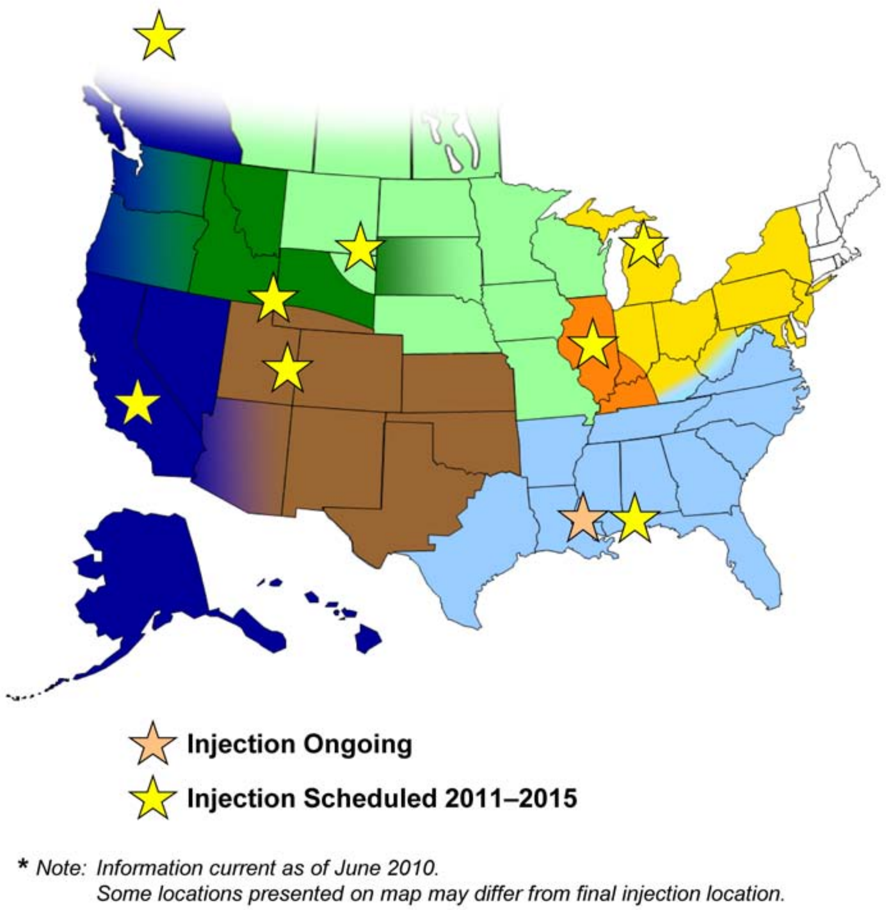
Best Practices Manual	Version 1 (Validation Phase)	Version 2 (Development Phase)	Final Guidelines (Post Injection)
Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations	2009	2017	2020
Site Screening, Site Selection, and Initial Characterization for Storage of CO_2 in Deep Geologic Formations	2010	2016	2020
Risk Assessment and Simulation for Geologic Storage of CO_2	2010	2017	2020
Drilling, Well Installation, Permitting, Operations, Mitigation, and Closure for CO_2 Storage in Deep Geologic Formations	2010	2017	2020
Public Outreach and Education for Carbon Storage Projects	2009	2016	2020
Terrestrial Sequestration of Carbon Dioxide	2010	**2016 – Post MVA Development Phase**	
Geologic Storage Formation Classification: *Understanding Its Importance and Impacts on CCS Opportunities in the United States*	2010		

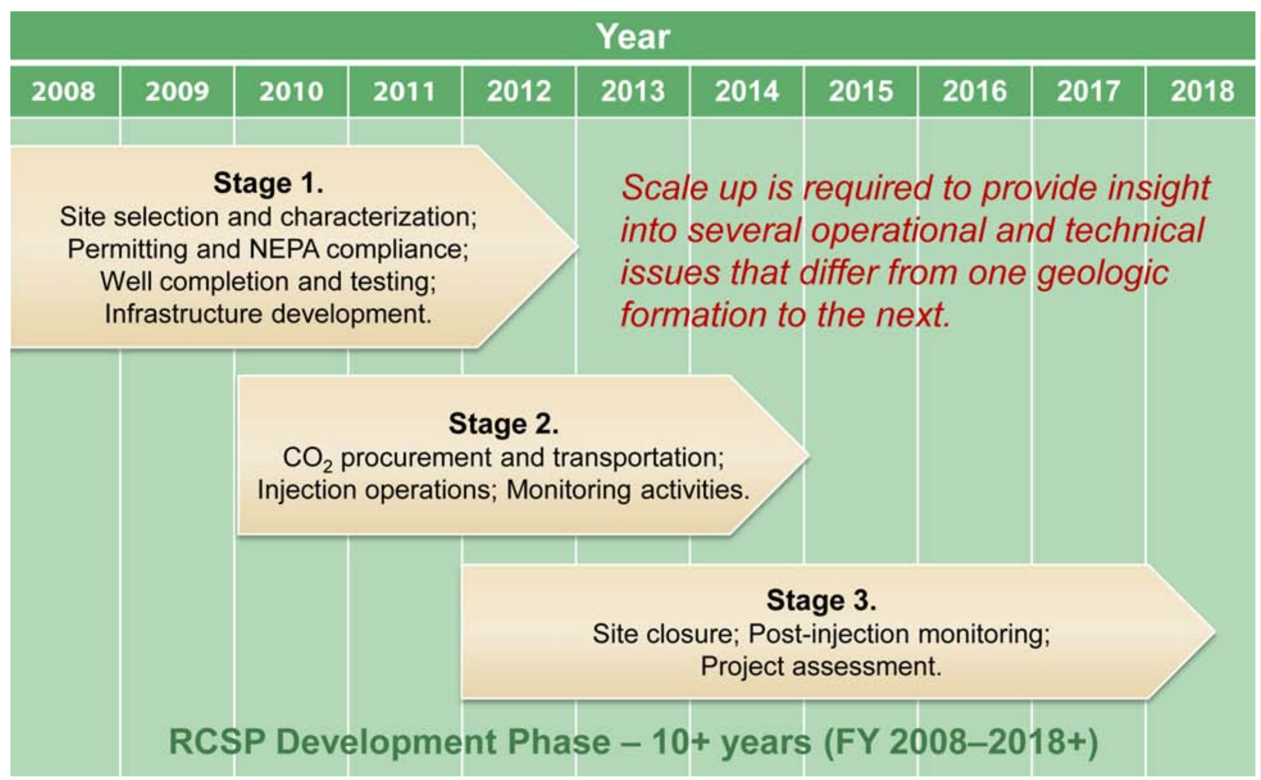
Regional Carbon Sequestration Partnerships

Development Phase CO_2 Storage Projects

The Development Phase (2008–2018+) builds on the experience obtained in the Characterization and Validation Phases and involves the injection of 1 million metric tons or more of CO_2 into regionally significant geologic storage formation environments. During this phase, the RCSPs will demonstrate that CO_2 capture, transportation, injection, and storage can be achieved safely, permanently, and economically at large scale. The geologic structures to be tested during these RCSP large-volume storage projects may become candidate sites for future near-zero emissions power plants. The primary goal of the Development Phase is to establish large-scale CCS projects across North America, where large volumes of CO_2 will be injected into a geologic storage formation to validate CO_2 storage potential (see map at bottom left). The RCSPs will design and explore various injection scenarios that fully utilize the infrastructure of their respective regions. Sources of CO_2 may include natural deposits, ethanol facilities, natural gas processing plants, and CO_2 captured from power plants. The Development Phase projects will be implemented in three stages, which will test key technologies during the project's life cycle (see graphic at bottom right). Results obtained from these efforts will provide the foundation for CCS technology commercialization throughout the United States, including providing experience that can be used to implement additional large-scale projects.

Development Phase goals include: (1) collect physical data to confirm potential resource and injectivity estimates made during the Characterization Phase; (2) validate the effectiveness of simulation models to predict and MVA technologies to measure CO_2 movement within the geologic formations, confirm the integrity of the seals, and confirm indirect storage in terrestrial ecosystems; (3) develop guidelines for well completion, operations, and closure in order to maximize storage potential and mitigate potential release; (4) develop strategies for optimizing geologic storage for various reservoir types; (5) develop public outreach strategies and communicate the benefits of CCS to various stakeholders; and, (6) satisfy the regulatory and permitting requirements for CCS projects.





DOE's Global CCS Collaborations

The Global Collaborations portion of DOE's Carbon Sequestration Program involves participation in international CCS projects in Canada, Norway, Germany, Australia, Algeria, and China and other international efforts to promote CCS, such as the CSLF and the NAEWG. The table at right highlights DOE's global CCS project involvement.

The CSLF, established by DOE, is a voluntary climate initiative of developed and developing nations that account for approximately 75 percent of all anthropogenic CO_2 emissions. Members engage in cooperative technology development aimed to facilitate the advancement of cost-effective carbon storage technologies for the separation and capture of CO_2; transportation of CO_2; and, long-term, safe storage of CO_2. The purpose of the CSLF is to make these technologies available internationally and to identify and address wider issues relating to CCS, such as regulatory and policy options. For more information, visit http://www.cslf.org.

The NAEWG was established in 2001 by the Secretary of Energy of the United States, the Secretary of Energy of Mexico, and the Canadian Minister of Natural Resources. The goals of the NAEWG are to foster communication and cooperation among the governments and energy sectors of the three countries on energy-related matters of common interest, and to enhance North American energy trade and interconnections consistent with the goal of sustainable development. This trilateral process fully respects the domestic policies, divisions of jurisdictional authority, and existing obligations of each country.

As part of this trilateral effort, a joint CO_2 mapping initiative between the three countries called the North American Carbon Atlas Partnership (NACAP) was started. Additional information on NACAP can be found on page 19 of *Atlas III*.

DOE's Global CCS Project Involvement

Location/Project	Operations	U.S. Involvement	U.S. Participant(s)	Reservoir	Operator/Lead	International Recognition
North America, Canada – Saskatchewan Weyburn-Midale	1.8 MMt CO_2/yr Commercial 2000	2000–2011	Lawrence Livermore National Laboratory, Schlumberger, Fugro, University of Columbia	Oil field Carbonate Enhanced Oil Recovery	Cenovus, Apache	U.S. – Canada Clean Energy Dialogue, IEA GHG R&D Programme, CSLF
North America, Canada – Alberta Zama Oil Field	227,000 Mt CO_2, 82,000 Mt H_2S Demo	2005–2009	PCOR Partnership	Oil field Carbonate Enhanced Oil Recovery	Apache (RCSP)	CSLF
North America, Canada – British Columbia Fort Nelson	> 1 MMt CO_2/yr, 1.8 MMt acid gas/yr Large-scale Demo	2009–2015	PCOR Partnership	Saline Formation	Spectra Energy (RCSP)	CSLF
Europe, North Sea – Norway Sleipner	1 MMt CO_2/yr Commercial 1996	2002–2011	Scripps, University of California, Lamont-Doherty, Columbia University	Marine Sandstone	StatoilHydro	CSLF, European Commission, IEA GHG R&D Programme
Europe, North Sea – Norway Snøhvit CO_2 Storage	700,000 Mt CO_2 Commercial 2008	2009–TBD	Lawrence Livermore National Laboratory	Marine Sandstone	StatoilHydro	—
Europe, Germany CO_2SINK, Ketzin	60,000 Mt CO_2 Demo 2008	2007–2010	Lawrence Berkeley National Laboratory	Saline Sandstone	GeoForschungsZentrum, Potsdam (GFZ)	CSLF, European Commission, IEA GHG R&D Programme
Europe, Iceland CarbFix	CO_2 stream from geothermal power plant	2009–2012	Columbia University	Hellisheidi Geothermal Power Plant	Reykjavik Energy	Icelandic, French, and U.S. (Columbia University) collaboration
Australia, Victoria Otway Basin	100,000 Mt CO_2 Demo 2008	2005–2010	Lawrence Berkeley National Laboratory	Gas Field Sandstone	CO_2CRC	CSLF
Africa, Algeria In Salah Gas	1 MMt CO_2/yr Commercial 2004	2005–2010	Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory	Gas Field Sandstone	BP, Sonatrach, StatoilHydro	CSLF, European Commission
Asia, China Ordos Basin	Assessment Phase CCS	2008–TBD	Lawrence Livermore National Laboratory, West Virginia University	Ordos Basin	Shenhua Coal	—

Issue	Agency	Authority	What is Regulated	FE Involvement
CO_2 Geologic Storage				
Injection, Monitoring, Safety	EPA/Office of Water	Safe Drinking Water Act	Underground injection and environmental monitoring of CO_2; draft rule published 8/2008; final rule expected 12/2010	EPA and FE are actively engaged in CCS regulatory and technical development. This interaction has helped to inform EPA's regulatory development process.
Injection on Federal Lands	U.S. Department of Interior/ Bureau of Land Management (BLM)	Federal Land Policy and Management Act and Minerals Leasing Act	Underground injection of CO_2 on Federal lands	FE participated in the preparation of several BLM Reports to Congress (e.g, under EPACT Sec. 369 and EISA Sec. 714).
State Role	Interstate Oil and Gas Compact Commission (IOGCC) and Ground Water Protection Council (GWPC)	State and Federal Statutes	Storage, including injection	FE is working with the IOGCC to examine the legal and regulatory framework for CO_2 storage, and the GWPC on State regulatory program data management for carbon storage.
Offshore	IOGCC	State and Federal Waters	Transport and Storage	FE is sponsoring IOGCC to conduct assessment of gaps for offshore storage.
CO_2 Transport				
Pipeline Safety	U.S. Department of Transportation	Interstate Commerce Act and Hazardous Liquid Pipeline Act	CO_2 pipeline operations including technical specifications	FE is working with the IOGCC and National Association of Regulatory Utility Commissioners to examine the regulatory framework for CO_2 pipeline siting, operation, and tariffs.
Pipeline Tariff Rate and Access	Federal Energy Regulatory Commission (FERC) / Surface Transportation Board	No Authority under Natural Gas Act or Interstate Commerce Act to set tariffs	Rate and Access Regulation (no siting or eminent domain)	FE and FERC are participating in the IOGCC Pipeline Transportation Task Force on CO_2 pipelines for carbon storage.

* Information current as of June 2010.

DOE's Interagency CCS Collaborations

Regulatory authority over many aspects of CCS continues to be examined by numerous agencies. Most of the interagency activities to date have focused on CO_2 transport and geologic storage. FE is actively coordinating with States and other Federal agencies on CCS-related rulemaking activities and engaging industry stakeholders in preparation for future regulatory action. This includes interacting with the U.S. Environmental Protection Agency (EPA), the U.S. Department of Interior's (DOI) Bureau of Ocean Energy Management, Regulation, and Enforcement (BOEMRE), DOI's Bureau of Land Management (BLM), the Interstate Oil and Gas Compact Commission (IOGCC), Ground Water Protection Council (GWPC), and the U.S. Department of Transportation (DOT) on issues related to CO_2 storage and transport. These regulatory activities are summarized in the chart to the left.

In addition, DOE is collaborating with the United States Geological Survey (USGS) and the DOI-BOEMRE on CCS site characterization and CO_2 geologic storage resource estimation for various geologic storage formations in the United States.

In 2007, the Energy Independence and Security Act (Public Law 110-140) authorized the USGS to conduct a national assessment of potential geologic storage resources for CO_2 in cooperation with the EPA and DOE. As a result of this legislation, the USGS developed a methodology that is being used by USGS geologists to assess the CO_2 storage potential in the United States at scales ranging from regional to sub-basinal. Storage assessment units are defined on the basis of common geologic and hydrologic characteristics. This methodology evaluates two types of storage processes (buoyant and residual) in saline formations at the individual storage assessment unit level. Results of the USGS assessment (2010–2013) will include illustrations and storage resource values.

The BOEMRE manages resources of the Outer Continental Shelf (OCS) pursuant to the Outer Continental Shelf Lands Act (OCSLA). Section 8(p)(1)(C) of the OCSLA authorizes the DOI to grant leases, easements, or rights-of-way on the OCS supporting the sub-seabed storage of CO_2 that is the byproduct of the production of electricity from sources other than oil and gas. The BOEMRE is currently developing regulations to implement its authority under Section 8(p)(1)(C). To support these regulations, BOEMRE is conducting research to develop best management practices for CO_2 sub-seabed storage on the OCS. The BOEMRE Resource Evaluation Division is investigating assessment methodologies that will enable it to estimate the potential total volume of CO_2 that could be stored in the OCS.

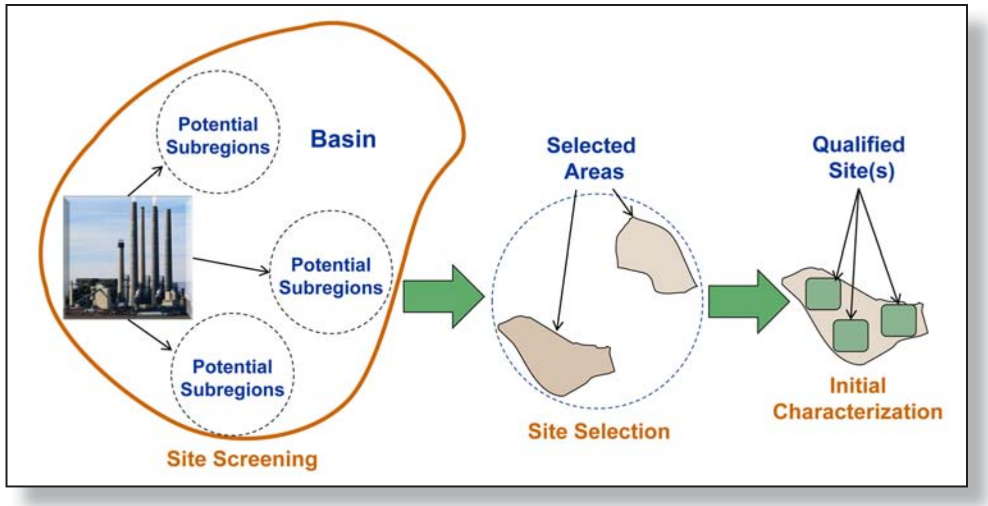
On February 3, 2010, President Obama sent a memorandum to the heads of 14 Executive Departments and Federal Agencies that established an Interagency Task Force on Carbon Capture and Storage. The Task Force's goal was to develop a comprehensive and coordinated Federal strategy to speed the commercial development and deployment of clean coal technologies. The Task Force, co-chaired by DOE and the EPA, was charged with proposing a plan to overcome the barriers to the widespread, cost-effective deployment of CCS within 10 years, with a goal of bringing 5 to 10 commercial demonstration projects online by 2016. The final report was published in August 2010 and is available at http://www.fe.doe.gov/programs/sequestration/ccstf/CCSTaskForceReport2010.pdf. For more information on the CCS Task Force, visit: http://www.whitehouse.gov/administration/eop/ceq/initiatives/ccs.

Site Characterization for Geologic Storage Sites

The process of identifying and maturing suitable geologic storage sites involves a methodical and careful analysis of the technical and non-technical aspects of potential sites. This process is analogous to the methods used in the petroleum industry to mature a project through a framework of resource classes and project status subclasses until the project begins producing hydrocarbons. A CO_2 Geologic Storage Classification System would likely follow the same processes developed by the petroleum industry in a bottom up progression based on analyses conducted to reduce the project development risk. The proposed framework would contain three distinct phases of evaluation (Exploration Phase, Site Characterization Phase, and Implementation Phase) corresponding to each resource class and further subdivided into project subclasses.

The Exploration Phase evaluates resources classified as Prospective Storage Resources and is divided into three project subclasses (Potential Subregions, Selected Areas, and Qualified Sites). Each project subclass undergoes an evaluation process (Site Screening, Site Selection, and Initial Characterization) that builds on previous analyses to pare down larger Potenitial Subregions into Qualified Site(s). The three evaluation processes are discussed in more detail below:

- **Site Screening** involves analysis of three components (regional geologic data, regional site data, and social data) to develop and rank a list of Selected Areas within a Potential Subregion to elevate to the **Site Selection** evaluation. This analysis highlights the most promising Selected Areas for geologic storage, while eliminating those that do not meet a developer's criteria.
- **Site Selection** involves analysis of the most promising **Selected Areas** in more detail to ensure only those that meet critical technical and economic criteria advance for further evaluation. Analysis is conducted on five separate components, including subsurface geologic data, regulatory requirements, model data, site data, and social data. At the completion of this stage, the developer will have a list of potential **Qualified Site(s)** that can be assessed during the final evaluation stage.



Graphical Representation of "Project Site Maturation" through the Exploration Phase.

- **Initial Characterization** involves analysis of one or more of the higher ranked **Qualified Site(s)**. This stage includes analysis of several components, including baseline data, regulatory requirements, model data, social data, and a site development plan. Upon completion results from this stage should provide enough information to qualify discovered storage at the site as **Contingent Storage Resource**.

At the completion of the Exploration Phase, a **Qualified Site** moves into the **Site Characterization Phase**, classifying the storage as **Contingent Storage Resources** with three project subclasses: **Development Not Viable**, **Development Unclarified or on Hold**, or **Development Pending**. Once the appraised **Qualified Site** is considered commercial, the project would move into the **Implementation Phase**. The project would first be classified as **Justified for Development**. Once all necessary approvals and permits have been obtained and capital funds committed, the project elevates to **Approved for Development**, which would give way to **Active Injection**. The successful characterization of a site is one of the most important steps in ensuring the safe and economic operation of a geologic CO_2 storage site.

For more information, NETL's "Site Screening, Selection, and Characterization for Storage of CO_2 in Deep Geologic Formations" is available at: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/BPM-SiteScreening.pdf.

Atlas III CO_2 Geologic Storage Estimates

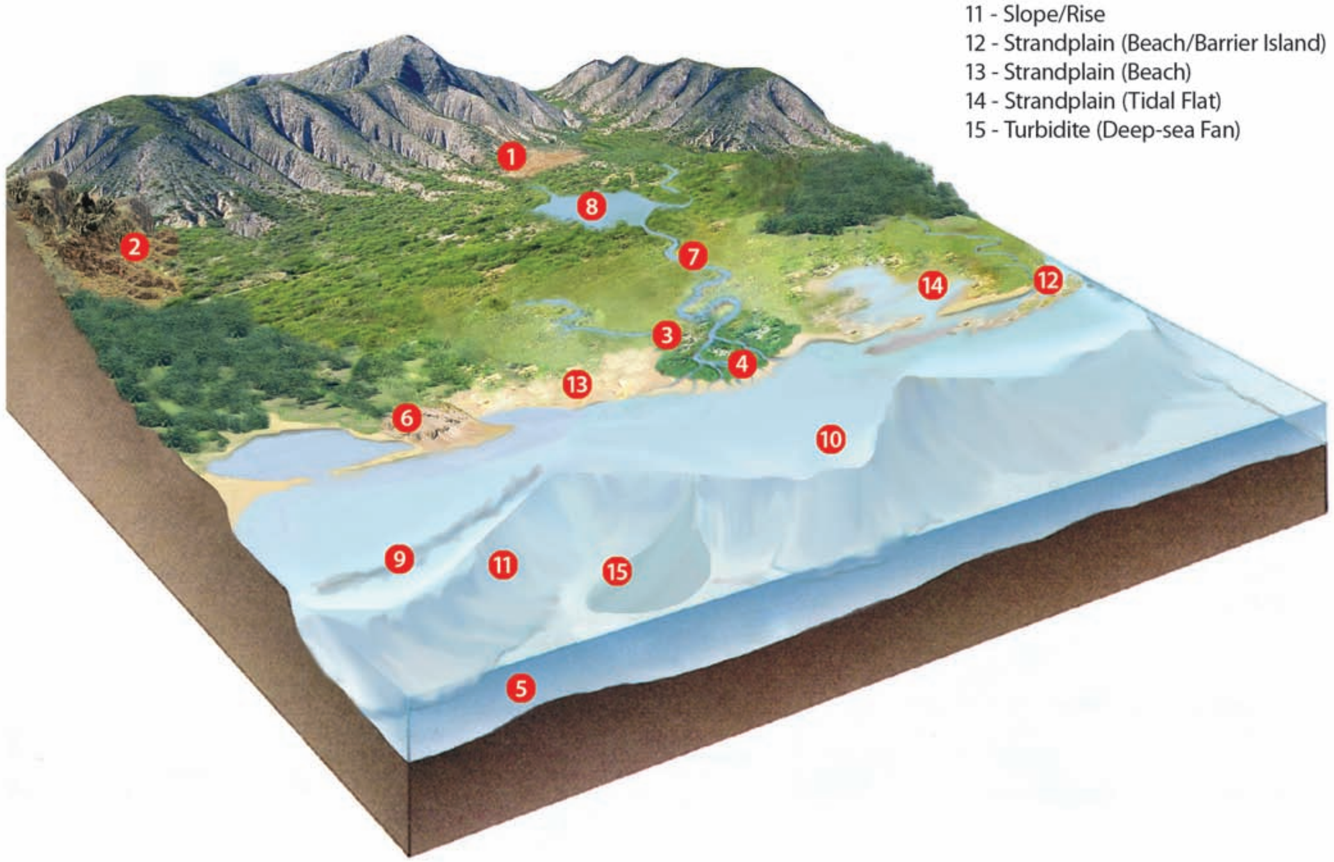
Carbon dioxide geologic storage information in Atlas III was developed to provide a high level overview of CO_2 geologic storage potential across the United States and parts of Canada. Areal extents of geologic formations and CO_2 resource estimates presented are intended to be used as an initial assessment of potential geologic storage. *Atlas III* provides essential information about a potential site prior to an Exploration Phase evaluation.

Petroleum Industry		CO_2 Geologic Storage
Reserves	Implementation	**Storage 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 Subregions

	Prospective Storage Resources	
Exploration	**Project Subclass**	**Evaluation Process**
	Qualified Site(s)	Initial Characterization
	Selected Areas	Site Selection
	Potential Subregions	Site Screening

Comparison of Petroleum Industry Classification and Proposed CO_2 Geologic Storage Classification. Adapted from SPE/WPC/AAPG/SPEE Resource Classification System. (© 2007 Society of Petroleum Engineers, Petroleum Resources Management System.)

(Note: this table should be read from the bottom to top)



1 - Alluvial (Alluvial Fan)
2 - Basalt (Lava Flow)
3 - Coal/Shale (Swamp)
4 - Deltaic (Delta)
5 - Deep Marine
6 - Eolian (Dunes)
7 - Fluvial (Stream)
8 - Lacustrine (Lake)
9 - Reef
10 - Shelf/Platform
11 - Slope/Rise
12 - Strandplain (Beach/Barrier Island)
13 - Strandplain (Beach)
14 - Strandplain (Tidal Flat)
15 - Turbidite (Deep-sea Fan)

Geologic Storage Formation Classes

Each type of geologic formation has different opportunities and challenges. While geologic formations are infinitely variable in detail, they are classified by geologists and engineers in the petroleum industry by their trapping mechanism, hydrodynamic conditions, lithology, and, more recently, by their depositional environment. The depositional environment, or the area where sediment was deposited over many years, influences how formation fluids are held in place, how they move, and how they interact with other formation fluids and solids (minerals). Certain geologic properties may be more favorable to long-term containment of liquids and gases, typically needed for CCS geologic storage reservoirs.

A primary goal of DOE's Carbon Sequestration Program is to classify the depositional environments of various formations known to have excellent reservoir properties that are amenable to geologic CO_2 storage. For fluid flow in porous media, knowledge of how depositional environments formed and directional tendencies imposed by the depositional environment can influence how fluid flows within these systems today and how CO_2 in geologic storage would be anticipated to flow in the future. Although the flow paths of the original depositional environment may have been degraded or modified by mineral deposition or dissolution since the geologic units were deposited, the basic stratigraphic framework created during deposition remains. Geologic processes working today also existed when the sediments were initially deposited. Analysis of modern day depositional analogs, evaluation of core, outcrops, and well logs from ancient subsurface formations provide an indication of how formations were deposited and how CO_2 within the formation is anticipated to flow.

There are three types of rocks: metamorphic, igneous, and sedimentary. Metamorphic rocks are not currently being evaluated for CO_2 storage. While igneous rocks comprise 95 percent of the Earth's crust, the only igneous rocks currently being evaluated for CO_2 storage are basalts. Most basalts have high amounts of calcium, which can react with CO_2 to form a mineral, calcite, resulting in permanent CO_2 storage. Sedimentary rocks are the most promising type of rock being evaluated for CO_2 storage. There are three types of sedimentary rocks: (1) clastic (broken fragments derived from preexisting rocks like sandstone); (2) chemical precipitates (such as carbonates [limestone] and rock salt); and (3) organics (plant or animal constituents that may form coal or limestone). At this time, most geologic storage reservoirs are either clastics or fractured carbonates (both precipitates and organic), where CO_2 is stored in the pore spaces between grains or fractures that are often filled with brine. In this type of CO_2 storage system impermeable layers are required to form a confining zone that prevents the upward migration of CO_2. For more information, NETL's "Geologic Storage Formation Classifications: Understanding Its Importance and Impacts on CCS Opportunities in the United States" is available at: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/Geologic_Storage.pdf.

Matrix of NETL CO_2 Geologic Storage Projects and Geologic Formation Classes

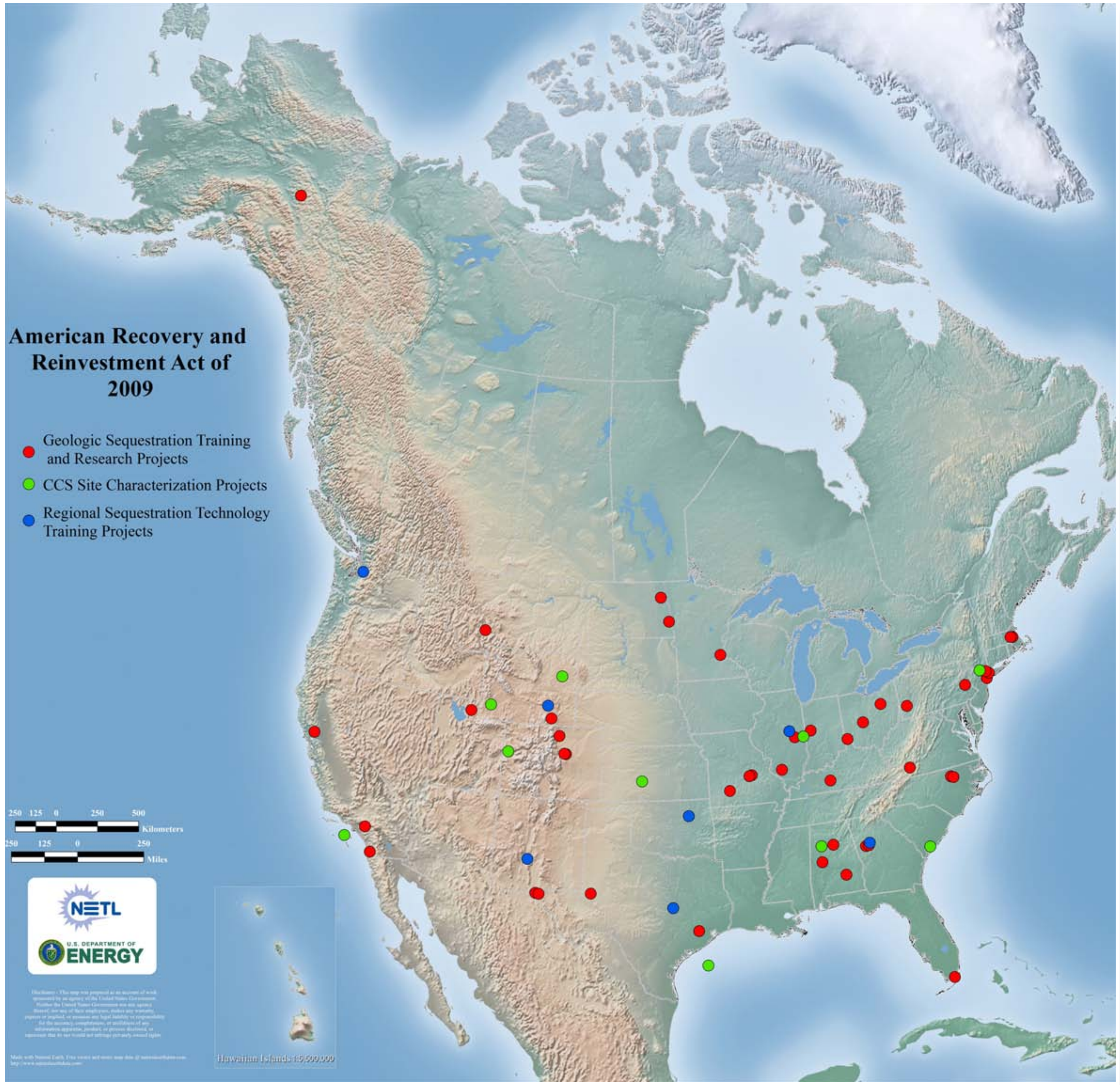
Project Type	High Potential Formations					Medium Potential Formations				Lower or Unknown Potential Formations	
	Deltaic	Shelf Clastic	Shelf Carbonate	Strandplain	Reef	Fluvial Deltaic	Eolian	Fluvial & Alluvial	Turbidite	Coal	Basalt (LIP)
Large Scale	–	1	–	–	1	3	–	1	–	–	–
Small Scale	3	2	4	1	2	–	–	2	–	5	1
Characterization	1	–	8	6	–	3	3	2	2	–	1

* The number in the cell is the number of investigations by NETL per geologic formation class.

Source: NETL's "Understanding Geologic Storage Formations Classifications: Importance to Understanding and Impacts on CCS Opportunities in the United States" (DOE/NETL-2010/1420)

American Recovery and Reinvestment Act of 2009

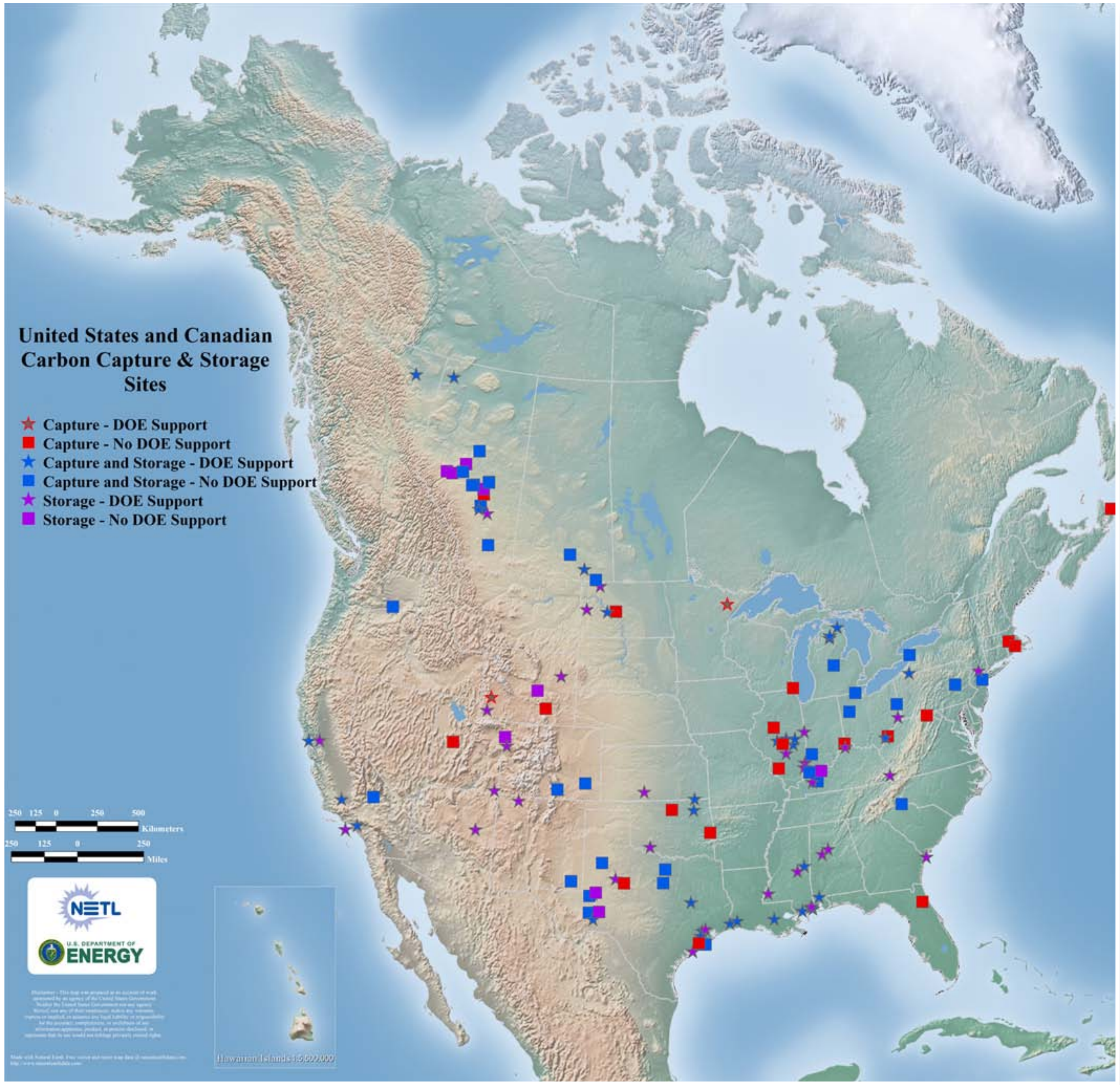
The American Recovery and Reinvestment Act (ARRA) of 2009 was passed on February 13, 2009, to (1) create new jobs and save existing ones; (2) spur economic activity and invest in long-term growth; and (3) foster unprecedented levels of accountability and transparency in Government spending. The primary objectives of the Fossil Energy portion of the Recovery Act are to: (1) demonstrate CCS technology to reduce GHG emissions from the electric power and industrial sectors of the U.S. economy; (2) become the world's leader in CCS science and technology; (3) implement projects to support economic recovery by creating new jobs in pursuit of a secure energy future. Within the funding appropriated by the Recovery Act, the Carbon Sequestration Program issued three Funding Opportunity Announcements. These included \$50 million in DOE funding to support 10 CCS Site Characterization Projects; \$7 million in DOE funding for Regional Sequestration Technology Training Projects; and almost \$13 million in DOE funding for University-based Geologic Sequestration Training and Research Projects. The CCS Site Characterization Projects received and additional \$50 million from ARRA Industrial Carbon Capture and Storage to characterize storage resources for industrial sources.



The objective of the CCS Site Characterization Projects is to characterize a minimum of 10 distinct "high-potential" geologic formations, including saline formations, depleting/depleted oil fields, and coal areas. Each project is focused on a minimum of one specific site, formation, or area not previously characterized with public data that represents a significant storage opportunity in a region with adequate seals that could be commercially developed in the future. The projects will increase understanding of the potential for these formations to safely and permanently store CO_2.

The objective of the Regional Sequestration Technology Training Projects is to facilitate development of a CCS workforce through regional CO_2 sequestration technology training in all aspects of long-term, underground CO_2 storage. Training is being accomplished through several activities, such as CCS short courses; regional CCS training conferences; targeted CCS training seminars; and transfer of the lessons learned from CO_2 storage projects.

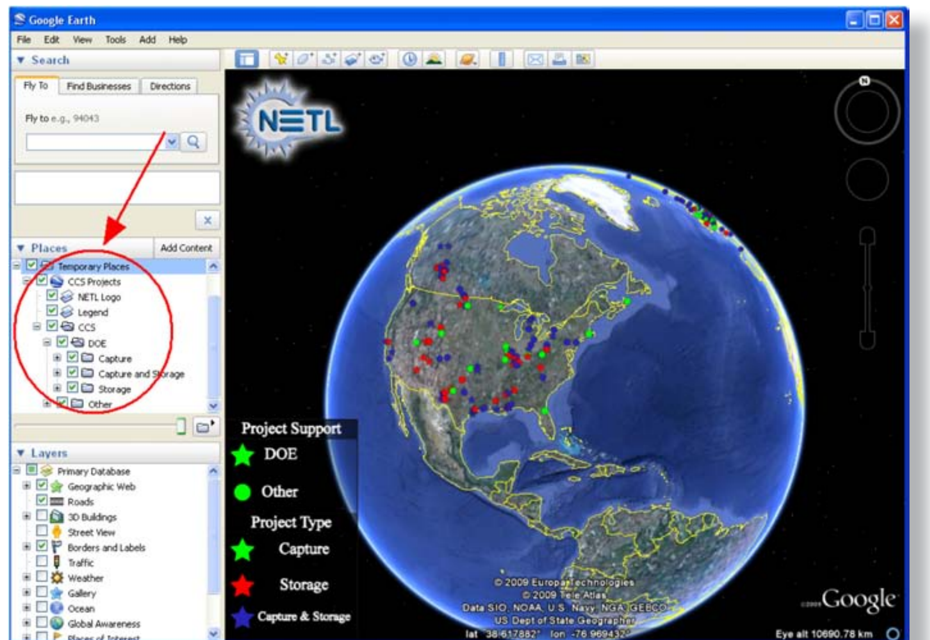
The objective of the University-based Geologic Sequestration Training and Research Projects is to provide training opportunities for graduate and undergraduate students that will provide the human capital and skills required for implementing and deploying CCS technologies. Training is being accomplished through fundamental research in the following areas: simulation and risk assessment; MVA; geological-related analytical tools; methods to interpret geophysical models; well completion and integrity for long-term CO_2 storage; and CO_2 capture.



NETL's CCS Worldwide Database

In November 2009, NETL launched its CCS Database, which includes active, proposed, canceled, and terminated CCS projects worldwide. This database provides the public with information regarding efforts by various industries, public groups, and governments towards development and eventual deployment of CCS technology. It lists technologies being developed for CO_2 capture, testing sites for CO_2 storage, project cost estimations, and anticipated dates of project completion. The database uses Google Earth to illustrate the location of projects and provide a link to further information. Project details are obtained from publically available information.

As of October 2010, the database contained 246 CCS projects worldwide. The 246 projects include 63 capture, 58 storage, and 125 for capture and storage in more than 20 countries across 5 continents. While most of the projects are still in the planning and development stage, or have recently been proposed, 8 are actively capturing and injecting CO_2. NETL will update the database as information regarding these projects is released to the public or new projects are announced.



NETL's CCS Database is available for download at: http://www.netl.doe.gov/technologies/carbon_seq/database/index.html. Access to the database requires use of Google Earth, as the NETL CCS database is a layer in Google Earth. Free downloadable software for Google Earth is available at http://earth.google.com/.

Public Outreach and Education for CCS Deployment

DOE charged the RCSPs with developing and implementing an outreach and education program that would (1) raise awareness and understanding of the general population in the RCSP regions with respect to long-term CO_2 storage in geologic formations for GHG reduction, and (2) educate communities in areas where CO_2 storage projects or long-term demonstrations are planned. Effective public outreach involves listening, sharing information, and addressing concerns through proactive community engagement. Conducting effective public outreach will not necessarily ensure project success, but underestimating its importance can contribute to delays, increased costs, and lack of community support.

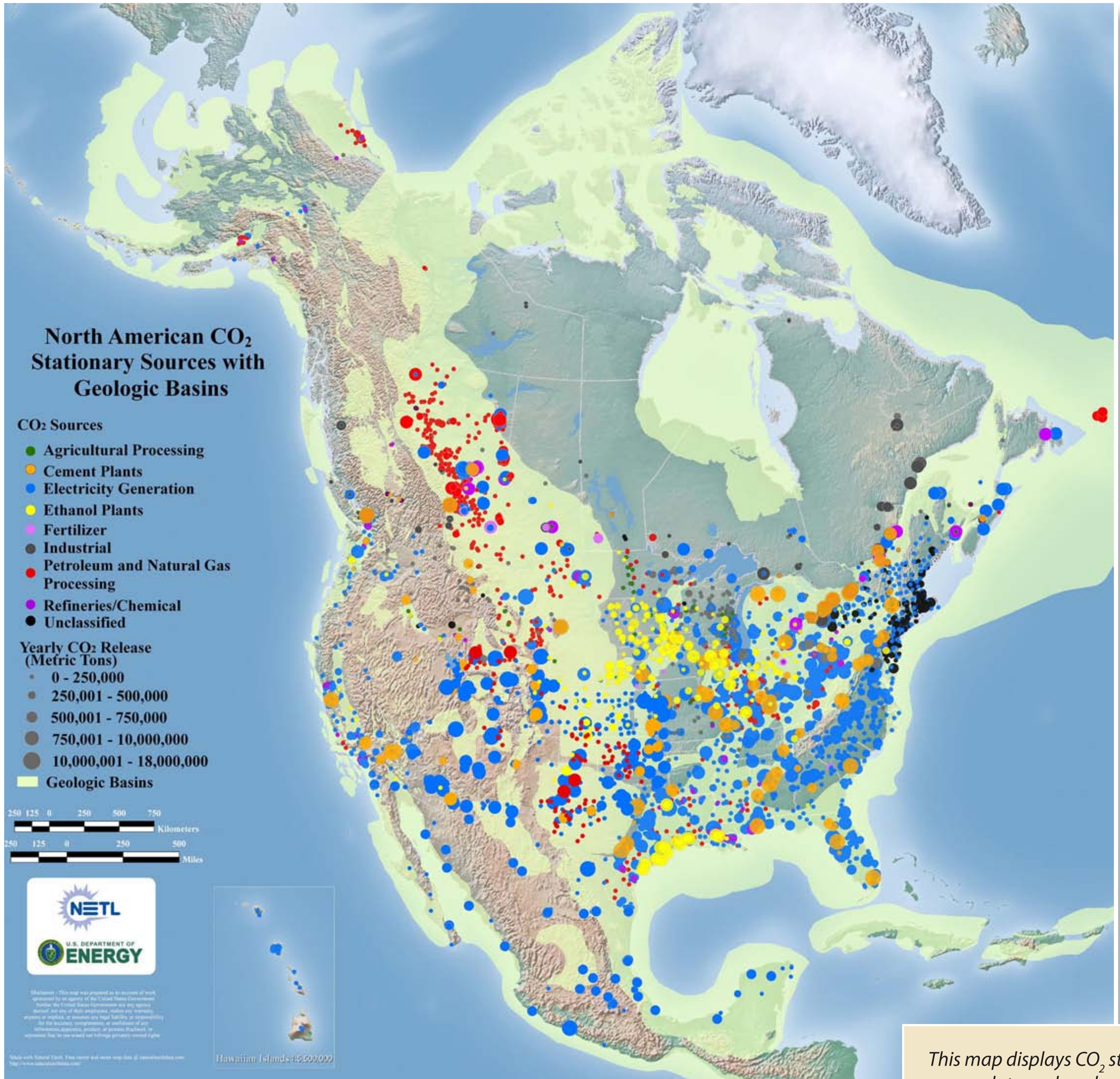
The RCSPs' concept of public outreach involves efforts to understand, anticipate, and address public perceptions and concerns about CO_2 storage in a community being considered for a project. Ideally, public outreach can lead to a mutually beneficial outcome where project developers and communities work together to implement a CO_2 storage project and then move ahead with the support of well-informed stakeholders who are comfortable with the project benefits and potential risks and trust the project team.

Public outreach begins at the onset of the project, continues through the close of the project, and involves each individual on the project team. In addition, public outreach encompasses an array of activities through which information about CO_2 storage projects is shared, and feedback is obtained from stakeholders. Stakeholders are defined as those parties who believe that they are affected by CO_2 storage project decisions.

As described in DOE's "Best Practices for Public Outreach and Education for Carbon Storage Projects," the RCSPs have identified the following best practices:

Physical Model Demonstration at a Midwest Geological Sequestration Consortium Open House. (Photo courtesy of Midwest Geological Sequestration Consortium.)

Best Practice	Description
Integrate Outreach with Project Management	By including outreach in the critical path of a CO_2 storage project, outreach activities will be more effective, in sync with other key project stages, and beneficial to the overall project; a key component is building in the time necessary to accomplish the various steps in advance of engaging the public.
Establish a Strong Team	It is essential to establish a clearly defined structure that delineates roles and responsibilities covering both internal and external communication and includes individuals who are knowledgeable about the technical details of the project, as well as individuals who have backgrounds in communication, education, and community relations.
Identify Key Stakeholders	Early CO_2 storage projects are being carried out in the context of national debates on climate change mitigation and, as a result, stakeholders may come from an area that extends beyond the project's location and regulatory jurisdiction. It is critical to identify all stakeholders in the project lifecycle. At the local level, these may include elected and safety officials, regulators, landowners, citizens, civic groups, business leaders, media, and community leaders. At the national level, these may include Government agencies, Congressional leaders, committee/subcommittee chairs and key staff, environmental groups, and the financial and legal community.
Conduct Social Characterization	Social characterization is an approach for gathering and evaluating information to obtain an accurate portrait of stakeholder groups, their perceptions, and their concerns about CO_2 storage. This approach can identify the factors that will likely influence public understanding of CO_2 storage within a specific community. The information gathered will enable the project team to develop better insights into the breadth of diversity among community members, local concerns and potential benefits, and assist in determining which modes of outreach and communication will be most effective.
Develop a Strategy and Communication Plan	The outreach strategy and communications plan ties together the information, planning, and preparation. The outreach strategy is tailored to the stakeholder needs and concerns of a particular CO_2 storage project. Specifics will include outreach objectives, outreach tasks, and events that coincide with the project stages, a timeline for outreach activities, and the roles and responsibilities of the outreach team. The outreach strategy will also identify key stakeholders and messages, and the timelines, roles, and responsibilities for producing outreach materials and managing outreach events. A component of the outreach strategy is a communications plan that focuses on representing the project directly to the public and through the media.
Develop Key Messages	CO_2 storage involves advanced science related to climate change, geology, and other fields of study; public policy related to energy, environment, and the economy; and issues related to risk, safety, and financial assurance. Therefore, identifying a set of key messages that can be consistently repeated in outreach activities and materials can help stakeholders develop a clearer understanding of the project and how their concerns will be addressed.
Develop Materials Tailored to Audiences	The development of outreach materials involves consideration of the intended audience. The amount of information and level of technical detail provided must be tailored to match the audience's degree of interest, education, and time constraints. Any concerns that have been identified, including perceived risks, should be addressed in language and formats suited to the intended audiences.
Proactively Manage the Program	Outreach programs should be actively managed to ensure that consistent messages are being communicated and that requests for information are fulfilled throughout the project lifecycle. The identification of an outreach leader or coordinator to manage, coordinate, and direct outreach is crucial for project success. The outreach lead will be supported in their efforts by the outreach team and other project team members. As a project unfolds, public perception will to be influenced by the extent to which the project and the project team are well coordinated and responsive.
Monitor the Program and Public Perceptions	Monitoring the performance of the outreach program allows the project team to stay abreast of how the community perceives the project and gauge the effectiveness of the outreach activities. Monitoring can also help identify any misconceptions about the project or CO_2 storage and develop outreach strategies to correct them.
Refine the Program as Warranted	The outreach team must be ready to adapt to changes in information about the site, unexpected events, and other conditions that may have a strong influence on the public's perception of CO_2 storage during project implementation.



This map displays CO_2 stationary source data and geologic basins which were obtained from the RCSPs and other external sources and compiled by NATCARB. Each colored dot represents a different type of CO_2 stationary source with the dot size representing the relative magnitude of the CO_2 emissions (see map legend).

North American Carbon Atlas Partnership

A Joint CO_2 Mapping Initiative between the United States, Canada, and Mexico

The United States, Canada, and Mexico formed a joint CO_2 mapping initiative called the North American Carbon Atlas Partnership (NACAP). The goal of NACAP is for each country to identify, gather, and share data for CO_2 stationary sources and geologic storage sites in the United States, Canada, and Mexico and display these in a geographic information system (GIS) for North America. In order to achieve this goal, two working groups, the Information Technology Working Group and the Methodology Working Group, were formed within NACAP and tasked to develop sub-elements of a framework to achieve the goal. The map at left shows a preview of the data expected to be included in this NACAP Atlas. This data includes the magnitude and location of CO_2 stationary sources, and the areal extent of potential geologic CO_2 storage resource for various formations in each country.

Development of this GIS system supports FE's Carbon Sequestration Program, the objectives of the NAEWG, and current topics being discussed under the Canada-U.S. Clean Energy Dialogue. It is expected that this initiative will serve as a key opportunity to foster collaboration among the three countries in the area of CCS. Results of this initiative are expected to be published in a NACAP Atlas and made available in 2012.

National Carbon Sequestration Database and Geographic Information System

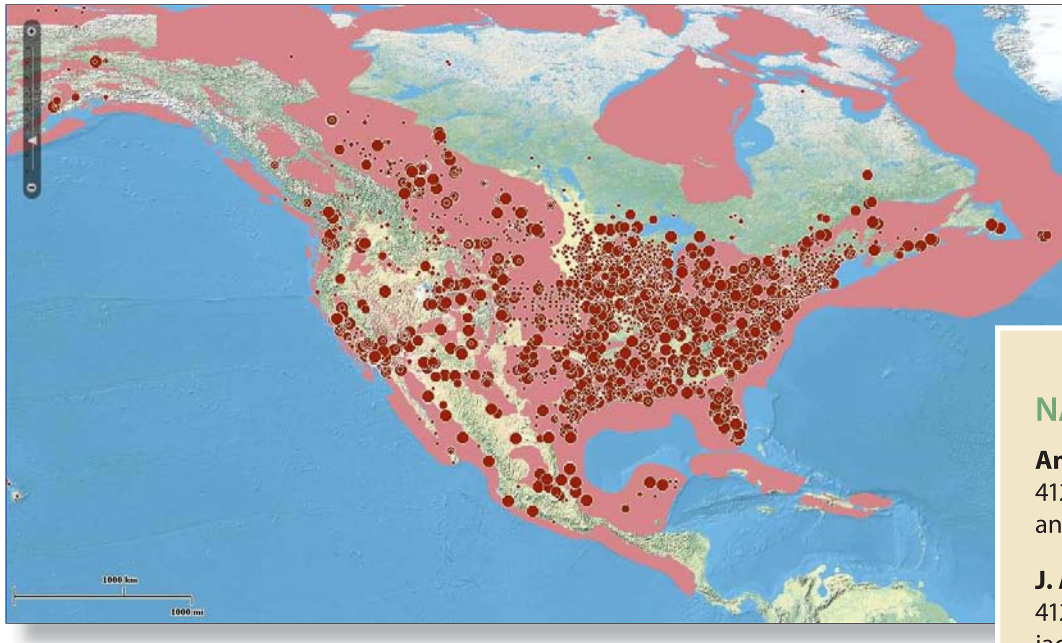
A National Look at Carbon Sequestration

The National Carbon Sequestration Database and Geographic Information System (NATCARB) provides Web-based data access to disparate data (CO_2 stationary sources, potential geologic CO_2, infrastructure, etc.) and analytical tools (pipeline measurement, storage resource estimation, cost estimation, etc.) required for addressing CCS deployment. Distributed computing solutions link the RCSPs and other publically accessible repositories of geologic, geophysical, natural resource, infrastructure, and environmental data. NATCARB, a first effort at a national carbon cyberinfrastructure, assembles the data required to address technical and policy challenges of CCS.

NATCARB online access is being modified to address the broad needs of all users. It includes not only GIS and database query tools for the high-end technical user, but also simplified displays for the general public, employing readily available Web tools, such as Google Earth™ and Google Maps™.

NATCARB organizes and enhances the critical information about CO_2 stationary sources and develops the technology needed to access, query and model, analyze, display, and distribute CO_2 storage resource data. Data are generated, maintained, and enhanced locally at each RCSP, or at specialized data warehouses and public servers (e.g., USGS-EROS Data Center, EPA, and the Geography Network), and assembled, accessed, and analyzed in real-time through a single geoportal.

All map layers and data tables used to construct the national estimates of CO_2 stationary sources and geologic storage resources are available for interactive display and download through the NATCARB website (http://www.netl.doe.gov/technologies/carbon_seq/natcarb/map_request.html).



In 2010, NATCARB will begin to provide CCS data covering all of North America for the general public, employing readily available Web tools like Google Earth™ and Google Maps™. This image shows the location of CO_2 stationary sources, inventoried and accessible through the NATCARB portal and displayed with a light-weight GIS viewer. At the same time, images of geologic basins that are potential areas for geologic CO_2 storage resources are displayed.

Close-up view of the American Electric Power integrated CCS project in West Virginia using NATCARB Google Earth™ viewer.

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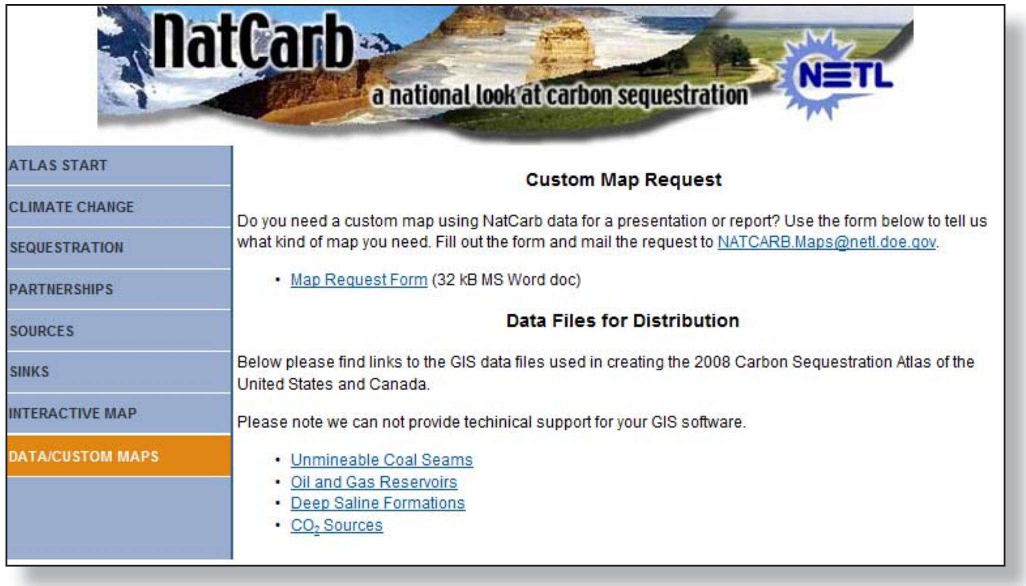
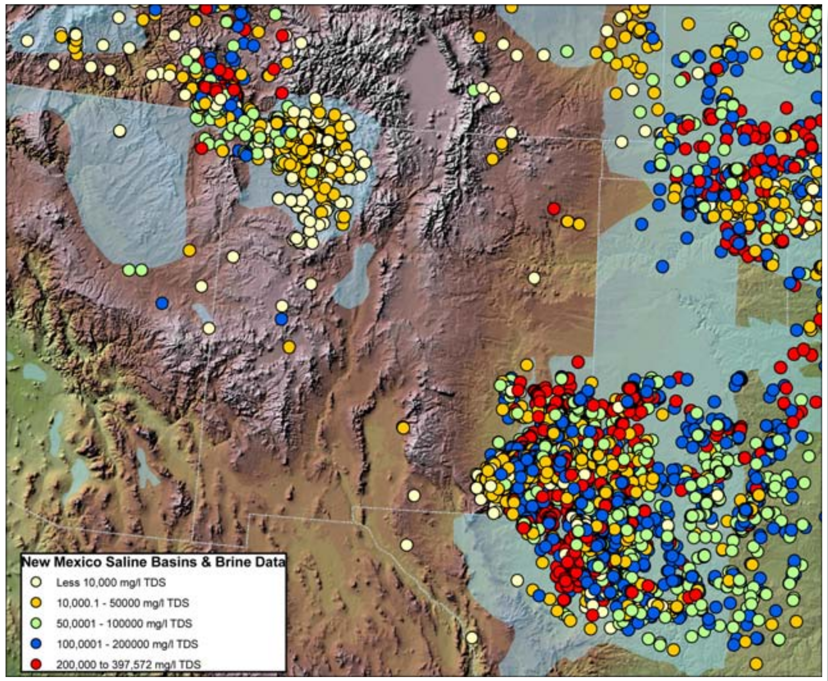
NATCARB Map and Data Requests

Please refer all NATCARB map and data requests to natcarb.maps@netl.doe.gov.

National Carbon Sequestration Database and Geographic Information System (cont'd)



NATCARB users have the ability to request custom maps and/or download data files from Atlas III.



This image shows the distribution of locations of over 10,000 brine samples in New Mexico. Data is categorized by total dissolved solids (TDS). Samples with less than 10,000 mg/l TDS are legally considered potential potable water and need to be protected (yellow dots). Formations containing TDS concentrations greater than 10,000 mg/l are potential sites that merit further evaluation for potential CO_2 storage (blue and red dots). Basins containing saline formations that have been evaluated are highlighted in blue. Data on brine geochemistry can be accessed and summarized with several additional online tools. All data were assembled as a custom map with a request through NatCarb.

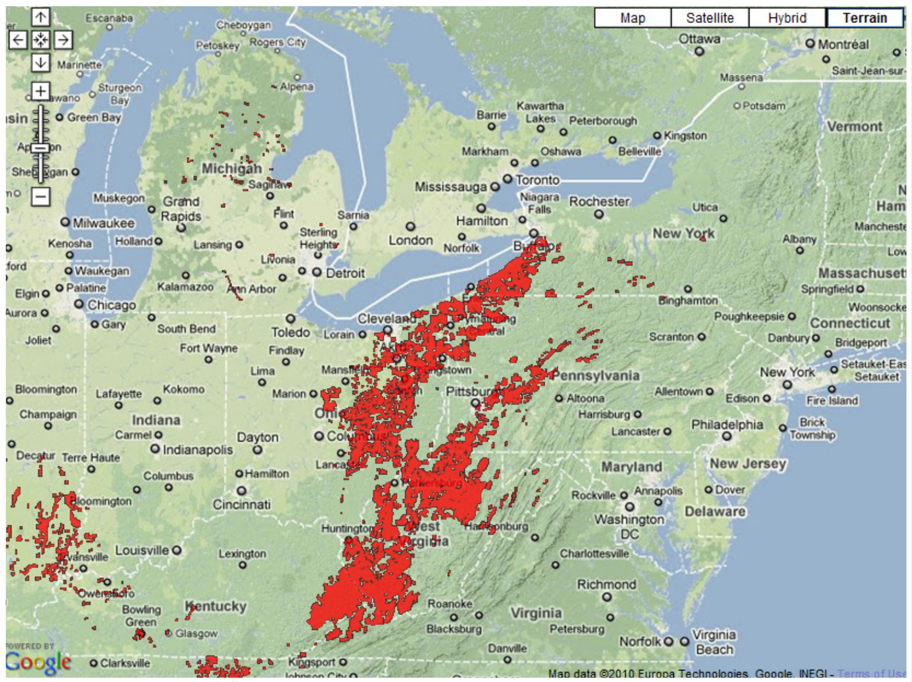
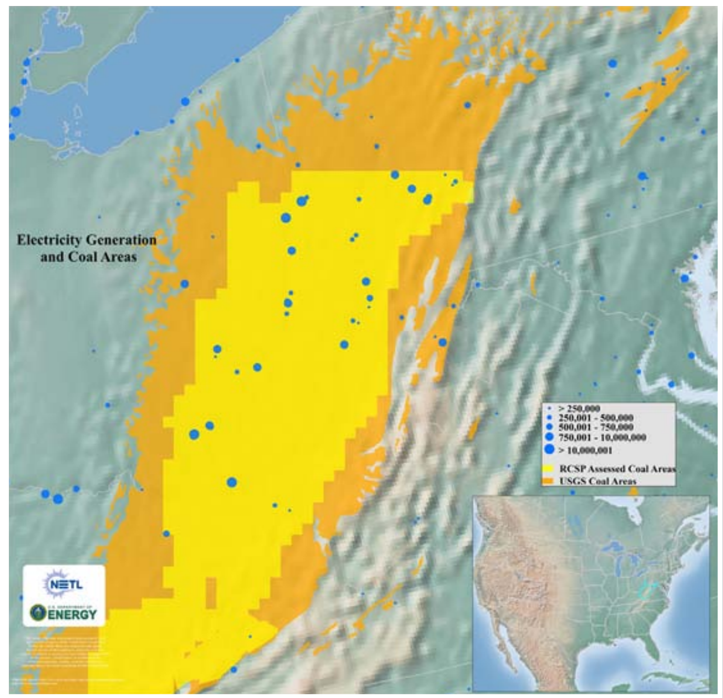


Image showing the extent of oil and gas reservoirs (red) in the northeastern United States. Similar data for saline formations and unmineable coal areas are accessible through NATCARB using Google Maps™.

Image showing the distribution of electric generation facilities ranked by metric tons of CO_2 emitted per year and the U.S. power distribution grid. The CO_2 stationary sources have been overlain on coal basins and assessed areas with unmineable coal areas that may serve as potential CO_2 storage sites.



CO_2 Stationary Source Emissions Summary

DOE's RCSPs have identified 4,507 CO_2 stationary sources with total annual emissions of more than 3,400 million metric tons (3,748 million tons) of CO_2. The RCSPs have documented the methods used to collect and calculate these emissions. A summary of those methods follows. For additional detail, refer to Appendix A "CO_2 Stationary Source Emissions Summary".

The CO_2 stationary sources documented by the RCSPs include power plants, ethanol plants, petroleum and natural gas processing facilities, cement and lime plants, agricultural processing facilities, industrial facilities, iron and steel production facilities, and fertilizer producing facilities. Estimation methods include the use of databases and emissions factors. Tables in Appendix A list the databases and emissions factors utilized for a particular CO_2 stationary source type. Not all databases or emissions factors were used by each of the RCSPs.

The documents used to identify each CO_2 stationary source, as well as the practical quantitative method (i.e., emission factors, continuous emissions-monitoring results, emission estimate equations, etc.) used to estimate CO_2 emissions from that source, are listed in Appendix A. In addition, the data sources to determine specific plant capacities, production outputs, or fuel usage data are listed by RCSP.

The approach to determine these methodologies was to identify CO_2 stationary sources within each RCSP region, and then assess the availability of CO_2 emission data or to apply an estimate of the CO_2 emissions based upon sound scientific and engineering principles. In each RCSP, the emissions were grouped by emission source and a methodology was established for each emission source category; then the methodology was utilized to estimate the CO_2 emissions from each emission source category. To summarize these efforts, nine tables containing CO_2 emission estimation methodologies and equations for the major CO_2 stationary source industries were created. During the RCSPs' Characterization Phase, each RCSP was responsible for developing GHG emission inventories and stationary source surveys within their respective boundary area.

Carbon dioxide stationary sources fall under one of the nine industry types. The table at right identifies the stationary sources included in various industry types.

For any stationary source within a given industry type, the RCSPs employed CO_2 emissions estimate methodologies that are based on the most readily available representative data for that particular industry type within the respective RCSP area. CO_2 emissions data provided by databases (for example, eGRID or ECOFYS) were the first choice for all of the RCSPs, both for identifying major CO_2 stationary sources and for providing reliable emission estimations. Databases are considered to contain reliable and accurate data obtained from direct emissions measurements via continuous emissions monitoring systems. When databases were not available, CO_2 stationary source facility production or fuel usage were coupled with CO_2 emissions factors to estimate annual CO_2 emissions from the production or fuel usage data. Emissions factors, fuel usage data, and facility production data were obtained from various databases, websites, and publications. Carbon dioxide stationary source spatial location data (latitude and longitude) were determined from a variety of sources. Some databases (eGRID) contain latitude and longitude information for each CO_2 stationary source. Where spatial location information was not available through an emissions database, other spatial location methods were utilized. These include the use of mapping tools (Google Earth™, TerraServer, and USGS Digital Orthophoto Imagery) equipped with geospatially defined data, along with web-based databases (Travelpost) containing latitude and longitude information for various U.S. locations.

A summary of the CO_2 stationary source emissions calculated and compiled by each RCSP appears in the "National Perspectives" section of Atlas III. Regional details of these CO_2 stationary source emissions appear in the "Regional Carbon Sequestration Partnerships Perspectives" section of Atlas III. Finally, a State summary of CO_2 stationary source emissions appears in Appendix C of Atlas III.

CO_2 Stationary Sources by Industry Category

Industry Type	CO_2 Stationary Sources Include
Electric Generating Plants	• Coal-, Oil-, and Natural Gas-Fired Power Plants
Ethanol Production Plants	• Ethanol Plants, Regardless of Feedstock Type
Agricultural Processing Facilities	• Sugar Production
Natural Gas Processing Facilities	• Natural Gas Processing Facilities
Industrial Facilities	• Aluminum Production Facilities • Soda Ash Production Facilities • Glass Manufacturing Facilities • Automobile Manufacturing Facilities • Iron Ore Processing Facilities • Compressor Stations • Paper and Pulp Mills
Iron and Steel Facilities	• Iron and Steel Producing Facilities
Cement and Lime Plants	• Lime Production Facilities • Cement Plants
Refineries and Chemical Facilities	• Petroleum Refinery Processing • Ethylene Production Facilities • Ethylene Oxide Production • Hydrogen Production Facilities
Fertilizer Production	• Ammonia Production

Methodology for Development of Geologic Storage Estimates for Carbon Dioxide

DOE's RCSPs were charged with providing a high-level, quantitative estimate of CO_2 storage resource available in subsurface environments of their regions. Environments considered for CO_2 storage were categorized into five major geologic systems: oil and gas reservoirs, saline formations, unmineable coal areas, shale, and basalt formations. Where possible, CO_2 storage resource estimates have been quantified for oil and gas reservoirs, saline formations, and unmineable coal areas; shale and basalt formations are presented as future opportunities and not assessed in *Atlas III*.

Carbon dioxide storage resource estimates in *Atlas III* are defined as the fraction of pore volume of sedimentary rocks available for CO_2 storage and accessible to injected CO_2. Storage resource assessments do not include economic or regulatory constraints. *Atlas III* estimates are based on the assumption that in situ fluids will either be displaced by the injected CO_2 or managed by means of fluid production, treatment, and/or disposal in accordance with current technical, regulatory, and economic guidelines. In addition, storage resource estimates are screened by criteria such as isolation from potable groundwater, isolation from other strata, TDS concentrations of 10,000 ppm or more, and maximum allowed injection pressure to avoid fracturing. Resource estimates do take into account geologic-based physical considerations, such as vertical thickness, fraction of porosity available for CO_2 storage, and fraction of the total area accessible to injected CO_2. In these CO_2 storage resource estimates, only physical trapping of CO_2 is considered.

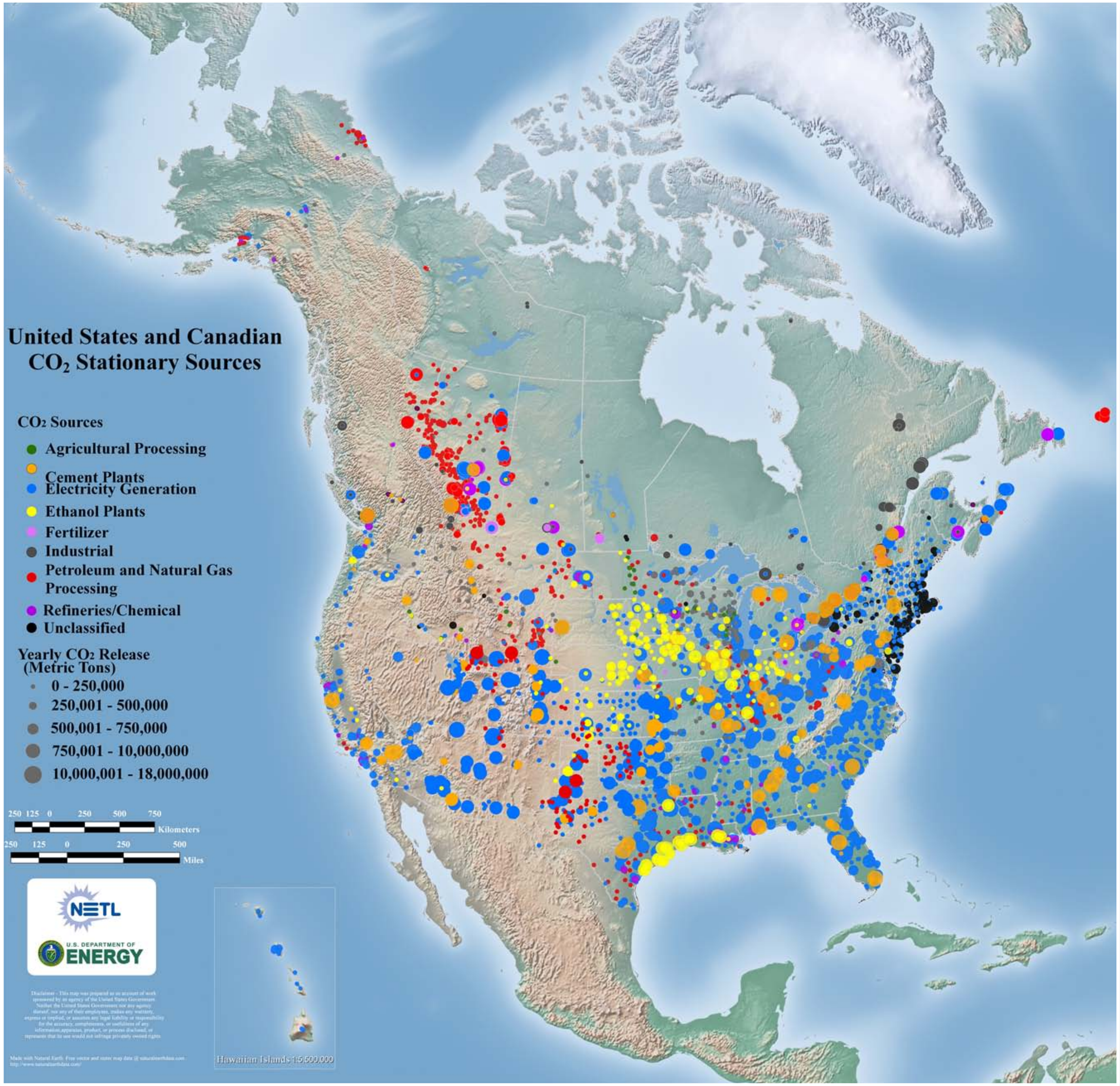
The methodologies used for estimating CO_2 geologic storage resource potential in *Atlas III* were designed to integrate results from all seven RCSPs and were based on volumetric methods for estimating subsurface volumes, in situ fluid distributions, and fluid displacement. Estimating subsurface volumes depends on geologic properties (area, thickness, and porosity of formations) and storage efficiency (the fraction of the accessible pore volume that will be occupied by the injected CO_2). Storage efficiency was determined using Monte Carlo simulation, which included efficiency terms to account for variations in a formation's geologic properties and displacement properties of in situ fluids and injected CO_2.

A summary of the national CO_2 storage resource estimates computed by each RCSP and compiled by NATCARB appears in the "National Perspectives" section of *Atlas III*. Regional details of these CO_2 storage resource estimates appear in the "Regional Carbon Sequestration Partnership Perspectives" section of *Atlas III*. A State summary of CO_2 storage resource estimates appears in Appendix C of *Atlas III*.

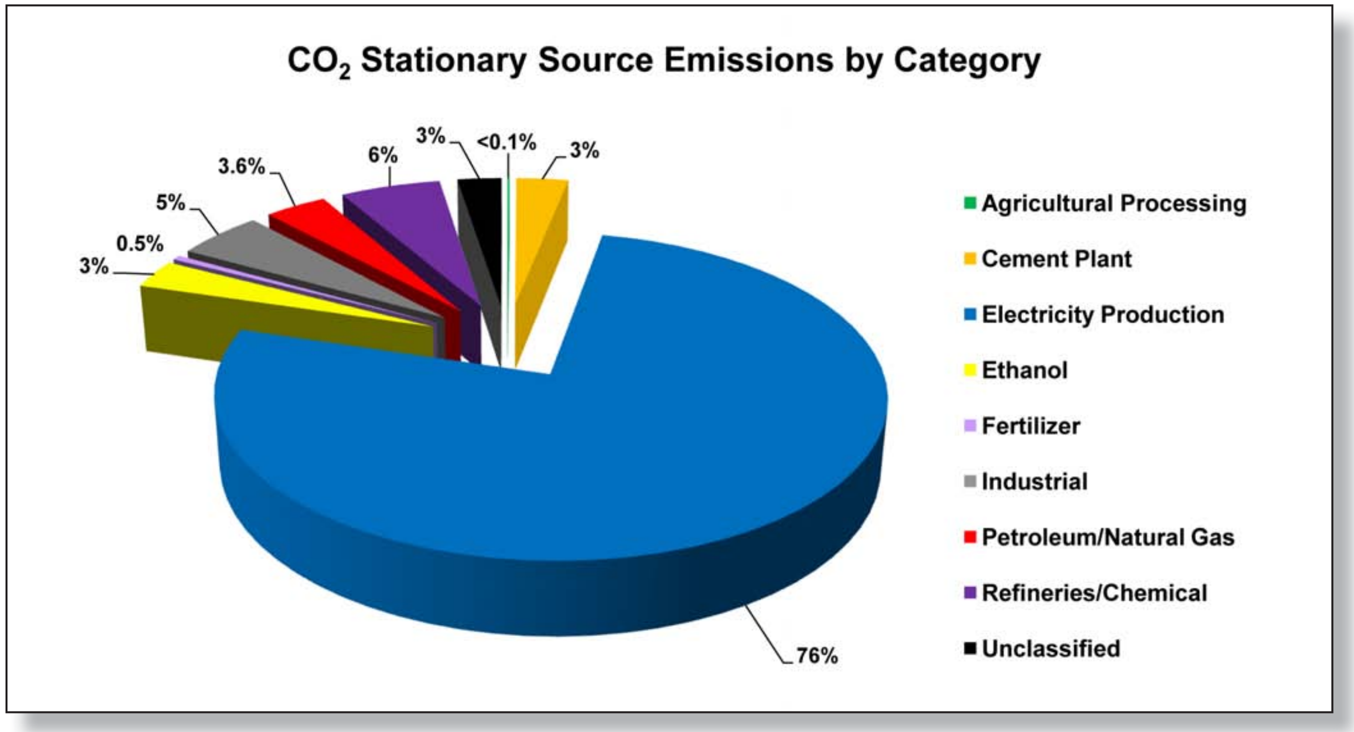
For additional information on the methodologies used by the RCSPs for the CO_2 resource estimates in *Atlas III*, please refer to the 2010 "Methodology for Development of Geologic Storage Estimates for Carbon Dioxide" in Appendix B of *Atlas III*.

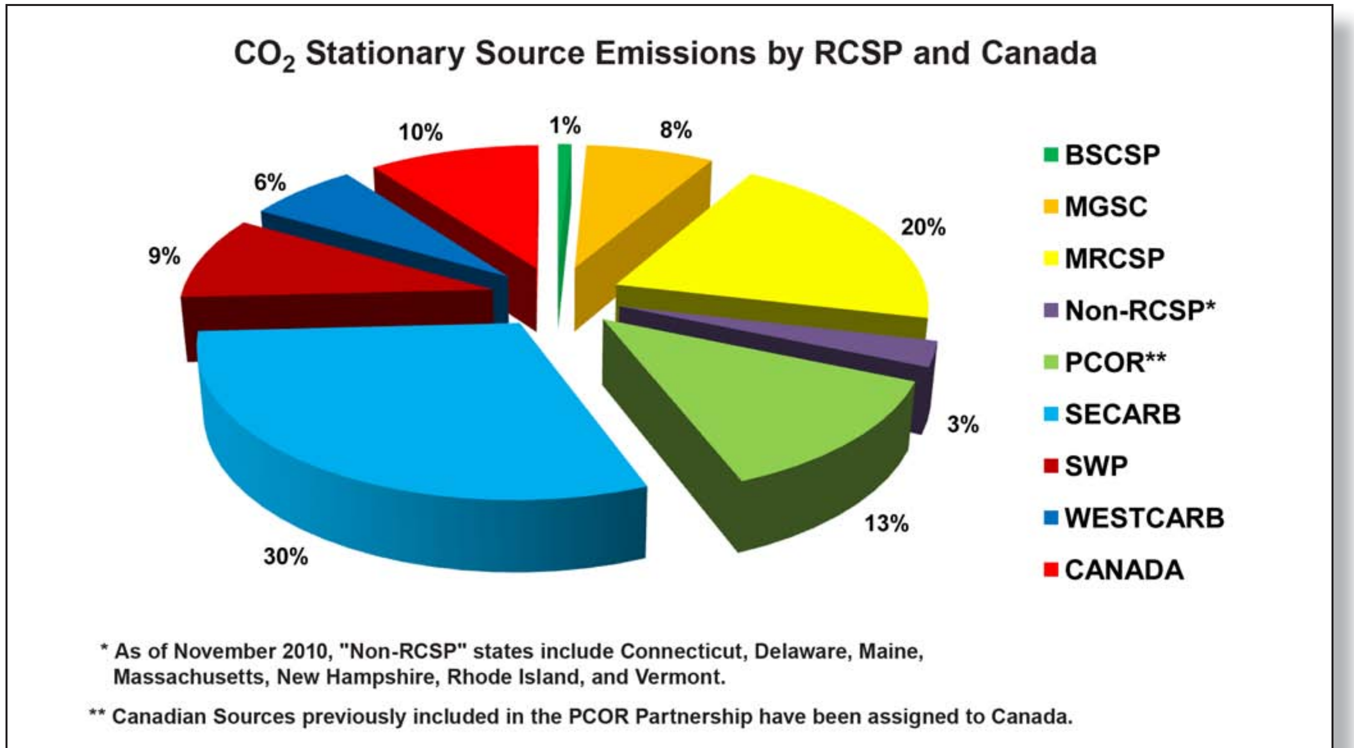
Regional CO_2 Storage Resource Estimates to Site-Specific CO_2 Storage Resource Estimates

Methodologies used in *Atlas III* are intended to produce high-level, regional and national scale CO_2 resource estimates of potential geologic storage in the United States and Canada. At this scale, the estimates of CO_2 geologic storage have a high degree of uncertainty. One reason for this uncertainty is the lack of wells penetrating the potential storage formation, resulting in undefined rock properties and heterogeneity of the formation. Because of this uncertainty, estimates from *Atlas III* are not intended to be used as a substitute for site-specific characterization and assessment. As CO_2 storage sites move through the site characterization process (see page 14 of *Atlas III*), additional site-specific data is collected and analyzed, reducing uncertainty. This data includes, but is not limited to, site-specific lithology, porosity, and permeability. Incorporation of this site-specific data allows for the refinement of CO_2 storage resource estimates and development of CO_2 storage capacities by future potential commercial project developers.



This map displays CO_2 stationary source data which were obtained from the RCSPs and other external sources and compiled by NATCARB. Each colored dot represents a different type of CO_2 stationary source with the dot size representing the relative magnitude of the CO_2 emissions (see map legend).





CO_2 Sources

There are two types of CO_2 emission sources: stationary sources and non-stationary sources. Carbon dioxide stationary source emissions come from a particular, identifiable, source, such as a power plant, while non-stationary source emissions include CO_2 emissions from the transportation sector and other diffuse sources. Carbon dioxide emissions from stationary sources can be separated from stack gas emissions and subsequently transported to a geologic storage injection site. The "United States and Canadian CO_2 Stationary Sources" map at left displays the location and relative magnitude of a variety of CO_2 stationary sources.

According to the EPA, total U.S. GHG emissions were estimated at 6,960 million metric tons (7,670 million tons) CO_2 equivalent in 2008.[1] This estimate includes CO_2 emissions, as well as other GHGs, such as methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. Annual GHG emissions from fossil fuel combustion, primarily CO_2, were estimated at 5,570 million metric tons (6,140 million tons) with 3,780 million metric tons (4,170 million tons) from stationary sources.

The "CO_2 Stationary Source Emissions by Category" pie chart contains values, gathered by the RCSPs and NATCARB (illustrated on the "United States and Canadian CO_2 Stationary Sources" map), showing that CO_2 stationary source emissions result largely from power generation, energy use, and industrial processes. While not all potential GHG sources have been examined, NETL's RCSPs have documented the location of 4,507 CO_2 stationary sources with total annual emissions of 3,470 million metric tons (3,825 million tons) of CO_2 in the United States. In Canada, the locations of CO_2 stationary sources with total annual emissions of 350 million metric tons (385 million tons) of CO_2 were also identified. The "CO_2 Stationary Source Emissions by RCSP and Canada" pie chart displays the amount of CO_2 stationary source emissions identified by each RCSP. For details on CO_2 stationary sources by State, see Appendix C.

1 EPA's 2010 U.S. Greenhouse Gas Inventory Report (April 2010), available at http://www.epa.gov/climatechange/emissions/downloads10/US-GHG-Inventory-2010_Report.pdf.

Sedimentary Basins

DOE's RCSPs have identified and examined the location of potential CO_2 injection formations in different sedimentary basins throughout the United States and Canada. These sedimentary basins collected sediments that lithified to become sedimentary rocks. If these sedimentary rocks are porous or fractured, they can be saturated with brine (water with a high TDS concentration), oil, or gas. If the sedimentary rock is permeable (e.g., many sandstones), it could be a target for injection of CO_2. If it is impermeable (e.g., many shales) it could act as a seal to prevent migration of CO_2. Necessary conditions for a CO_2 storage site are the presence of both a reservoir with sufficient injectivity and a seal to prevent migration.

Brine is water that contains appreciable amounts of salts that have either been leached from the surrounding rocks or from sea water that was trapped when the rock was formed. The EPA has determined that a saline formation used for CO_2 storage must have at least 10,000 ppm of TDS. Total dissolved solids is a measure of the amount of salt in water. Most drinking water supply wells contain a few hundred ppm or less of TDS.

Oil and gas reservoirs are often saline formations that have proven traps and seals allowing oil and gas to accumulate over millions of years. Many oil and gas fields containing stacked formations (different reservoirs) have characteristics that make them excellent target locations for geologic storage, including good porosity.

Supercritical CO_2

It is common to hear CCS experts talk about storage of CO_2 in the "supercritical" condition. Supercritical CO_2 means that the CO_2 is at a temperature in excess of 31.1 °C and a pressure in excess of 72.9 atm (about 1,057 psi); this temperature and pressure defines the critical point for CO_2. At such temperatures and pressures, the CO_2 has some properties like a gas and some properties like a liquid. In particular, it is dense like a liquid but has viscosity like a gas. The main advantage of storing CO_2 in the supercritical condition is that the required storage volume is hugely less than if the CO_2 were at "standard" (room) pressure conditions. This reduction in volume is illustrated in the figure at right. The blue numbers show the volume of CO_2 at each depth compared to a volume of 100 at the surface.

Temperature naturally increases with depth in the Earth's crust, as does the pressure of the fluids (brine, oil, or gas) in the rocks. At depths below about 800 meters (about 2,600 feet), in most places on Earth, the natural temperature and fluid pressures are in excess of the critical point of CO_2. This means that CO_2 injected at these temperatures and pressures will be in the supercritical condition. The pressure of CO_2 must be greater than the naturally existing fluid pressure in order to get the CO_2 into the reservoir. Large temperature differences between the injected CO_2 and the surrounding rock are not recommended, but, the CO_2 will take on the temperature of the surrounding rock as it moves into the reservoir. Hence, even if not injected under supercritical conditions, it will—in most cases—end up in the supercritical condition in the reservoir.

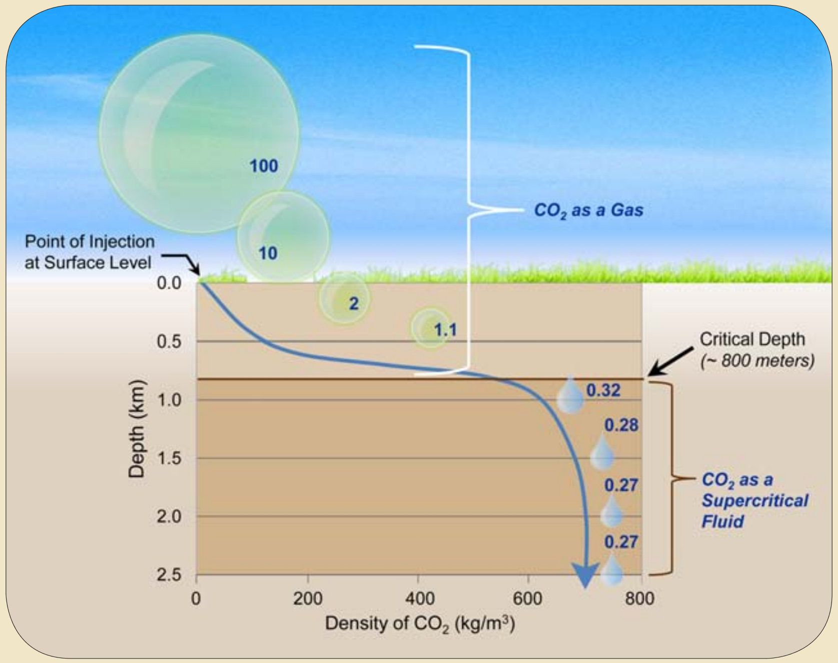
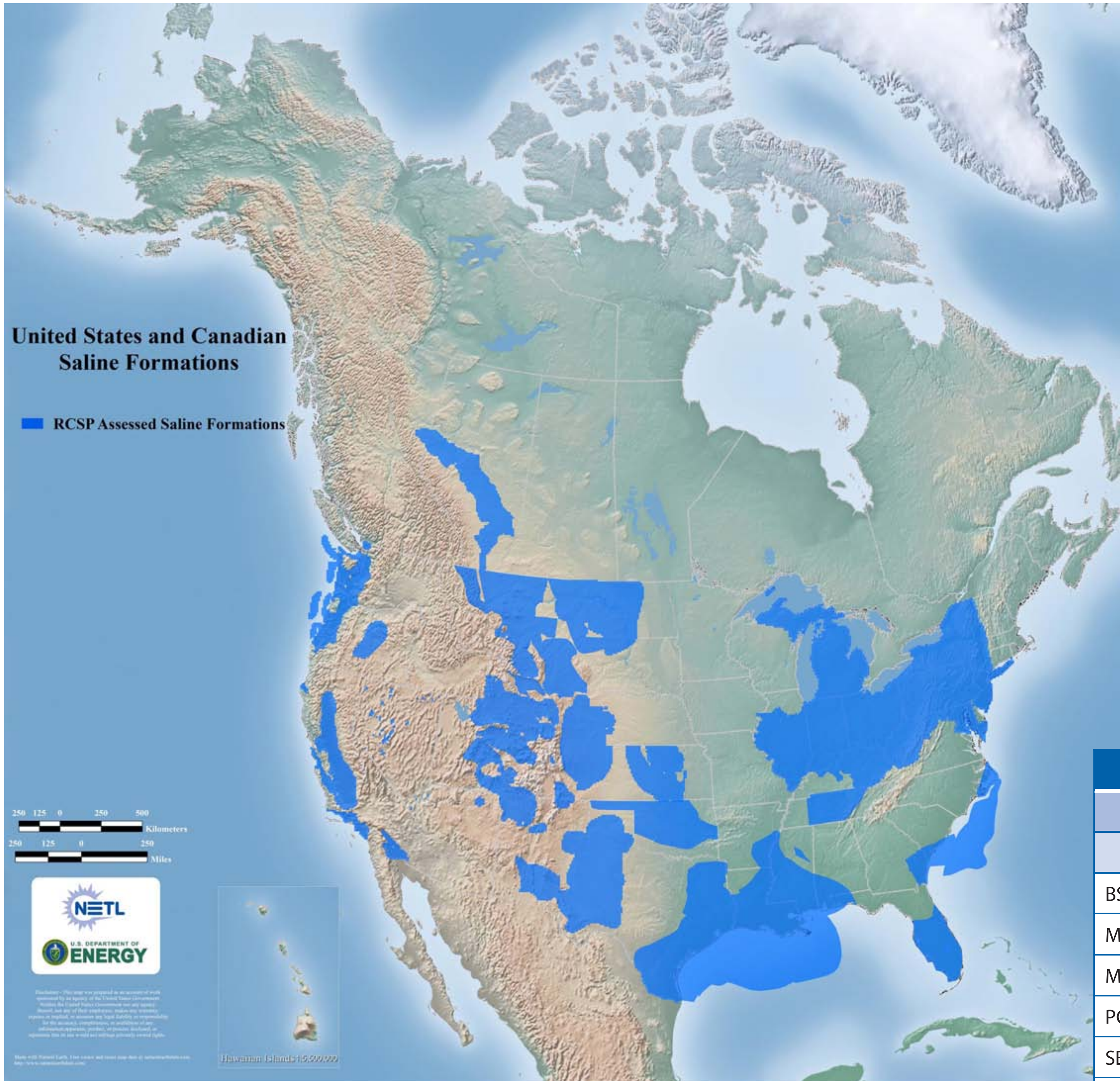


Illustration of Pressure Effects on CO_2 (based upon image from CO_2CRC)



This map displays saline formation data that were obtained by the RCSPs and other sources and compiled by NATCARB. Carbon dioxide geologic storage information in Atlas III was developed to provide a high-level overview of CO_2 geologic storage potential across the United States and parts of Canada. Areal extents of geologic formations and CO_2 resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCS project developers a starting point for further investigation. Furthermore, this information is required to indicate the extent to which CCS technologies can contribute to the reduction of CO_2 emissions and is not intended to serve as a substitute for site-specific assessment and testing. Please refer to page 14 for additional information on this level of assessment. Please note that saline formation data resulting in a straight edge in the map above is indicative of an area lacking sufficient data and is subject to future investigation.

Saline Formations

Saline formations are layers of porous rock that are saturated with brine. They are much more extensive than coal areas or oil- and gas-bearing rock and represent an enormous potential for CO_2 geologic storage. However, less is known about saline formations because they lack the characterization experience that industry has acquired through resource recovery from oil and gas reservoirs and coal seams. Therefore, there is an amount of uncertainty regarding the suitability of saline formations for CO_2 storage.

While not all saline formations in the United States have been examined, the RCSPs have documented the locations of saline formations with an estimated CO_2 storage resource ranging from 1,653 billion metric tons to more than 20,213 billion metric tons (from 1,822 billion tons to more than 22,281 billion tons) of CO_2. At current CO_2 emission rates, calculations indicate more than 450 years of storage potential in assessed saline formations. For details on saline formation CO_2 storage resource by State, see Appendix C.

CO_2 Storage Resource Estimates for Saline Formations by RCSP

	Low		High	
RCSP	Billion Metric Tons	Billion Tons	Billion Metric Tons	Billion Tons
BSCSP	221	244	3,041	3,352
MGSC	12	13	160	176
MRCSP	46	51	183	202
PCOR	165	182	165	182
SECARB	908	1,001	12,527	13,809
SWP	219	241	3,013	3,321
WESTCARB	82	90	1,124	1,239
Total	**1,653**	**1,822**	**20,213**	**22,281**

Oil and Gas Reservoirs

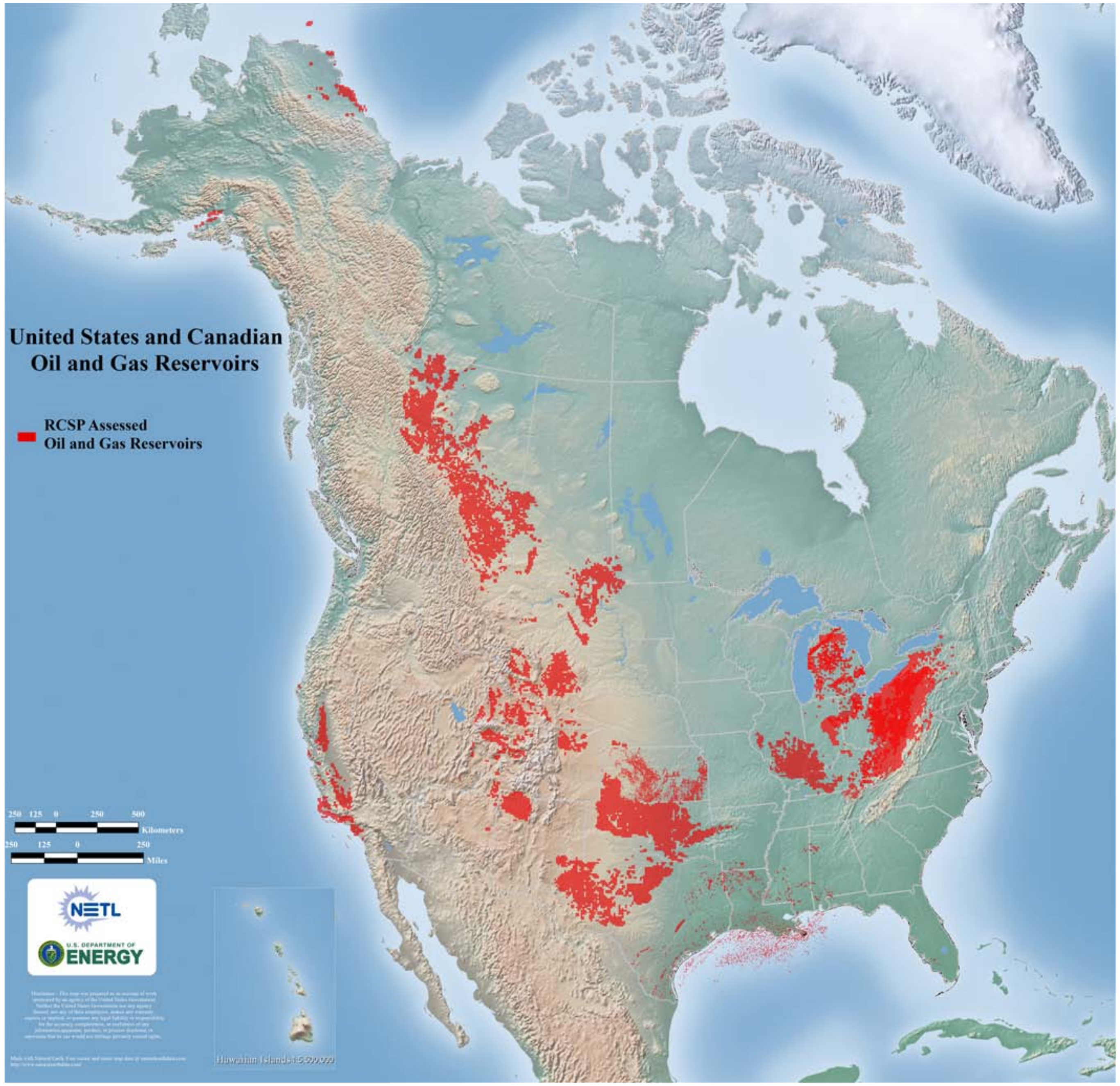
Mature oil and gas reservoirs have held crude oil and natural gas over millions of years. They consist of a layer of permeable rock (usually sandstone, but sometimes carbonates) with a layer of nonpermeable rock also called caprock (usually shale) above, such that the caprock forms a seal that holds the hydrocarbons in place. The characteristics that have held the oil and gas in the reservoirs for millions of years make them excellent target locations for geologic storage of CO_2. An added benefit of oil and gas reservoirs is that they have been extensively explored, which generally results in a wealth of data available to plan and manage proposed CCS efforts.

As a value-added benefit, CO_2 injected into a mature oil reservoir can enable incremental oil to be recovered. A small amount of CO_2 will dissolve in the oil, increasing the bulk volume and decreasing the viscosity, thereby facilitating flow to the wellbore. Typically, primary oil recovery and secondary recovery via a water flood produce 30–40 percent of a reservoir's original oil in place (OOIP). A CO_2 flood allows recovery of an additional 10–15 percent of the OOIP. NETL's work in this area is focused on increasing the amount of CO_2 that remains in the ground as part of CO_2-enhanced oil recovery (CO_2-EOR).

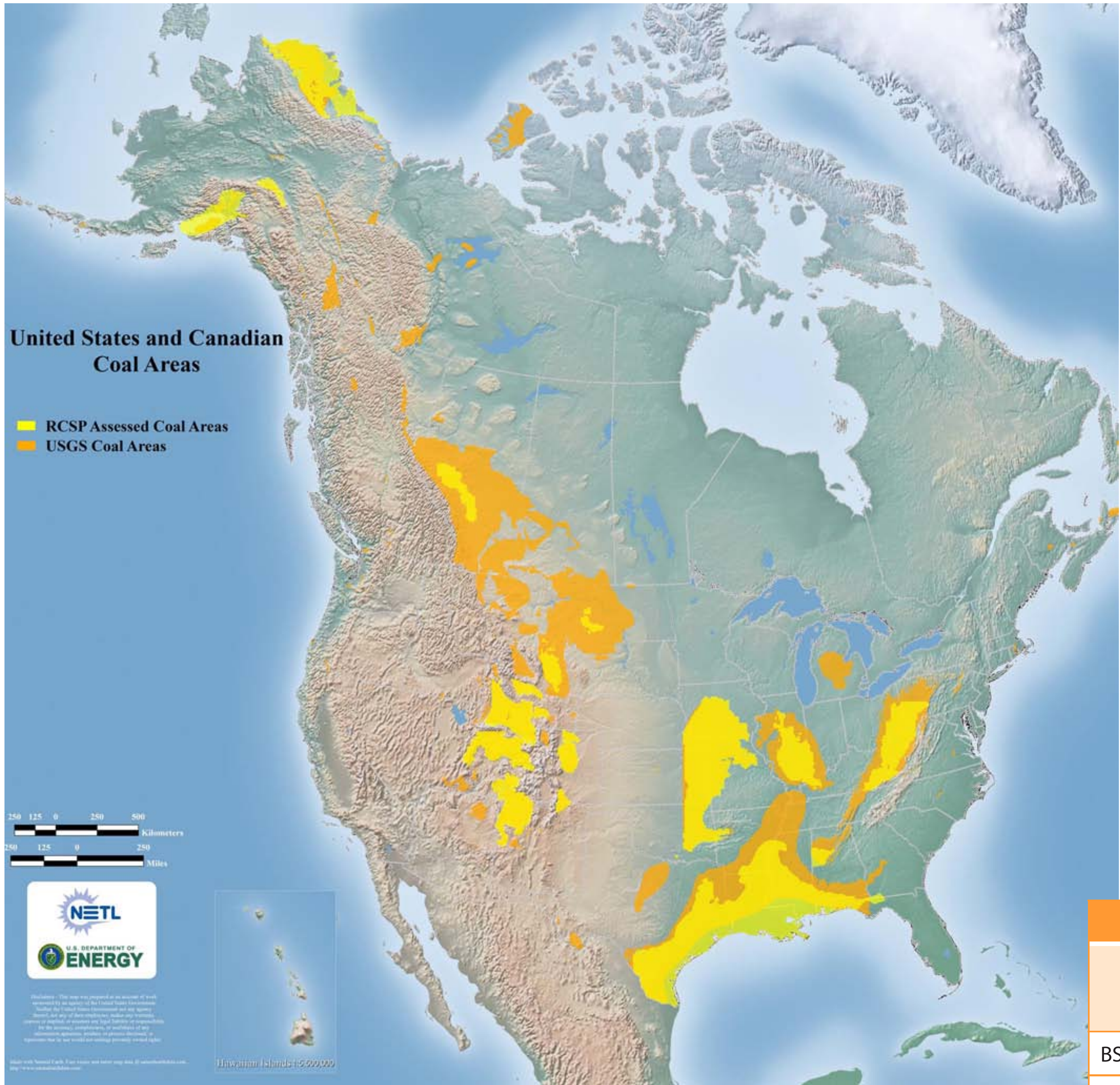
While not all potential mature oil and gas reservoirs in all States and provinces have been examined, the RCSPs have documented the location of almost 143 billion metric tons (155 billion tons) of CO_2 storage resource in 29 States and 4 provinces. At current CO_2 emission rates, calculations indicate more than 40 years of storage potential in assessed oil and gas reservoirs. For details on oil and gas CO_2 storage resource by State, see Appendix C.

CO_2 Storage Resource Estimates for Oil and Gas Reservoirs by RCSP

RCSP	Billion Metric Tons	Billion Tons
BSCSP	2	2
MGSC	1	1
MRCSP	17	19
PCOR	25	26
SECARB	32	35
SWP	62	68
WESTCARB	4	4
Total	**143**	**155**



This map displays oil and gas reservoir data that were obtained by the RCSPs and other sources and compiled by NATCARB. Carbon dioxide geologic storage information in Atlas III was developed to provide a high-level overview of CO_2 geologic storage potential across the United States and parts of Canada. Areal extents of geologic formations and CO_2 resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCS project developers a starting point for further investigation. Furthermore, this information is required to indicate the extent to which CCS technologies can contribute to the reduction of CO_2 emissions and is not intended to serve as a substitute for site-specific assessment and testing. Please refer to page 14 for additional information on this level of assessment.



Unmineable Coal Areas

Coal seams that are too deep or too thin to be economically mined are viable for CO_2 storage. All coals have varying amounts of methane adsorbed onto pore surfaces. Wells can be drilled into unmineable coalbeds to recover this coalbed methane (CBM). Initial CBM recovery methods, such as dewatering and depressurization, leave a considerable amount of methane in the formation. Additional recovery can be achieved by sweeping the coalbed with CO_2. Depending on coal rank, 3 to 13 molecules of CO_2 are adsorbed for each molecule of methane released, thereby providing an excellent storage site for CO_2 along with the additional benefit of enhanced coalbed methane (ECBM) recovery. The adsorption process bonds the CO_2 to the coals, causing the CO_2 to be physically and permanently trapped on the coal provided sufficient pressure is maintained. The adsorption process coupled with the recovery of economically valuable methane gas makes unmineable coal seams attractive options for CCS.

While not all unmineable coal areas have been examined, the RCSPs have documented the location of 60 billion to 117 billion metric tons (65 billion to 128 billion tons) of potential CO_2 storage resource in unmineable coal areas distributed over 21 States and 1 province. At current CO_2 emission rates, calculations indicate more than 15 years of storage potential in assessed coal areas. For details on unmineable coal area CO_2 storage resource by state, see Appendix C.

This map displays unmineable coal area data that were obtained by the RCSPs and other sources and compiled by NATCARB. Carbon dioxide geologic storage information in Atlas III was developed to provide a high-level overview of CO_2 geologic storage potential across the United States and parts of Canada. Areal extents of geologic formations and CO_2 resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCS project developers a starting point for further investigation. Furthermore, this information is required to indicate the extent to which CCS technologies can contribute to the reduction of CO_2 emissions and is not intended to serve as a substitute for site-specific assessment and testing. Please refer to page 14 for additional information on this level of assessment. Please note that unmineable coal area data resulting in a straight edge in the map above is indicative of an area lacking sufficient data and is subject to future investigation.

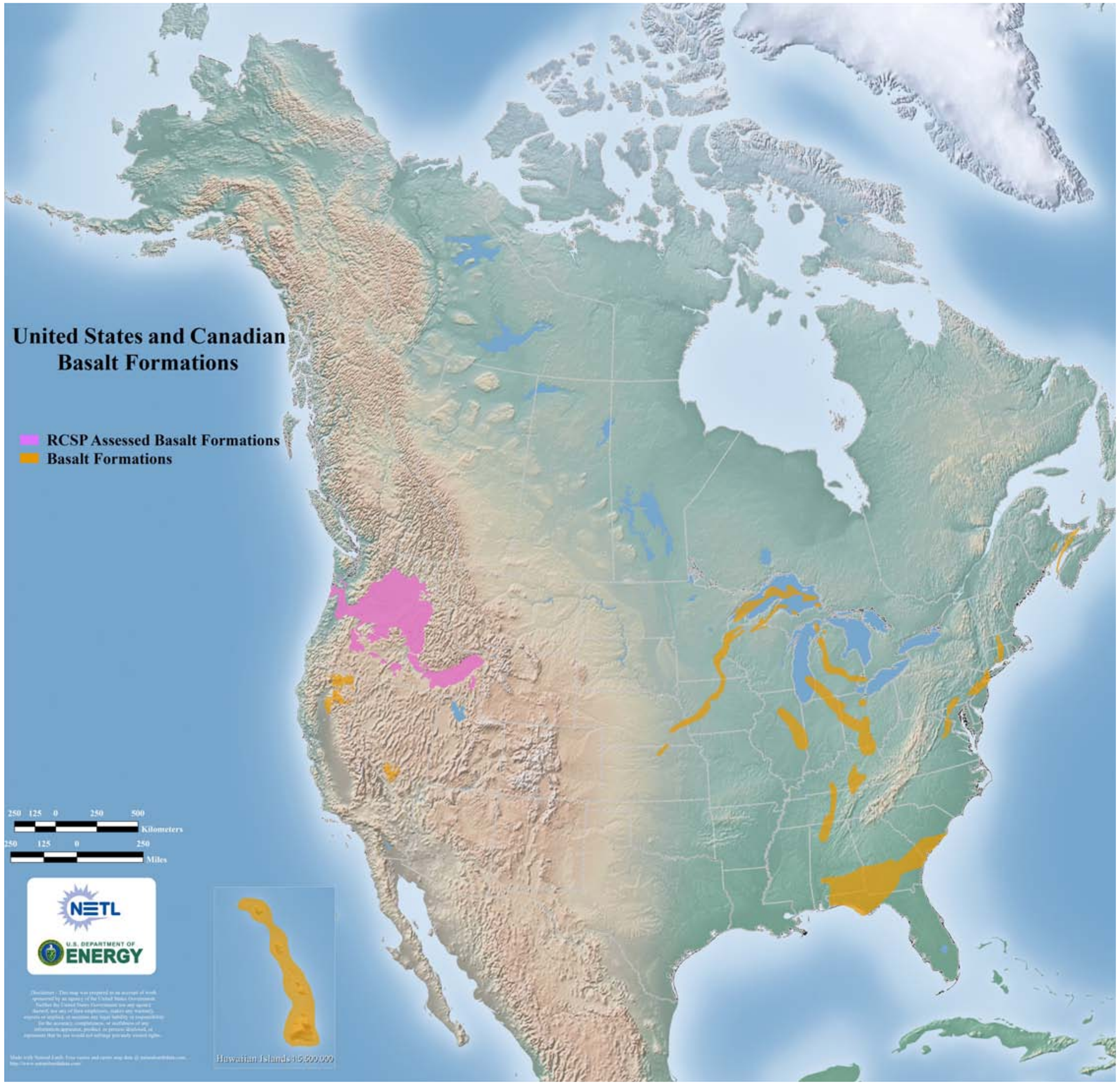
CO_2 Storage Resource Estimates for Unmineable Coal Areas by RCSP

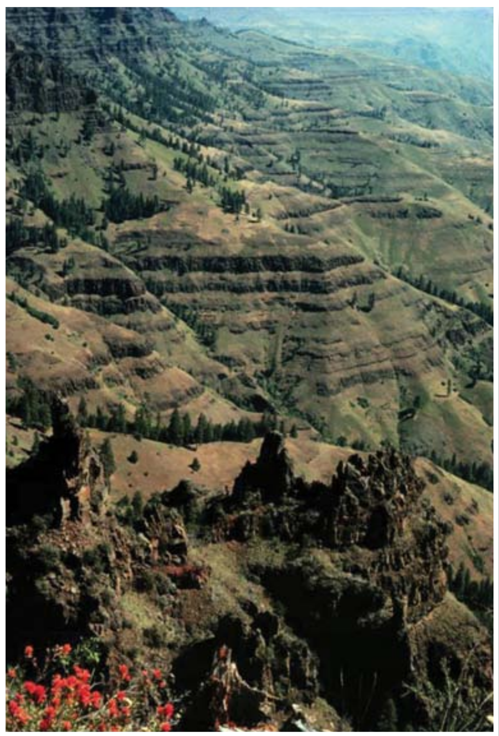
RCSP	Low		High	
	Billion Metric Tons	Billion Tons	Billion Metric Tons	Billion Tons
BSCSP	12	13	12	13
MGSC	2	2	3	3
MRCSP	1	1	1	1
PCOR	1	1	1	1
SECARB	33	36	75	83
SWP	1	1	2	2
WESTCARB	10	11	23	25
Total	**60**	**65**	**117**	**128**

Basalt Formations

Another potential CO_2 storage option DOE is investigating is basalt formations. The relatively large amount of potential storage resource in basalts, along with their geographic distribution, make them an important formation type for possible CO_2 storage, particularly in the Pacific Northwest and the Southeastern United States. Basalt formations are geologic formations of solidified lava. These formations have a unique chemical makeup that could potentially convert all of the injected CO_2 to a solid mineral form, thus isolating it from the atmosphere permanently. Some key factors affecting the capacity and injectivity of CO_2 into basalt formations are effective porosity of flow top layers and interconnectivity. DOE's current efforts are focused on enhancing and utilizing the mineralization reactions and increasing CO_2 flow within basalt formations.

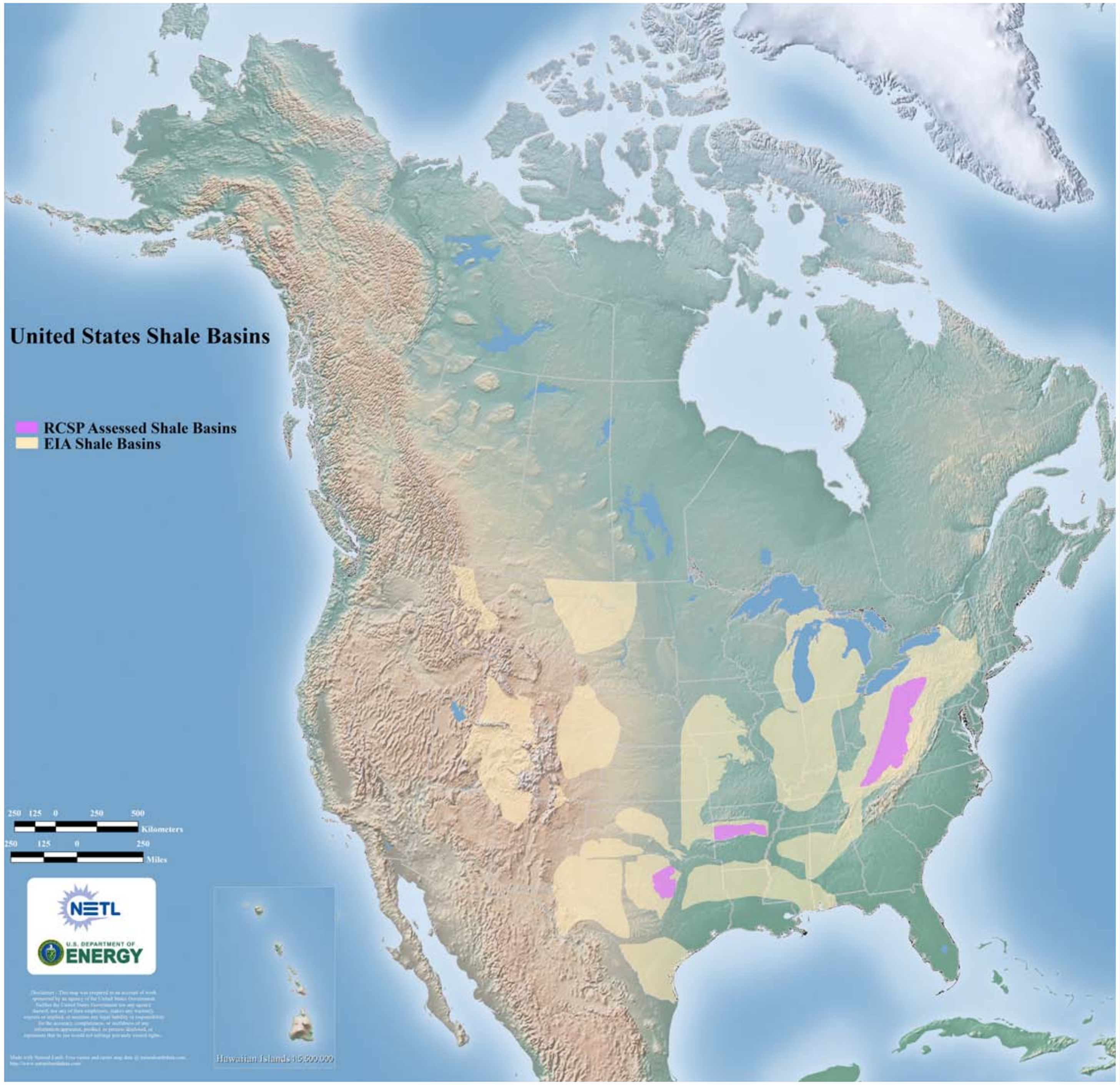
The chemistry of basalts potentially allows the injected CO_2 to react with magnesium and calcium in the rocks to form the stable carbonate mineral forms of calcite and dolomite. This mineralization process shows promise of being a valuable tool for CCS since the mineralization process permanently locks carbon in the solid mineral structure. Thus, basalts may offer one of the safest options for the long-term isolation of CO_2 from the atmosphere because of the unique capacity for permanent incorporation of injected CO_2 into carbonates via mineralization. However, more research is needed to understand the time frames and actual chemical inputs and outputs of a basalt CO_2 injection.





Columbia River Basalt.

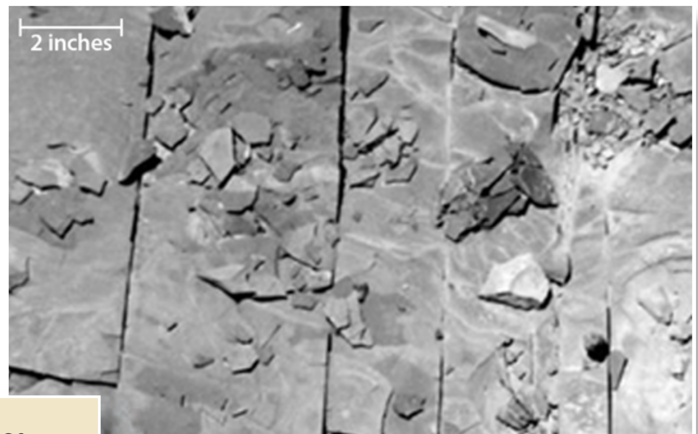
This map displays basalt formation data that were obtained by the RCSPs and other sources and compiled by NATCARB. Carbon dioxide geologic storage information in Atlas III was developed to provide a high-level overview of CO_2 geologic storage potential across the United States and parts of Canada. Areal extents of geologic formations presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCS project developers a starting point for further investigation. Furthermore, this information is required to indicate the extent to which CCS technologies can contribute to the reduction of CO_2 emissions and is not intended to serve as a substitute for site-specific assessment and testing. Please refer to page 14 for additional information on this level of assessment. Carbon dioxide storage in basalt formations is an area of current research. Before basalt formations can be considered viable storage targets, a number of questions relating to the basic geology, the CO_2 trapping mechanisms and their kinetics, and monitoring and modeling tools need to be addressed. As such, Atlas III presents a map of these potential future storage opportunities, but provides no CO_2 storage resource values for basalt formations.



Organic-Rich Shale Basins

As CCS moves toward commercialization, additional CO_2 storage options may be explored. One option already under consideration is the possibility of utilizing organic-rich shales. Shales are formed from silicate minerals that are degraded into clay particles that accumulate in areas of still water over millions of years. The plate-like structure of these clay particles causes them to accumulate in a flat manner, resulting in rock layers with extremely low permeability in the vertical direction. Therefore, shales are most often used in a geologic storage system as a confining seal or caprock.

If the horizontal permeability in shales is preferentially increased through engineering, CO_2 storage becomes feasible. Recent technological advances in the form of horizontal drilling and hydraulic fracturing have increased interest in organic-rich shales in the energy sector for natural gas production. With horizontal drilling and hydraulic fracturing, operators are basically engineering the porosity and permeability into organic-rich shales to create flow pathways. These technologies, coupled with the fact that CO_2 is preferentially adsorbed over methane, will improve the feasibility of using CO_2 for enhanced gas recovery in much the same way as ECBM recovery. While additional engineering of the rocks would add to the cost, the potential for hydrocarbon production could potentially offset the cost.



Natural fractures "joints" in Devonian-age shale, typical of fractures in Marcellus Shale. (Image from www.geology.com)

This map displays organic-rich shale basins data that were obtained by the RCSPs and other sources and compiled by NATCARB. Carbon dioxide geologic storage information in Atlas III was developed to provide a high-level overview of CO_2 geologic storage potential across the United States and parts of Canada. Areal extents of geologic formations presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCS project developers a starting point for further investigation. Furthermore, this information is required to indicate the extent to which CCS technologies can contribute to the reduction of CO_2 emissions and is not intended to serve as a substitute for site-specific assessment and testing. Please refer to page 14 for additional information on this level of assessment. Carbon dioxide storage in organic-rich shale basins is an area of current research. Before organic-rich shale basins can be considered viable storage targets, a number of questions relating to the basic geology, the CO_2 trapping mechanisms and their kinetics, and monitoring and modeling tools need to be addressed. As such, Atlas III presents a map of these potential future storage opportunities, but provides no CO_2 storage resource values for organic-rich shale basins.

Federal Lands

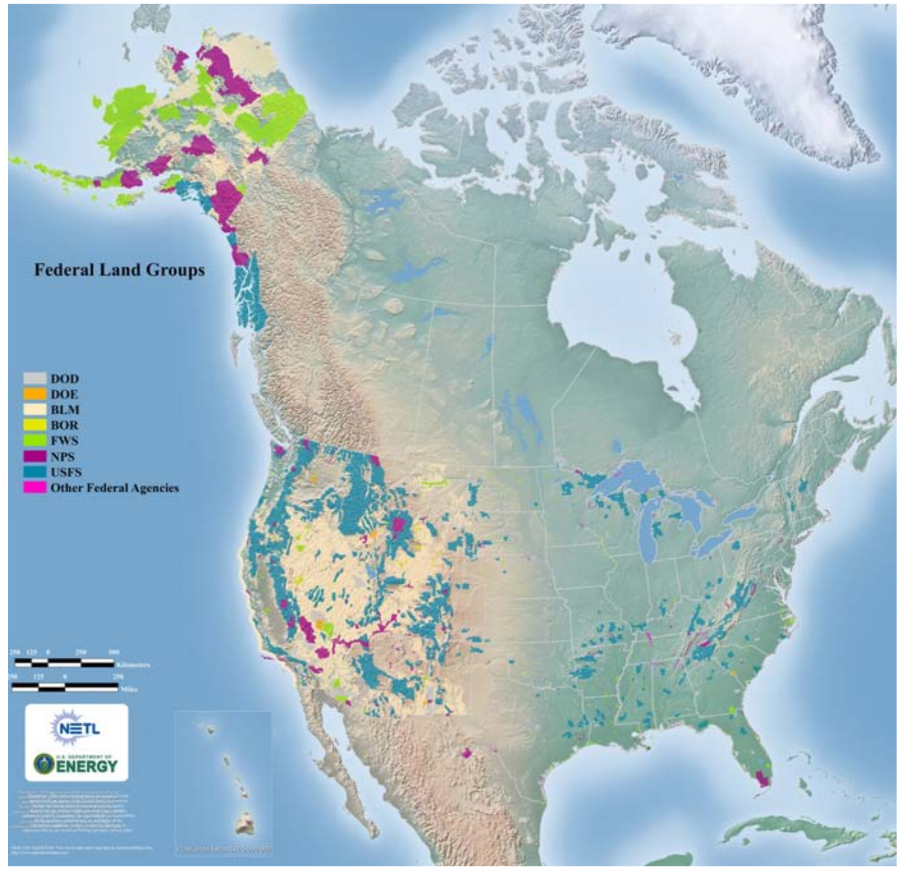
Land Management

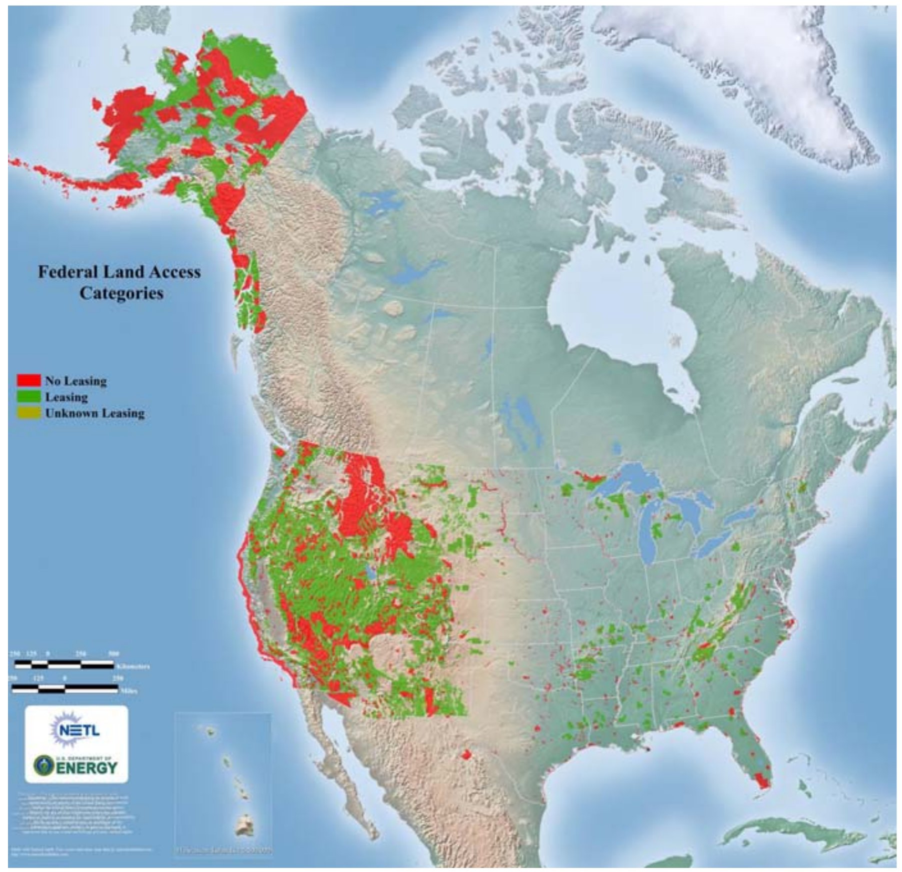
The Federal Government owns about 2.91 million km^2 (1.13 million $miles^2$) of land, almost 30 percent of the total U.S. land mass. A recent study used USGS spatial data to identify lands owned and/or administered by the Federal Government. The source dataset categorizes Federal landholdings under 65 separate Government bodies. However, to obtain a manageable description of Federal landholdings, these 65 categories were reorganized into 8 land groups according to common Department or Agency ownership (bottom left): (1) Department of Defense (DOD); (2) DOE; (3) Bureau of Land Management (BLM); (4) Bureau of Reclamation (BOR); (5) U.S. Fish and Wildlife Service (FWS); (6) National Park Service (NPS); (7) U.S. Forest Service (USFS); and (8) other Federal agencies. The BLM and the FWS, both in the DOI, and the USFS, of the Department of Agriculture (DOA), manage the vast majority of Federal acreage—about 2.45 million km^2 (0.95 million $miles^2$).

An assessment of Federal leases with respect to oil and gas resources, per Section 364 of the Energy Policy and Conservation Act (EPCA) of 2005, was completed by the DOI. Utilizing this study, it was recognized that certain agencies do not lease or are restricted from leasing lands under their management—for example NPS or FWS lands—and a net value of 1.62 million km^2 (0.63 million $miles^2$) was derived (bottom middle).

The BLM and USFS manage almost 99 percent of the leasable lands, 1.60 million km^2 (0.62 million $miles^2$), the vast majority of which is located in the Rocky Mountain States and further west. Potentially leasable lands from the BLM and USFS are listed in the table at bottom right. Additional restrictions may be added for the protection of wildlife and ecosystems.

The advantage of using Federal Lands for CO_2 storage projects in the western states is the ability to assemble sufficient land from a single owner. Federal Lands east of the Mississippi River occur in smaller, more widely distributed blocks, and CCS utilization in the Eastern United States will most likely be on non-Federal Lands.





Leasable Federal Lands (million km^2)			
RCSP	BLM	USFS	Total
BSCSP	0.11	0.00	0.11
MGSC	0.00	0.01	0.01
MRCSP	0.00	0.04	0.04
PCOR	0.03	0.08	0.11
SECARB	0.00	0.08	0.08
SWP	0.17	0.16	0.33
WESTCARB	0.64	0.28	0.92
TOTAL	**0.95**	**0.65**	**1.60**

Federal Lands (cont'd)

CO_2 Storage Resource

The estimated CO_2 geologic storage resource beneath leasable Federal Lands ranges from 266 billion to 3,172 billion metric tons (292 billion to 3,497 billion tons). This is about 15 percent of the onshore CO_2 storage resource presented in *Atlas III*.

Carbon dioxide geologic storage resource beneath Federal Lands and CO_2 stationary sources on Federal Lands are listed by RCSP in the table at left. The majority of leasable Federal Land is found in the WESTCARB region, while the majority of CO_2 storage resource beneath Federal Lands is found in the BSCSP and the SWP regions.

The RCSPs have identified 4,507 total CO_2 stationary sources in the United States and Canada (please refer to pages 24 and 25 for more information). Of those, 3,474 are within 100 miles of Federal Lands (77 percent of the total CO_2 stationary sources identified by the RCSPs). Of those, 2,196 emit over 10,000 metric tons per year and are included in the table at left.

The distribution of CO_2 storage resource beneath Federal Lands for saline formations, oil and gas reservoirs, and unmineable coal areas is displayed below (bottom left, middle, and right below, respectively).

Federal Lands CO_2 Storage Potential and CO_2 Stationary Sources

RCSP	Percent of Leasable Acreage	Percent of Average Storage	Number of CO_2 Stationary Sources	Annual CO_2 Emissions
BSCSP	6.9	57.8	111	26
MGSC	0.0	0.2	182	247
MRCSP	0.0	0.7	260	559
PCOR	0.1	0.6	487	315
SECARB	0.1	11.3	638	1,004
SWP	0.2	21.1	223	310
WESTCARB	0.6	8.3	295	218
TOTAL			**2,196**	**2,679**

CO_2 Storage Resource Estimates for Saline Formations Beneath Federal Lands by RCSP

RCSP	Low		High	
	Billion Metric Tons	Billion Tons	Billion Metric Tons	Billion Tons
BSCSP	133	147	1,834	2,022
MGSC	0	0	6	6
MRCSP	4	5	16	18
PCOR	6	7	6	7
SECARB	26	28	353	390
SWP	48	53	662	730
WESTCARB	19	21	257	284
TOTAL	**237**	**261**	**3,136**	**3,457**

CO_2 Storage Resource Estimates for Oil and Gas Reservoirs Beneath Federal Lands by RCSP

RCSP	Low		High	
	Billion Metric Tons	Billion Tons	Billion Metric Tons	Billion Tons
BSCSP	1	2	1	2
MGSC	0	0	0	0
MRCSP	1	1	1	1
PCOR	4	5	4	5
SECARB	0	0	0	0
SWP	7	8	7	8
WESTCARB	1	1	2	2
TOTAL	**15**	**16**	**16**	**18**

CO_2 Storage Resource Estimates for Unmineable Coal Areas Beneath Federal Lands by RCSP

RCSP	Low		High	
	Billion Metric Tons	Billion Tons	Billion Metric Tons	Billion Tons
BSCSP	9	10	9	10
MGSC	0	0	0	0
MRCSP	0	0	0	0
PCOR	0	0	0	0
SECARB	3	3	7	7
SWP	0	0	1	1
WESTCARB	1	1	3	3
TOTAL	**14**	**15**	**20**	**22**

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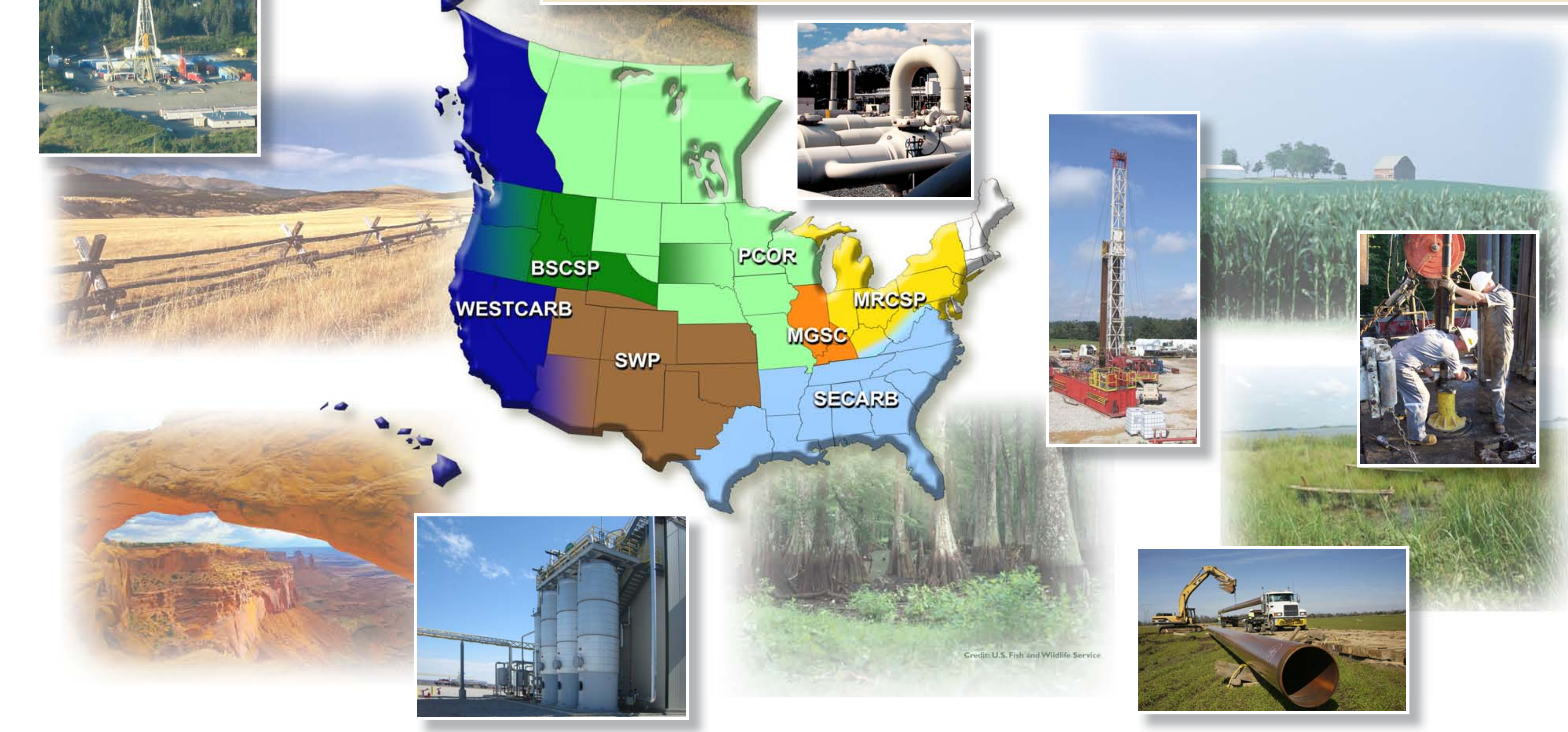
Please note for all maps:

Made with Natural Earth. Free vector and raster map data at naturalearthdata.com.

http://www.naturalearthdata.com/

Regional Carbon Sequestration Partnerships' Perspectives

Information contained in the following Regional Carbon Sequestration Partnerships' (RCSP) Perspectives Section was obtained from each RCSP. This information was collected and analyzed as part of the efforts of the RCSPs, and is not intended to be a comprehensive assessment of CCS. For additional information, please visit the RCSP websites (listed on page 8).



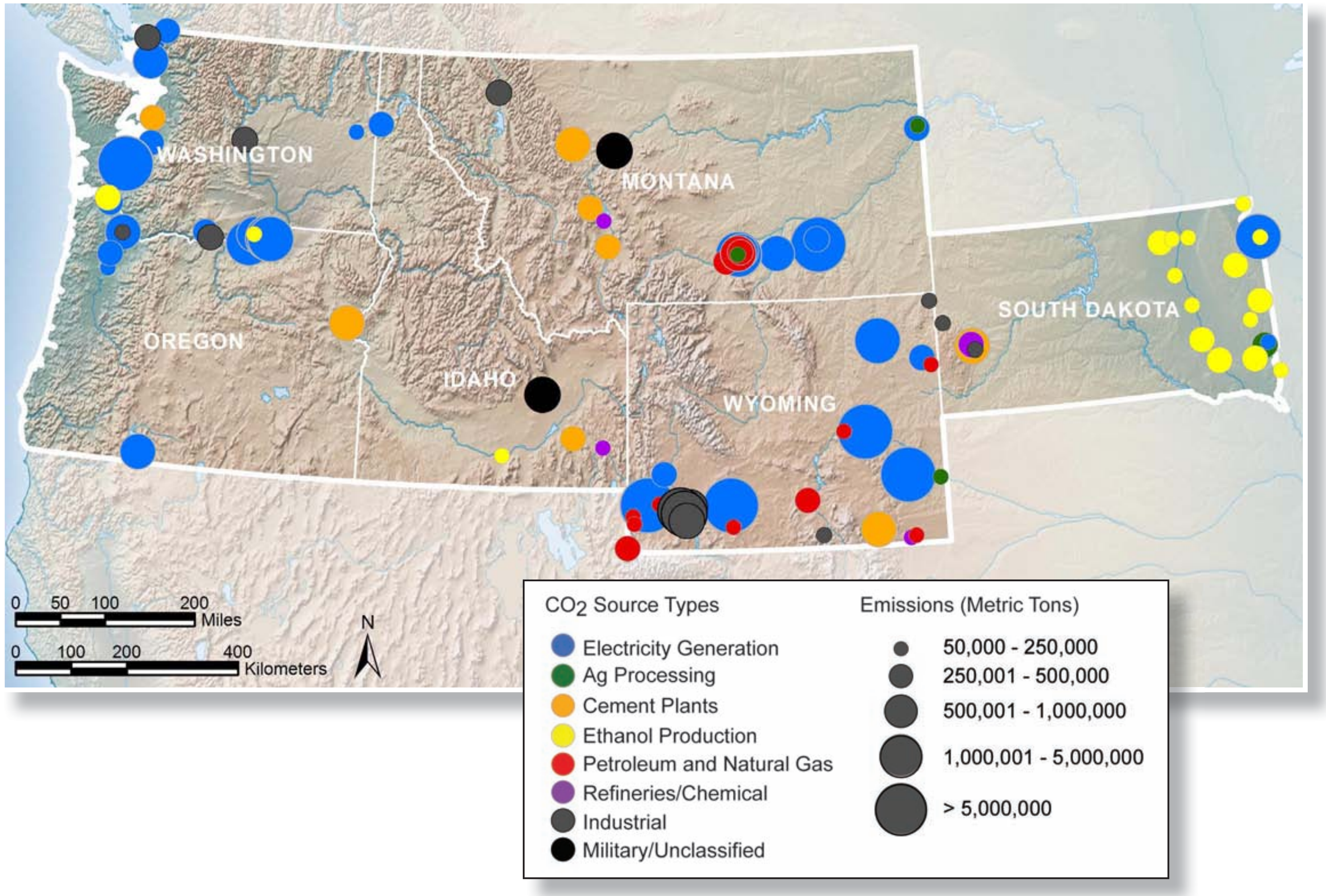
Big Sky Carbon Sequestration Partnership

The Big Sky Carbon Sequestration Partnership (BSCSP) is working on developing safe, effective, and economical approaches for capturing and permanently storing CO_2 to reduce the region's GHG emissions. The BSCSP relies on existing technologies from the fields of engineering, geology, chemistry, biology, GIS, and economics to develop novel approaches for both geologic and terrestrial carbon storage in the region. The BSCSP also engages in economic and regulatory analyses, public education and outreach, and regional demonstration projects to deploy and evaluate new technologies.

The BSCSP represents a coalition of more than 60 organizations including universities, national laboratories, private companies, State agencies, Native American tribes, and international collaborators. BSCSP partners are engaged in several aspects of BSCSP projects and contribute to the efforts to deploy carbon storage projects in the Big Sky region.

The BSCSP region encompasses Montana, Wyoming, Idaho, South Dakota, and eastern Washington and Oregon. The regional characterization of potential storage sites conducted during the Characterization Phase efforts confirmed that the region holds a wealth of potential carbon storage sites. East of the Rocky Mountains, there are large saline formations capable of storing many gigatons of CO_2, while the western part of the region has basalt formations that also have the potential to store many hundreds of years' worth of regional CO_2 emissions. In addition, the BSCSP land area includes vast acreage of agricultural, range, and forest lands that can be managed for greater storage of soil carbon and carbon in the biomass. The Big Sky region is also rich in energy resources including coal, oil and gas, and renewable sources of energy.

BIG SKY CARBON
SEQUESTRATION PARTNERSHIP

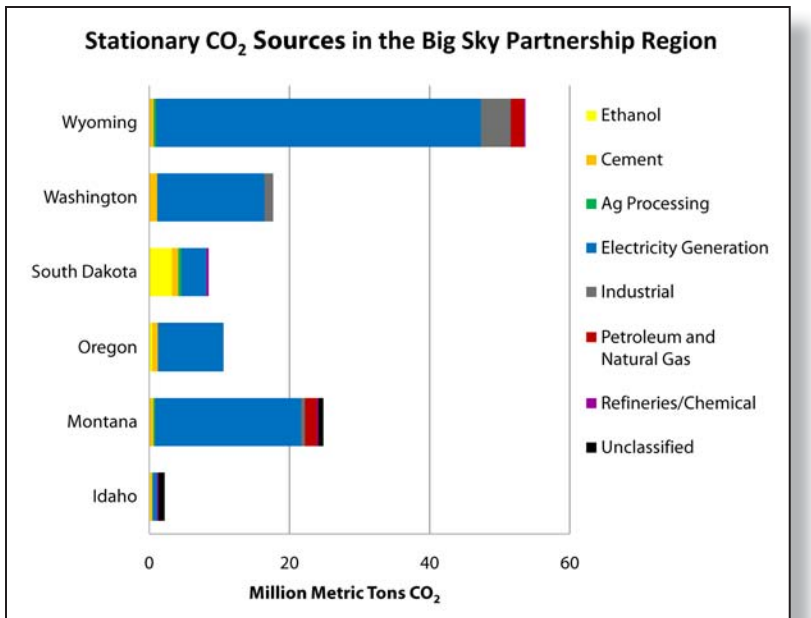


BSCSP CO_2 Sources

The BSCSP estimates that the region annually produces more than 110 million metric tons (120 million tons) of CO_2 from stationary sources. While the Big Sky region currently produces only a small fraction of U.S. CO_2 emissions, it is a key area for fossil energy development and has a growing population. Electricity generation accounts for a large proportion (82 percent) of the region's CO_2 emissions. The region produces electricity from a variety of sources including hydroelectric, coal, natural gas, nuclear, wind, biomass, petroleum, other gases, and geothermal. Other sources of CO_2 emissions in the region include cement production (4 percent), ethanol production (3 percent), petroleum production and transmission (3 percent), soda ash production (3.5 percent), military operations (1 percent), and aluminum production (1 percent). Agricultural processing, ammonia production, chemical processing, lime production, and paper production make up less than 1 percent of the region's remaining CO_2 emissions.

According to U.S. census data estimates for 2009, the region has a population of 14.38 million and a growth rate of 11 percent from 2000 to 2009, with the largest growth occurring in Idaho, Oregon, and Washington. Montana and Wyoming produce two-thirds of the CO_2 emissions in the region due to the high dependence on coal-fired electric generation and fossil fuel operations. More than half of the electrical power produced in Idaho, Oregon, and Washington is generated from hydroelectric plants.

As part of ongoing activities, the BSCSP continues to update annual emissions estimates and stationary sources as new information becomes available. Work also includes characterizing the potential geologic storage sites in the vicinity of these stationary sources.

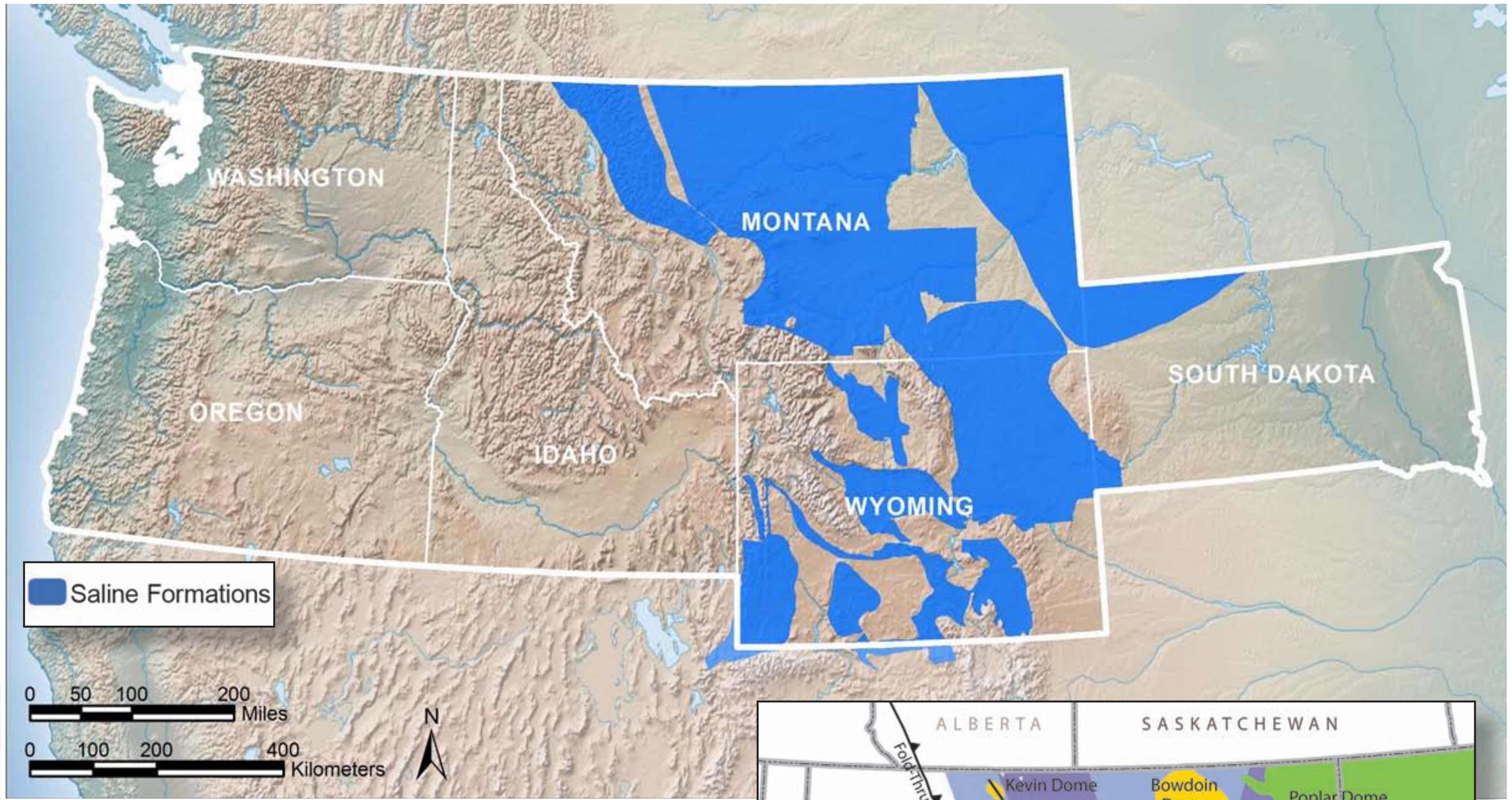


Laramie River Station coal plant in Wyoming. (Courtesy of Basin Electric Power Cooperative)

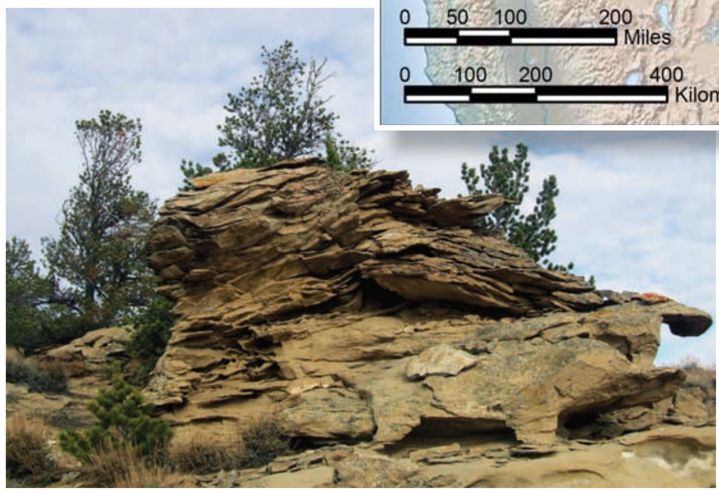
Cenex oil refinery in Billings, Montana. (Courtesy of Greg Goebel)

BSCSP Saline Formations

Saline formations throughout the BSCSP region offer great potential for future storage activities. Extensive deep saline formations are present in Paleozoic and Mesozoic formations of Montana and Wyoming's sedimentary basins. These basins account for greater than 3 million km^2 underlain by sedimentary units potentially suitable for storage. BSCSP estimates greater than 200 billion metric tons (220 billion tons) CO_2 could be stored in the region's saline formations, sufficient for storing the State region's cumulative anthropogenic CO_2 for centuries. The proximity of these saline formation resources to large stationary sources of CO_2 combined with existing infrastructure in the region provides a favorable setting for carbon storage.



Potential formations for storage within the BSCSP region are dominated by porous and permeable sandstone, limestone, and dolostone. These units are interbedded with evaporates and shales that create interlayered reservoirs separated by trapping seals. Formations with poor water quality, having greater than 10,000 ppm TDS, are potential targets for carbon storage.

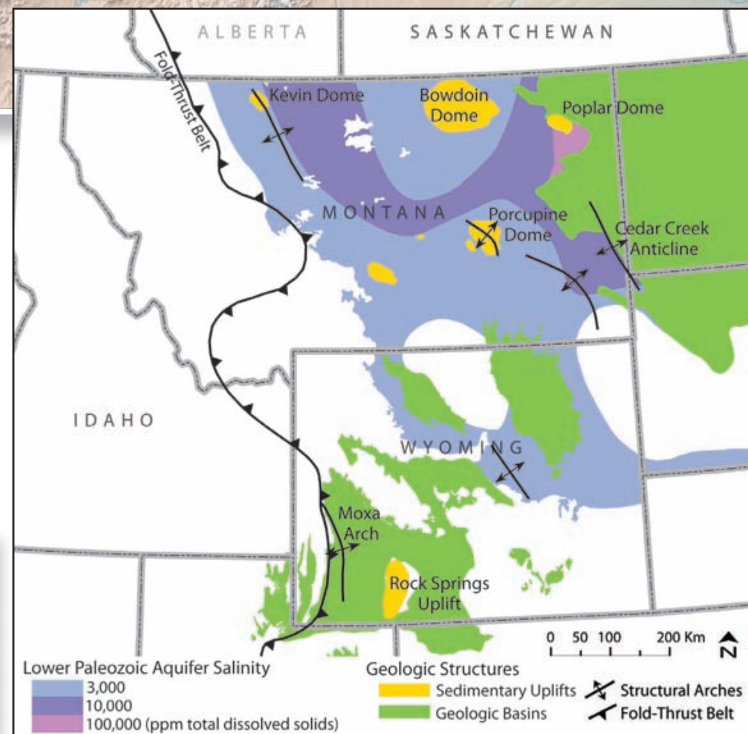


Saline rock formations near Belfry, Montana. (Courtesy of John Talbott, BSCSP)

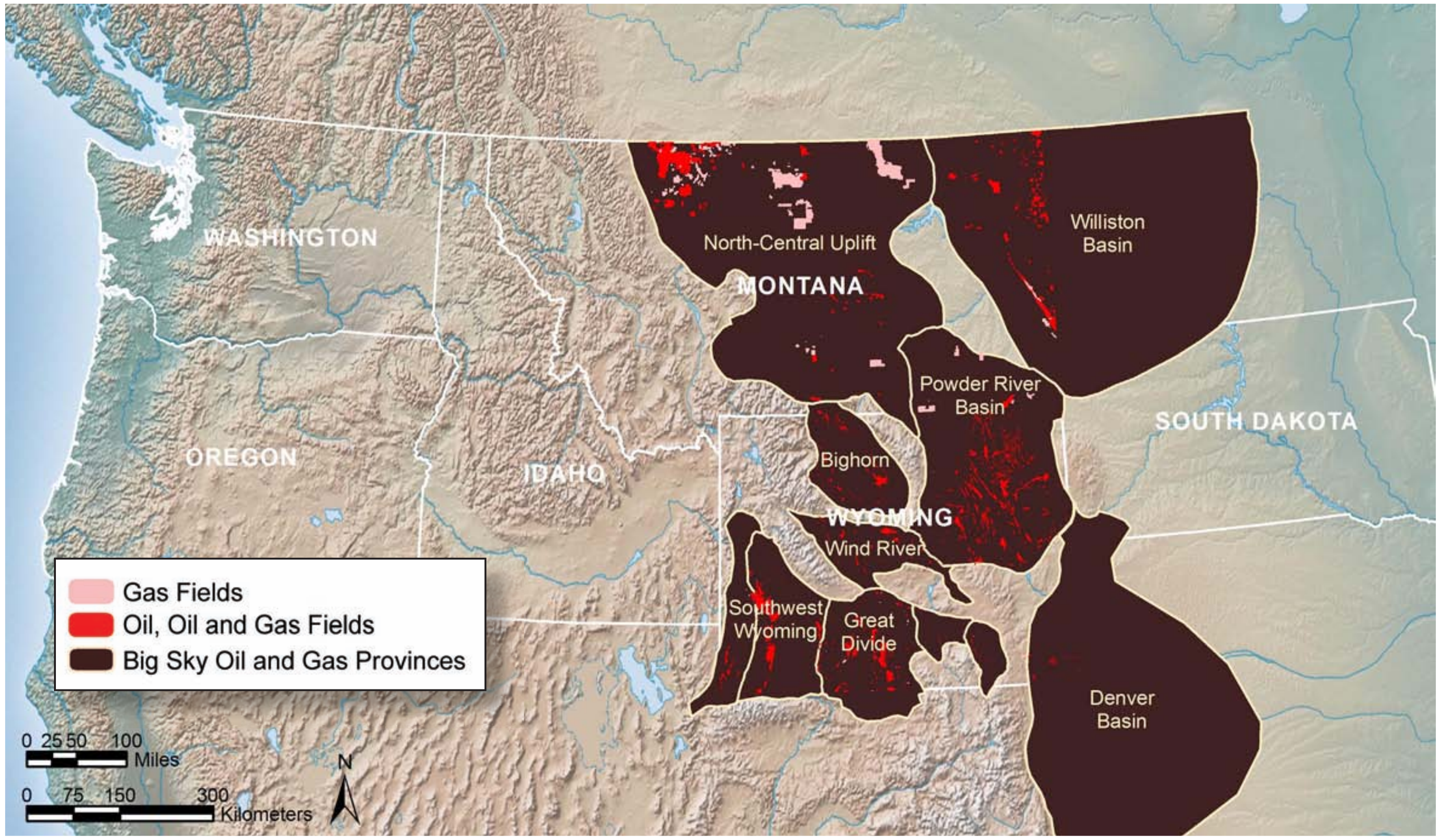
Several of these reservoirs currently host vast, naturally occurring accumulations of CO_2, demonstrating the potential of these units to efficiently trap CO_2. BSCSP is currently conducting research at Kevin Dome, a naturally occurring CO_2 reservoir in northern Montana. Kevin Dome is geologically similar to several other large structural features that occur in eastern Montana (Bowdoin Dome, Porcupine Dome, Poplar Dome, and Cedar Creek Anticline). Characterizing the dome, which has successfully trapped large volumes of CO_2 for tens of millions of years, will lead to a better understanding of the potential of these additional domes as carbon storage sites.

Saline Formation CO_2 Storage Resources in the BSCSP Region (million metric tonnes)

Basin Name	Low Estimate	High Estimate
Montana Thrust Belt	2,490	34,233
North-Central Montana	67,889	933,469
Southwest Montana	1,868	25,680
Williston Basin	58,442	803,581
Powder River Basin	14,287	196,446
Big Horn Basin	10,649	146,420
Wind River Basin	13,574	186,639
Wyoming Thrust Belt	5,362	73,725
Southwestern Wyoming	46,608	640,864
Total	**221,168**	**3,041,056**



Geologic structures and formation salinity in Montana and Wyoming.



BSCSP Oil and Gas Reservoirs

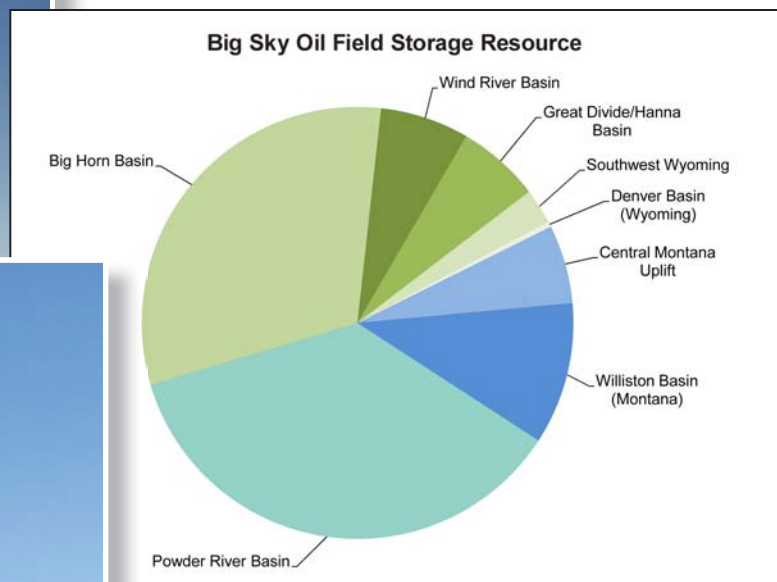
Within the BSCSP region mature oil and gas reservoirs have contained crude oil and natural gas for millions of years. These reservoirs are primarily located in the sedimentary basins of Wyoming and Montana. Based on cumulative oil production to date from these reservoirs, the region could store more than 1.5 billion metric tons (1.6 billion tons) of CO_2.

The major oil and gas producing regions within the BSCSP include: (1) Williston Basin covering the northeastern region of Montana, as well as parts of South and North Dakota; (2) Powder River Basin (PRB) spanning southeastern Montana and northeastern Wyoming; (3) Bighorn Basin in north-central Wyoming and south-central Montana; and (4) Wind River Basin in central Wyoming. Other significant oil and gas production occurs in Montana's North-Central Uplift and southwest Wyoming basins, such as the Greater Green River, Great Divide, and Hanna Basins, and the Wyoming Thrust Belt. There are more than 500 oil and gas fields in Montana and more than 1,400 in Wyoming with an estimated 278 million and 1.2 billion metric tons (306 million and 1.32 billion tons) of storage resource, respectively. The largest of these fields is located in the PRB and could potentially store 131 million metric tons (144 million tons) of CO_2, more than the region's current annual CO_2 emissions.

Enhanced oil recovery offers an economic incentive for carbon storage in oil and gas reservoirs. Current EOR operations within the BSCSP region include individual projects in the PRB, Green River, and Wind River Basins that utilize CO_2 produced from a natural gas processing plant on the Moxa Arch in the western Green River Basin. Plans are in progress to expand the delivery of this CO_2 to many other fields within the Bighorn Basin, the Williston Basin, and the Laramie Basin.

Oil pumpjack near Plentywood, eastern Montana. (Courtesy of Montana Board of Oil and Gas)

Exploration well south of the Big Snowy Mountains, Wheatland County, Montana. (Courtesy of Dave Bowen, MSU)



Proportion of CO_2 Storage Resource by Basins in the BSCSP Region.

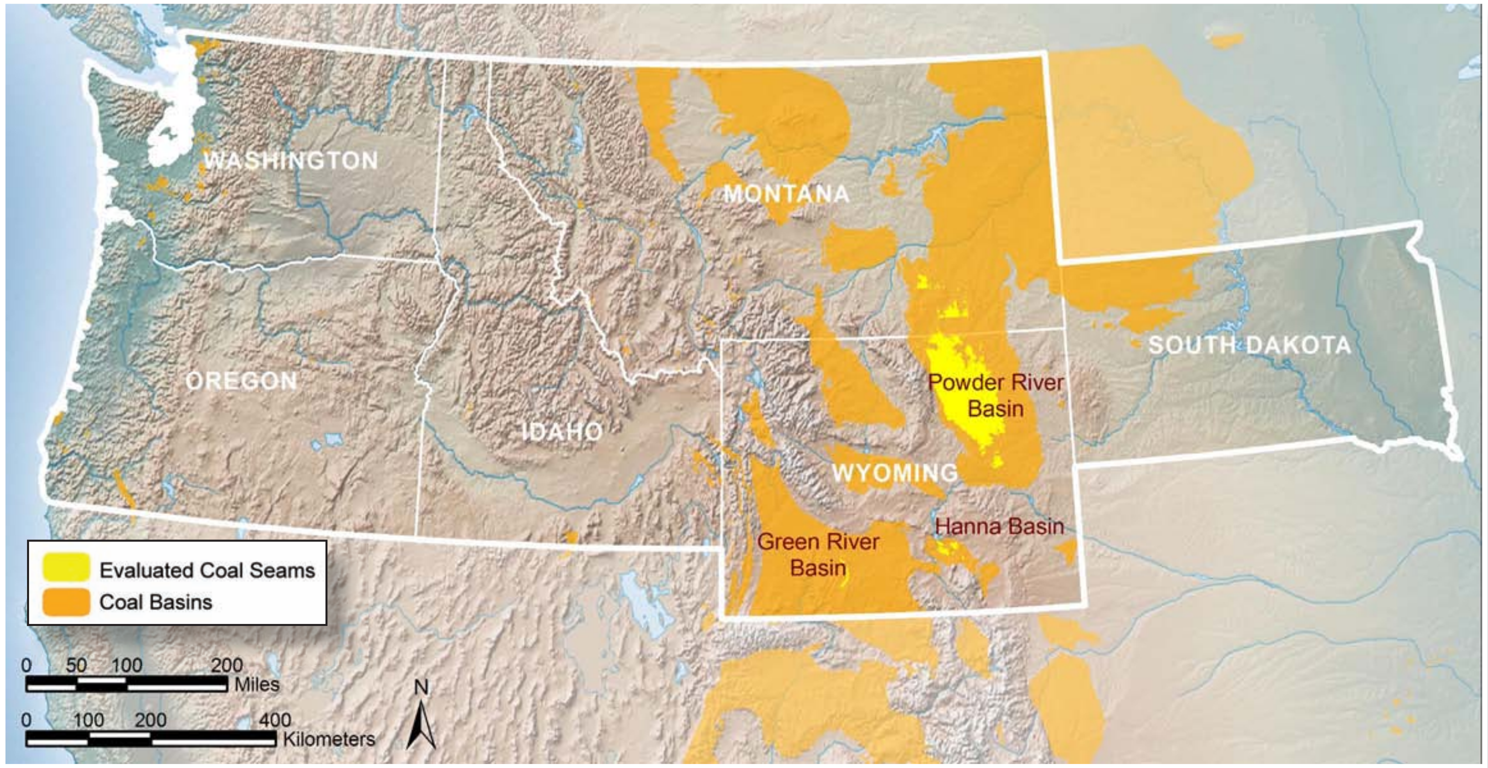
Drill site in Richland County, eastern Montana. (Courtesy of Enerplus Resources [USA] Corp.)

BSCSP Unmineable Coal Areas

The Big Sky region contains significant coal and CBM resources. Three of the largest reserves include the Powder River, Green River, and Hanna Basins. While these resources are important for power generation, there is CO_2 storage potential within coal seams that are too deep or too thin to be economically mined.

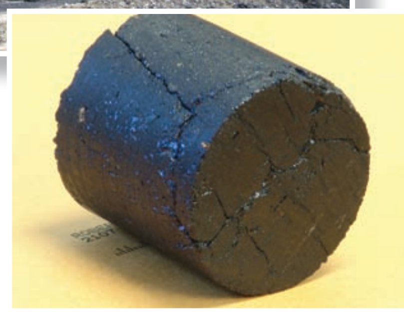
Unmineable coal is generally defined as coal buried under 1,000 feet or more of overburden. The nature of the PRB coal zone makes this basin exceptionally important for carbon storage in the region. The large unmineable area in the PRB has an average thickness of 73 feet. The coal has a high natural permeability, which is necessary for storing CO_2 due to the tendency of coal to swell when in contact with CO_2. During carbon storage in coal seams, CO_2 molecules displace methane molecules from adsorption sites within the coal matrix. The CO_2/methane displacement ratio for the subbituminous coal of the PRB is much higher than coals of higher rank, which suggests that the PRB may be an ideal location for carbon storage.

BSCSP calculations estimate that the total CO_2 storage resource in the unmineable coal seams in the PRB is more than 11 billion metric tons (12 billion tons), largely due to the expansive Wyodak-Anderson coal field. Storage resource for the Green River and Hanna basins is 44 million and 255 million metric tons (48.5 million and 281 million tons) of CO_2, respectively. Although the southern Wyoming coal basins are smaller storage resources, these unmineable coal seams are attractive economic prospects because of ECBM recovery through injection of CO_2. The increased methane production resulting from this process can help offset the cost of CCS.



Rosebud Mine, Montana. (Courtesy of Lindsey Tollefson, BSCSP)

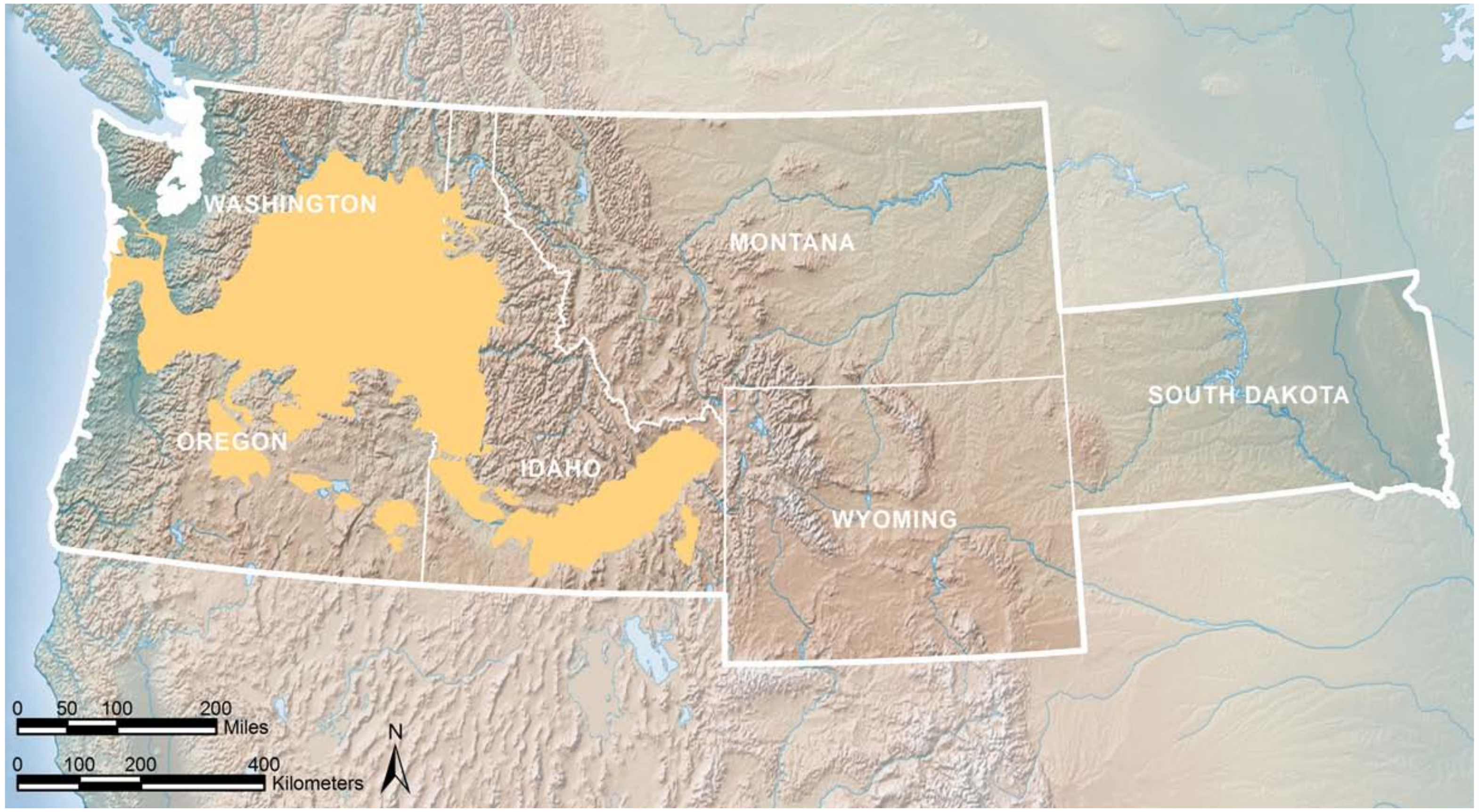
Surface coal mine near Gillete, Wyoming. (Courtesy of Greg Goebel)



Sample core of coal. (Courtesy of Eric Robertson, INL)

Coal Storage Resources in the BSCSP Region		
Basin	**Coal Seam**	**Estimated Storage Volume (million metric tons)**
Green River Basin	Black Butte Total	28
	Point of Rocks Total	16
Hanna Basin	Ferris 23 Total	9
	Ferris 25 Total	22
	Ferris 31 Total	10
	Ferris 50 Total	20
	Ferris 65 Total	3
	Hanna 77 Total	73
	Hanna 78 Total	48
	Hanna 79 Total	37
	Hanna 81 Total	23
	Johnson 107 Total	11
Powder River Basin	Knobloch Total	133
	Rosebud Total	140
	Wyodak-Anderson Total	11,522
	Partnership Total	**12,093**

Basin Totals	
Basin	**Estimated Storage Volume (million metric tons)**
Green River	44
Hanna	255
Powder River	11,794
Partnership Total	**12,093**



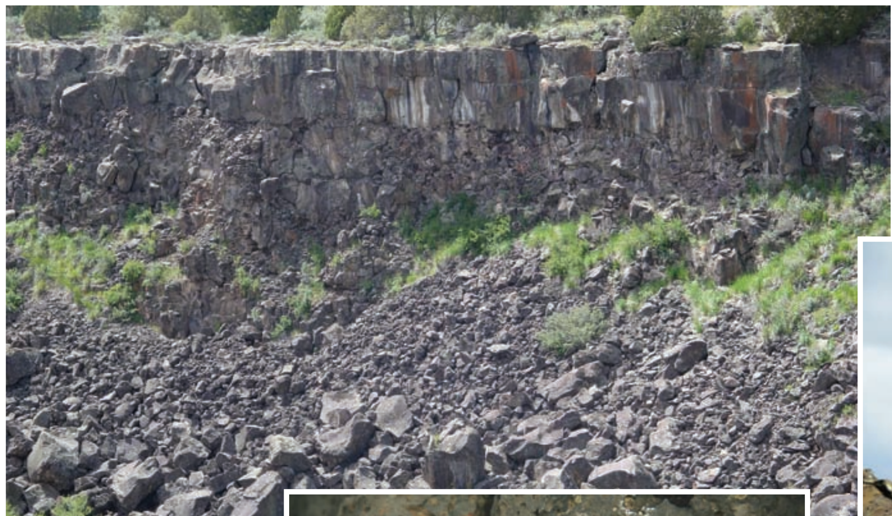
BSCSP Basalt Formations

Basalt formations are prevalent in the Big Sky region, and while less studied than other potential storage sites for CO_2, they may play an important role in geologic storage due to their unique geochemical and physical properties. Worldwide, basalts offer significant long-term storage potential estimated in the range of 33 billion to 134 billion metric tons (36.3 billion to 148 billion tons). These estimates suggest that the five largest basalt provinces could store 10,000 years of the world's CO_2 emissions. Basalt provinces are globally distributed and could significantly expand CO_2 storage options in regions where conventional storage is limited or non-existent.

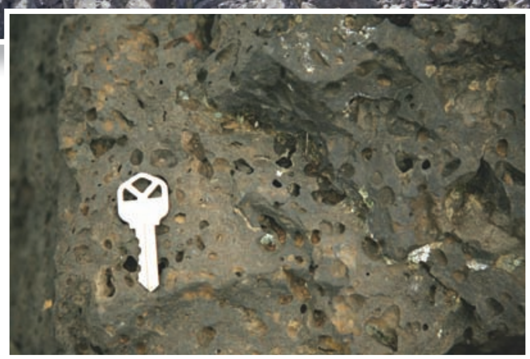
Large basalt provinces in Washington, Oregon, and Idaho were formed as lava flows cooled on the Earth's surface millions of years ago. As successive flows cooled over time, layers of basalt were formed similar to a stack of pancakes, each tens to hundreds of feet thick. The tops of the lava flows quickly cooled and are full of cracks and bubbles, while the interior of flows cooled slowly and are dense and impermeable. Researchers have found that the porous and permeable flow tops have enormous resource to store CO_2, while the interflow zones have low permeability and act as effective caprocks.

Laboratory tests have shown that basalts are highly reactive and have the unique capability to chemically trap CO_2 in a short period of time. When basalts have been exposed to supercritical CO_2 in the laboratory, minerals in the basalt react with the CO_2 and water to form limestone or calcium carbonate. This process traps the CO_2 in a solid form and permanently isolates it from the atmosphere. This process of mineralization happens in other rock types but at much slower time scales.

In the BSCSP region, the Columbia River Basalt Group covers approximately 164,000 km^2 and has been extensively studied. To date, an extensive knowledge base has been created, including numerous laboratory experiments, a first of its kind seismic survey, and baseline surveys to further the understanding of carbon storage in basalts. The BSCSP is conducting a small-scale pilot test to expand laboratory findings to in situ environments.



At left, an example of a basalt flow. (Courtesy of Travis McLing, INL)

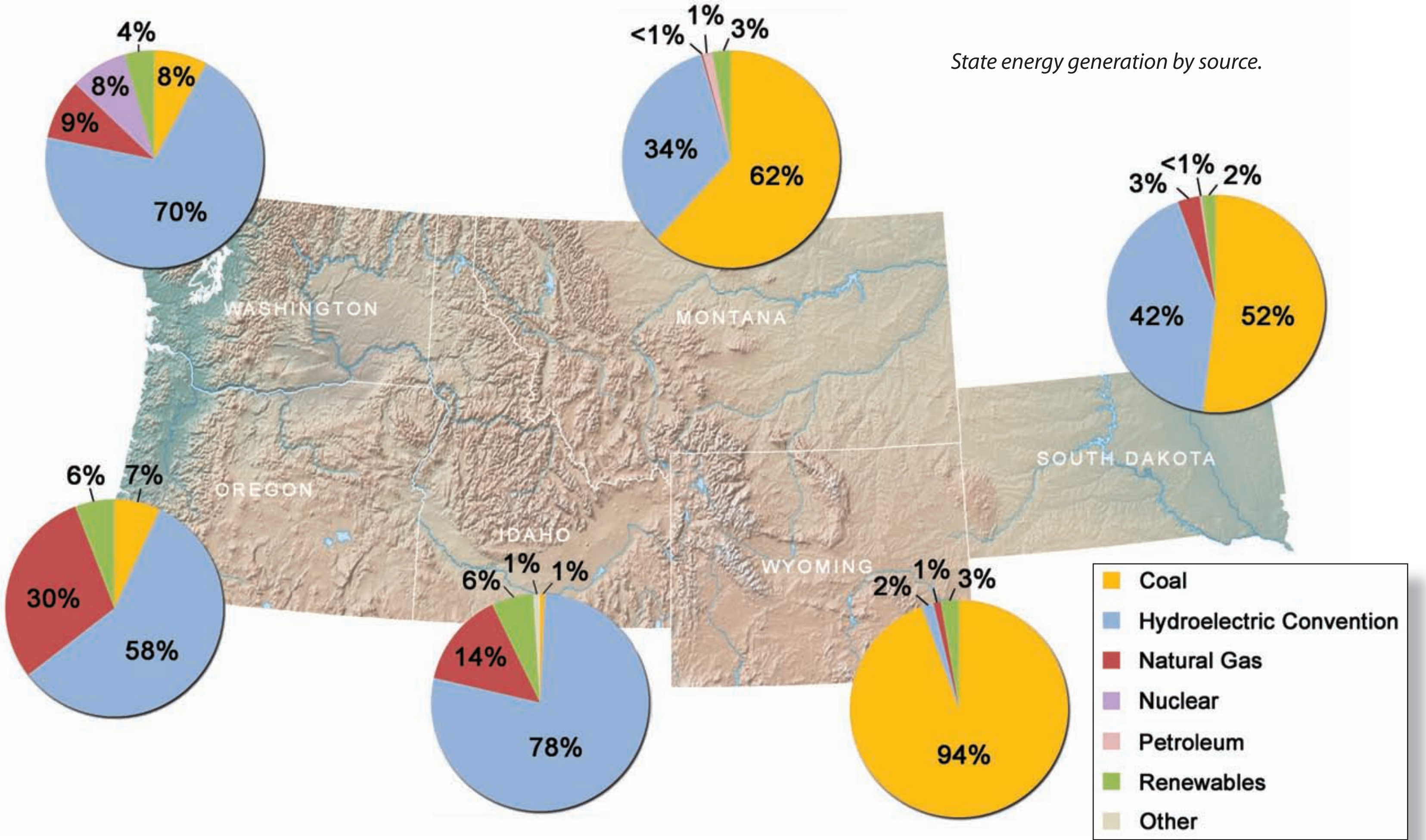


Surface vesicles of a basalt rock. (Courtesy of Sarah Koenigsberg)

Basalt outcrop in eastern Washington. (Courtesy of Sarah Koenigsberg)

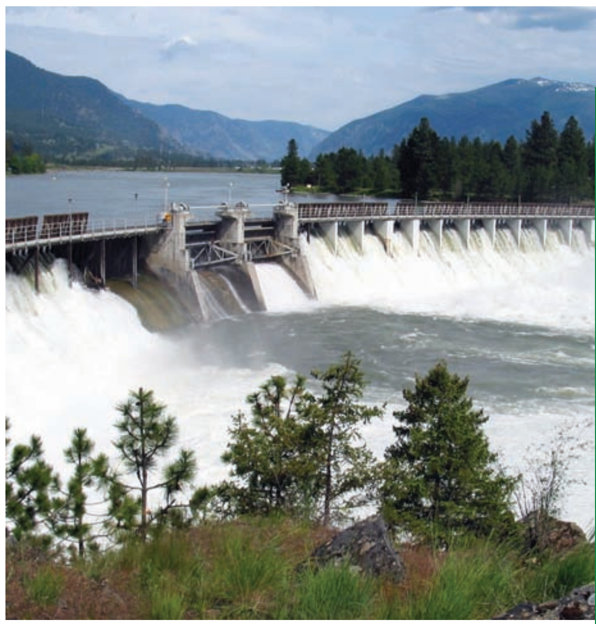
Energy Use and Policy in the Big Sky Region

The Big Sky region is rich in natural resources and in energy resources. The region produces 264.7 million megawatt hours of electricity from a large variety of sources. In the face of climate change and uncertain economic times, the Big Sky region is taking several steps to be a leader in producing green energy and reducing its CO_2 emissions. Electricity in the Big Sky region is produced from hydropower, coal, natural gas, nuclear, wind, wood-derived fuels, biomass, petroleum, other gases, and geothermal. The region as a whole produces most of its electricity from hydroelectric and coal. However, the individual States in the region have unique and contrasting energy profiles. For example, more than half of the electric power generated in Washington, Oregon, and Idaho is from hydroelectric, while more than two-thirds of the electric power generated in Montana and Wyoming is generated from coal. Montana has the largest coal reserves (24 percent) in the Nation and Wyoming is ranked third with 13 percent. For this reason, these States and others in the Big Sky region have been at the forefront of developing a regulatory framework for CCS.



State energy generation by source.

To date, Wyoming, Montana, Washington, and North Dakota have developed specific statutory requirements to regulate geologic storage of CO_2. Additionally, Oregon, South Dakota, and Washington also have terrestrial storage statutes to establish registries and to promote carbon markets for agricultural and forestry practices. The tables on this page display the current status of regulations developed in the Big Sky region and expected activities in the next legislative sessions.

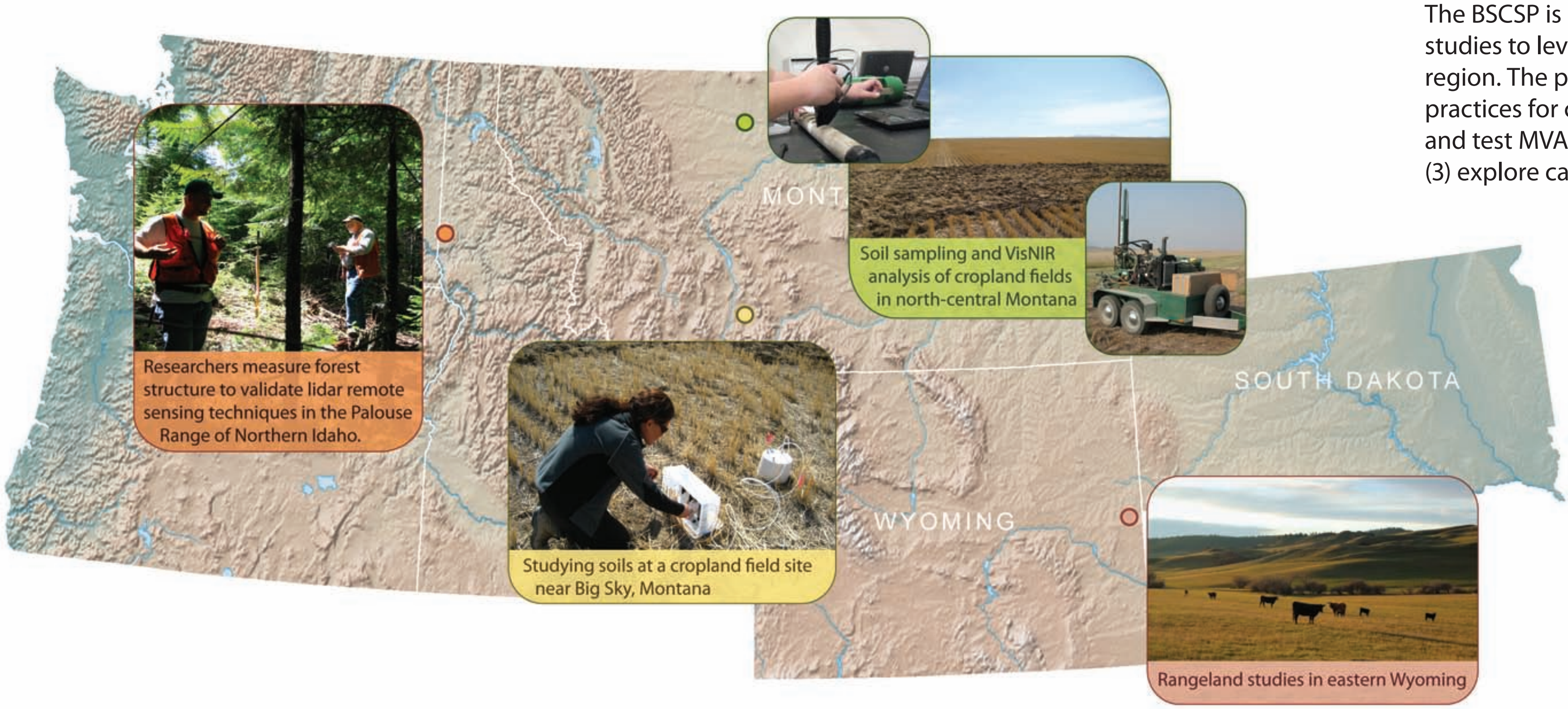


Hydroelectric dam near Thompson Falls, Montana. (Courtesy of Montana PPL)

Status of Geologic Storage Regulations in the Big Sky Region

Requirements	Wyoming	Montana	North Dakota	Washington
Underground Injection Control Primacy	Yes	No	Yes	Yes
Who owns the pore space?	Surface Owner	Surface Owner	Surface Owner	State
What is dominant: pore space or mineral estate?	Mineral estate dominant—no injection in structures with hydrocarbons	Equal Standing	Equal Standing	Equal Standing
Who is the Regulating Agency?	WY Dept. of Env. Quality/ WY Oil and Gas Compact Commission	MT Board of Oil and Gas/ MT Dept. of Env. Quality/ MT Dept. of Natural Resources & Conservation	Industrial Commission/ Health Department	WA Dept. of Ecology
What are the unitization requirements?	75%	60%	60%	Not Defined
Financial responsibility	Surety Bond TBD plus liability policy	Surety Bond TBD	Surety Bond TBD	Financial Assurance Mechanism
Release of Liability to third party	N/A	After 30 years	After 10 years	Minimum of 20 years post-injection
What is the Area of Review beyond predicted plume size?	1 Mile	½ Mile	¼ Mile	10 Miles

**Table current as of November 2010.*



Researchers measure forest structure to validate lidar remote sensing techniques in the Palouse Range of Northern Idaho.

Soil sampling and VisNIR analysis of cropland fields in north-central Montana

Studying soils at a cropland field site near Big Sky, Montana

Rangeland studies in eastern Wyoming

BSCSP Terrestrial Research

The BSCSP is engaged in several terrestrial storage research and pilot studies to leverage the wide range of natural landscapes within the region. The program is designed to: (1) determine best management practices for carbon storage in croplands and rangelands, (2) identify and test MVA technologies that reduce the costs of verification, and (3) explore carbon market opportunities.

Carbon markets: This project, completed in 2009, created resources that enable landowners to develop carbon storage projects on their land and provided hands-on guidance on identifying land management practices that maximize carbon storage and portfolio development. Results include a Terrestrial Handbook for landowners and enrollment of tribal, croplands, and rangelands in carbon markets. The table below shows the numbers of landowners, acres, and metric tons enrolled and traded to date.

Detection of soil carbon using alternative methods: Traditional laboratory methods of measuring soil carbon content can be intensive, time consuming, and costly. Emerging in situ technologies have the potential to provide rapid, accurate, and precise analysis of soil constituents. The BSCSP is testing two different technologies in an effort to reduce the costs and time required to verify carbon in soils.

Using remote sensing as a tool to detect land management on the ground: Researchers are using computer models and satellite images to accurately identify agricultural practices specified in carbon contract agreements and estimate carbon storage potential. Results to date, validated with site visits, have shown that fields managed with intensive tillage can be distinguished from no-till farming using remote sensing techniques.

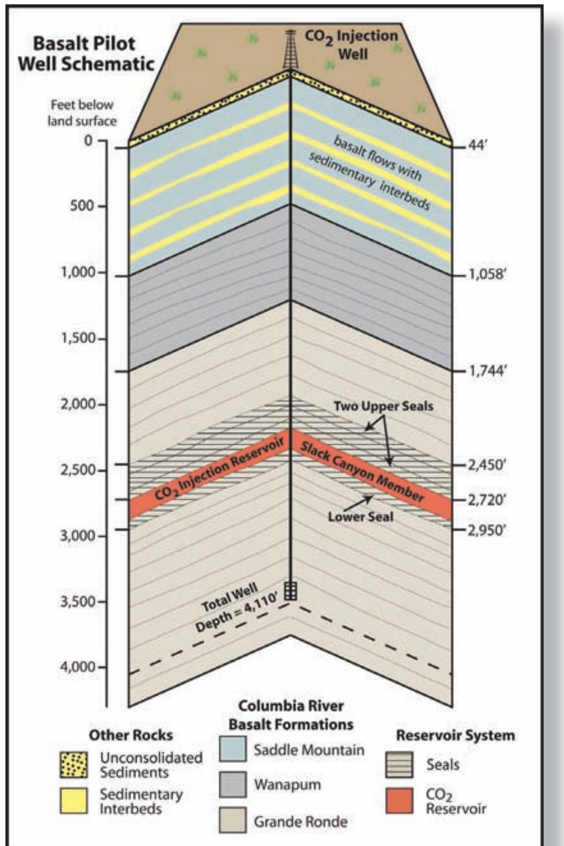
Determining how much carbon is stored in the trees: Lidar remote sensing, combined with field surveys and forest stand growth modeling, is being used to characterize and predict rates of aboveground carbon storage in forests of the Northern Rocky Mountains. The work is designed to establish a standard methodology by which carbon may be quantified across broader forested regions.

Results of Carbon Market Development in the BSCSP Region

		Number of Landowners	Acres	Tons Contracted	Tons Traded to Date
Tribal Portfolio	Nez Perce Reforestation	NA	2,205	14,027	14,027
	Fort Peck Tribe Grazing	NA	189,218	500,000	
Private/State Lands Portfolio	Cropland Pool #1	68	117,745	152,410	85,500
	Cropland Pool #2	106	172,642	175,321	28,500
Rangeland Offset Pools	Rangeland Pool #1	6	268,637	327,639	98,900
	Rangeland Pool #2	44	247,307	263,445	31,100
	Rangeland Pool #3	9	44,799	52,225	10,800
	Totals	**233**	**1,042,553**	**1,485,067**	**268,827**

BSCSP Validation Phase Geologic Pilot Tests

The BSCSP's Validation Phase pilot is being conducted in southeastern Washington basalts. The objectives of the test are to: (1) address the critical technical issues associated with the injection, fate, and transport of supercritical CO_2 in one or more interflow zones in a deep basalt formation; (2) work with industry partners to ensure that characterization test activities support their needs; (3) participate in public outreach and education activities; and (4) work with State regulators and environmental groups to ensure timely support of necessary permitting.

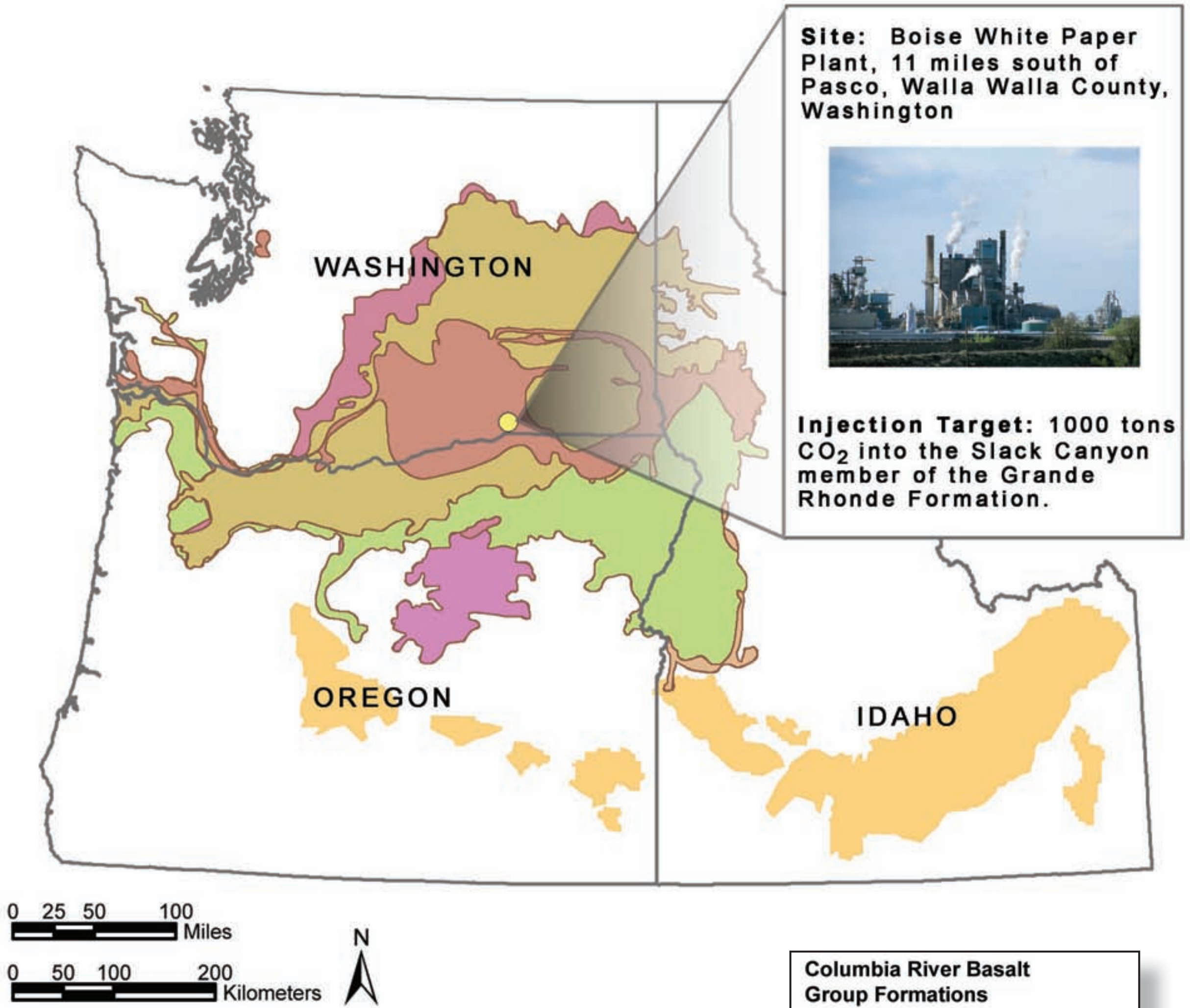


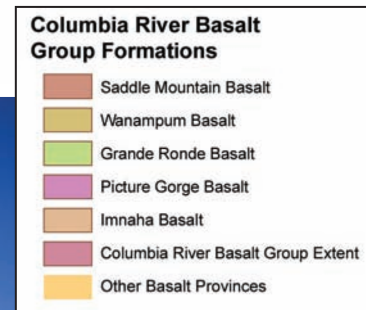
Project Activities and Accomplishments to Date

Most of the geologic characterization, baseline monitoring, and modeling activities have been completed. An innovative multi-component seismic survey was completed in December 2007 that resulted in the first known success of surface-based seismic imaging of Columbia River basalt geology. Two shallow soil gas probes were installed to establish background concentrations for CO_2 and other gases. Drilling of the well began in January 2009 and total depth was reached in April 2009 at 4,110 feet. Image logs indicated the presence of potential caprock and reservoir zones and water and rock samples were pulled during drilling for baseline data. Thirty-two rotary-drilled sidewall cores were taken from multiple zones with excellent recovery. Permits for drilling and injection have been approved by the Washington Department of Ecology. Additionally, extensive stakeholder and public outreach activities have produced community support for the project.

Key Findings and Results to Date

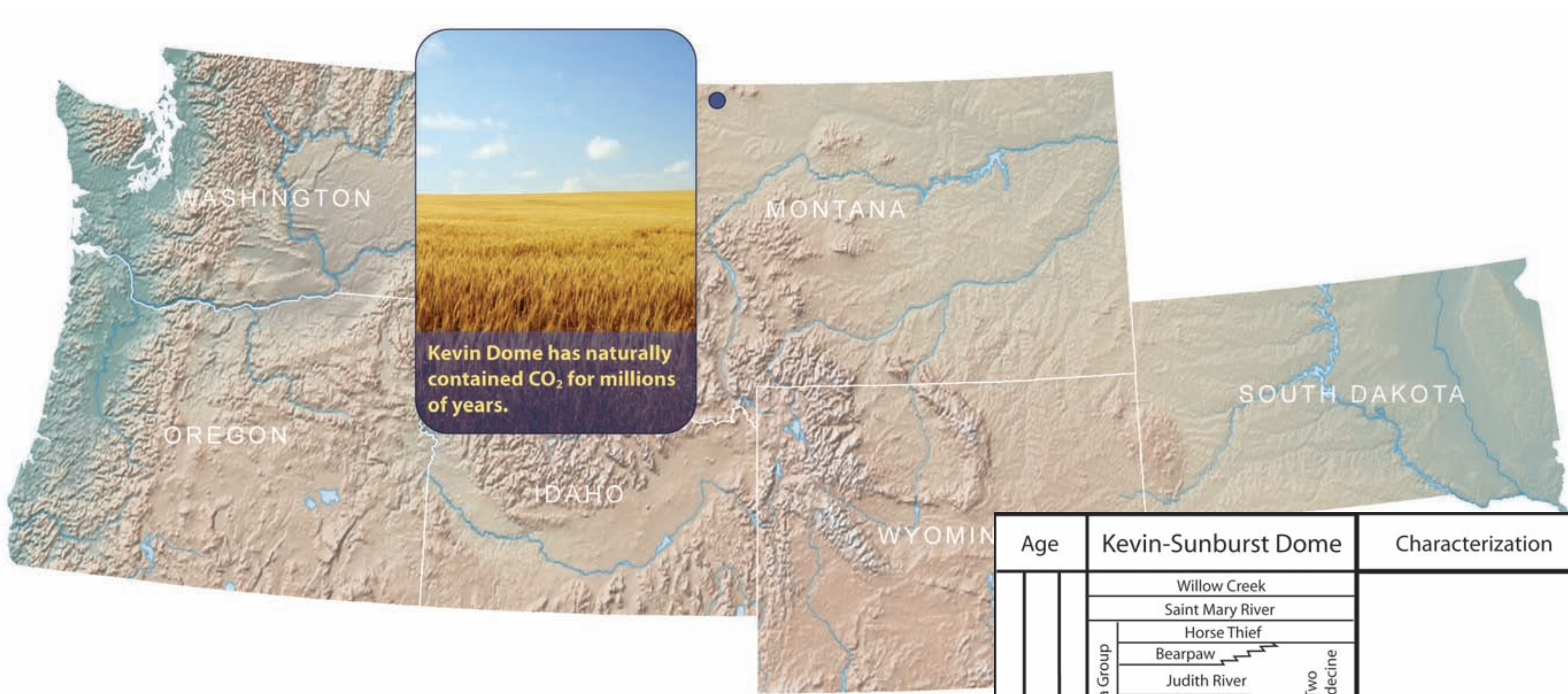
Seismic results showed no deep-seated surface or subsurface faults and that a thick succession of basalt layers is present and undisturbed by large-scale faulting. Extensive hydrologic testing resulted in the selection of an injection zone in the Grande Ronde and a 14-day injection simulation of 1,000 metric tons (1,100 tons) indicates that the maximum plume radius of injected supercritical CO_2 is 180 feet after 1 year. Carbon dioxide injection is anticipated in Winter 2010.





Installing sensors for seismic survey at Validation Phase Pilot Site. (Courtesy of Sarah Koenigsberg)

Validation Phase Geologic Pilot Site near Wallula, Washington. (Courtesy of Sarah Koenigsberg)



Development Phase Geologic Pilot Tests

Based upon the Validation Phase research, the BSCSP is considering a Development Phase project at Kevin Dome in north-central Montana. Kevin Dome covers approximately 1,800 km^2 and contains a large reservoir of naturally occurring CO_2 that has been trapped in place for millions of years. The CO_2 is in the upper Devonian Duperow (carbonate) Formation and above the spill point of the dome. Validation Phase research has found that the Kevin Dome area has the potential for approximately 1.37 billion metric tons (1.51 billion tons) of additional storage.

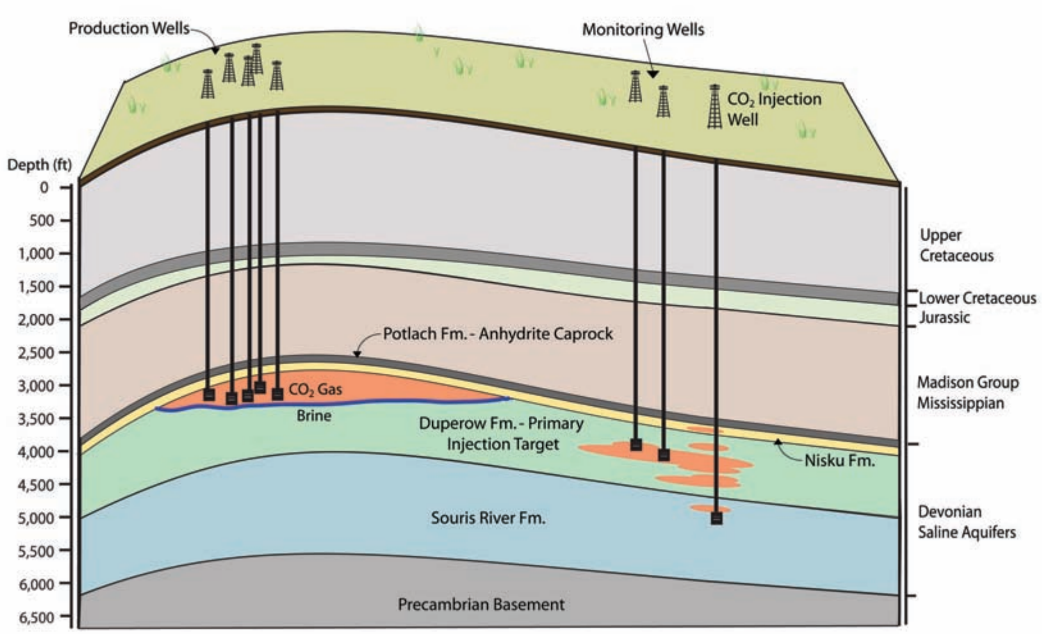
Project Objectives

The overall goal of the project would be to demonstrate that Kevin Dome is a viable and safe target for regional CO_2 emissions. Other objectives include improving understanding of: (1) the potential of domes for geologic storage, (2) the evaluation and comparison of geochemical changes that have occurred to reservoir rocks exposed to CO_2 for millennia and recently exposed rocks, (3) geomechanical and geophysical characteristics of caprocks in naturally occurring reservoirs, and (4) evaluation of stacked storage and detection of a smaller pool of CO_2 stored above a larger volume.

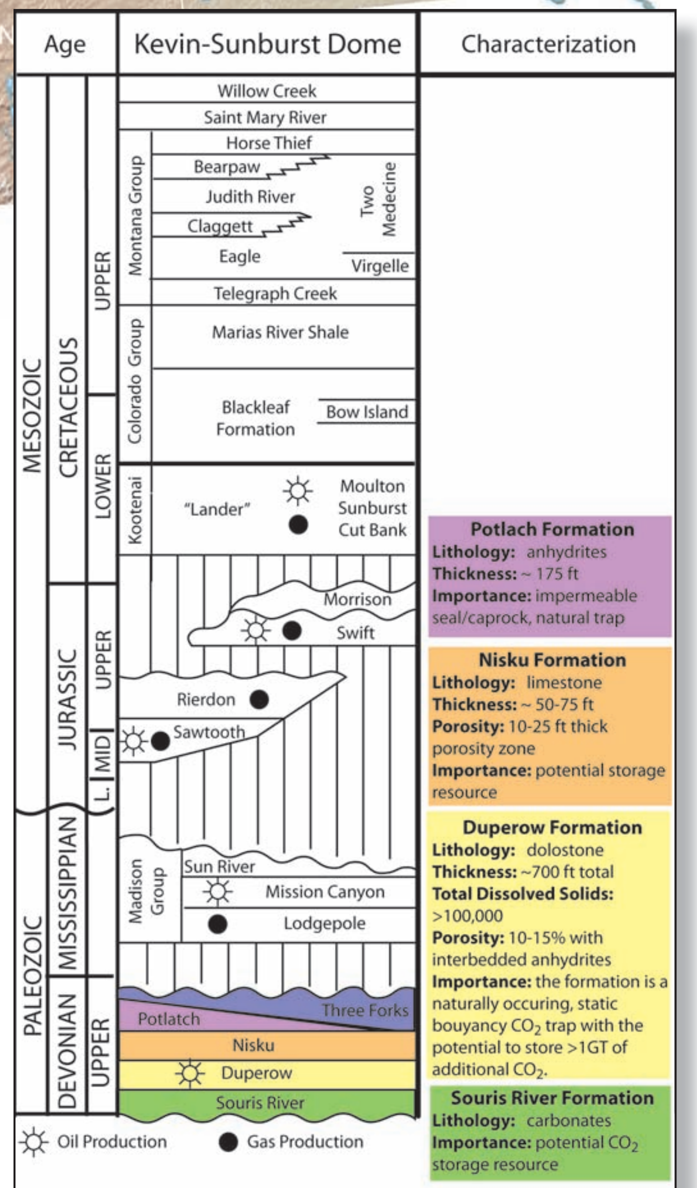
Project Overview

To evaluate the dome as a regional carbon storage site, BSCSP and an industrial partner are proposing to drill five CO_2 production wells into Kevin Dome, pipe the CO_2 approximately 7 miles to a location north of the dome, and then re-inject the CO_2 into three separate reservoirs. The primary injection target would be the Duperow saline formation below the gas-brine water contact. The CO_2 would also be injected into one reservoir above (Nisku) and one reservoir below (Souris River) the Duperow to evaluate these reservoirs for storage potential. Four monitoring wells and one injection well would also be installed. Expected production and storage from the project would be 1 million metric tons (1.1 million tons) over 4 years. Primary MVA techniques proposed include 4-D seismic, geochemical sampling, and pressure monitoring along with other techniques.

Kevin Dome Phase III Schematic



Schematic graphic of Kevin Dome in northcentral Montana.



Stratigraphic column highlighting formations of interest at Kevin Dome.

Integrating CCS into the BSCSP Community

The BSCSP is involved in a wide range of education and outreach activities to engage with stakeholders and further the understanding of CCS science and projects in the region. The primary objectives of the BSCSP outreach program are to: (1) provide information on regional carbon storage opportunities, (2) inform and engage with the public on the pilot projects and regional characterization efforts, (3) facilitate communication and collaboration between stakeholders, and (4) promote CCS education to a variety of groups. The following showcases a few examples of BSCSP outreach activities.


Onsite tour of BSCSP Validation Phase Geologic Pilot Test near Wallula, Washington.

Basalt Validation Phase Pilot

For the BSCSP Validation Phase pilot, project factsheets, press releases, and key messages have been developed and distributed to the community. More than 30 meetings with key stakeholders have been held in nearby communities to build support for the project. The lead scientists have hosted multiple lab and site tours for interested stakeholders and concerned citizens. Student interns from regional colleges are currently working on the project. These efforts have resulted in little to no public opposition towards the project, positive press, and improved public trust and community relations.


Teachers working on CCS lesson plans.

BSCSP Annual Meeting

The BSCSP annually hosts a 2-day conference on BSCSP projects and related topics. The meeting has presentations by speakers from across the Nation on science, policy, and technology of CCS. The meeting is attended by academics, industry, environmental non-profits, politicians, ranchers, small business owners, and students, and audience participation is encouraged. The BSCSP has had 383 participants attend the meeting over the past 3 years (2007, 2008, and 2009).


BSCSP Outreach Coordinator Lindsey Tollefson speaking to a group of teachers in Billings, Montana.

Legislative Symposia

The BSCSP engages with legislators, committees, and staffers in the Big Sky region during legislative sessions. This activity is carried out by giving presentations in State capitols and providing technical information to policymakers on BSCSP projects and CCS. This effort has proved to be particularly useful as two of five States with comprehensive legislation on CCS are in the Big Sky region.


BSCSP Director Lee Spangler speaking with the public at a legislative symposium in Helena, Montana.

Teacher Education Workshop

The BSCSP also works to educate teachers on the latest CCS science. A teacher education workshop was conducted in Billings, Montana, to provide resources to teach climate change and CCS lessons to middle and high school students. Twenty-two teachers from the region attended the training, having access to more than 3,900 students combined.

Big Sky Carbon Sequestration Partnership Contacts

If you have any questions, comments, or would like more information about the BSCSP, please contact the following individuals:

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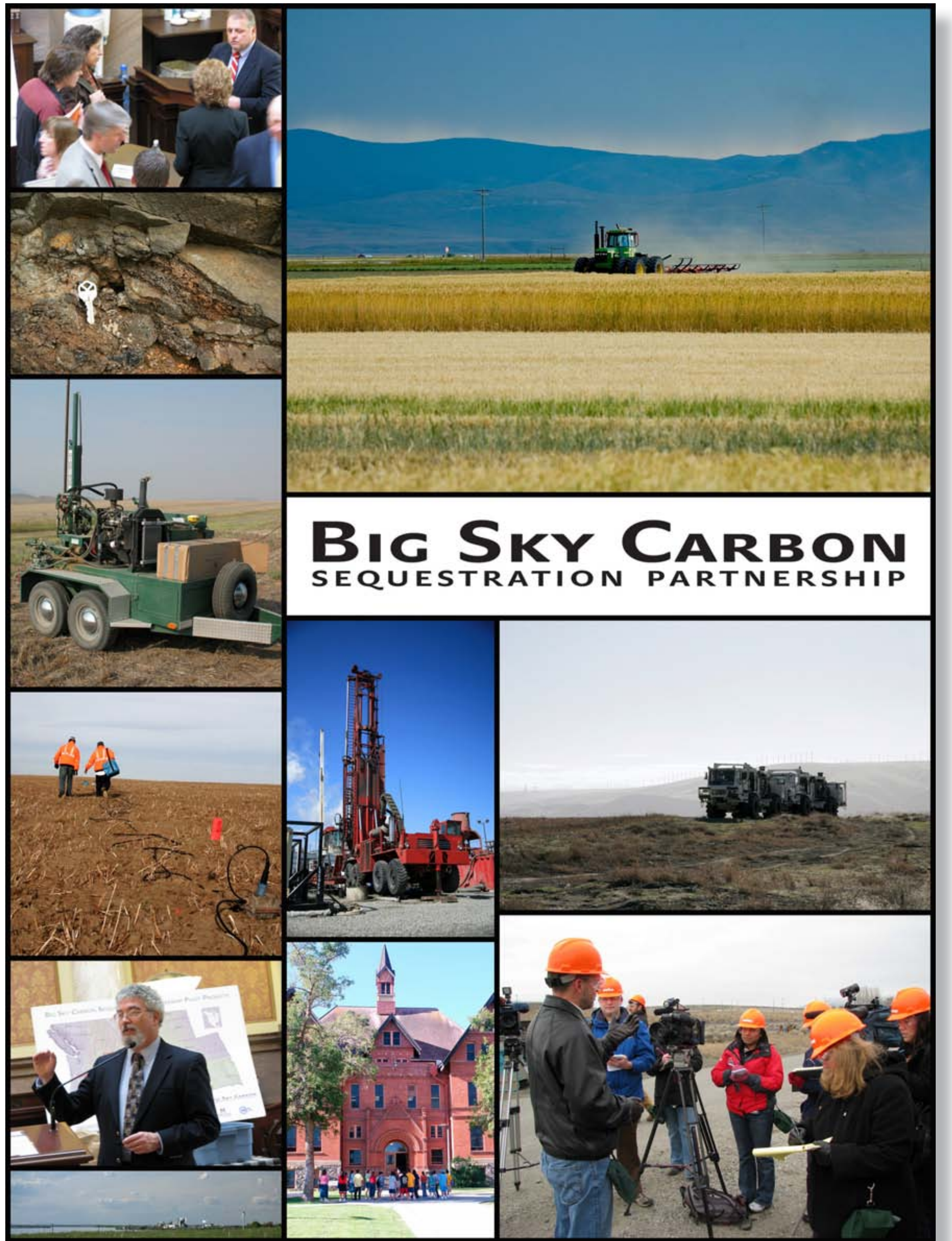
Please visit: http://www.bigskyco2.org.

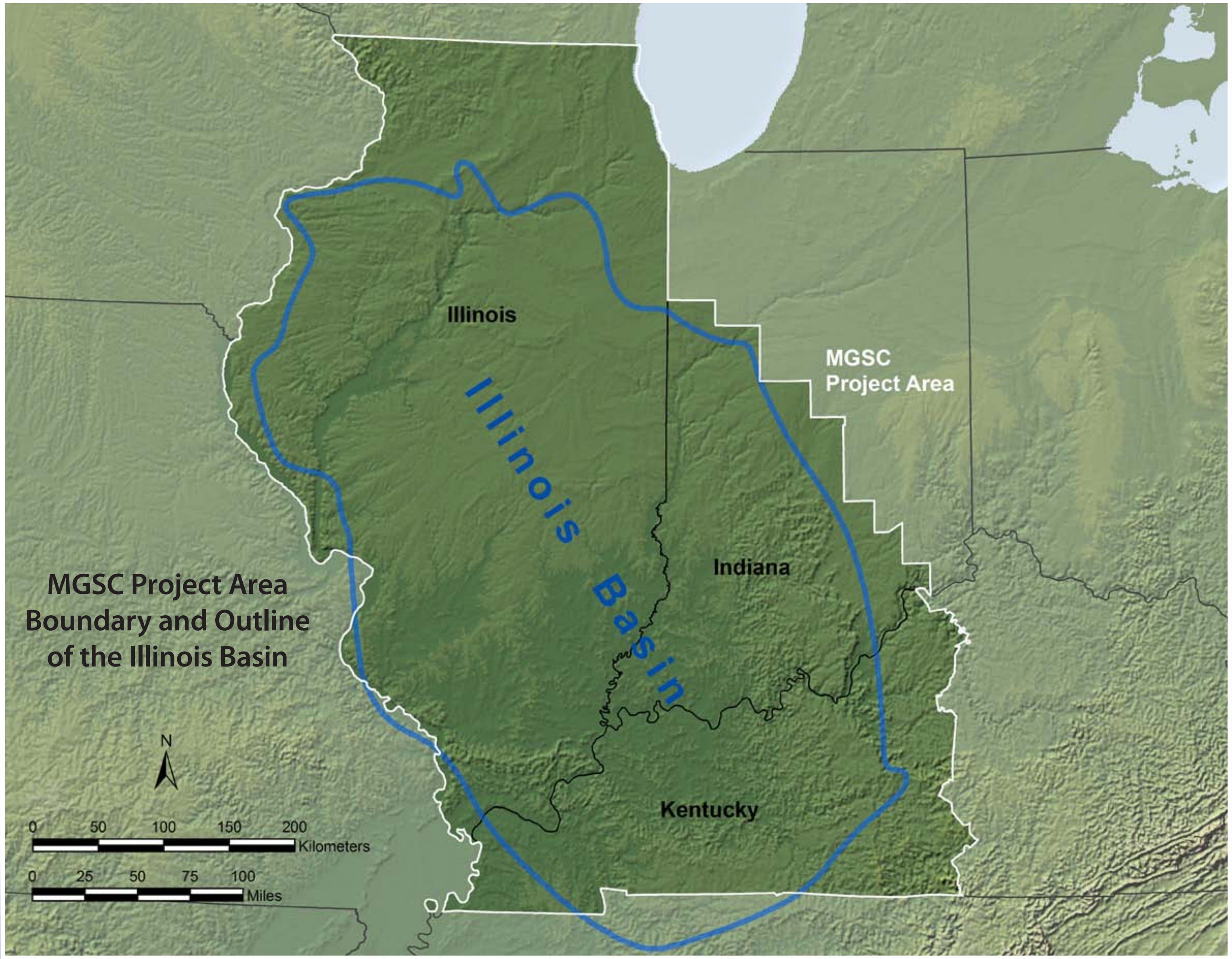


Midwest Geological Sequestration Consortium

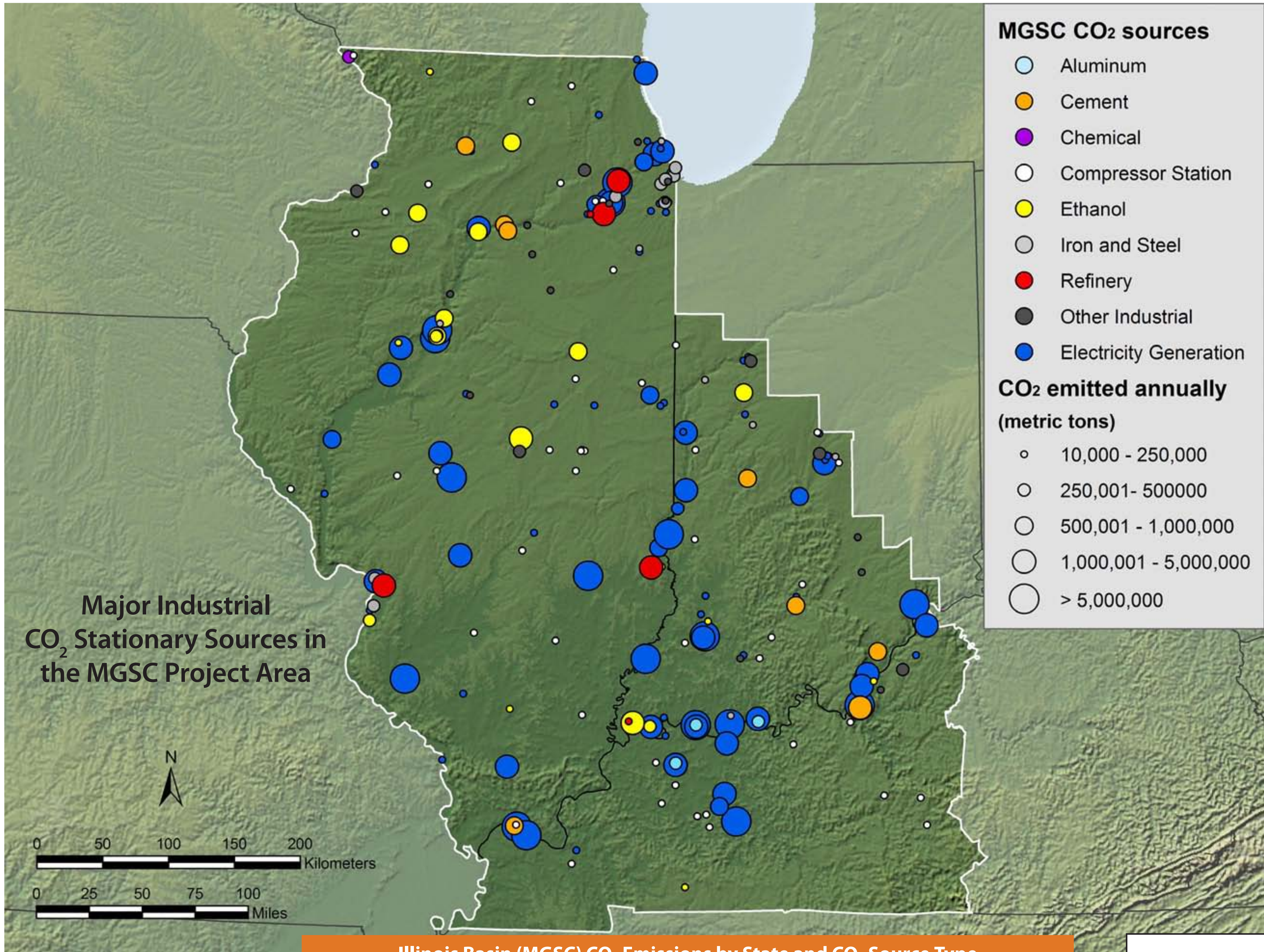
The Midwest Geological Sequestration Consortium (MGSC) is a consortium of the geological surveys of Illinois, Indiana, and Kentucky joined by private corporations, professional business associations, the Interstate Oil and Gas Compact Commission, three Illinois State agencies, and university researchers to assess carbon capture, transportation, and geologic storage processes and their costs and viability in the Illinois Basin region. The Illinois State Geological Survey is the Lead Technical Contractor for the MGSC, which covers all of Illinois, southwest Indiana, and western Kentucky.

To avoid atmospheric release of CO_2 from fossil fuel combustion and thereby reduce the potential for adverse climate change, the MGSC is investigating options for geologic CO_2 storage in the 155,400-km^2 (60,000-mi^2), oval-shaped, geologic feature known as the Illinois Basin. Within the basin there are deep, uneconomic coal resources, numerous mature oil fields, and deep saline formations with potential to store CO_2. MGSC's objective is to determine the technical and economic feasibility of using these geologic formations for long-term storage.

The Illinois Basin is geologically unique because all three potential geological storage opportunities exist in close proximity to substantial CO_2 sources and, in some cases, may be accessed from one site.



Typical central Illinois Basin landscape.



MGSC CO_2 Sources

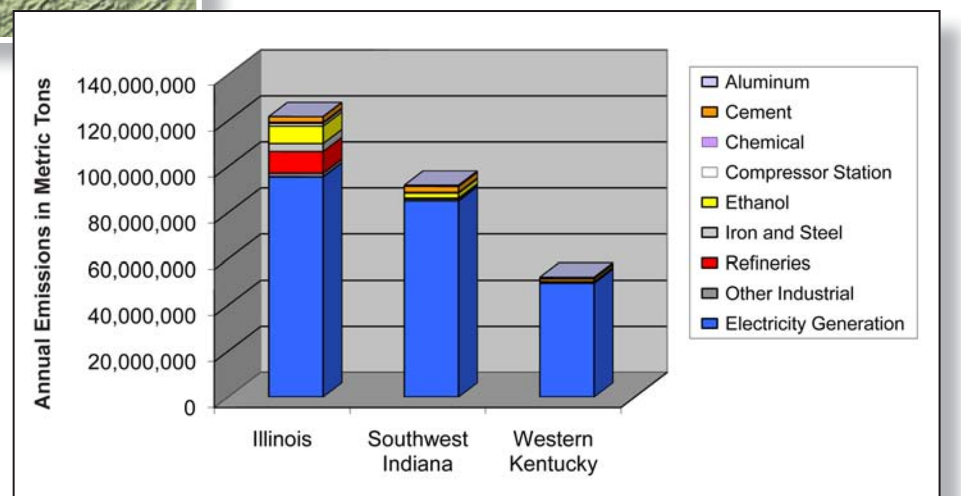
The Illinois Basin region has annual CO_2 emissions exceeding 265 million metric tons (292 million tons), with a carbon equivalent of 72 million metric tons (80 million tons) from major industrial stationary sources. Recent data show that slightly less CO_2 was emitted than in previous years due in part to a decrease in the output from natural gas-fired electricity generation facilities coupled with an increase in nuclear and wind-generated power. The shift in energy sources may reflect temporary conditions in the region.

Coal-fired, electricity generation facilities are the most dominant fixed sources, some of which burn almost 4.5 million metric tons (5 million tons) of coal per year. The distribution of emissions from these plants is highly skewed. The four largest plants, in megawatt capacity, emit about 25 percent of total CO_2 emissions; the 11 largest plants emit greater than 50 percent of total CO_2 emissions; and the 25 largest plants emit greater than 80 percent of total CO_2 emissions. The Illinois Basin region contributes about 11 percent of the total U.S. CO_2 emissions from electric power generation plants. Coal is the dominant fossil fuel for these plants and contributes 97 percent of the Illinois Basin CO_2 emissions from stationary sources of electricity.

Carbon dioxide emissions from the manufacturing sector vary from industry to industry, and account for approximately 13 percent of the total tabulated emissions in the Illinois Basin region.

Illinois Basin (MGSC) CO_2 Emissions by State and CO_2 Source Type

Source Type	Illinois Basin Annual CO_2 Emissions (million metric tons)			
	Illinois	Southwest Indiana	Western Kentucky	Total
Aluminum	0	0.5	0.7	1.2
Cement	2.5	2.6	1.1	6.2
Chemical	0.4	0	0	0.4
Compressor Station	1.2	0.3	0.1	1.7
Ethanol	7.6	2.2	0.2	9.9
Iron and Steel	3.5	0.1	0	3.6
Refineries	9.3	0.2	0	9.6
Other Industrial	1.7	0.9	0.4	3.0
Electricity Generation	95.5	85.1	49.5	230.1
Total	**121.7**	**91.8**	**52.0**	**265.6**



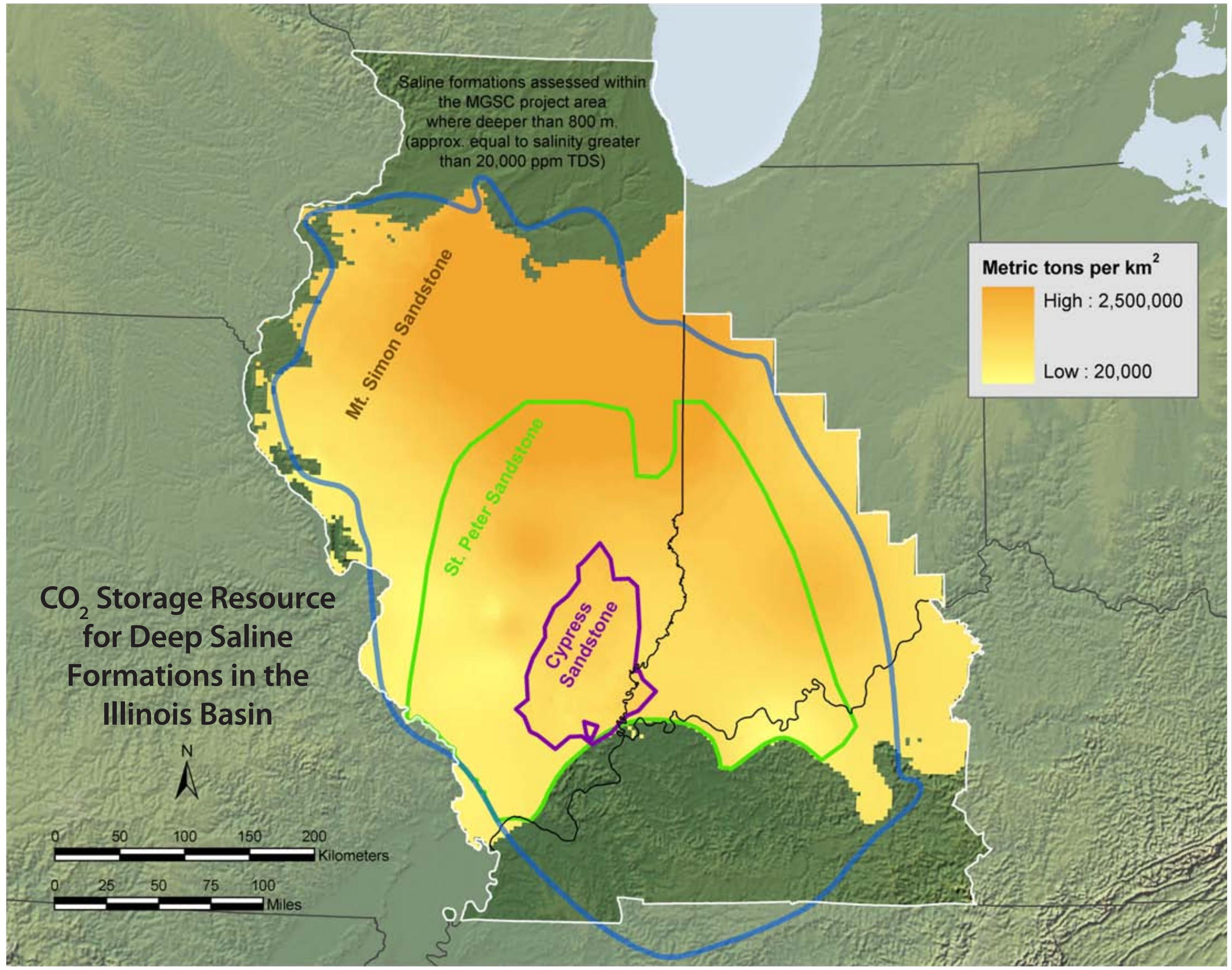
MGSC Illinois Basin Saline Formations

Four saline reservoirs in the Illinois Basin are being studied for CO_2 storage potential: (1) the Mississippian Cypress Sandstone, (2) the Ordovician St. Peter Sandstone, (3) the Cambro-Ordovician Knox Supergroup, and (4) the Cambrian Mt. Simon Sandstone.

The Cypress Sandstone is the most widespread and prolific petroleum bearing sandstone in the Illinois Basin; however, areas with thick Cypress tend to have a large water bearing zone that may be considered a saline storage target. The porous and permeable sandstone can reach a thickness of 200 feet, although it is generally less than 100 feet thick and displays considerable variation in thickness and lateral extent. It is the shallowest of the saline reservoirs assessed, and is found at depths reaching approximately 3,000 feet in parts of the Illinois Basin. Shale beds and a laterally continuous carbonate, the Beech Creek (Barlow) Limestone, form the overlying seal for the Cypress Sandstone.

The St. Peter Sandstone is a widespread, porous, and permeable quartz sandstone that is generally fine-grained with good lateral continuity. Seals above the St. Peter include several hundred feet of dense limestone and dolostone overlain by 45.7 to 76.2 meters (150 to 250 feet) of Maquoketa Shale.

The Knox Supergroup directly underlies the St. Peter Sandstone and consists of several thousand feet of dolostone and minor sandstone. The Knox is an integrated reservoir and seal interval. Much of the Knox is non-porous dolostone, but scattered throughout are porous and fractured zones (some with vuggy to cavernous porosity) that have permeability suitable for CO_2 injection. The Knox may be particularly important as a storage target in parts of the Illinois Basin where the Mt. Simon Sandstone is too deep or absent. Seals above the Knox are the same as the St. Peter Sandstone (Upper Ordovician carbonates and shales). A multi-State characterization study of the Knox and St. Peter Sandstone is in progress.



The Mt. Simon Sandstone is commonly used for natural gas storage in the northern Illinois Basin. Although water in the upper Mt. Simon is considered potable in northernmost Illinois, the formation is saline-filled in the remainder of the State—and no oil or natural gas resources have been discovered in this unit. The Mt. Simon has fair to good permeability and porosity, and the overlying strata contain impermeable limestone, dolomite, and shale intervals. The depth of the Mt. Simon ranges from approximately 610 to 4,267 meters (approximately 2,000 to 14,000 feet) below the surface. At its greatest thickness in the Illinois Basin, the Mt. Simon is over 793 meters (2,600 feet) thick. The Mt. Simon does not outcrop in Illinois, but correlative units are exposed in southern Wisconsin, southeastern Minnesota, and Missouri. The Mt. Simon exists in the subsurface throughout much of Indiana, Iowa, Michigan, and Ohio. In the southern region of the basin, the potential CO_2 reservoir facies are either deep or may be absent due to post-depositional erosion, especially towards the southwest.

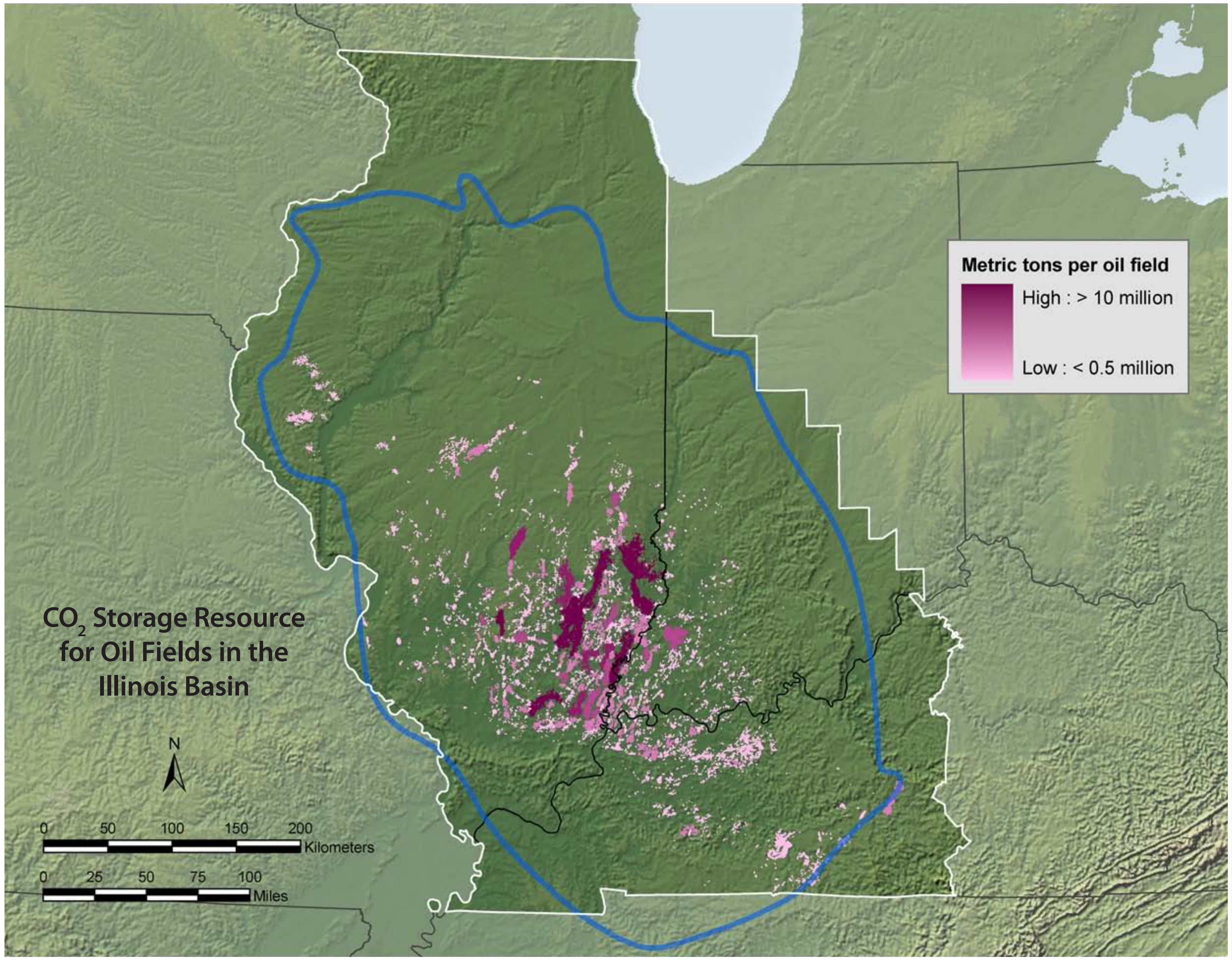
A GIS-based volumetric methodology was used to quantify the storage resource of the saline formations. For the current study, the latest range of storage efficiency factors was used, and reservoir area was extended eastward to complement the area defined by MRCSP. The total storage resource for the Illinois Basin is estimated to be 12 to 161 billion metric tons (13 to 177 billion tons).

Reservoir	CO_2 Storage Resource* (billion metric tons)
Cypress Sandstone	0.2–2.3
St. Peter Sandstone	0.6–7.8
Mt. Simon Sandstone	11–151
Total	**12-161 billion metric tons**

* Using storage efficiency (E) factors of 0.4% and 5.5%, respectively, which represent the P_{10} and P_{90} estimates.

State	CO_2 Storage Resource* (billion metric tons)
Illinois	8.4–116
Indiana	2.9–39
Kentucky	0.4–5.6
Total	**12–161 billion metric tons**

* Using storage efficiency (E) factors of 0.4% and 5.5%, respectively, which represent the P_{10} and P_{90} estimates.



MGSC Illinois Basin Oil and Gas Reservoirs

Due to the established effectiveness of CO_2 enhanced oil recovery (EOR), oil reservoirs offer the most potential for economic offset of the costs associated with carbon storage in the Illinois Basin. To assess this potential, a basin-wide EOR estimate was made based on a new understanding of the OOIP in the basin, the CO_2 storage resource, the assessed EOR resource, the geographic distribution of EOR potential, and the type of recovery mechanism (miscible vs. immiscible). The resource target for EOR in the Illinois Basin is 137 to 207 million m^3 (860 to 1,300 million barrels [bbl]) recoverable with a consequent storage resource of 140 to 440 million metric tons (154 to 485 million tons) of CO_2.

With cumulative oil production for the basin about 0.67 billion m^3 (4.2 billion bbls), nearly 1.5 billion m^3 (10 billion bbl) of oil remain primarily as unrecovered resources in known fields. To assess the recovery potential of a part of this resource and the concurrent stored CO_2 volumes, geologic modeling and compositional reservoir simulation were carried out. Parts of nine fields were used to create generic geological models for the most prolific oil bearing reservoirs in the basin: the Aux Vases and Cypress Sandstones and the St. Genevieve Limestone. These models incorporated data from greater than 1,000 total wells, 120 wells with core, greater than 2,000 core sample points, 12,000 field acres, and 20 flow zones. Structure and isopach maps were developed deterministically from well logs, whereas porosity and permeability distributions were developed geostatistically from core analysis data for use in the reservoir simulator. Processes simulated included miscible and immiscible flooding, based on reservoir pressure and temperature, and both continuous and water-alternating-gas CO_2 injection scenarios.


Installation of downhole pressure sensor.


Oil tank battery.


Oil production well.

State	CO_2 Storage Resource (million metric tons)	Estimated EOR* (million barrels)
Illinois	106–358	632–979
Indiana	20–47	124–162
Kentucky	14–35	104–138
Total	**140–440 million metric tons**	**860 million–1.3 billion barrels**

* The EOR volume was estimated based on a series of oil recovery factors for specific geologic units and miscibility type that were applied to the OOIP as assessed per oil field.

MGSC Illinois Basin Unmineable Coal Areas

The Illinois Basin holds substantial remaining coal resources, totaling 258 billion metric tons (284 billion tons). Extraction techniques range from surface mining to room-and-pillar and longwall subsurface methods, with most mining occurring around the margins of the basin. Most of the basin's remaining coal resources are moderate to high in sulfur content. Consequently, market share has been lost to low-sulfur, western coal from the PRB, and Illinois coal production has declined by half since 1990. The opportunity to store CO_2 in coals currently considered to be unmineable is based on both technical and economic considerations and could be supported by the production of CBM displaced from these coals.

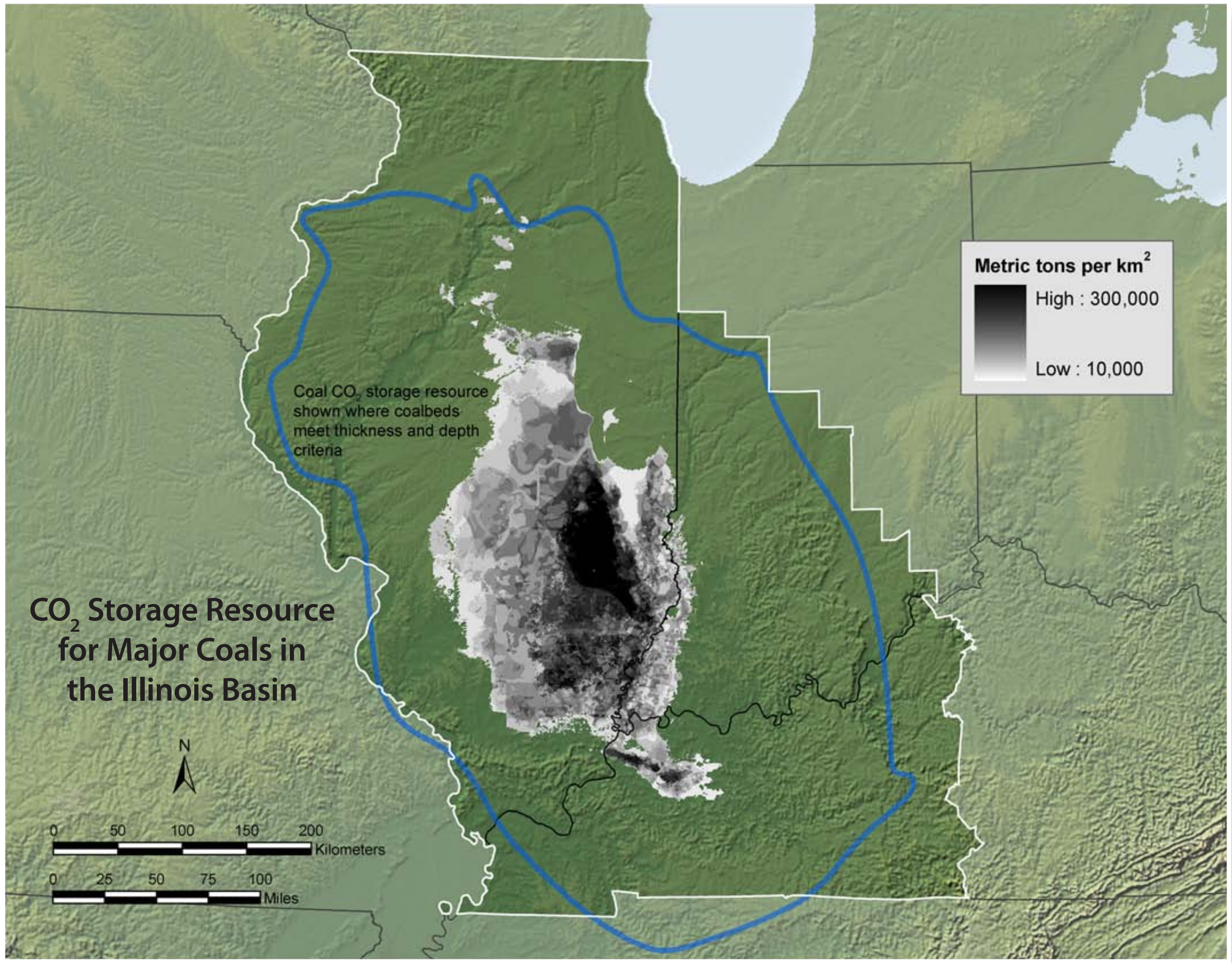
With respect to defining unmineable coal, no consideration is given to coals at depths less than 152 meters (less than 500 feet). From 152 to 305 meters (500 to 1,000 feet) in depth, coals from 0.48 to 1.1 meters (1.5 to 3.5 feet) are considered storage targets. A seam less than 1.1 meters (less than 3.5 feet) in thickness is currently unmineable with existing equipment. It would be costly to develop new equipment compared to mining seams of greater thickness, which remain an abundant part of the resource base. Below 305 meters (1,000 feet) in depth, all seams greater than 1.1 meters (greater than 1.5 feet) in thickness are considered a storage target.

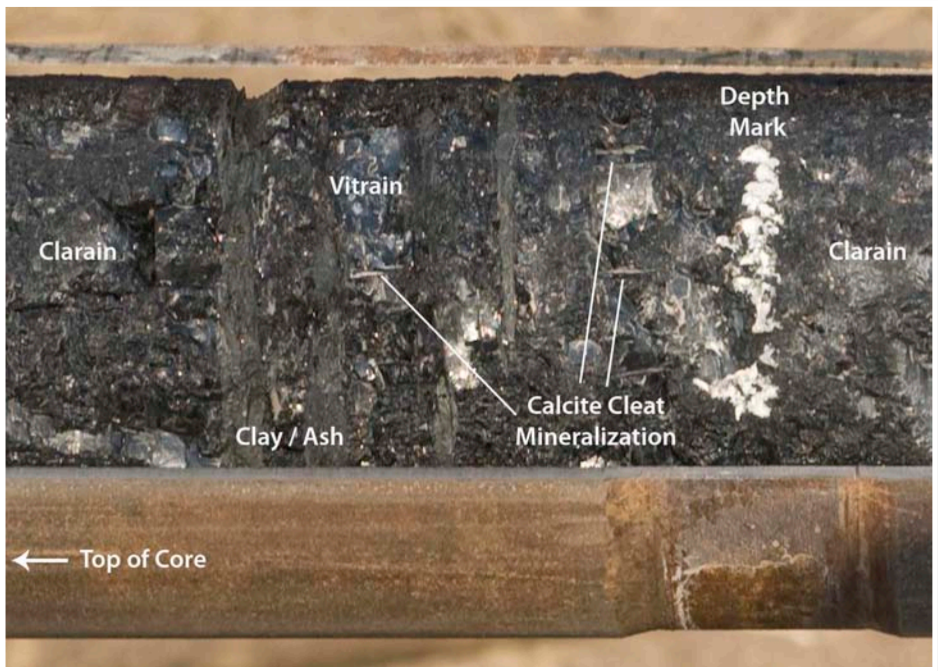
Key characteristics of seven coals were mapped throughout the Illinois Basin, including thickness, depth, elevation, moisture content, ash content, heating value, temperature, and expected reservoir pressure. Most data were available for the Herrin and Springfield coals, the major coal seams in the basin. Gas contents for Illinois Basin coals are in the range of 3.12 to 4.68 m^3/metric ton (100 to 150 standard cubic feet [scf]/ton) for the better samples; CO_2 adsorption can range from 14.1 to 21.9 m^3/metric ton (450 to 700 scf/ton) at 2,068 kPa (300 psi). Using a GIS-based volumetric methodology, the latest storage efficiency factors yield a total storage resource estimate for the Illinois Basin of 1.6 to 3.2 billion metric tons (1.8 to 3.5 billion tons).

State	CO_2 Storage Resource* (million metric tons)	Estimated ECBM** (billion scf)
Illinois	1,470 to 2,900	2,700 to 9,800
Indiana	86 to 170	150 to 600
Kentucky	68 to 134	130 to 470
Total	**1.6 to 3.2 billion metric tons**	**3.0 to 10.9 trillion scf**

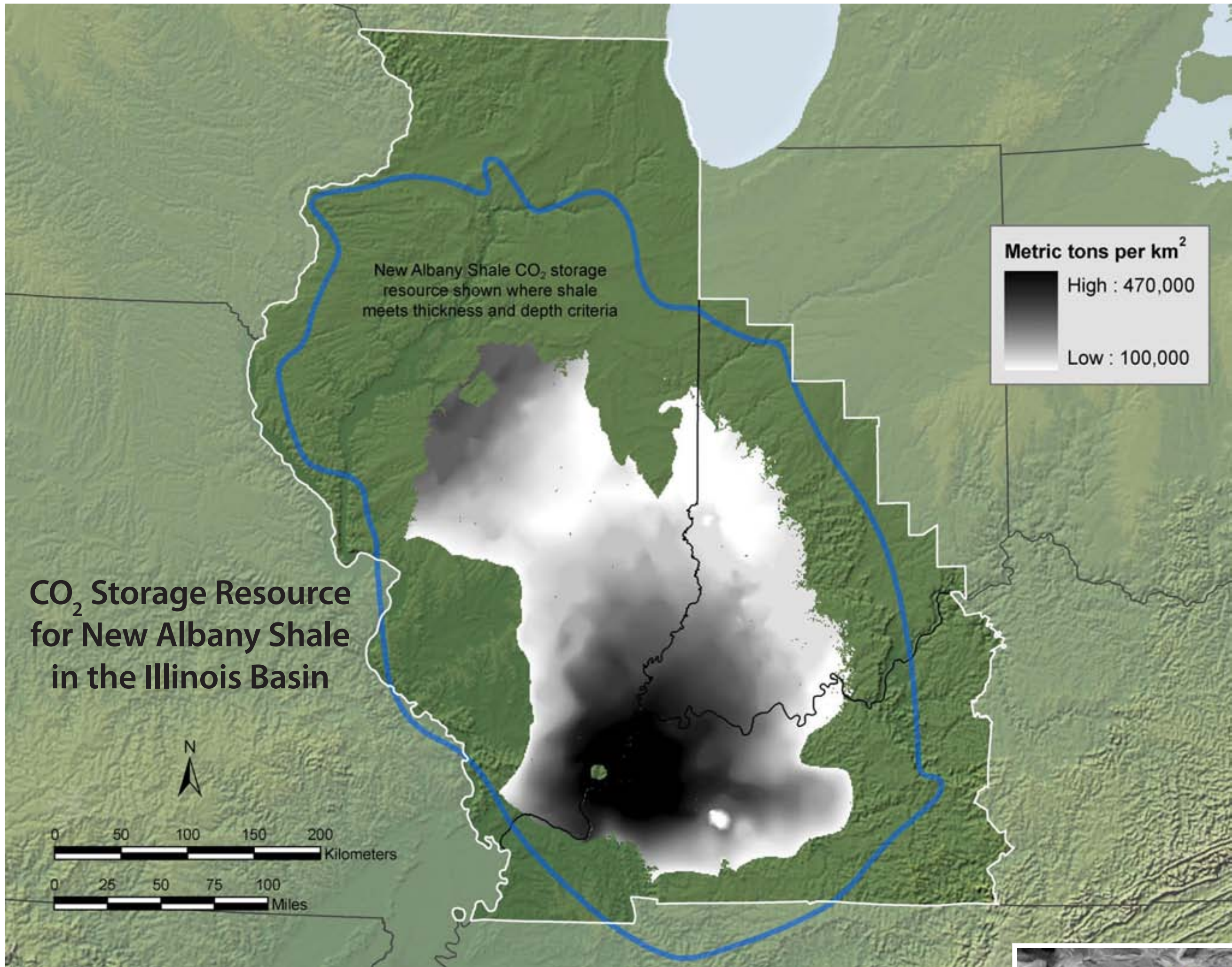
* Using storage efficiency (E) factors of 39% and 77%, respectively, which represent the P_{10} and P_{90} estimates.

**ECBM was estimated based on a methane recovery factor that was applied to the original gas-in-place volume per coal seam for unmineable coal areas as described above.





Banded horizons in Springfield Coal core. Core was drilled vertically and is shown rotated 90 degrees.



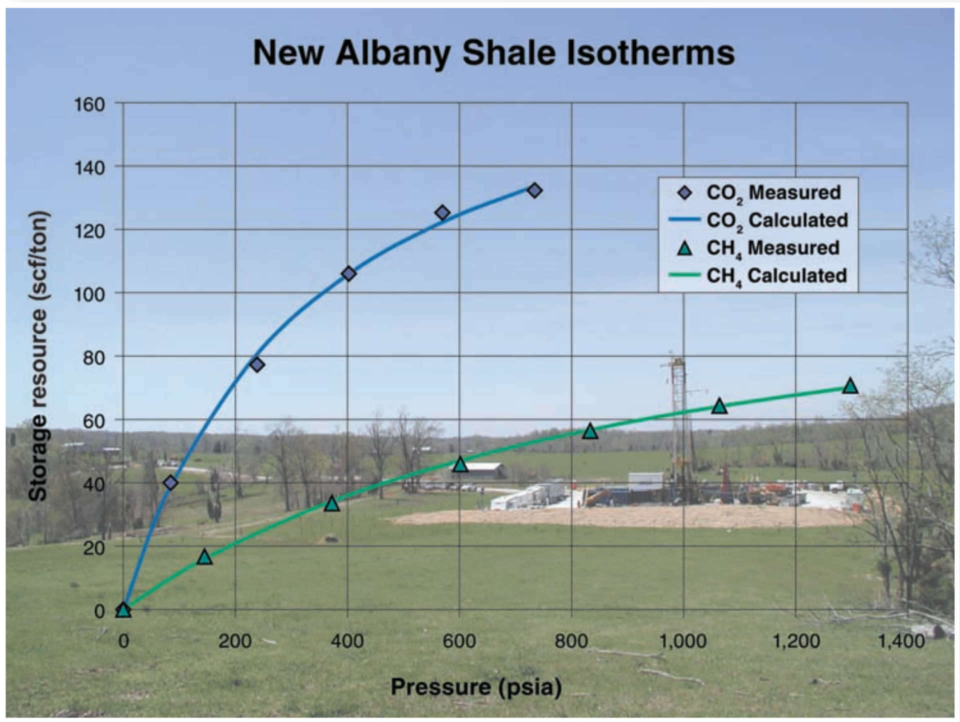
MGSC Illinois Basin Organic-Rich Shale Basins

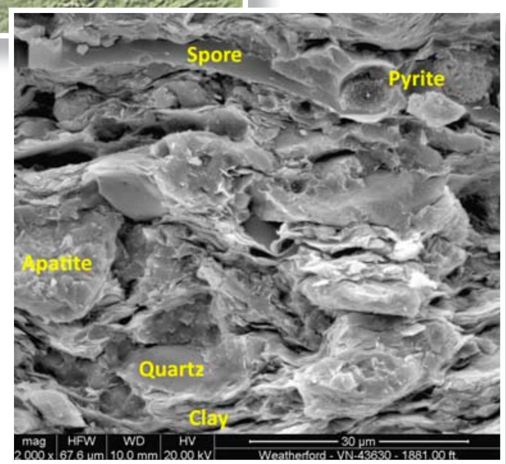
The New Albany Shale is a black, organic-rich shale and is a commercially productive gas reservoir in Indiana and Kentucky. This shale is being assessed for its storage potential by: (1) evaluation of the total organic content (TOC) in the shale, and (2) analysis and calculation of shale isotherm adsorption for several cores in the basin.

The organic carbon content of the shale is directly related to the CO_2 adsorption, which is being calculated and mapped in the basin. Two different approaches are used—the first is to calculate TOC values from density logs, and the second is to calculate TOC from published analytical data. Both sets of information are compiled into databases for comparison and map construction. Interpretation of the data suggests some anomalous values in the eastern portion of the basin, but more work is needed to further define the significance of the anomalies.

Secondly, shale cores are being analyzed for isotherm adsorption data and calculations made for storage potential. Preliminary data from several wells, including the Blan Well in Hancock County, Kentucky, suggest that the shale can adsorb in the range of three to four times the equivalent amount of methane.

The New Albany Shale is the primary seal for Silurian and Devonian oil and gas reservoirs, and it may act as a secondary seal for storage in deeper Paleozoic reservoirs, like the Mt. Simon and St. Peter Sandstones. Initial volumetric estimates indicate that up to 15 billion metric tons (17 billion tons) of CO_2 could be stored in the organic-rich shale of the Illinois Basin, but this estimate is being refined by considering the distribution and quantity of organic matter in the shale, low permeability and rate of CO_2 injection, chemical reactions between the oxidizing fluids and the inorganic portion of the shale, variations in shale lithology, and displacement efficiencies.





Photomicrograph (2,000X magnification) of black shale, from 1,881 feet deep in Kentucky Geological Survey No. 1 Blan well.

New Albany Shale outcrop.

MGSC Validation Phase Field Tests

The MGSC, along with its industry partners, has conducted a series of four field validation tests in the Illinois Basin to assess the potential for CO_2 storage in oil reservoirs and coal seams. Value-added benefits for oil reservoirs and coalbeds are the potential for EOR and ECBM production, respectively.

Loudon Field – Enhanced Oil Recovery

In 2007, a huff 'n' puff EOR project was conducted, where CO_2 was injected into a producing well, shut-in, and allowed to penetrate the formation. The producing well was then placed back on production. Located within Loudon Field in Fayette County, Illinois, 39 metric tons (43 tons) of CO_2 were injected during the test into the Mississippian Weiler Sandstone formation at a depth of approximately 1,550 feet.

Project highlights:

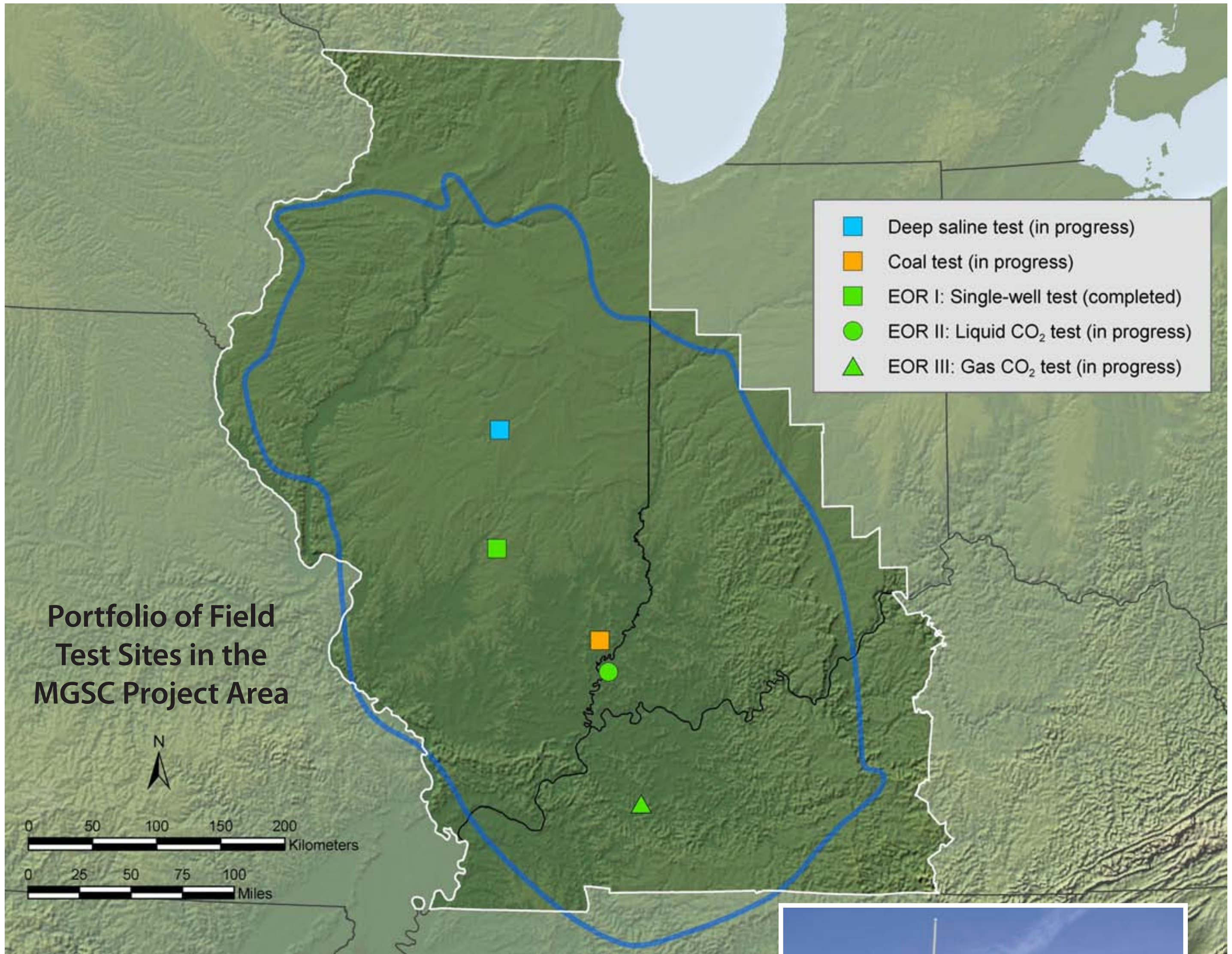
- 39 metric tons (43 tons) of CO_2 were injected over a 5-day period.
- Incremental oil production during the first 2 months following the soak period was approximately 95 bbl.
- Results indicate that the Illinois Basin oilfield may have a value-added benefit as a precursor to build and invest in the infrastructure to establish a storage industry within the basin.

Mumford Hills Field – Enhanced Oil Recovery

Carbon dioxide injection started in Fall 2009 at the EOR II site in the Mumford Hills field in Posey County, Indiana. The primary injected zone is analogous to the oil producing Cypress Sandstone within the Illinois Basin. The reservoir is located at an average depth of 1,900 feet deep and consists of thick wedges of fine-grained sandstone, and the subsurface pressure and temperature are suitable to sustain a liquid CO_2 flood. Carbon dioxide injection was completed in Summer 2010. Post-CO_2 water pressure transient tests will be underway in Fall 2010 to identify changes in permeability.

Project highlights:

- Injected 5,000 metric tons (5,500 tons) of CO_2 into a Mississippian sand in a single injector for approximately 8 months.
- Miscible liquid CO_2 flood tripled the daily oil rate, and cumulative oil production increased 1,300 bbl over the baseline.
- Two to three additional months of CO_2 injection will be followed by up to 9 months of water-injection monitoring through Summer 2011.
- No out-of-zone CO_2 detected or significant CO_2 produced.



Injection pump skid with CO_2 supply tanker in the background, Mumford Hills EOR II site.

Solar-powered data collection system, Mumford Hills EOR II site.

CO_2 injection well at the Sugar Creek EOR III site.

Production well, Sugar Creek EOR III site.

CO_2 injection skid and storage tank at the Tanquary coal test site.

Sugar Creek Field – Enhanced Oil Recovery

In early Summer 2009, CO_2 injection started at the EOR III site in the Sugar Creek field in Hopkins County, Kentucky. The subsurface pressure and temperature are suitable for a high-pressure, immiscible CO_2 flood using an existing water injection well. The reservoir is located at a depth of 1,850 feet and consists of fine-grained sandstone packages interbedded with shales. Carbon dioxide injection was completed in Summer 2010, and monitoring of water injection and MVA will be ongoing from Fall 2010 through Summer 2011.

Project highlights:

- Injected 6,600 metric tons (7,270 tons) of CO_2 in a Mississippian sandstone in a single injector over a 1-year period.
- Immiscible CO_2 flood, increased cumulative oil production by 1,000 bbl of oil.
- 12 months of water injection following the CO_2 injection will be monitored through mid-Summer 2011.

Tanquary Site – Coalbed Methane

The CBM project involved drilling four new wells into the Springfield coal seam at a depth of 900 feet in the western part of Wabash County, Illinois. Two wells were drilled in Fall 2007 and two in Spring 2008. During the Summer 2008, CO_2 injection began and lasted through early January 2009.

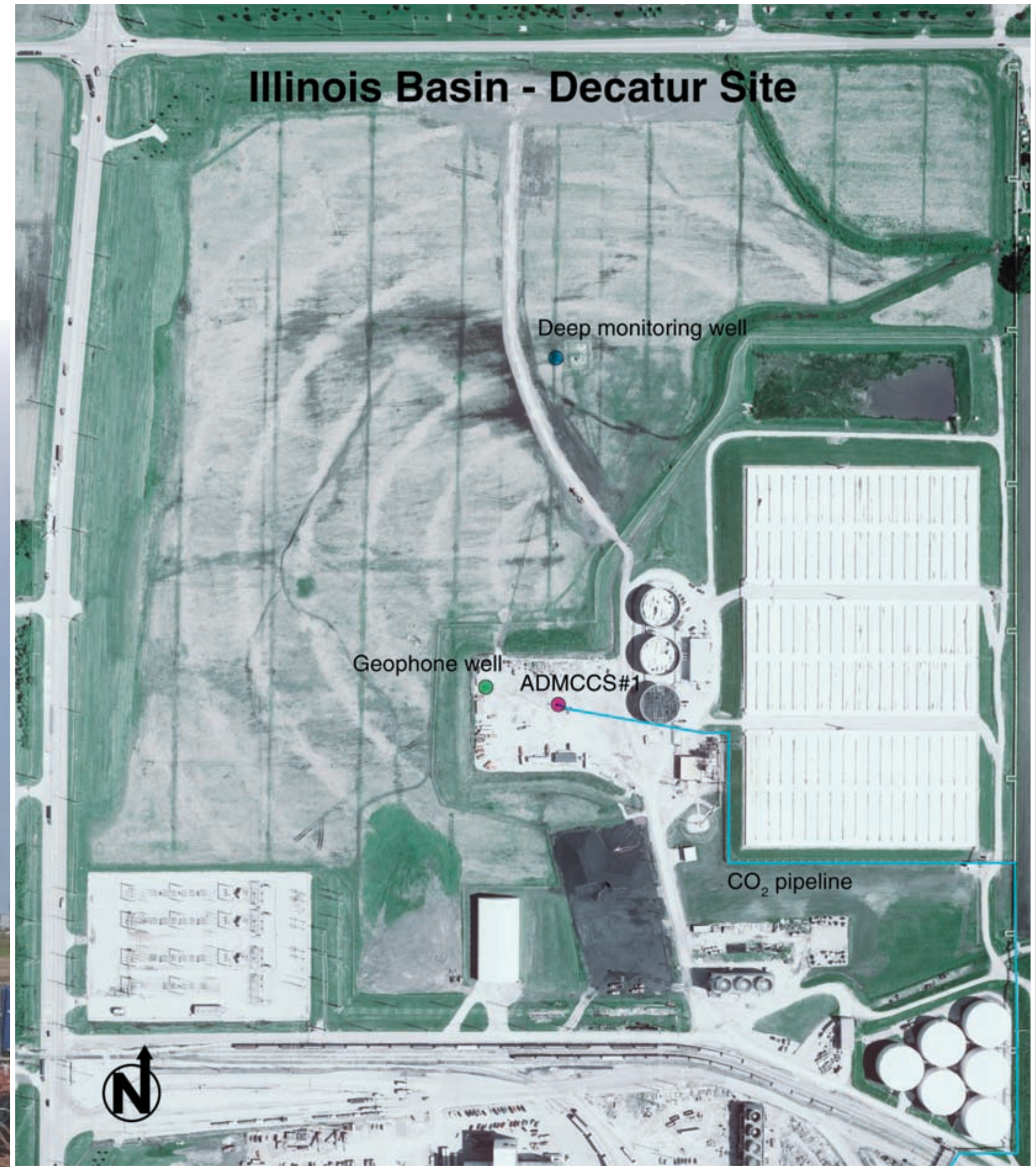
Project highlights:

- Injected 91 metric tons (100 tons) of CO_2 in a 7-foot coal seam at a depth of 900 feet over approximately 6 months.
- Desorbed methane gas measured at monitoring wells, indicating potential of ECBM in Illinois Basin coals.
- Post-CO_2 water pressure transient tests planned through Fall 2010 to identify changes in permeability due to CO_2.
- No out-of-zone CO_2 detected or significant CO_2 produced.

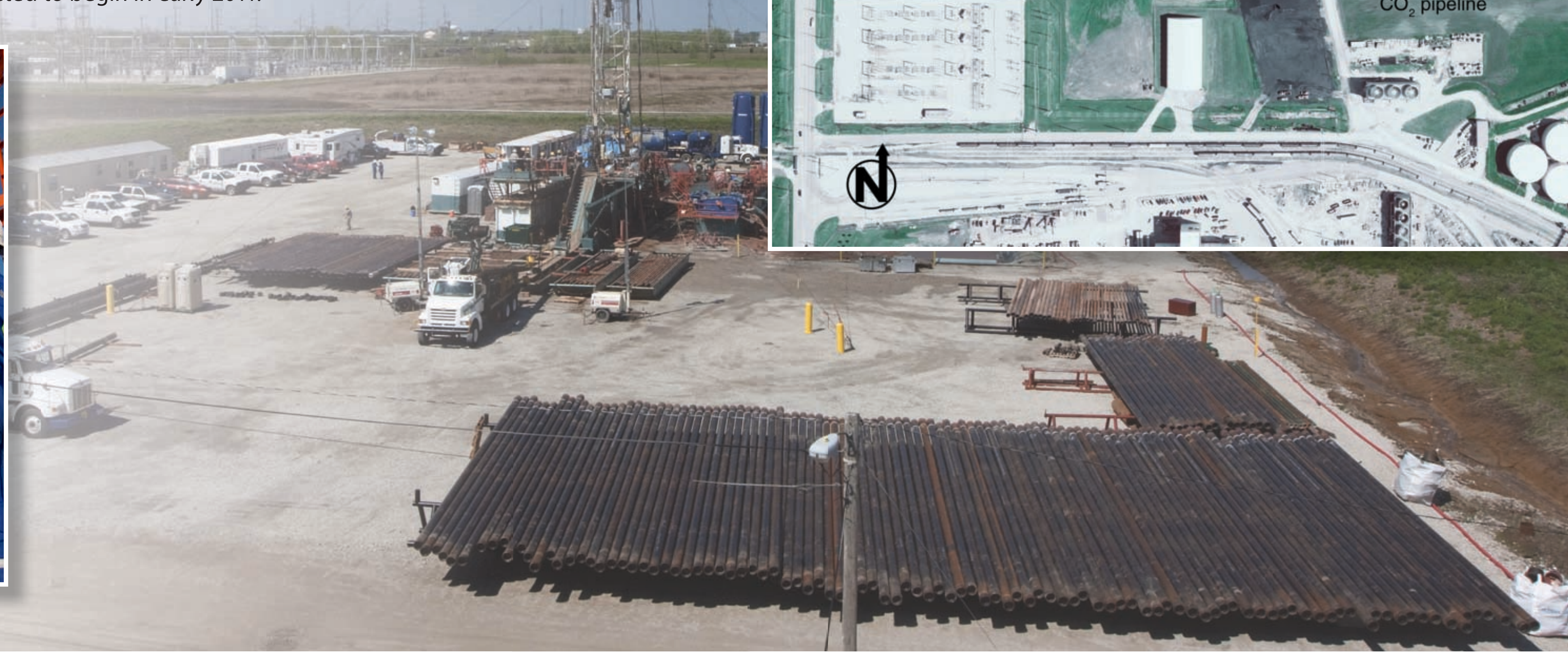
MGSC Development Phase Demonstration Project

The MGSC has partnered with Archer Daniels Midland Company (ADM) and Schlumberger Carbon Services to conduct a large-scale deployment of geologic storage of 1 million metric tons (1.1 million tons) of CO_2 over 3 years. This large-scale injection will occur at the ADM plant site in Decatur, Illinois, into the Mt. Simon Sandstone saline formation, one of the most significant potential carbon storage resources in the United States, at a depth of 2,135 meters (7,000 feet). A comprehensive MVA program, including shallow groundwater, soil gas, resistivity, and atmospheric monitoring was started in March 2008 and continued with the completion of four regulatory shallow groundwater monitoring wells in mid-2010. The final Underground Injection Control permit was received in January 2009. Drilling of the 2,200-meter (7,230-feet) well commenced in February 2009 and was completed in May 2009. A groundbreaking event hosted in April 2009 brought more than 200 visitors to the site. A geophysical well was drilled and completed in September 2009. This 975-meter (3,200-feet) well has geophones cemented in place for enhanced seismic data acquisition during repeat walk-away vertical seismic profiles planned throughout the project. A 3-D seismic data baseline survey was completed in January 2010. An in-zone monitoring well is planned and will be drilled and completed in Fall 2010 pending permit approval. The compression/dehydration facility is nearing completion and a pipeline to carry CO_2 from the ethanol production facility to the wellhead is completed. Injection of CO_2 is expected to begin in early 2011.

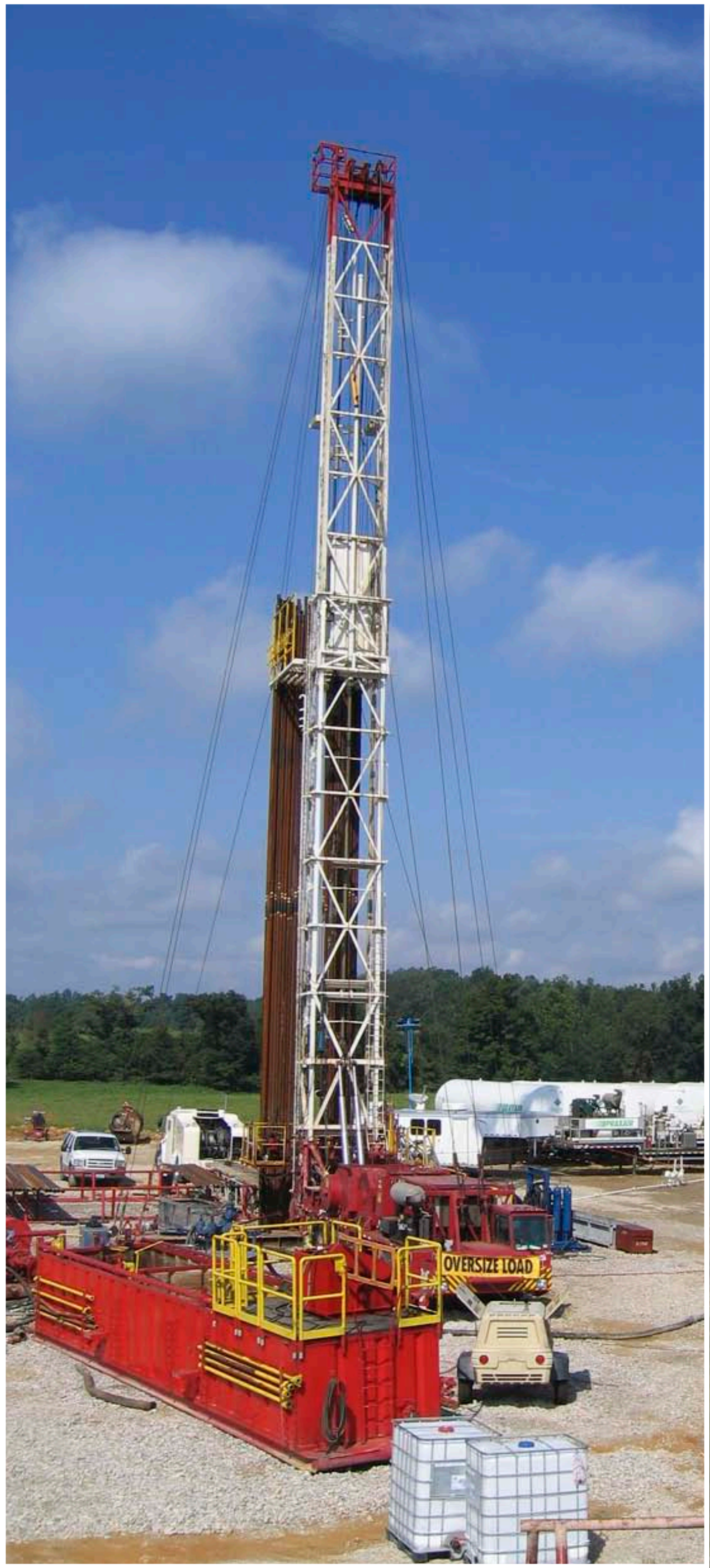
At right: Aerial View of the Illinois Basin—Decatur site.



Installation of injection well passive seismic monitoring system.



Above: Drilling of injection well at the Illinois Basin—Decatur site; long string casing is in the foreground.



MGSC Commercialization Opportunities

The States within the Illinois Basin region are actively considering initiatives that would facilitate deployment of geologic storage. Agencies within the tri-State area are engaged in promoting clean coal technology research and commercialization studies.

Commercial opportunities for storage and coal gasification in concert continue to be researched, including projects such as the Taylorville Energy Center and the ADM Industrial Sources Project. Illinois has completed a CO_2 pipeline feasibility study and is working with other Midwestern States to determine best approaches for moving forward. In addition to the pipeline study, private sector development of a pipeline to transport CO_2 from the Illinois Basin to the Gulf Coast is under consideration. The MGSC and partners continue to engage in storage research and in supplying information to interested commercial parties.

Progress continues on the construction of Duke Energy's IGCC generation facility at Edwardsport, Indiana. This commercial-scale (632-megawatt) facility will use CCS technologies to reduce the emission of some of the approximately 4.5 million metric tons (approximately 5 million tons) of CO_2 to be produced annually. Carbon dioxide will therefore be available for enhanced recovery operations in the region, including potential enhanced gas recovery (EGR) from the New Albany Shale.

In 2007, the Kentucky State Legislature funded a broad program of carbon storage and EOR/EGR projects to demonstrate the potential for storage in the Commonwealth. The Kentucky Consortium for Carbon Storage was formed by the Kentucky Geological Survey to conduct the tests. The first project resulted in the Kentucky Geological Survey No. 1 Blan well in Hancock County, a 2,477-meter (8,126-foot) deep saline injection test of the Knox Supergroup. Several zones in the Knox were identified as principal reservoirs in the well during injection tests. A total of 293 metric tons (323 tons) of supercritical CO_2 was injected at a pump-limited rate of 4.1 barrels per minute.

Erora Group, LLC, is planning to build an IGCC plant in Henderson County, Kentucky. The Cash Creek project will produce natural gas and electricity from gasified coal, and received its final air quality permit in March 2010. Erora plans to sell the CO_2 to Denbury Resources for use in EOR in the Gulf Coast region.

ConocoPhillips and Peabody Energy have announced plans for a coal-to-natural gas plant in Muhlenberg County, Kentucky. The plant, called the Kentucky NewGas Energy Center, will be capable of producing 60 to 70 billion cubic feet of natural gas yearly and will be carbon capture ready. The facility received a draft air permit in late 2009.

Above: CO_2 injection testing in the Blan No. 1 well, Hancock County, Kentucky.

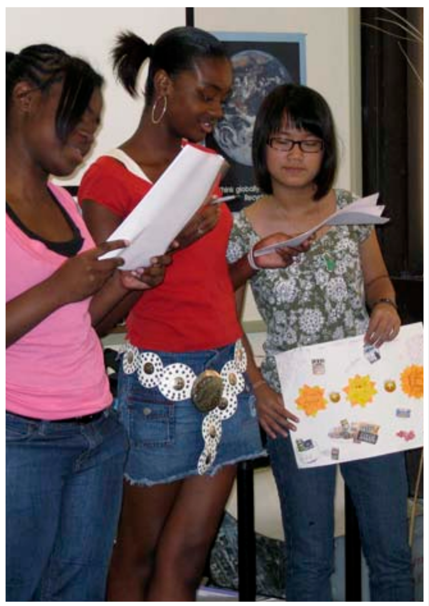
At right: Aerial image of ADM plant, Decatur, Illinois.

Integrating CCS into the MGSC Community

Public outreach and communication has been a priority during Validation Phase and Development Phase activities. In Validation Phase, the MGSC produced project-specific brochures for local landowners. The brochures focused on describing the project and the type of activities landowners could expect to see in the area during the project. Monitoring, verification, and accounting personnel, project management, and field personnel spoke with local officials and landowners to notify them of activities associated with the project and to answer any questions. Site posters describing operations were produced and kept on location for drop-in visitors.

Since the announcement of Development Phase, the MGSC has focused on outreach surrounding the Illinois Basin-Decatur Project. A variety of outreach materials, including fact sheets, posters, presentations, and models, have been utilized to provide information about the project specifics and CCS in general to all major stakeholders in the Decatur area. Decatur, Illinois, is a community of 81,860 people located in central Illinois. The Illinois Basin-Decatur Project is located within 30 miles of the proposed Taylorville Energy Center, an integrated IGCC plant with geologic storage. Central Illinois is developing regional understanding and expertise in the siting and development of CCS projects. A key focus of this effort has been on comprehensive regional outreach and education. By taking a regional approach to CCS outreach, the MGSC has utilized and facilitated collaborations within State government, regional economic development organizations, academic communities, and industrial partners in order to provide factual and informative CCS materials.

The MGSC has engaged the public through a series of invited briefings and public information meetings held in association with the UIC permit process. The public has been informed of the project at multiple events, including public meetings, hearings, and invited landowner briefings. These events provide the public with the opportunity to provide input. Additionally, a series of legislative briefings have been conducted in Washington D.C. over the last 3 years. A teacher education program was developed in Decatur, Illinois, early in Development Phase, and the MGSC has hosted Keystone Workshops for teachers in the tri-state region. The MGSC recently received funding through the Recovery Act to create the Sequestration Training Education Program (STEP). STEP will be conducting workshops, training, and e-learning throughout the region. Outreach is an ongoing process for this project and will continue until project completion.



Students at the CCS Summer Academy, Parkland Community College.

Chinese delegates visit the Illinois Basin—Decatur site.

Presentation of MGSC projects to international visiting scientists.

Demonstration of the carbon dioxide storage physical model.

Midwest Geological Sequestration Consortium Contacts

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Please visit: http://www.sequestration.org.

Midwest Regional Carbon Sequestration Partnership

The Midwest Regional Carbon Sequestration Partnership (MRCSP) was formed to assess the technical potential, economic viability, and public acceptability of carbon storage within its region, which consists of nine neighboring States: Indiana, Kentucky, Maryland, Michigan, New Jersey, New York, Ohio, Pennsylvania, and West Virginia. The MRCSP is led by Battelle Memorial Institute and includes nearly 40 organizations from the research community, energy industry, universities, non-government, and government organizations. The region has a diverse range of CO_2 sources and many opportunities for geologic and terrestrial storage.

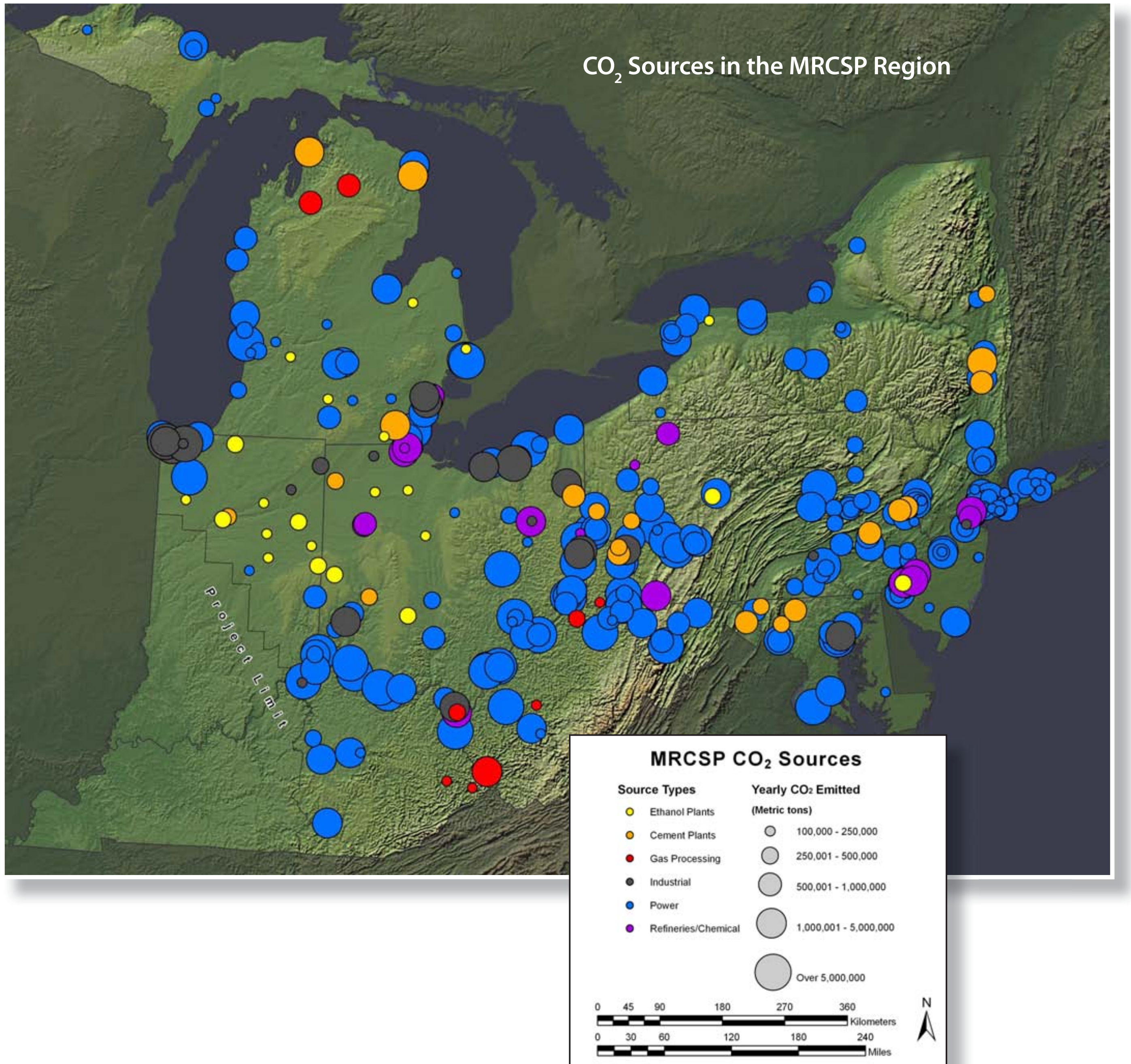
Potential locations for geologic storage in the MRCSP States extend from the deep rock formations in the broad sedimentary basins and arches in the western portion of the region to the offshore continental shelf in the east. Research and testing has established many promising geologic units for CO_2 storage, including deep saline rock formations, depleted oil and gas reservoirs, organic shale layers, and coalbeds. Geological surveys from the nine MRCSP States completed an assessment of the potential for geologic storage that indicates there is resource to permanently contain hundreds of years of CO_2 emissions from the region. Reports, data, and maps generated by the research were integrated into a GIS available for use on the MRCSP website (http://www.mrcsp.org). MRCSP research on terrestrial carbon storage focused on land use types offering the best opportunities for terrestrial storage, including croplands, mine lands, and wetlands. These efforts helped to quantify the resource of the major land use components and to identify land use and management options to enhance storage opportunities in the region.

Michigan Basin field test successfully injected CO_2 into a deep saline formation, concluding in March 2008.

MRCSP
MIDWEST REGIONAL
CARBON SEQUESTRATION
PARTNERSHIP

Geologic test site.

CO_2 pipeline from a gas processing plant in Michigan.



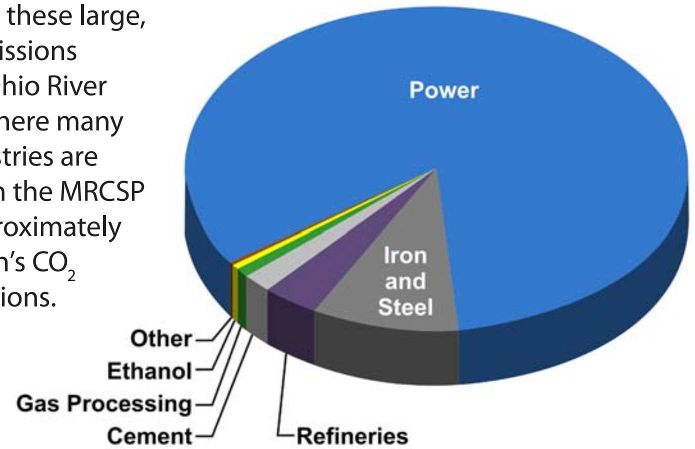
MRCSP CO_2 Sources

A Snapshot of the MRCSP Region:

- Nine States: Indiana, Kentucky, Maryland, Michigan, New Jersey, New York, Ohio, Pennsylvania, and West Virginia.
- Population: 80.4 million (26 percent of U.S. population).
- Gross Regional Product: $3,114 billion (27 percent of U.S. economy).
- 26.3 percent of all electricity generated in the United States.
- 85 percent of the region's CO_2 emissions are related to electricity generation and 75 percent of electricity produced in the region is generated by coal.

CO_2 Sources in the MRCSP Region

Due to its large, diverse economy, the MRCSP region includes a variety of CO_2 sources. While distributed sources, such as agriculture, transportation, and home heating, account for a large portion of CO_2 emissions in the MRCSP region, over half of CO_2 emissions are linked to stationary sources. In total, 699 million metric tons (770 million tons) of CO_2 is emitted each year from these large, fixed point sources. Emissions are highest along the Ohio River Valley and coastlines where many power plants and industries are located. Power plants in the MRCSP region account for approximately 85 percent of the region's CO_2 stationary source emissions.



Stationary CO_2 Source Emissions in the MRCSP Region (million metric tons CO_2 per year)											
Category	MRCSP	MRCSP%	Northeastern Indiana	Eastern Kentucky	Maryland	Michigan	New Jersey	New York	Ohio	Pennsylvania	West Virginia
Power	582	85%	31.2	36.5	30.5	75.3	19.3	50.1	128.4	126.6	84.2
Iron and Steel	67.1	10%	26.3	2.4	4.5	9	0.28	0	17.43	3.2	4
Refineries	23.9	3.50%	3.9	2.1	0	0.71	4.5	0	5.3	7.2	0.11
Cement	14.5	2.10%	0.37	0	1.51	3.5	0	2.4	1.4	4.6	0.83
Gas Processing	5.7	0.80%	0	0.42	0	1.2	0	0	0	0.14	3.9
Ethanol	4	0.60%	1.8	0	0	0.68	0	0.13	1.1	0.28	0
Other	1.5	0.20%	0	0	0	0	0	0	1	0.49	0
Total	**699**	**100**	**63.6**	**41.5**	**36.5**	**90.4**	**24.1**	**52.6**	**154.7**	**142.4**	**93**

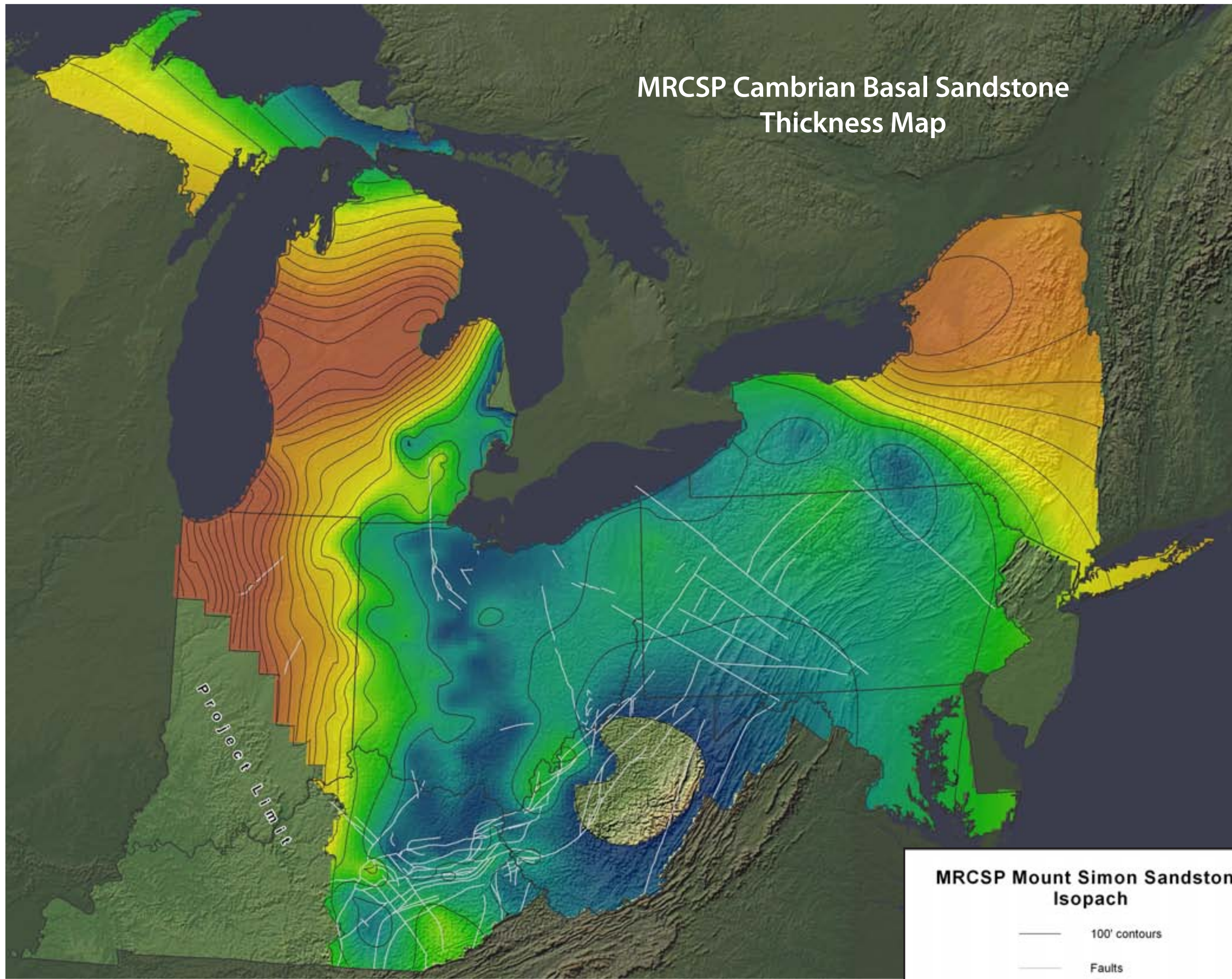
CO_2 storage field tests were completed near several existing point sources in key geologic areas as part of the MRCSP Validation Phase research.

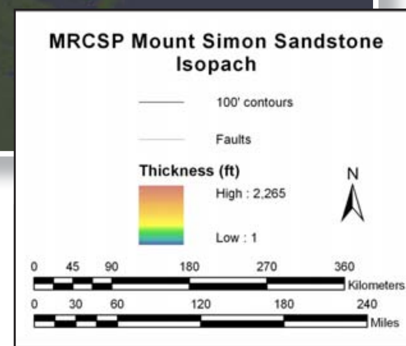
MRCSP Saline Formations

Deep saline rock formations are, by far, the MRCSP region's largest resource for long-term geologic CO_2 storage. The estimated CO_2 storage resource for the region is very large compared to the present-day emissions, enough to accommodate CO_2 emissions from large point sources for hundreds of years. NATCARB research suggests storage resource of 45,700 million to 183,000 million metric tons (50,375 million to 202,000 million tons) within deep saline rock formations in the MRCSP region. Saline formations in the MRCSP region are widespread, close to many large CO_2 sources, and are thought to be suitable for future storage needs. Storage capacity is not evenly distributed across the region.

Thick sequences of sedimentary rocks are present throughout most the western MRCSP States in the form of broad basins and arches. In the eastern States, coastal plain deposits along the continental shelf are potential storage zones. The rocks are saturated with dense brine fluids. In addition, the region is considered a fairly stable geologic setting. The rock formations have been correlated and mapped in the region in stratigraphic charts based primarily on rocks encountered in oil and gas wells. These data were used to characterize geologic storage opportunities in deep saline formations in the MRCSP region.

The storage resource in each reservoir is largely a function of its spatial extent, thickness, and porosity. Given its presence in much of the MRCSP region, the deep saline rock formation with the largest resource in the region is the Mt. Simon Sandstone, followed by the St. Peter Sandstone and the Medina/Tuscarora Sandstone. Other notable storage formations include the Rose Run Sandstone, the Oriskany Sandstone, and the Sylvania Sandstone. Due to the lack of exploratory wells in areas, such as in the deepest portion of the Appalachian Basin in Pennsylvania, some areas of the MRCSP region may have additional storage options, such as porosity zones in the Knox Dolomite. Offshore areas along the East Coast and Great Lakes also contain significant storage resource not included in the assessment. While Michigan has the highest storage potential, all of the MRCSP States have capacity to store large amounts of CO_2 in deep saline formations.



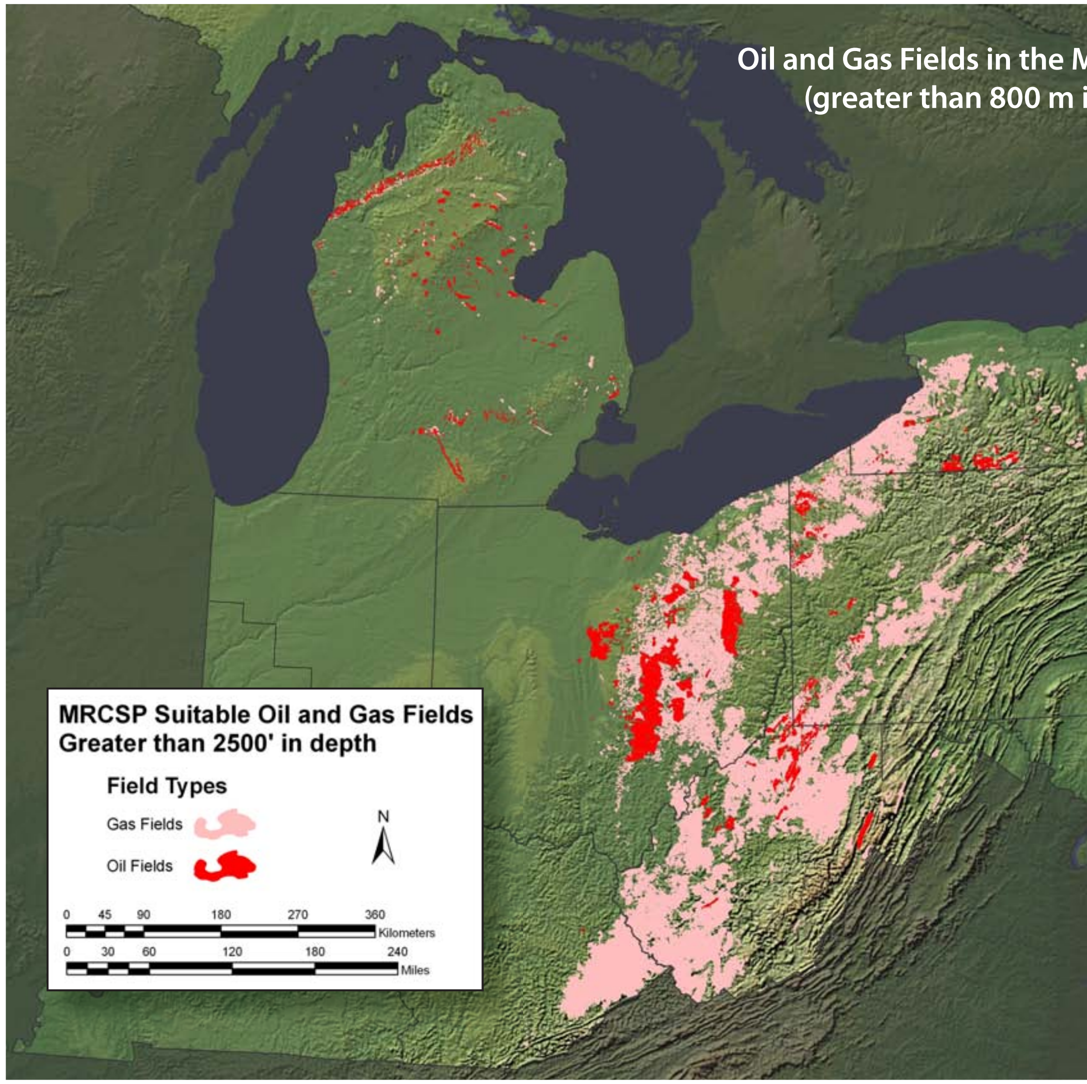


Deep Saline Formation	Potential CO_2 Storage Resource* (million metric tons)		
	Low	Medium	High
Mount Simon Sandstone	16,900	42,200	67,600
St. Peter Sandstone	8,800	22,000	35,200
Rose Run Sandstone	6,100	15,300	24,400
Lockport Group	4,500	11,300	18,100
Medina/Tuscarora Sandstone	4,000	10,000	16,000
Bass Islands Group	1,560	3,900	6,040
Sylvania Sandstone	1,510	3,800	3,500
Oriskany Sandstone	720	1,800	2,880
Dundee Limestone	440	1,100	2,730
Waste Gate	440	1,090	1,760
Conasauga	420	1,060	1,750
Potsdam	210	520	1,700
Rome Trough Sandstones	120	310	830
Total Deep Saline	**45,700**	**114,300**	**183,000**

**Note: New Jersey storage estimates are in progress and not included in this table.*

A core sample of the rock is shown above.

Shown below: MRCSP CO_2 injection testing in the Mt. Simon Sandstone deep saline formation.



Drilling operations at the Ohio CO_2 storage test well in Tuscarawas County, Ohio. Both CO_2 storage units and natural gas were discovered in this well.

MRCSP Oil and Gas Reservoirs

Commercial exploration in the region began in 1859 with the discovery of oil in a shallow well drilled by "Colonel" Edwin Drake in Titusville, Pennsylvania. Since then, the MRCSP region has produced over 5 billion bbl of oil and more than 50 trillion cubic feet of natural gas. In addition, the MRCSP region includes four of the top seven, natural gas storage States in the Nation. Such large volumes of gas storage resource (both natural and engineered) strongly suggest that CO_2 gas can be successfully managed in subsurface reservoirs within the region. There also is potential for value-added production of oil and natural gas associated with CO_2 storage. The oil and gas fields in the region are most concentrated in the Appalachian and Michigan sedimentary basins. NATCARB research suggests that oil and gas fields have a potential storage resource of 16,800 million metric tons (18,500 million tons) of CO_2. Much of this resource is intermixed with deep saline formations. In fact, it may be difficult to differentiate the two in many areas.

Oil and gas reservoirs cover large portions of the Appalachian Basin with significant fields in eastern Ohio, western Pennsylvania, western West Virginia, and eastern Kentucky. Key oil and gas formations in the Appalachian basin include Devonian Shales, "Clinton"/Medina/Tuscarora Sandstones, the Oriskany Sandstone, and the Rose Run Sandstone. Within the Michigan Basin, oil and natural gas reservoirs are concentrated along the Niagaran reef trend and Devonian Antrim Shales in the northwestern margin of the basin and the southern margin of the basin. Enhanced oil recovery has only been applied at few fields in the region. Studies have suggested that a large amount of oil and gas remains in place in many reservoirs. Thus, there is high potential for EOR/EGR associated with CO_2 storage in the MRCSP region.

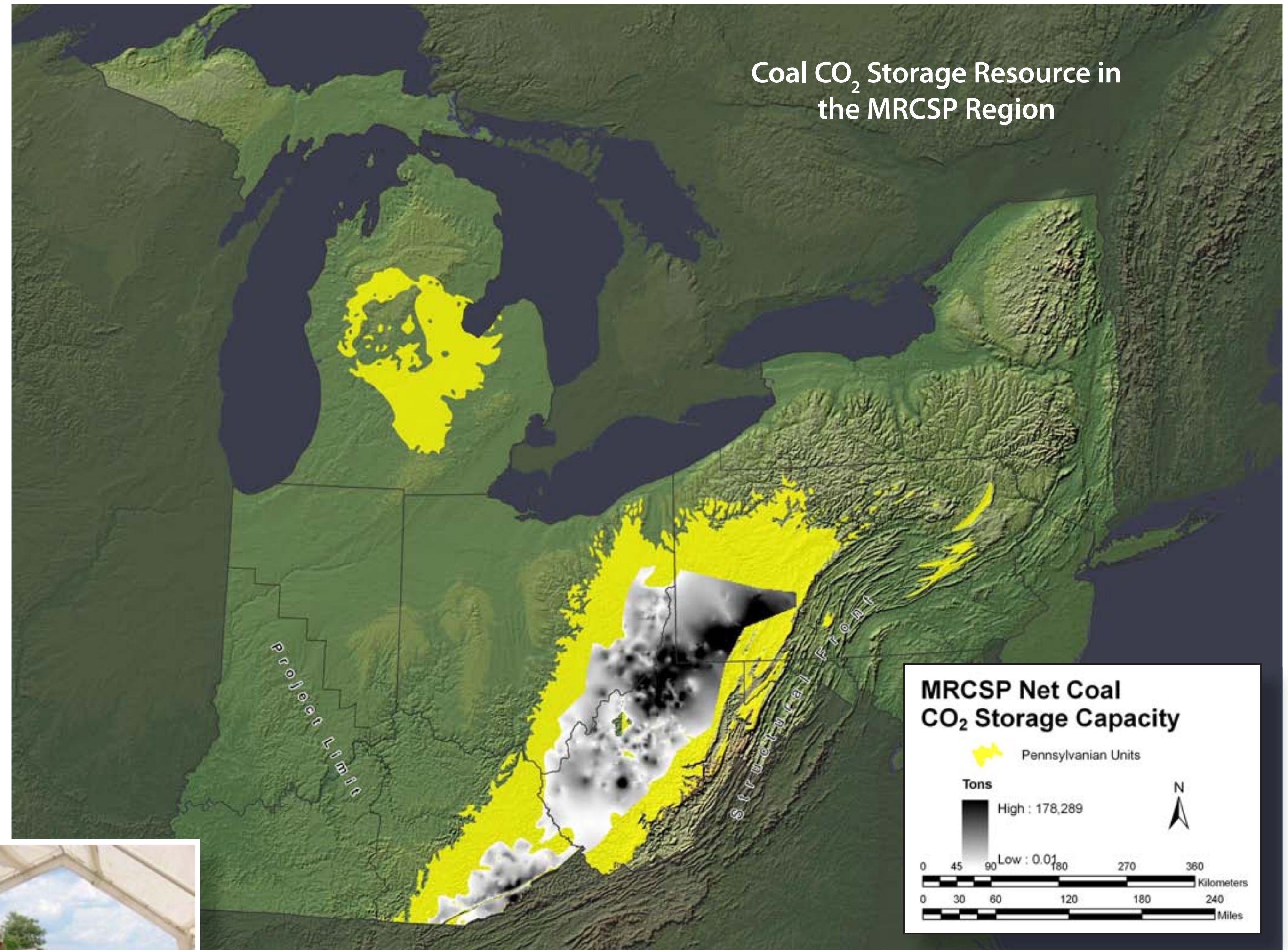
MRCSP Oil and Gas Reservoirs		
State	Number of Fields	Area (acres)
Northeastern Indiana	181	46,062
Eastern Kentucky	69	51,313
Michigan	1,348	3,499,199
New York	106	1,089,152
Ohio	1,807	3,608,518
Pennsylvania	948	1,128,991
West Virginia	232	761,042

EOR operations in Michigan.

MRCSP Unmineable Coal Areas

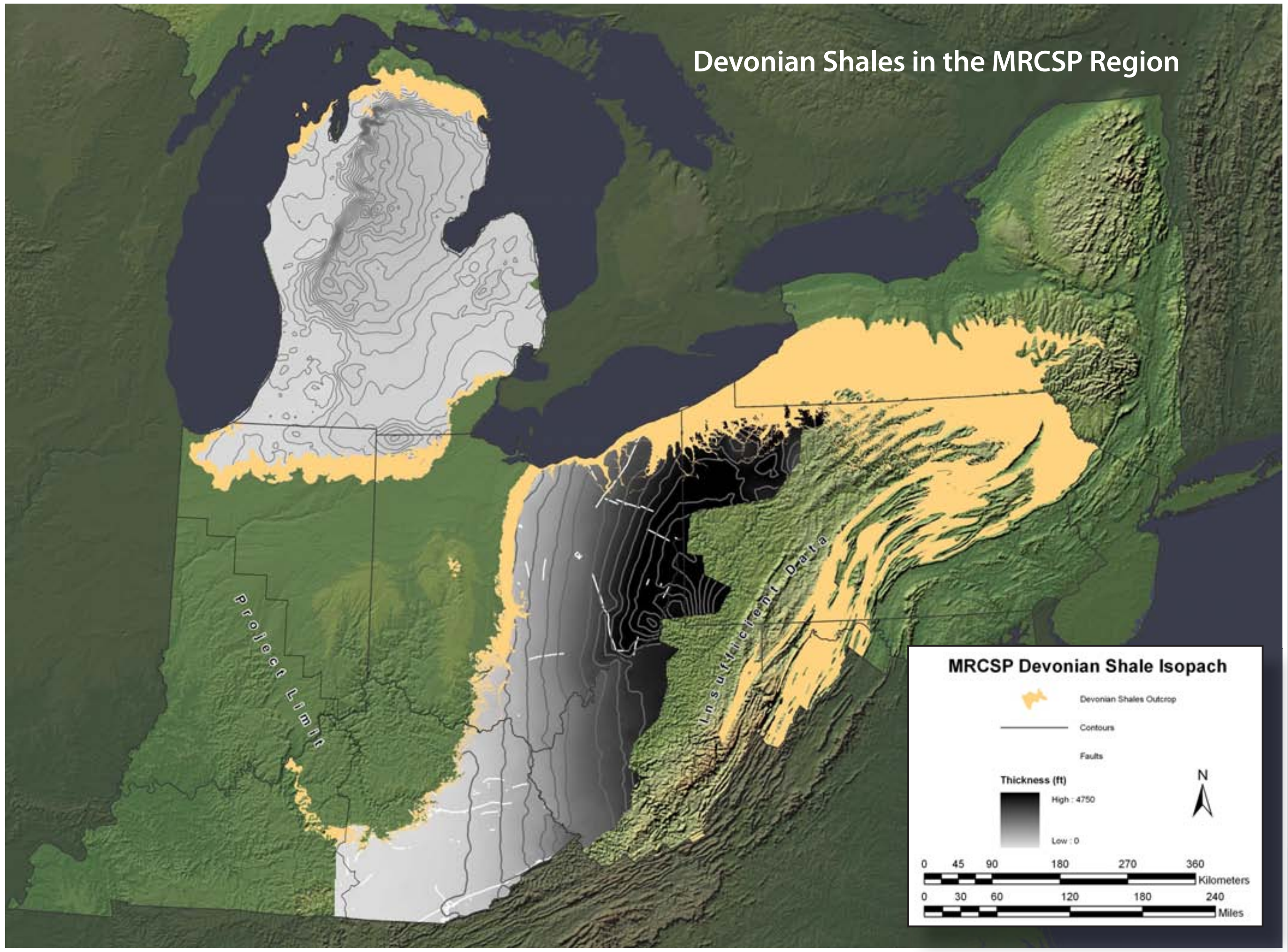
The MRCSP region contains the second- (West Virginia), third- (Kentucky), fourth- (Pennsylvania), and fourteenth- (Ohio) leading coal-producing States in the Nation. Bituminous coal seams are located in the Appalachian and Michigan Basins and anthracite coal seams are located in Pennsylvania. Deep unmineable coal seams in the Appalachian Basin with the highest resource for CO_2 storage are located along the Ohio River Valley in Kentucky, Ohio, Pennsylvania, and West Virginia.

There is also potential for using CO_2 for ECBM recovery in the Appalachian Basin. In the last decade, significant CBM production has occurred in some of these historic 'gassy' coals, particularly in southern West Virginia. CBM is locally produced from at least 24 pools in Pennsylvania, and historic and modern CBM fields occur also in the northern portion of West Virginia. Furthermore, CBM production has been reported in eastern Kentucky, and in Ohio, historic CBM production occurred as early as 1924. Interest in CBM production and exploration is growing in the basin, as well as interest in CO_2 storage potential. As part of the MRCSP Validation Phase program, coal samples were tested from a well in Pennsylvania at depths over 1,000 feet to better define CO_2 storage potential for the region.



MRCSP researchers sampling deep coal seams in Pennsylvania.

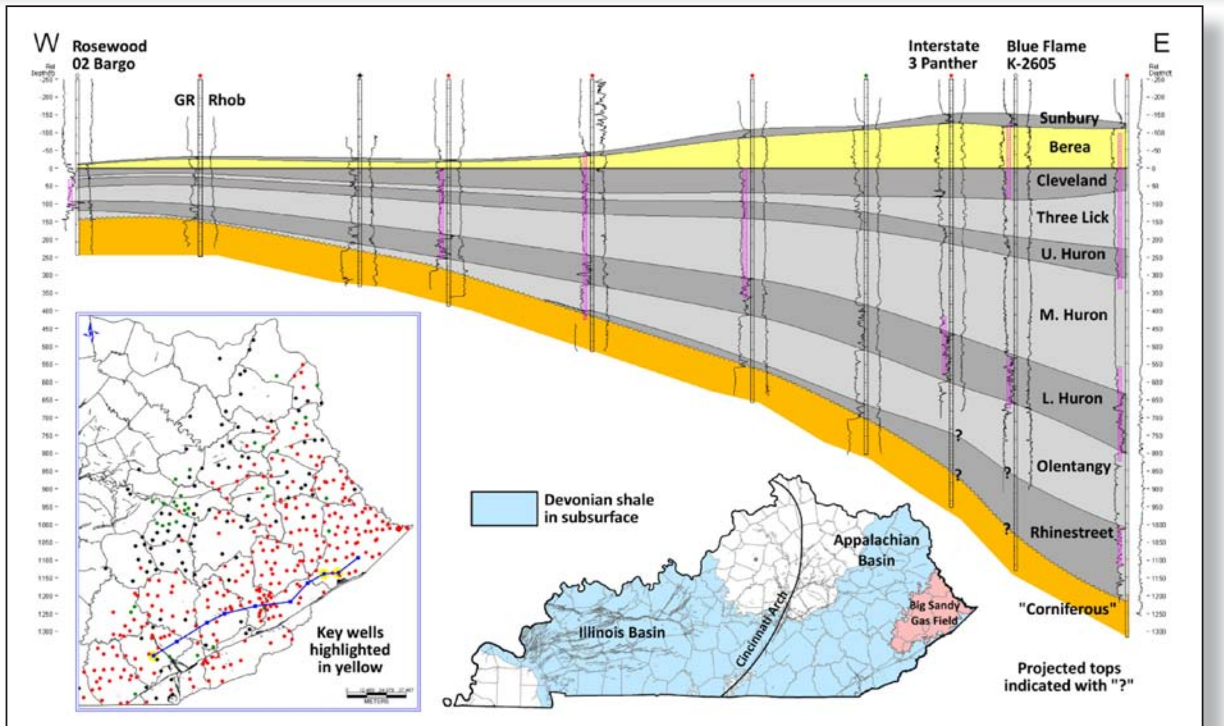
Skyland coalbed in Kentucky.



MRCSP Organic-Rich Shale Basins

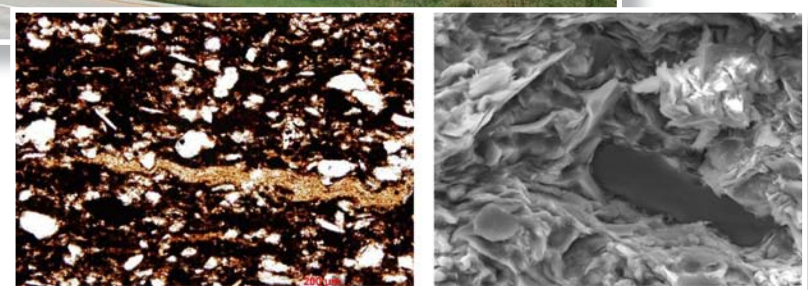
The MRCSP region contains widespread, thick deposits of organic-rich shales. These organic-rich shales are often multifunctional: they act as seals for underlying reservoirs, as source rocks for oil and gas reservoirs, and unconventional gas reservoirs themselves. Analogous to storage in coalbeds, CO_2 injection into unconventional carbonaceous shale reservoirs could be used to enhance existing gas production. As an added feature, it is believed the carbonaceous shales would adsorb the CO_2, permitting long-term CO_2 storage, even at relatively shallow depths.

Organic-rich shales are thickest in Kentucky, Ohio, West Virginia, and portions of Pennsylvania. In addition, shales are present throughout the Michigan Basin. Analysis of these rock formations indicates that they may have the CO_2 storage resource of 2,230 million to 29,680 million metric tons (2,460 million to 32,720 million tons). While laboratory research based on adsorption data from organic-rich gas shales suggests CO_2 storage is possible and may provide a mechanism for EGR, these processes have not been demonstrated with field projects in the MRCSP region.



Geologic cross section showing thickening trend of Devonian shales in eastern Kentucky.

An outcrop of Devonian Ohio shale in eastern Kentucky.



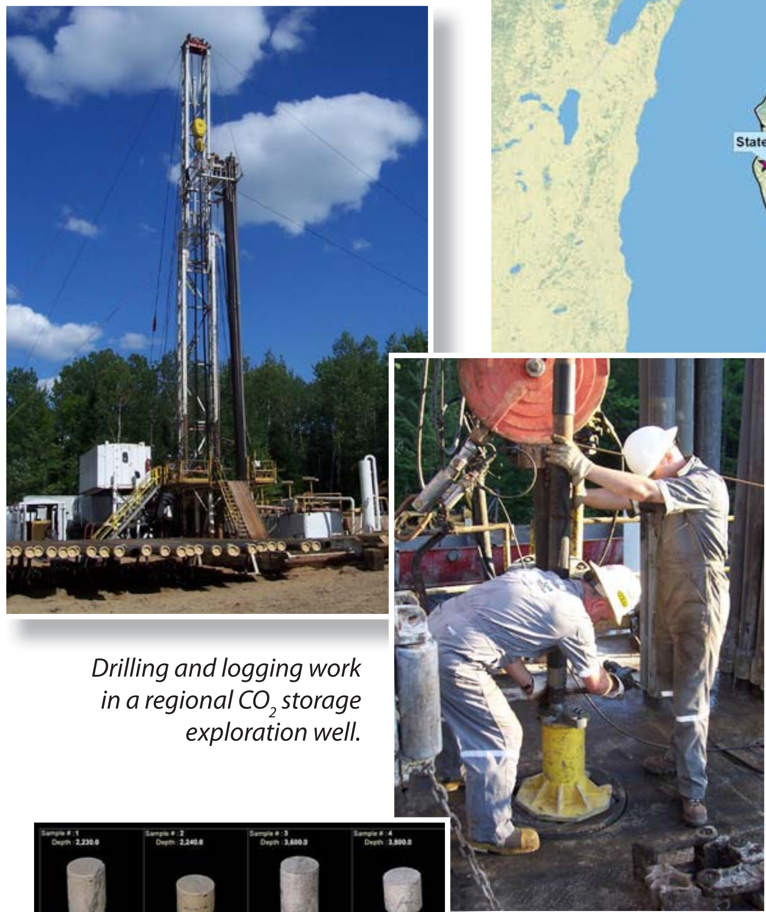
Photomicrograph of shale samples showing organic material.

MRCSP Regional Exploration and Characterization of Geological CO_2 Storage Zones

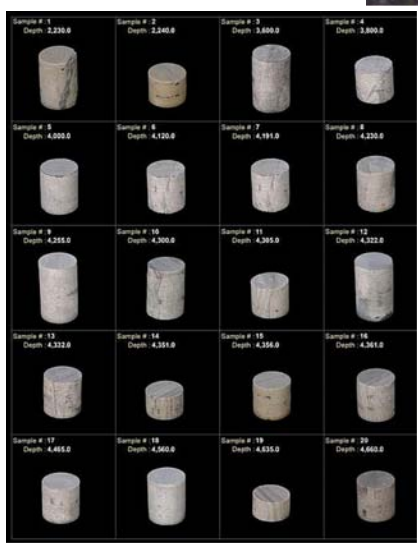
Many of the deep rock formations being considered for CO_2 storage in the MRCSP region are not typically drilled or logged for commercial purposes, because they have no economic value. However, there is opportunity to drill new oil and gas wells deeper and/or complete additional logging and testing to characterize these rock formations at much lower expense than for dedicated test wells. In conjunction with the MRCSP and other DOE-funded research projects, regional oil and gas drilling activities were leveraged by "piggybacking" on new wells and focusing characterization efforts on formations of particular interest for CO_2 storage at depths greater than 3,000 feet.

The overall objectives of this concerted effort were to develop an improved understanding of the geologic formations in the Midwestern United States and, in the process, identify formations of interest for CO_2 storage and determine the geologic patterns in their regional distribution. The emphasis in developing this framework was on obtaining information needed for quantitative assessments of geologic storage potential, such as formation thickness, structural controls, permeability, and porosity data.

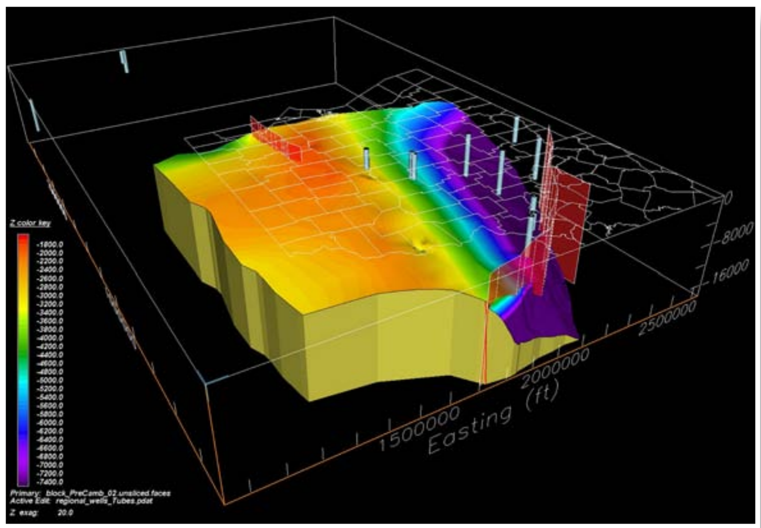
To date, over 20 individual wells have been drilled to deeper depths and characterized, helping to fill critical data gaps in the understanding of deeper regional storage potential. A combination of mud logging, wireline logging, rock core collection, and geotechnical testing was completed on the wells. This regional exploration and characterization work has led to the discovery of unexpected CO_2 storage zones. In fact, some formations that were believed to have little or no injection potential due to insufficient data are now considered real possibilities for CO_2 storage.



Drilling and logging work in a regional CO_2 storage exploration well.

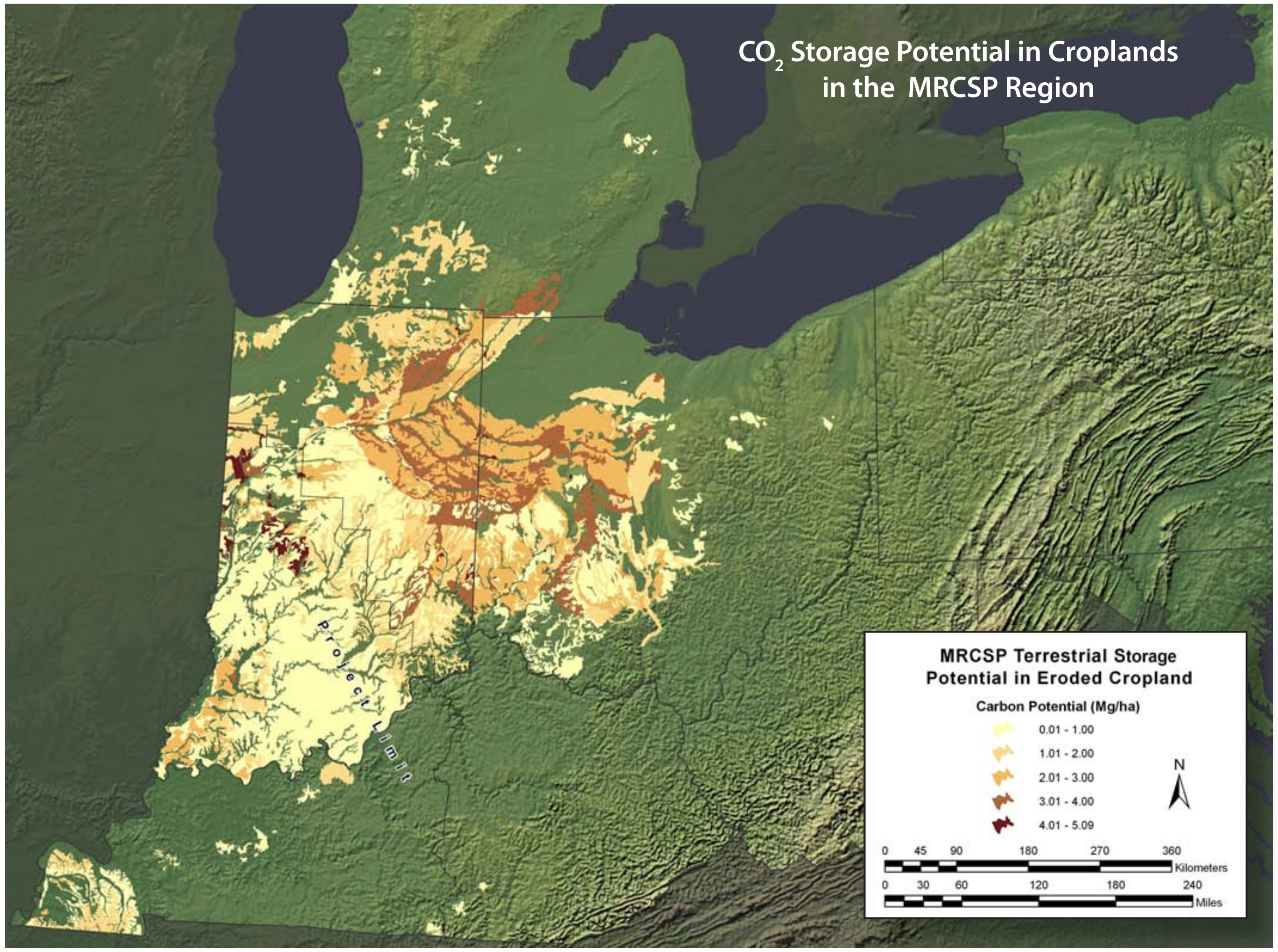


Sidewall rock core plugs sampled from a deep well.



3-D block diagram of deep rock formations and regional 'piggyback' exploration wells.

Geophysical image log of large pore spaces (dark areas) in a deep well that was part of the regional characterization program.



Category	Area (Mha)	Storage Potential (million metric tons CO_2 per year)							
		IN	KY	MD	MI	OH	PA	WV	Total
Cropland	10.7	4.4	1.1	0	3.7	4	0.4	0	**14**
Eroded Cropland	1.6	6.6	0	0	0.7	4	0	0	**11**
Marginal Land (Forest)	6.5	19.5	16.9	3.7	16.2	17.7	17.7	7.7	**99**
Mineland	0.6	0	0.7	0.4	0.7	0.7	1.1	1.8	**6**
Wetland	3.4	2.9	0	1.8	8.8	0.7	0	0	**14**
Total	22.8	33.5	18.8	5.9	30.2	27.2	19.1	9.6	**144**

*Mha = million hectares

MRCSP Terrestrial Research

Terrestrial ecosystems in the MRCSP States offer a viable opportunity for carbon storage because of the extensive farmlands, wetlands, minelands, and forests in the region. There are over 22 million hectares (or 88,000 square miles) of land in the MRCSP region that could be utilized for enhanced carbon storage. Characterization Phase studies on the region (which did not include New Jersey or New York) indicated the potential to store 144 million metric tons (159 million tons) of CO_2 per year in these areas.

- Field tests of carbon storage techniques on agricultural soils and reclaimed minelands were conducted, as there is strong commercial interest in these areas, coupled with the potential for large-scale emissions abatement. Studies also were performed to demonstrate the terrestrial resource of restored tidal marshes. Additional field validation tests are planned to help identify ways to enhance the natural resource of forested wetlands.
- Recent work by Ohio State University demonstrated agriculture management practices to enhance carbon storage, including no-till and conservation tillage; cover cropping; perennial crops; intensive-grazing pasture management; and restoration of marginal farmland back to prairie. Studies consistently showed that large improvements were made with regard to carbon storage when crop residues are used with no-till and conservation tillage practices. An additional benefit observed was the improvement in soil quality and agronomic productivity. Soil carbon storage rates ranged from 0.25 to 1.0 Mg C ha-1 yr-1, depending on soil properties and best management practices implemented.
- West Virginia University determined that the rate of soil carbon storage in the near surface for mine lands reclaimed to pasture or grassland ranged between 0 to 3 Mg C ha-1 yr-1. Furthermore, reclaiming mined land to forest increases the amount of carbon stored significantly due to carbon accumulation in aboveground biomass, litter layer, and soils.
- The study on tidal marshland restoration conducted by University of Maryland concluded that the restored and natural marsh at the Blackwater National Wildlife Refuge are storing carbon on the surface at the rate of 3.4 Mg C ha-1 yr-1, which is a conservative estimate because subsurface carbon storage is not included.

Field validation tests will be conducted in restored forested wetlands in New Jersey to quantify carbon stores and carbon flux rates.

Reclaimed mineland, New Hill, West Virginia.

Tidal marsh study, Blackwater National Wildlife Refuge, Maryland.

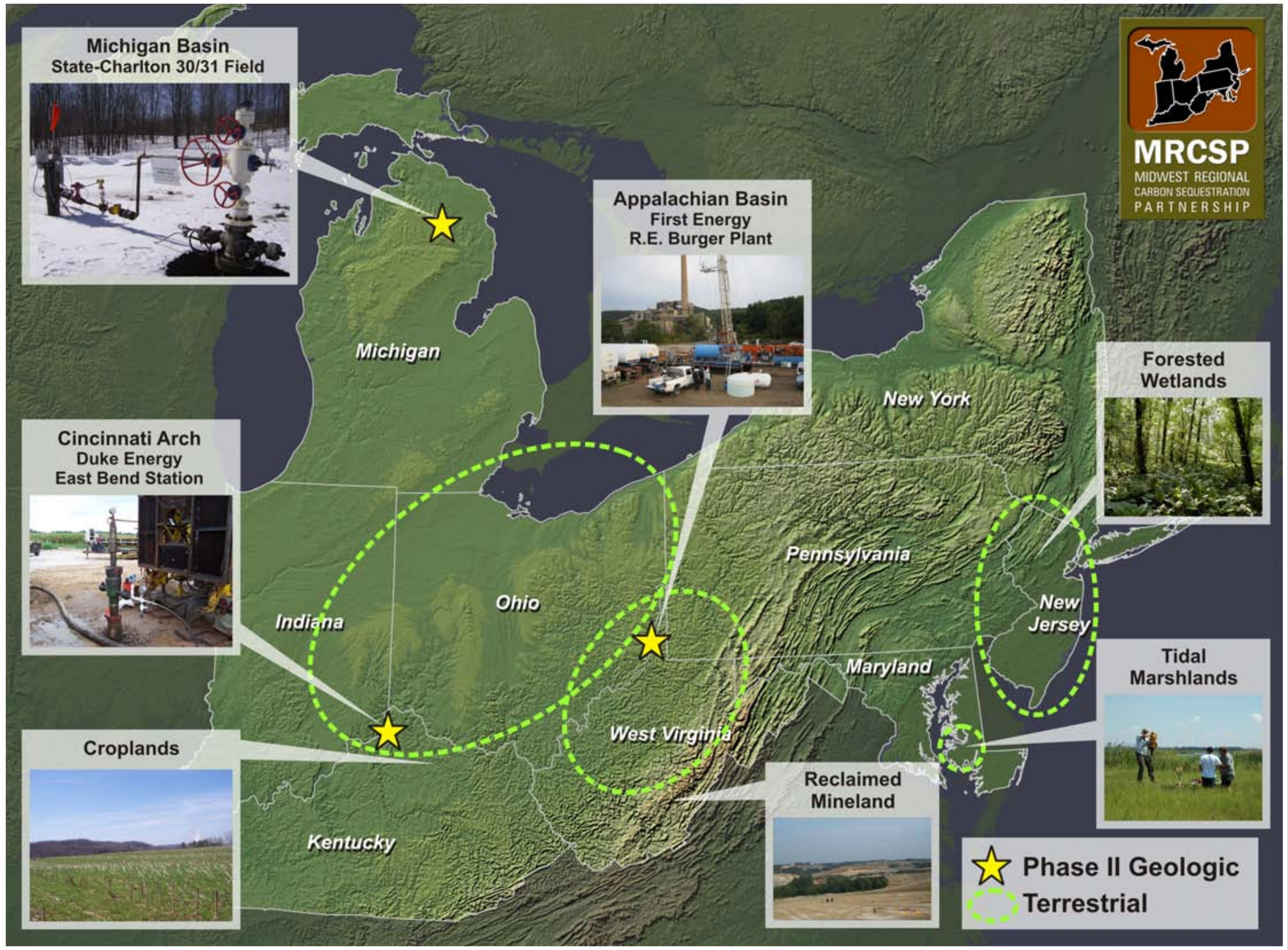
MRCSP Validation Phase Field Tests

Characterization Phase of MRCSP research characterized carbon storage opportunities in the region. Validation Phase efforts included validation of initial efforts with field testing. Three terrestrial and three geologic field tests were completed to demonstrate the safety and effectiveness of carbon storage. The field tests provide significant results for the entire region and better define the technical and economic aspects of CCS.

Terrestrial storage field tests included croplands, reclaimed mine lands, and wetlands. The objective of these tests was to measure the potential increase in carbon storage with different farming and land use practices. The field work was designed to quantify the carbon storage possible in these environments.

Geologic tests took place along distinct, regional geologic features within the MRCSP region:

Regional Geologic Feature	Host Site Location
Michigan Basin	Core Energy State—Charlton 30/31 Field, Otsego Co., Michigan
Cincinnati Arch	Duke Energy East Bend Generating Station, Rabbit Hash, Kentucky
Appalachian Basin	FirstEnergy R.E. Burger Plant, Shadyside, Ohio



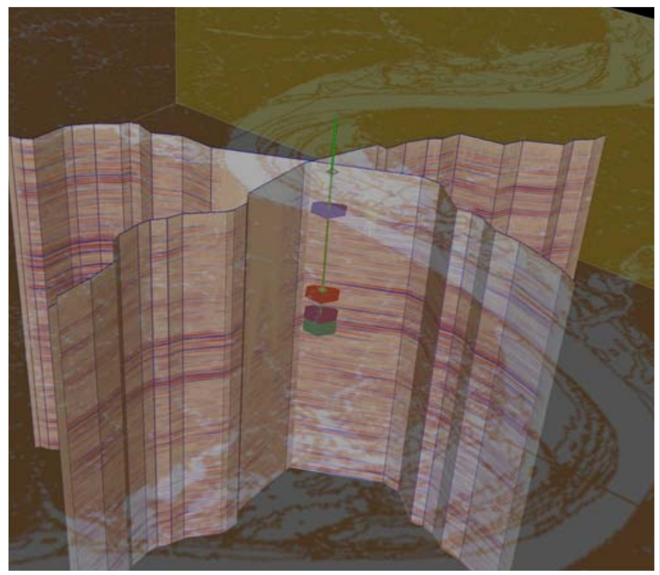
Members of the MRCSP research team injected CO_2 into deep saline formations located thousands of feet below the surface. Each geologic field test involved a network of monitoring devices and techniques to monitor the injection, delineate the movement of CO_2 in the formation, and confirm that the injection proceeded as planned.

The Michigan Basin test demonstrated industrial-scale CO_2 storage potential in the Bass Islands Dolomite. Injection rates of 600 metric tons per day were sustained. The test results should be applicable to other parts of the Michigan Basin, which is an attractive target in the region. A fairly significant volume of CO_2 (approximately 60,000 metric tons [61,100 tons]) was injected, utilizing CO_2 from the nearby gas processing plant.

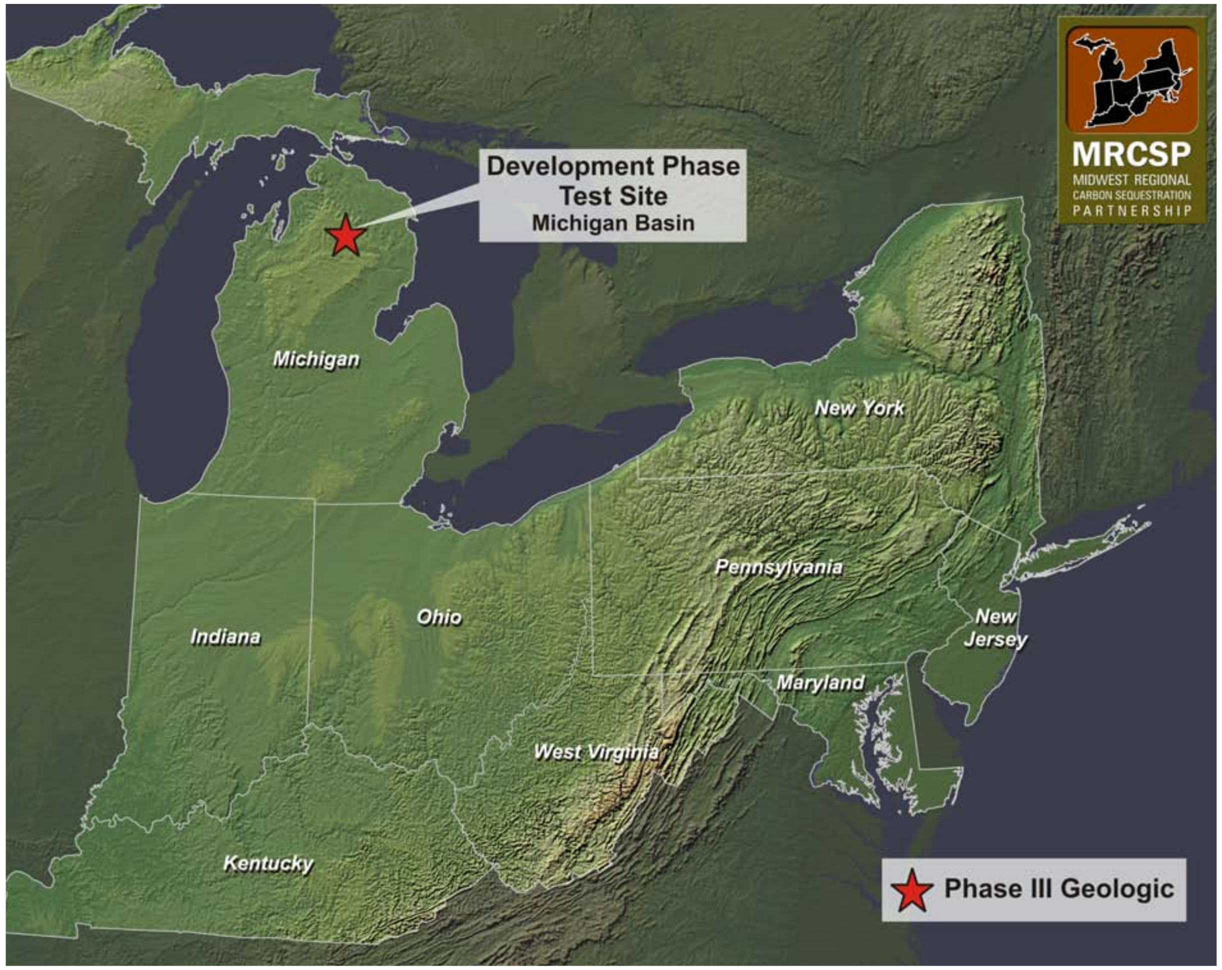
One thousand metric tons of CO_2 were injected at the Duke Energy East Bend Generating Station. The primary research objective was to demonstrate CO_2 storage in the Mt. Simon Sandstone, a major CO_2 storage target for the region (and the United States). The test was aimed at better understanding regional trends (i.e., permeability, porosity, geochemistry, and mineralogy) and CO_2 injection testing in the Mt. Simon Sandstone.

The R.E. Burger Plant was chosen as a Validation Phase small-scale validation test site because of its central location to one of the Nation's major power generation corridors, the Ohio River Valley, and because it was expected to provide access to geologic formations having significant expected storage resource across the region. Specific geologic formations that were assessed include the Oriskany Sandstone, the Salina Formation, and the Clinton Formation, which are located from 5,900 to 8,300 feet below the surface. Although less than 50 metric tons (55 tons) was injected, the test results will help to develop best practices and better understand the regional geology for its storage potential.

In addition, research is taking place to develop a regulatory framework for storage, characterize additional geologic targets, and evaluate carbon capture technologies suitable for sources in the region. A piggyback drilling program was conducted at a site in Tuscarawas County, where a deep test well was installed to build knowledge of the regional geology.



Processed image of 2-D seismic survey transects. Color discs correspond to the top surface of major geologic formations.



MRCSP Development Phase Field Tests

The MRCSP Development Phase field test continues to consider the successful use and application of carbon storage technology as part of a regional strategy to reduce the amount of CO_2 that is emitted into the atmosphere. Carbon storage in conjunction with natural gas processing is a near-term option for CO_2 injection projects.

MRCSP members, including the Michigan Geological Repository for Research and Education at Western Michigan University, have concluded that there is significant storage resource in Michigan. The presence of oil and gas demonstrate that capping formations are in place and effective. In addition to the State's natural resources, Michigan has proven experience with EOR and natural gas storage technology.

The primary proposed site for the MRCSP's large-scale, saline injection test is located on a State-owned land management area in Otsego County, Michigan, approximately 10 miles south of the successful Validation Phase demonstration. The Development Phase site lies within 1 mile of a gas processing and compression facility, which is the CO_2 source for the test. The facility currently produces 640 metric tons (750 tons) per day of high purity CO_2, which is removed from the natural gas produced from Antrim shales in the area. During the test, a total of 1 million metric tons (1.1 million tons) of CO_2 would be injected into the St. Peter Sandstone over a 4-year period. The St. Peter formation is second only to the Mt. Simon Sandstone as a regional resource for CO_2 storage. As such, the Development Phase field test would better define the feasibility of CO_2 storage in much of the MRCSP region. A secondary storage formation could be the Bass Island Dolomite, which was the same formation used in the Validation Phase geologic field test.

Artist's rendering of potential Development Phase site.

Integrating CCS into the MRCSP Community

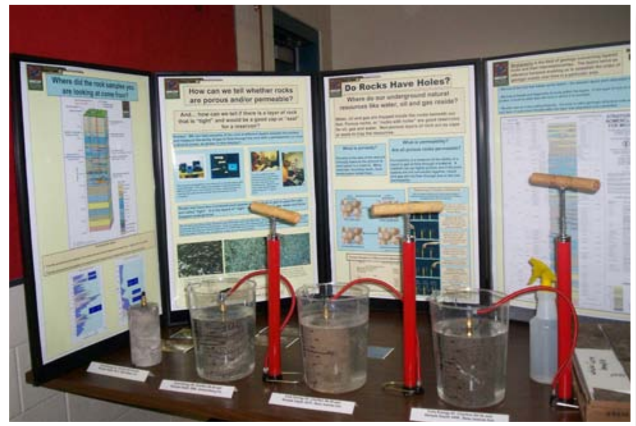
The MRCSP outreach program was designed to build a foundation of public awareness for carbon storage. The MRCSP approach relied on insight from social science literature involving the role of values and perceptions in developing opinions about a new technology, as well as principles of good science communication. Surveys in the United States and abroad provided empirical data about factors affecting public acceptance of carbon storage.

A stakeholder outreach effort to communicate project progress to the local community, general public, and scientific community was undertaken with each field test in Ohio, Kentucky, and Michigan. This effort involved identification of stakeholders, proactive engagement with these stakeholders, and development of informational materials. An outreach team including members from each host site was established to develop a site-specific strategy and outreach plan for key stages of the project. The team members provided diverse perspectives upon which the project could draw—technical understanding of planned activities, invaluable knowledge about local culture and politics, and experience for effectively communicating with local residents.

The outreach team provided contact points in the local area and project-related information on the MRCSP website. The host sites held informational meetings for nearby residents, including a series of exhibits and take-home materials, as well as opportunities for one-on-one discussions with technical staff. Other activities included facility tours for RCSP members and media interactions. All three of the Validation Phase geologic storage field tests were completed successfully in terms of relations with the industrial hosts, outreach to the local communities, permitting, and test logistics.

Tour stop at the DTE gas processing plant during a MRCSP Partners Meeting, Michigan.

Open house for neighbors at the East Bend Electricity Generating Station in Kentucky.



Hands-on display developed by Western Michigan University to communicate key geologic concepts.

Presentation provided to employees at the R.E. Burger plant in Ohio.

Midwest Regional Carbon Sequestration Partnership Contacts

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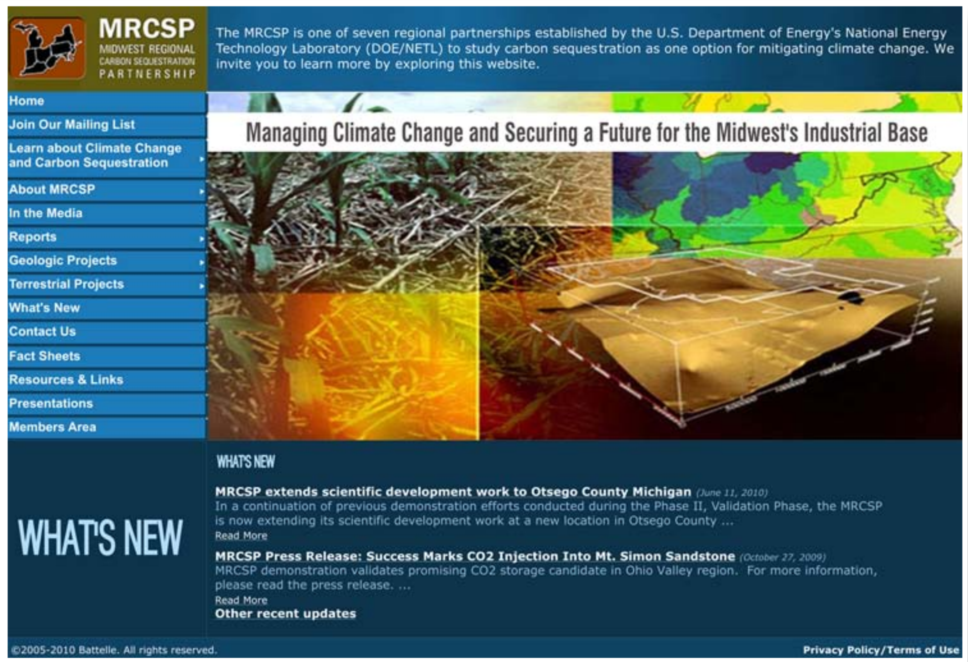


Please visit: http://www.mrcsp.org.

Plains CO_2 Reduction Partnership

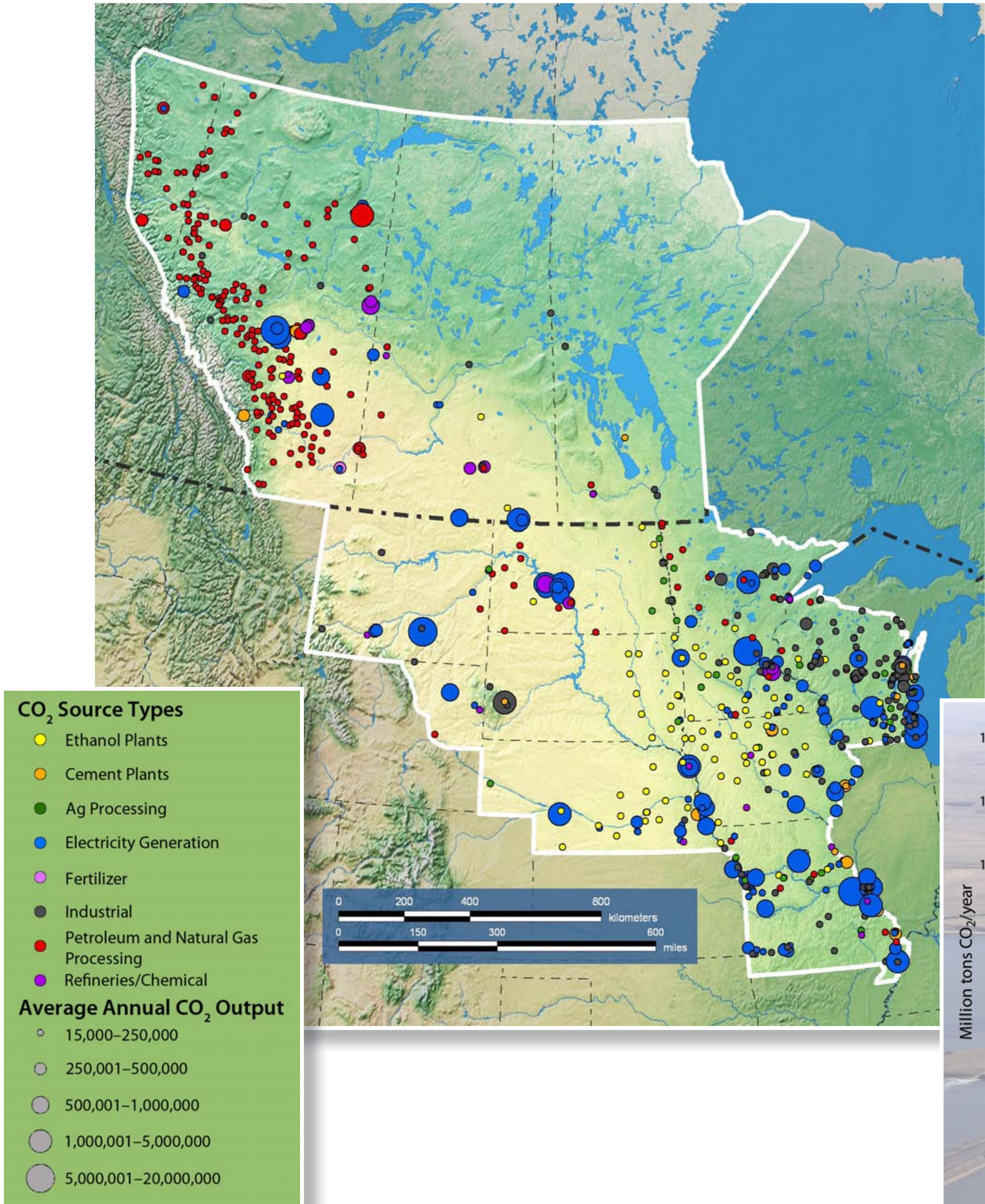
The Plains CO_2 Reduction (PCOR) Partnership is investigating and demonstrating various storage technologies to provide a safe, effective, and efficient means of managing CO_2 emissions across central North America.

Regional characterization activities conducted by the PCOR Partnership confirmed that while numerous large stationary CO_2 sources are present, the region also has tremendous potential for CO_2 storage. The varying natures of the sources and storage sites reflect the geographic and socioeconomic diversity across this nearly 3.6 million km^2 (1.4 million mi^2) area of central North America.

Geologic formations deep beneath the surface of the region hold tremendous potential to store CO_2. Oil fields, already considered to be capable of storing CO_2, can be found in roughly half the region, while formations of limestone, sandstone, and coal suitable for CO_2 storage exist in basins that, in some cases, extend over thousands of square miles. In many cases, large sources in the region are proximally located to large-volume storage sites, some with key infrastructure already in place.

The PCOR Partnership region is also rich in agricultural lands that hold tremendous potential for terrestrial storage. The Prairie Pothole region that stretches from northwestern Iowa, across the Dakotas, and into Saskatchewan and Alberta holds promise as an area that can provide additional and significant terrestrial CO_2 storage opportunity.

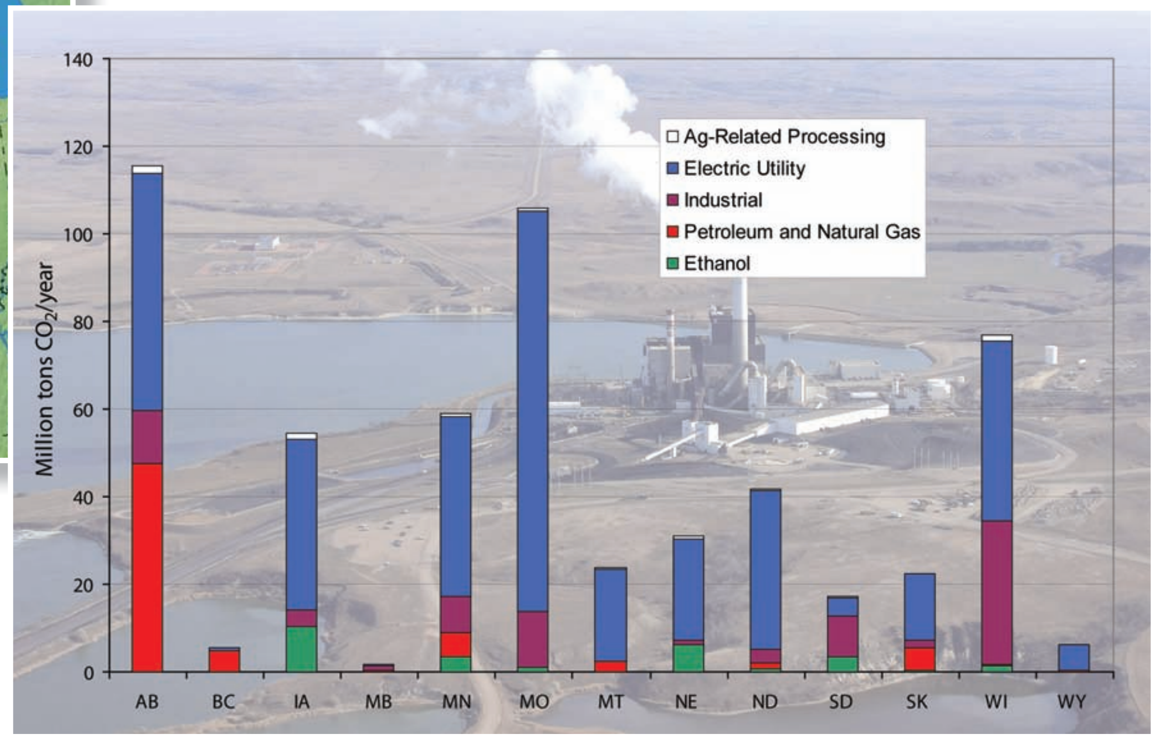
Since its inception in 2003, the PCOR Partnership has included the support of approximately 100 public- and private-sector stakeholders from the central interior of North America and adjacent areas that have expertise in power generation; oil and gas exploration; and production, geology, engineering, the environment, agriculture, forestry, and economics. These partners are the backbone of the PCOR Partnership and provide data, guidance, and practical experience with the various facets of geologic and terrestrial storage of CO_2.



PCOR Partnership CO_2 Sources

The PCOR Partnership project has identified, quantified, and categorized 927 stationary sources in the region that have an annual output of greater than 13,600 metric tons (15,000 tons) of CO_2. These stationary sources have a combined annual CO_2 output of nearly 510 million metric tons (562 million tons) or 9.7 trillion cubic feet. Although not a target source of CO_2 for geologic storage, the transportation sector in the U.S. portion of the PCOR Partnership region contributes an additional 171 million metric tons (188 million tons) of CO_2 to the atmosphere annually.

The annual output from the various stationary sources ranges from 9.1 million to 16.3 million metric tons (10 million to 18 million tons) for the larger coal-fired electric generation facilities, to fewer than 91,000 metric tons (100,000 tons) for industrial and agricultural processing facilities that make up the majority of the sources in the region. In some cases, the distribution of the sources with the largest CO_2 output is coincident with the availability of fossil fuel resources, namely, coal, natural gas, and oil. This relationship is significant with respect to geologic storage opportunities. Many of the smaller sources are concentrated around more heavily industrialized metropolitan regions, such as southeastern Minnesota, southeastern Wisconsin, and eastern Missouri.



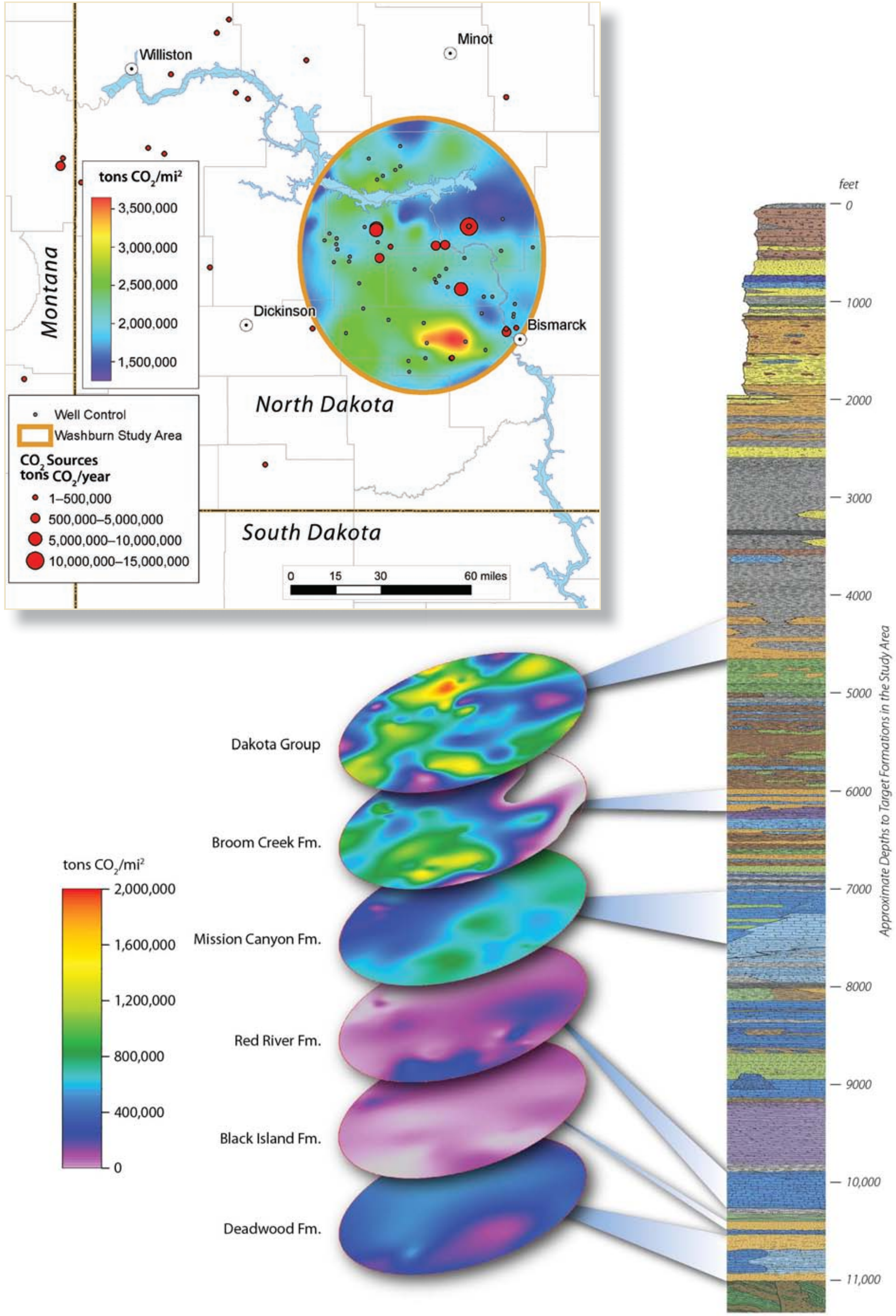
* The data represents only the large stationary sources within the PCOR Partnership extent.

PCOR Partnership Saline Formations

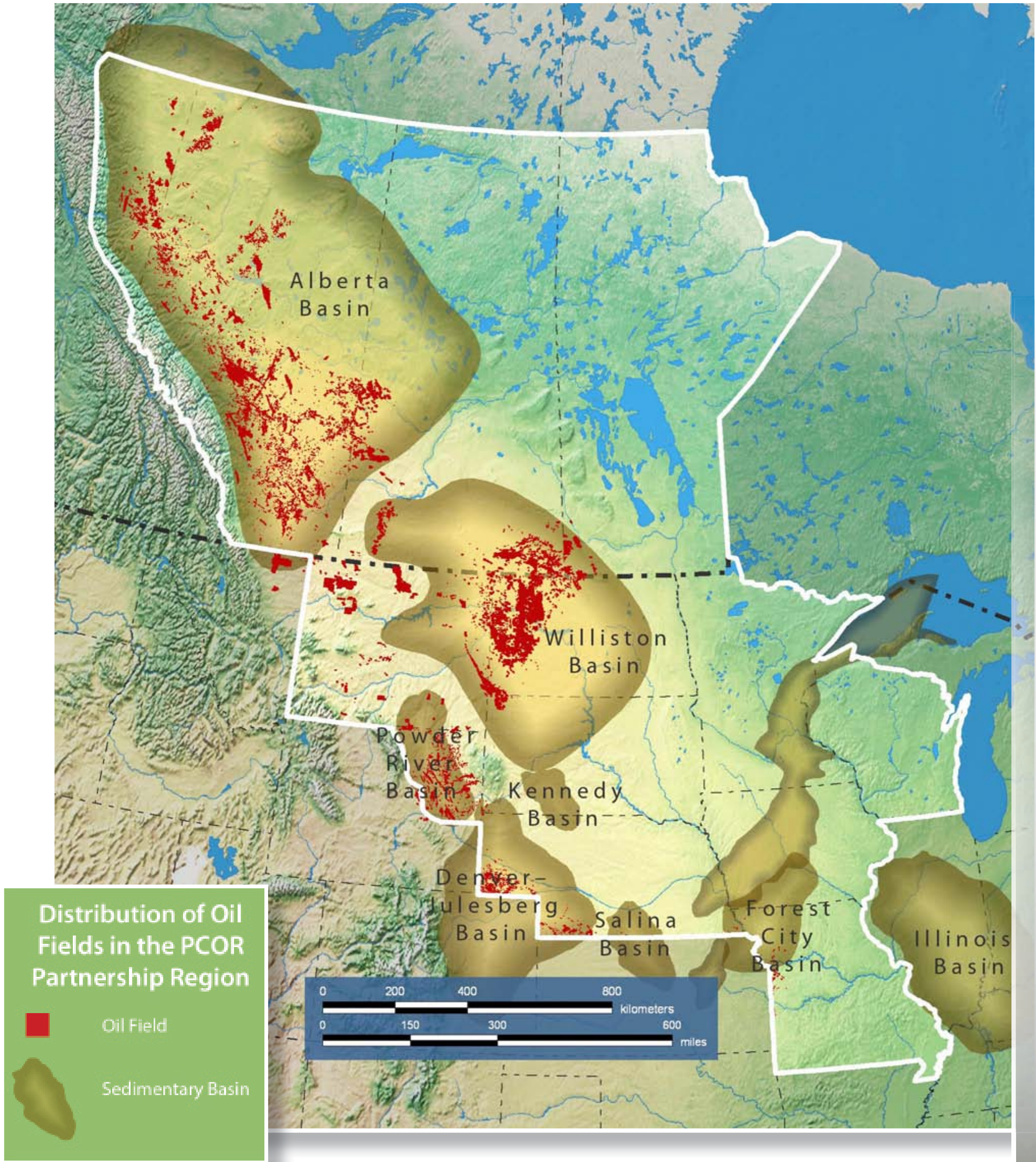
In many sedimentary basins, there may be more than one potential target horizon for CO_2 storage, each with an appropriate seal to ensure safe, long-term storage. A great example of stacked target horizons can be found in the North Dakota portion of the Williston Basin.

As part of ongoing regional characterization efforts, the PCOR Partnership conducted a detailed evaluation of the potential CO_2 storage resource of several stacked brine-saturated formations. This area of investigation encompasses 6,100 mi^2; is underlain by over 9,800 feet of sedimentary rock; and was selected because of its proximity to seven large, coal-fired industrial sources of CO_2.

Publicly available well file information was used to develop petrophysical models that provided the basis for estimating the CO_2 storage resource of 11 potential target injection intervals in seven different formations. The total CO_2 storage resource in the evaluated brine-saturated formations in this area of the Williston Basin is estimated to be about 11.7 billion metric tons (13 billion tons).



Reconnaissance-level estimates indicate that the Mississippian Madison Formation in the Williston Basin could store over 109 billion metric tons (120 billion tons) of CO_2, while two formations in the Lower Cretaceous system in Alberta, Canada, and Nebraska could store upwards of 63.5 billion metric tons (70 billion tons). These saline systems were selected for broad evaluation based on their regional continuity, fluid properties, and readily available data.



Basin	Cumulative Incremental Recovery (million stb)	CO_2 Storage Potential (Bcf)	CO_2 Storage Potential (million tons)
Williston	1023	8186	502
Powder River	381	3049	187
Denver–Julesberg	25	199	12
Alberta	6000	4856	2773

PCOR Partnership Oil and Gas Reservoirs

Oil is drawn from the many oil fields in the PCOR Partnership region from depths ranging from 2,500 to 16,000 feet. Although oil was discovered in this region in the late 1800s, widespread development and exploration did not begin until the late 1940s and early 1950s. The body of knowledge gained in the nearly 70 years of exploration and production of hydrocarbons in this region is a significant step toward understanding the mechanisms for secure storage of significant amounts of CO_2.

Reconnaissance-level CO_2 storage resource was estimated for selected oil fields in the Williston, Powder River, Denver-Julesburg, and Alberta Basins. Two calculation methods were used, depending on the nature of the available reservoir characterization data for each field. The estimates were developed using reservoir characterization data obtained from the petroleum regulatory agencies and/or geological surveys from the oil-producing States and provinces in the PCOR Partnership region. Results of the estimates for the evaluated fields (using a volumetric method) in the four basins indicate a storage resource of over 3.2 billion metric tons (3.5 billion tons) of CO_2.

Absent non-market-based incentives, CO_2 storage in many geologic formations is not generally economically viable under current market conditions. However, EOR miscible flooding is a proven, economically viable technology for CO_2 storage that can provide a bridge to future non-EOR-based geologic storage; that is, a portion of the revenue generated by CO_2-EOR activities can pay for the infrastructure necessary for future geologic storage in saline formations. It is expected that major oil fields subjected to this type of recovery process would retain a significant portion of the injected CO_2 (including the amount recycled during production) as a long-term storage solution.

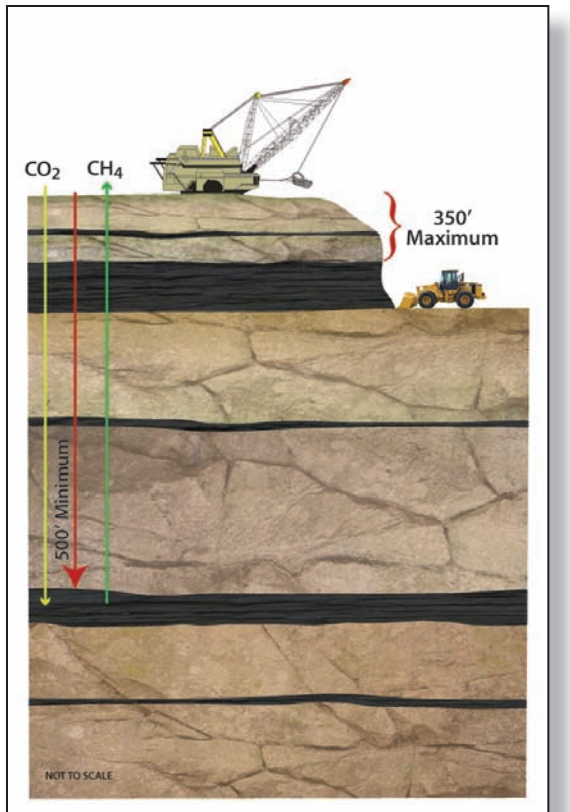
Pump jack in western North Dakota oil field.

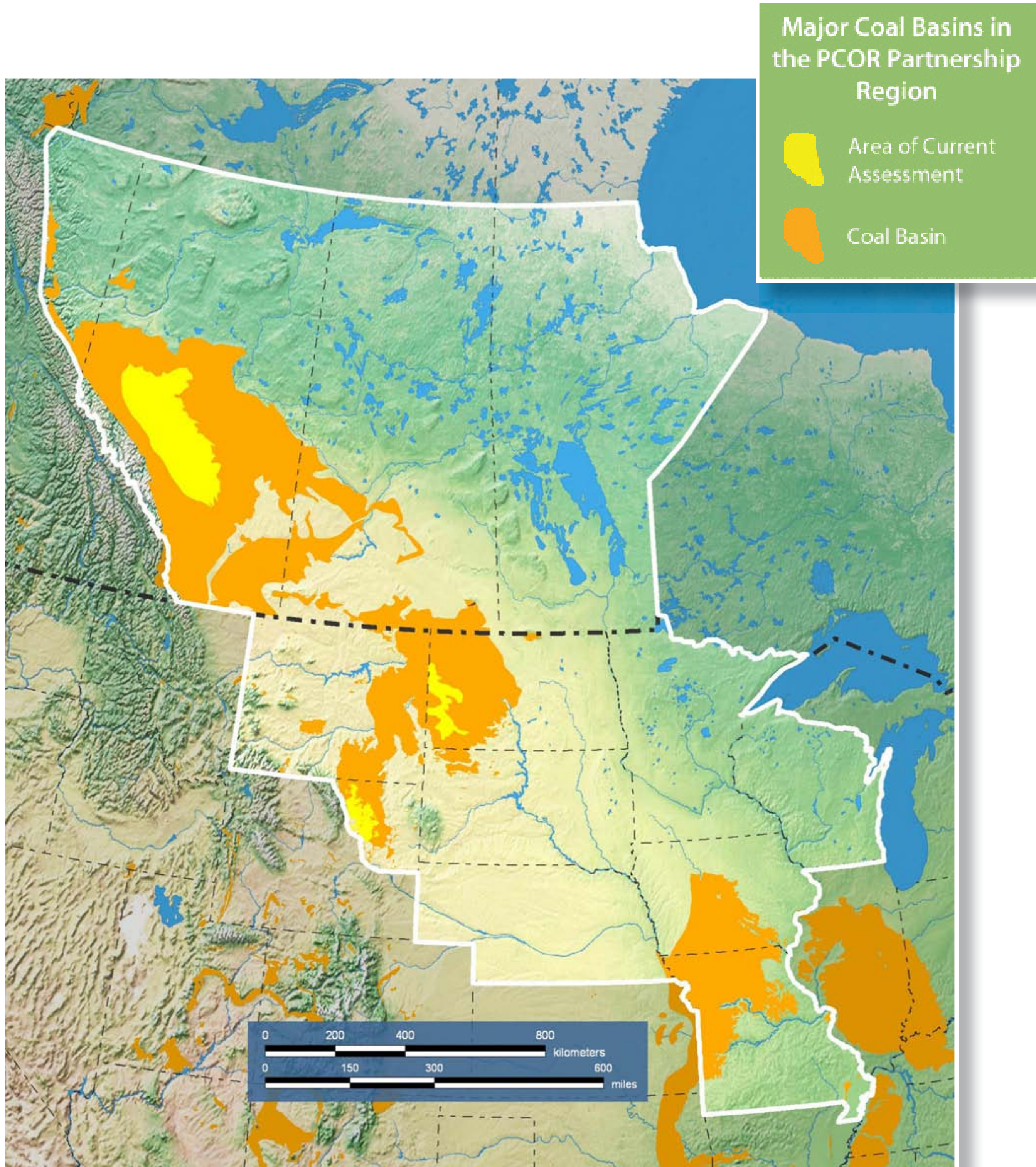
PCOR Partnership Unmineable Coal Areas

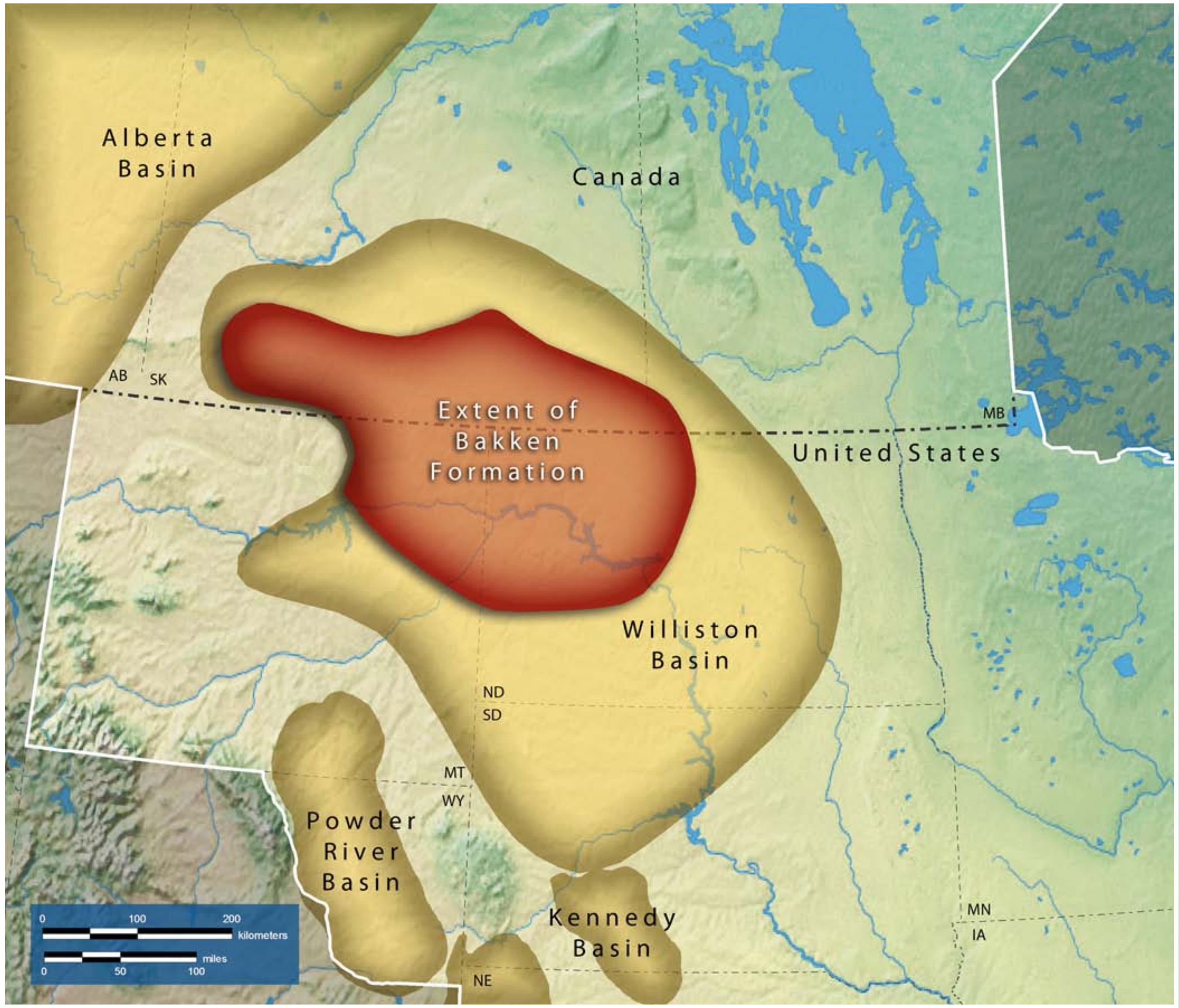
Many coal seams throughout central North America are too deep or too thin to be economically mined. However, many of these coals have varying amounts of methane adsorbed onto pore surfaces, and wells can be drilled into the coalbeds to recover this CBM. In fact, CBM is the fastest growing source of natural gas in the United States and accounted for 7.2 percent of domestic production in 2003.

As with oil reservoirs, the initial CBM recovery methods, dewatering and depressurization, can leave methane (CH_4) in the coal seam. Additional CBM recovery can be achieved by sweeping the coalbed with CO_2, which preferentially adsorbs onto the surface of the coal, displacing the methane. For the coals in the PCOR Partnership region, it is possible that up to 13 molecules of CO_2 can be adsorbed for each molecule of methane released, thereby providing an excellent storage site for CO_2. Similar to depleting oil reservoirs, unmineable coalbeds may be a good opportunity for CO_2 storage.

Three major coal horizons in the PCOR Partnership region have been characterized with respect to CO_2 storage: the Wyodak-Anderson bed in the Powder River Basin, the Harmon-Hanson interval in the Williston Basin, and the Ardley coal zone in the Alberta Basin. The total maximum CO_2 storage potential for all three coal deposits is approximately 7.3 billion metric tons (8 billion tons). In northeastern Wyoming, the CO_2 storage potential for the areas where the coal overburden thickness is greater than 1,000 feet could store all of the current annual CO_2 emissions from nearby power plants for about the next 150 years.







PCOR Partnership Organic-Rich Shale Opportunities

The Bakken Formation is an important source rock for oil in the Williston Basin. The Bakken occurs across most of western North Dakota and parts of Montana, Saskatchewan, and Manitoba. It typically consists of three members: the upper and lower members, comprising organic-rich shales, and the middle member, comprising dolomitic siltstone and sandstone. Total organic carbon within the shales may be as high as 40 percent, with estimates of total oil in place across the entire Bakken Formation approaching 500 bbl.

While the hydrocarbon resource within the Bakken Formation is large, it is considered to be an unconventional oil play because it is typically characterized by low porosity and permeability. Despite its unconventional nature, the significance of oil production from the Bakken Formation can be demonstrated by the recent growth in oil production activity, which uses advanced well drilling and stimulation technologies to improve oil productivity in these tight, but oil-rich, rocks.

The potential role of the Bakken with respect to CO_2 storage may also be substantial. The rocks of the Bakken Formation are largely "oil-wet;" consequently, the use of water for secondary EOR operations can be detrimental to the maintenance of the reservoir. Supercritical CO_2 has been identified as a possible agent for EOR operations in the Bakken Formation without damaging a reservoir's long-term productivity.

Though detailed predictions of the potential CO_2 storage capacity of the Bakken Formation have not yet been determined, the large estimates of its oil resources reveal it is possible that the Bakken could store hundreds of millions to billions of tons of CO_2. The storage of CO_2 in nonconventional oil and gas reservoirs like the Bakken Formation is a likely area of investigation for the future.

Drilling for Bakken oil in western North Dakota.

PCOR Partnership Validation Phase Activities

Terrestrial Field Validation Test

The PCOR Partnership region includes the Prairie Pothole Region, a major biogeographical zone encompassing nearly 347,000 mi^2 that includes portions of Minnesota, Iowa, Montana, and North and South Dakota in the United States, and portions of Alberta, Saskatchewan, and Manitoba. Prior to European settlement, this region may have supported more than 48 million acres of wetlands. However, fertile soils in this region have prompted extensive cultivation and the resulting extensive loss of native wetlands. As part of the PCOR Partnership, the University of North Dakota Energy & Environmental Research Center; Ducks Unlimited, Inc. (DU); Ducks Unlimited Canada, Inc.; the USGS Northern Plains Wildlife Research Center; and North Dakota State University have demonstrated optimal practices for terrestrially storing CO_2 at multiple sites across the Prairie Pothole Region.

Work by DU and the USGS for the PCOR Partnership demonstrated that restoration of previously farmed wetlands results in the rapid replenishment of soil organic carbon at an average rate of 1.1 tons per acre per year. These results show that restored prairie wetlands are an important near-term opportunity for storing atmospheric CO_2.

Collecting soil samples for carbon analysis.

Lignite Field Validation Test

Approximately 82 metric tons (90 tons) of CO_2 was injected over a roughly 2-week period into a 10- to 12-foot-thick coal seam at a depth of approximately 1,100 feet. Monitoring, Verification, and Accounting techniques were selected based on the characteristics of the site and several of techniques were utilized. After analysis of all gathered data, it was determined that relatively simple downhole measurements of pressure and pH provided effective MVA data at the site. Additionally, a combination of seismic image tomography and reservior saturation tool (RST) measurements was found to provide significant MVA augmentation. These techniques demonstrated that the CO_2 was contained within the coal seam for the duration of the approximately 3-month monitoring period. This validation test affirmed that CO_2 can be safely injected and stored in an unmineable lignite seam.

Initial examination of core from the Lignite Field Validation Test.

Zama Field Validation Test

From October 2005 through September 2009, the Zama Oil Field in northwestern Alberta, Canada, has been the site of sour gas (approximately 70 percent CO_2 and 30 percent hydrogen sulfide injection for the simultaneous purpose of EOR, hydrogen sulfide disposal, and storage of CO_2. The PCOR Partnership conducted MVA activities at the site throughout this period while Apache Canada, Ltd., undertook the injection and hydrocarbon recovery processes. This project has been recognized by the Carbon Sequestration Leadership Forum as being uniquely able to fill technological gaps with regard to geologic storage of CO_2.

Zama gas plant.

The Zama project was designed to address the issue of monitoring CO_2 storage at EOR sites in a cost-effective and reliable manner. The primary issues that were addressed include: (1) determination of CO_2 and/or hydrogen sulfide release, or lack thereof, from the pinnacle; (2) development of reliable predictions regarding long-term fate of injected acid gas; and (3) generation of data sets that would support the development and monetization of carbon credits associated with the geologic CO_2 storage. To address these issues, a variety of research activities has been conducted at multiple scales of investigation in an effort to fully understand the ultimate fate of the injected gas. Geologic, geomechanical, geochemical, and engineering work has been used to fully describe the injection zone and adjacent strata in an effort to predict the long-term storage potential of this site.

Through these activities, confidence in the ability of the Zama Field to provide long-term containment of injected gas has been achieved. This project focused on one of the hundreds of pinnacles that exist in the Zama Field; many of the results obtained can be applied not only to additional pinnacles in the Alberta Basin, but to similar structures throughout the world.

Preparation of the injection well for the huff 'n' puff test.

Williston Basin Oil Field Validation Test

The PCOR Partnership worked with Eagle Operating Company to determine the effect of injecting CO_2 into a deep, high-pressure carbonate formation in the Northwest McGregor Oil Field of North Dakota. Carbon dioxide was injected into the target oil reservoir using a huff 'n' puff approach. The approach was economically attractive because small-volume injections can be an effective means of evaluating the response of a reservoir to CO_2, with respect to both EOR and CO_2 storage.

The pilot-scale test injected 400 metric tons (440 tons) of CO_2 into a single well. After a 2-week "soaking" period the well was then placed back into production. Productivity of the oil well more than doubled over the course of the 3-month production period. Activities conducted at this field validation site yielded previously unavailable insight regarding: (1) the effectiveness of small-scale CO_2 injection using the huff 'n' puff approach, and (2) the effectiveness of geophysical technologies (RST and vertical seismic profiling) to identify and delineate the occurrence of CO_2 in a deep carbonate oil reservoir.

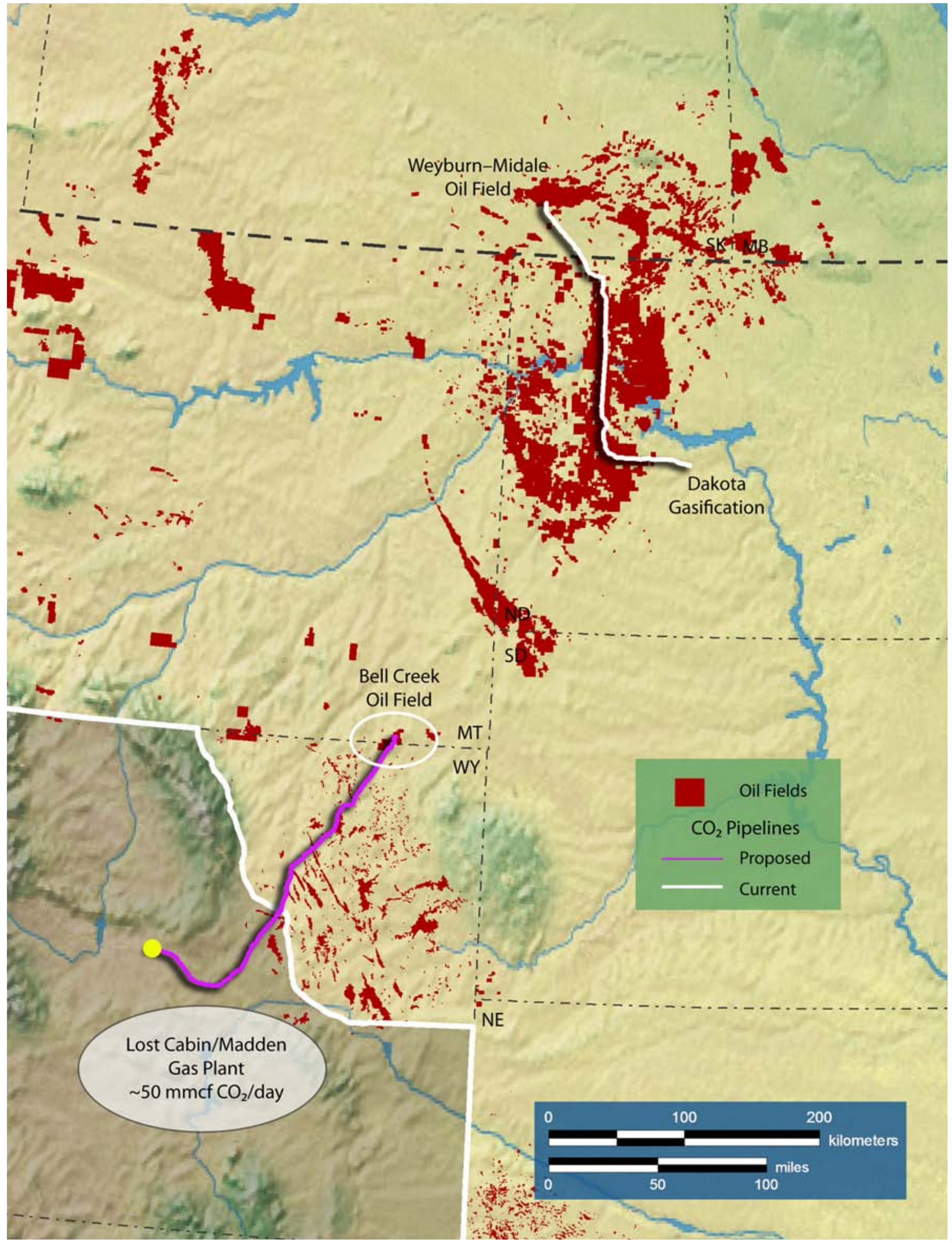
PCOR Partnership Development Phase— The Bell Creek Oil Field

The PCOR Partnership is working with Denbury Resources to evaluate the efficacy of developing a robust and practical MVA, risk management, and simulation project associated with a commercial-scale injection of CO_2 for the purpose of simultaneous EOR and CO_2 storage. The project, which will be conducted in the Bell Creek Oil Field in Powder River County, southeastern Montana, will provide insight regarding the impact of CO_2 on oil production and CO_2 storage within a sandstone reservoir in the Cretaceous Muddy Formation.

The Bell Creek project will bring CO_2 from the Lost Cabin gas plant in north-central Wyoming through a 226-mile pipeline. Once online, the EOR project will utilize nearly 900,000 metric tons (1 million tons) of CO_2 per year and is estimated to recover an incremental 35 million bbl of oil of the project's 20- to 25-year life.

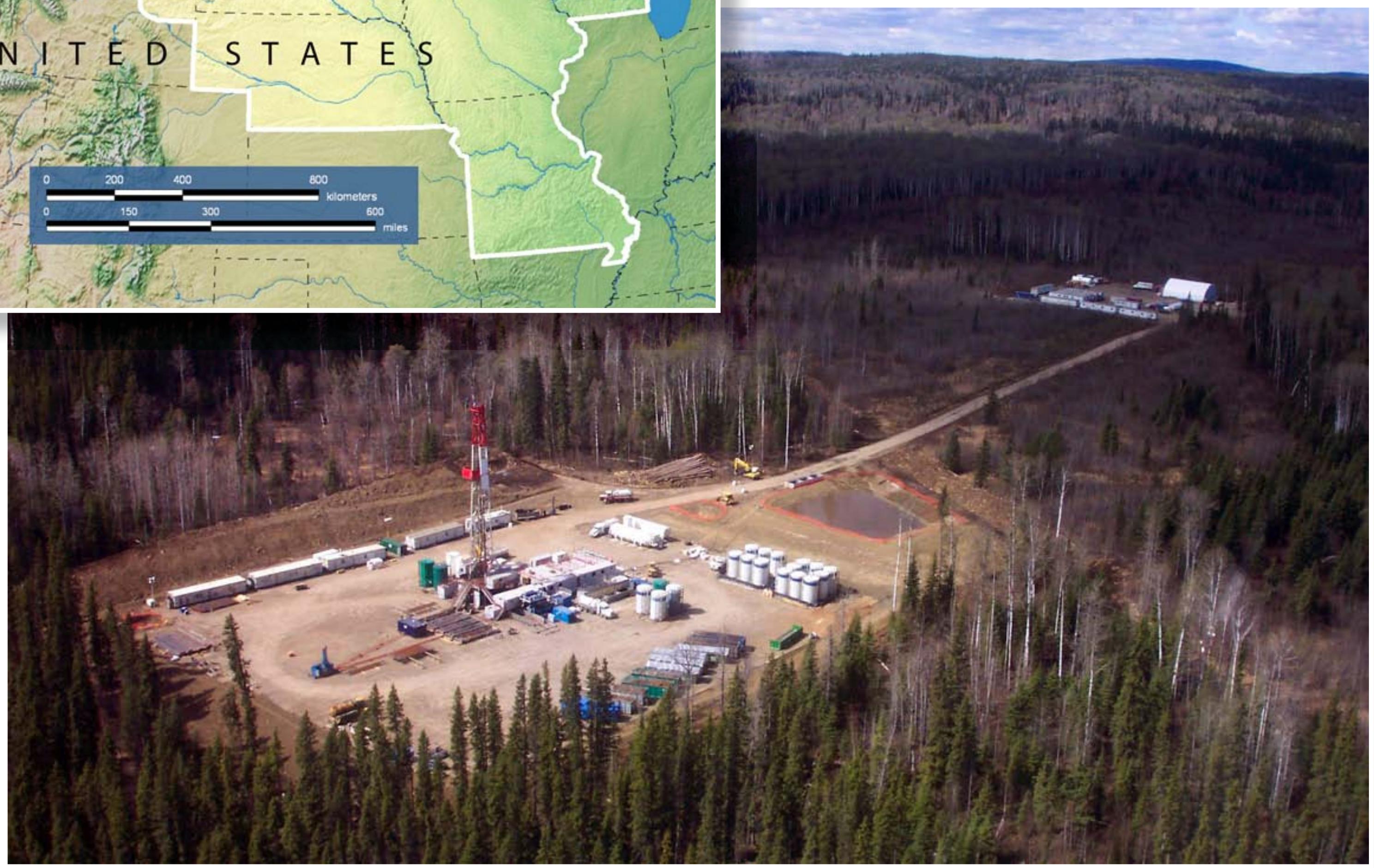
The Bell Creek project provides a significant opportunity to develop a set of cost-effective MVA protocols for large-scale anthropogenic CO_2 storage associated with an EOR operation.

Gas plant infrastructure.



PCOR Partnership Development Phase—The Fort Nelson CCS Feasibility Project

The Fort Nelson CCS Feasibility project, an international collaboration led by Spectra Energy that includes industry, government, universities, and technologists has initiated what may ultimately be the largest application of deep saline geologic storage in the world. If proven feasible, this project will provide permanent storage of 1.3 million to 2.2 million metric tons (1.4 million to 2.4 million tons) of CO_2 per year from the Fort Nelson gas processing facility, the largest processing facility in the region and the largest of its type in North America. While providing a substantial reduction in CO_2 emissions, this project will also facilitate the development of significant shale gas reserves in the Horn River Basin to provide North American markets with clean natural gas. Research aspects of the effort are being designed to provide proof of concept for geologic CO_2 storage in deep saline formations and serve as a model for follow-on CCS projects using geologic CO_2 management at other gas-processing facilities in the region and around the world. The PCOR Partnership is playing a key role in the development of an integrated risk management, reservoir simulation, and MVA strategy.



Drilling exploratory well in the Fort Nelson area.

The Fort Nelson CCS project has several strategic advantages:

- Fort Nelson gas-processing plant currently captures CO_2.
- Site located near growing production.
- Northeast British Columbia natural gas boom expected to double production.
- Site located near deep saline formations suitable for permanent CO_2 storage.

Integrating CCS into the PCOR Partnership Community

Large-scale, practical, and environmentally sound CO_2 storage realities in the region cannot occur without an informed and supportive public.

For this reason, the PCOR Partnership has developed a number of outreach tools intended to educate and inform the public and decision makers about issues related to CO_2 storage:

- A variety of PowerPoint presentations.
- Display booth and materials.
- Public website.
- Members-only website.
- Knowledge in brief—fact sheets on key topics and validation projects.
- Knowledge in-depth—over 50 scientific and technical reports.
- Five documentaries available on DVD—co-productions of Prairie Public Broadcasting (PPB) and the PCOR Partnership.
- Proceedings from the annual PCOR Partnership meetings and access to other meeting materials.
- A 65-page regional atlas.

The PCOR Partnership and PPB have developed an award-winning documentary series. These documentaries are aired on PPB and made available to other public television stations throughout the United States and Canada.

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PCOR Partnership 2003 – Present

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Please visit: http://www.undeerc.org\pcor.

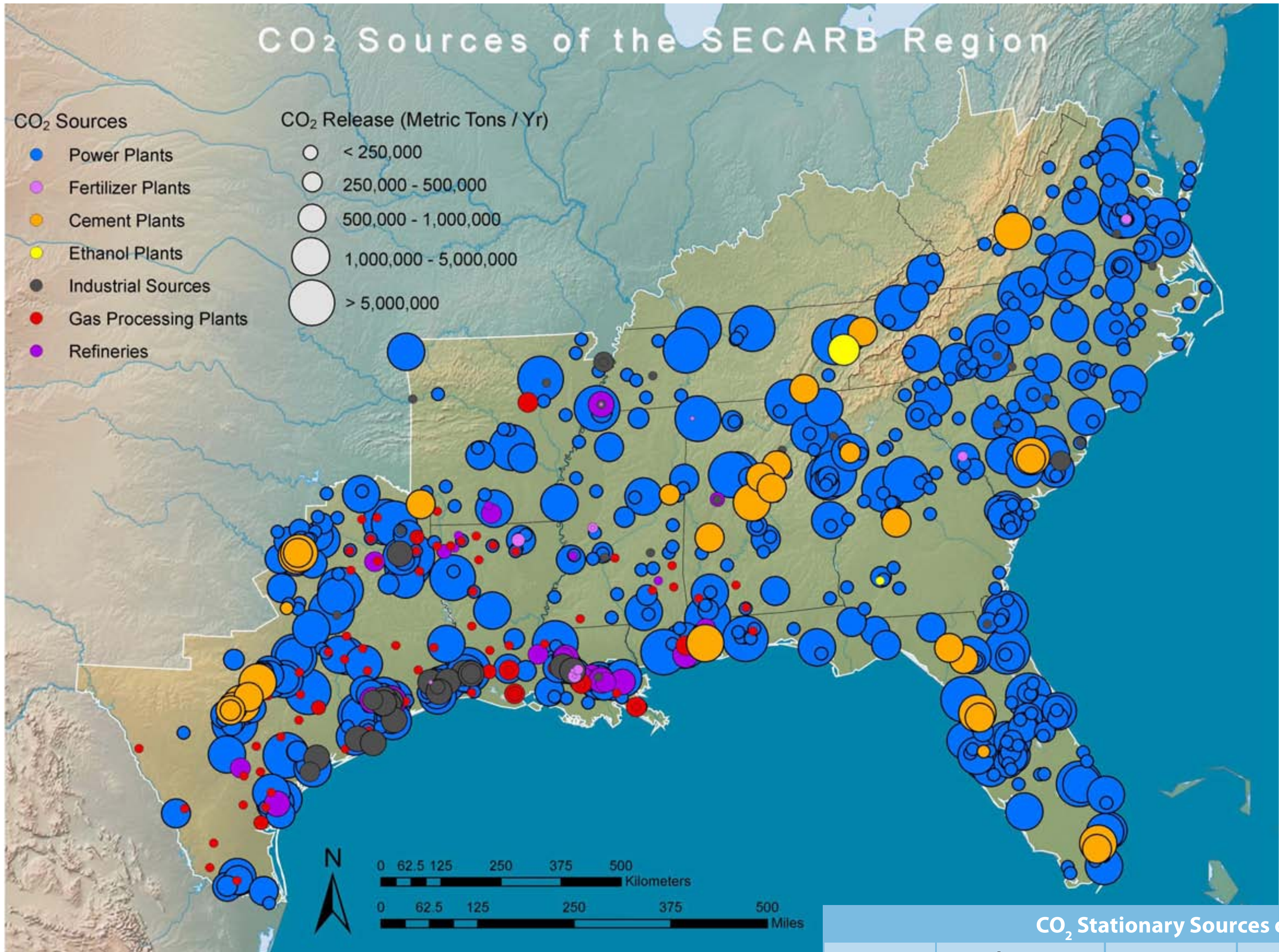
The Southeast Regional Carbon Sequestration Partnership

The Southeast Regional Carbon Sequestration Partnership (SECARB), managed by the Southern States Energy Board (SSEB), represents a 13-State region, including Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Texas, and Virginia, and portions of Kentucky and West Virginia. SECARB is comprised of over 100 participants representing Federal and State governments, industry, academia, and non-profit organizations.

The primary goal of SECARB is to develop the necessary framework and infrastructure to conduct field tests of carbon storage technologies and to evaluate options and potential opportunities for the future commercialization of carbon storage in the region. The SECARB partners are accomplishing this goal by designing and operating six field tests across the region. Four are small-scale projects under the Validation Phase and two are large-scale under the Development Phase.

In addition, SECARB continues to characterize the region's geologic storage options, both onshore and offshore; identify barriers and opportunities for the wide-scale construction of pipelines to transport CO_2 for the purposes of storage, EOR, and other commercial uses; monitor Federal and State regulatory and legislative activities; and support local, regional, national, and international education and outreach efforts related to the SECARB and the RCSP initiative.

SECARB
Southeast Regional Carbon Sequestration Partnership



SECARB CO_2 Sources

There are more than 900 large, stationary sources of CO_2 in the SECARB region, which are targets for future carbon storage projects. Their total annual emissions are estimated at slightly over 1 billion metric tons (1.2 billion tons) of CO_2. Fossil fuel-fired (coal, oil, or gas) power plants are the largest contributors, accounting for approximately 80 percent of the total CO_2 emissions.

The SECARB region also hosts a number of non-power related stationary sources of CO_2. These include, in descending order of CO_2 contribution, refineries, ethylene plants, cement plants, gas processing plants, iron and steel plants, and ethylene oxide plants.

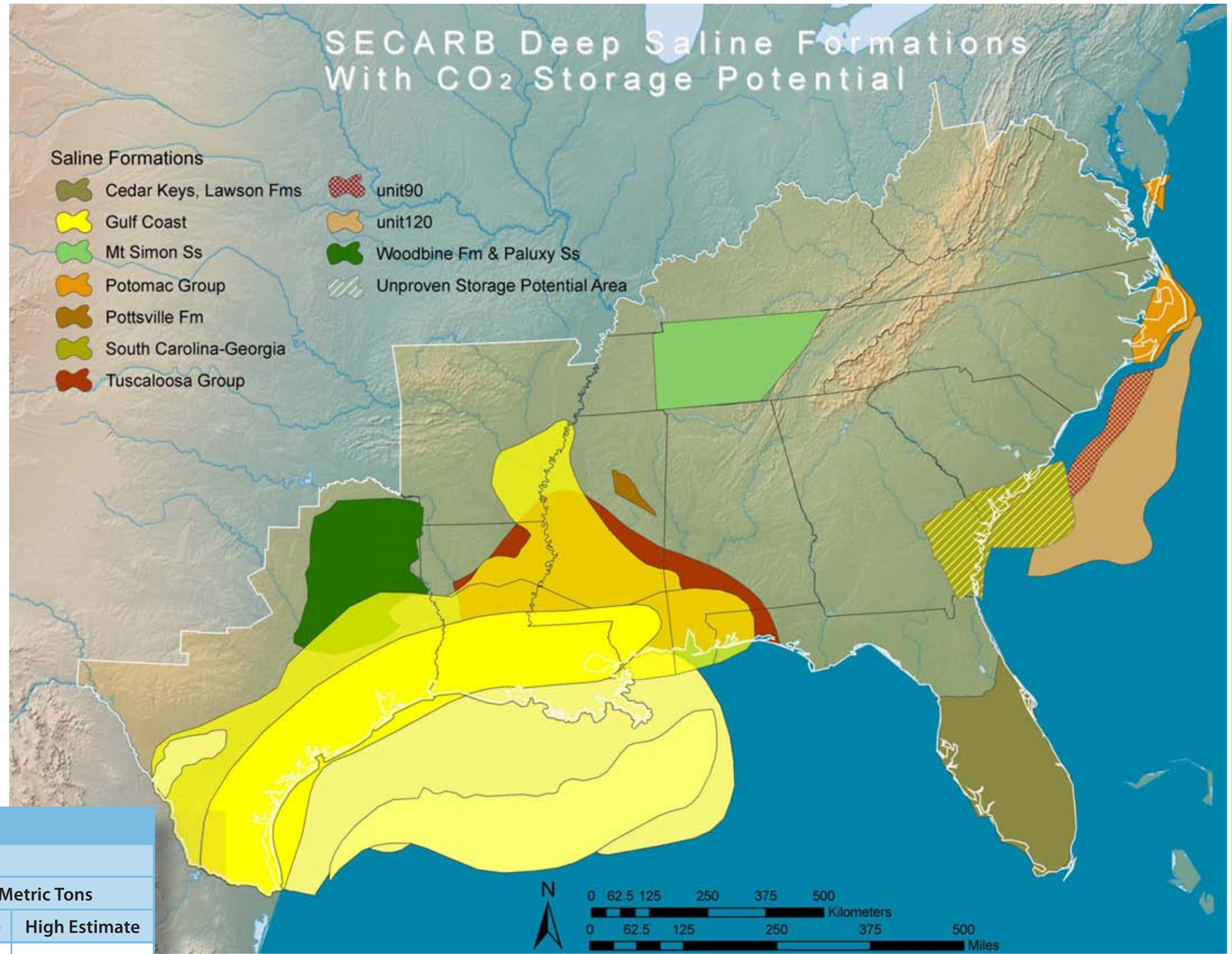
CO_2 Stationary Sources of the SECARB Region (million metric tons of CO_2 per year)

State	Electric Generation*	Fertilizer*	Cement Plants*	Ethanol*	Industrial*	Petroleum/ Natural Gas*	Refineries/ Chemical*	Total*
AL	71.1	0.2	5.4	0.0	0.5	0.3	1.3	80
AR	32.9	0.0	0.9	0.0	0.3	0.5	0.8	35
FL	137.0	0.0	5.5	0.0	0.1	0.1	0.0	143
GA	88.0	0.9	1.0	0.0	0.1	0.0	0.0	90
LA	52.6	4.6	0.8	0.0	9.6	5.9	28.3	102
MS	28.3	0.6	0.5	0.0	0.1	0.8	3.6	34
NC	76.7	0.0	0.0	0.0	0.1	0.0	0.0	77
SC	36.1	0.0	3.8	0.0	0.4	0.0	0.0	40
TN	61.8	0.0	1.5	0.4	0.2	0.0	1.8	66
TX**	237.6	0.0	11.1	0.0	42.5	4.8	37.2	373
VA	44.6	0.7	1.1	0.0	0.2	0.0	0.0	46
TOTAL	**866.7**	**6.8**	**31.5**	**0.4**	**54.2**	**12.4**	**72.9**	**1,085**

SECARB shares KY and WV with other RCSPs. Data for these States can be found under MGSC and/or MRCSP.
*Units are all in million metric tons.
** Eastern Texas, TRRC Districts 1–6.

SECARB Deep Saline Formations

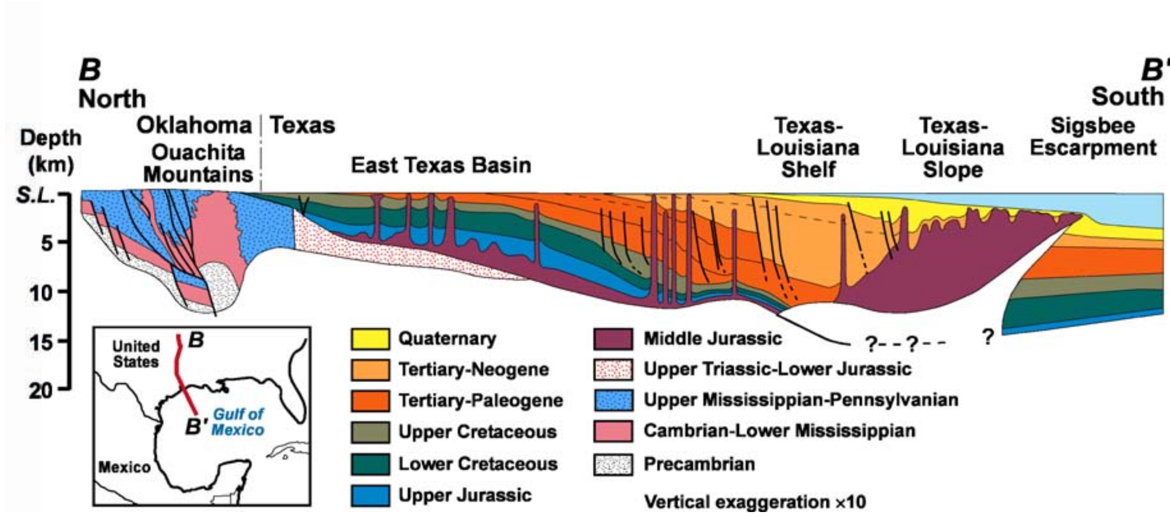
Much of the CO_2 storage resource of the SECARB region lies in a thick wedge of sandstones in several sub-basins along the Gulf Coast. Sandstones of the Cretaceous Tuscaloosa Formation and the Paluxy Formation host the current SECARB field tests. Overlying Tertiary formations extend offshore, and a recent reassessment of these units has quantified additional storage potential. Other Cretaceous formations that provide significant storage potential include sandstones in Texas, from South Carolina to Georgia, the subseabed in the Atlantic Ocean offshore of the Carolinas and Virginia, and carbonates and sandstones in Florida. Initial mapping shows saline formations with potential storage in the Mt. Simon of Tennessee and Pottsville of Mississippi. With further assessment, this storage potential may be increased, as well as additional CO_2 storage resource mapped in southern Georgia and Arkansas. Current assessment shows that the saline formations in the SECARB region have the potential to store 919 billion to 12,522 billion metric tons (1,013 billion to 13,803 billion tons) of CO_2.



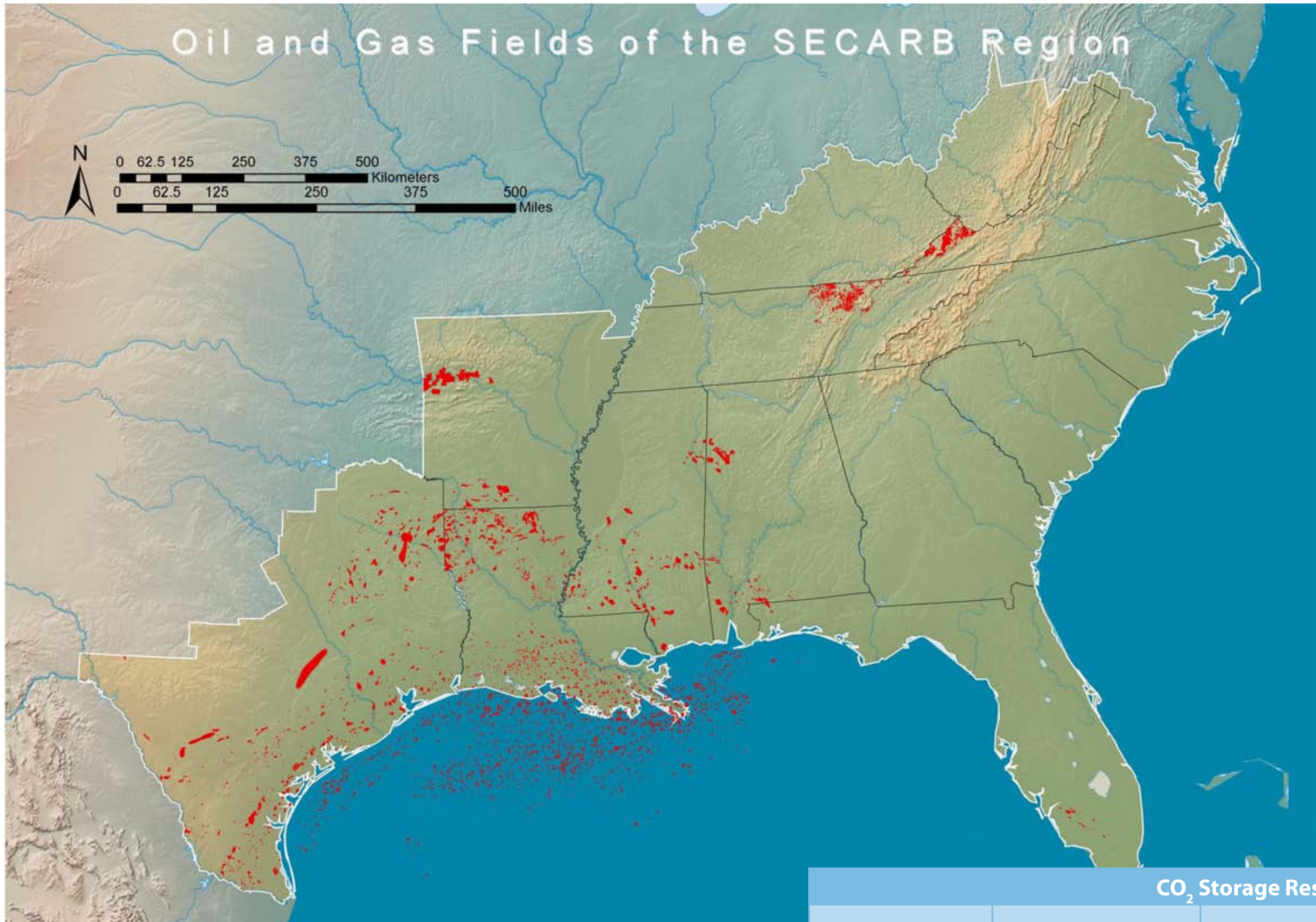
CO_2 Storage Resource Estimate for Saline Formations

Saline Formations	State	CO_2 Storage Resource			
		Trillion Cubic Feet		Billion Metric Tons	
		Low Estimate	High Estimate	Low Estimate	High Estimate
Gulf Coast Basins (Pliocene)	Multiple States*	2,571	35,345	136	1,870
Gulf Coast Basins (Miocene)	Multiple States*	7,582	104,173	401	5,512
Gulf Coast Basins (Oligocene)	Multiple States*	2,488	34,215	132	1,810
Gulf Coast Basins (Eocene)	Multiple States	2,959	40,684	157	2,153
Gulf Coast Basins (Tertiary Undivided)	Multiple States	323	4,435	17	235
Gulf Coast Basins (Olmos)	TX**	8	116	0.4	6
Tuscaloosa Group	Multiple States	103	1,412	5	75
Woodbine and Paluxy Formations	TX**	96	1,324	5	70
Pottsville Formation	MS	21	289	1.1	15
Mt. Simon Sandstone	TN	9	130	0.5	7
Potomac Group	Multiple States*	34	467	2	25
South Carolina-Georgia Basins	Multiple States*	239	1,129	12.6	60
Cedar Keys, Lawson Formations	FL	210	2,886	11	153
Offshore Atlantic (Unit 120)	Federal Offshore	673	9,258	36	490
Offshore Atlantic (Unit 90)	Federal Offshore	59	807	3	43
TOTAL*		17,375	236,668	919	12,522

SECARB shares KY and WV with other RCSPs. Data for these States can be found under MGSC and/or MRCSP.
* Including offshore Federal Waters.
** Eastern Texas, TRRC Districts 1–6.



Geologic cross section across the Gulf Coast showing the thick wedge of Cretaceous and Tertiary age sediments that offer numerous large capacity saline formations. Source: Modified from Arbenz (1988), Plate II, cross section D-D' and Salvador (1991), Plate 6, cross section B-B'.



SECARB Oil and Gas Reservoirs

The SECARB region has a rich history of oil and gas production, particularly in the Gulf Coast states of Louisiana, Mississippi, and eastern Texas. As such, considerable information exists about the geologic settings and reservoir properties of these potential CO_2 storage sites.

The region has produced nearly 7 billion cubic meters (m^3) (44 billion barrels) of oil and nearly 9.4 trillion m^3 (332 trillion cubic feet) of natural gas. Application of CO_2-EOR could add 1.2 billion m^3 (7.3 billion barrels) of oil to these totals. These oil and gas reservoirs provide opportunities for storing CO_2, assuming the water and low pressure hydrocarbons occupying this pore space can be efficiently displaced with injected CO_2.

CO_2-EOR production wellhead. (Courtesy of BEG, UT Austin)

CO_2 Storage Resource Estimates for Oil and Gas Reservoirs

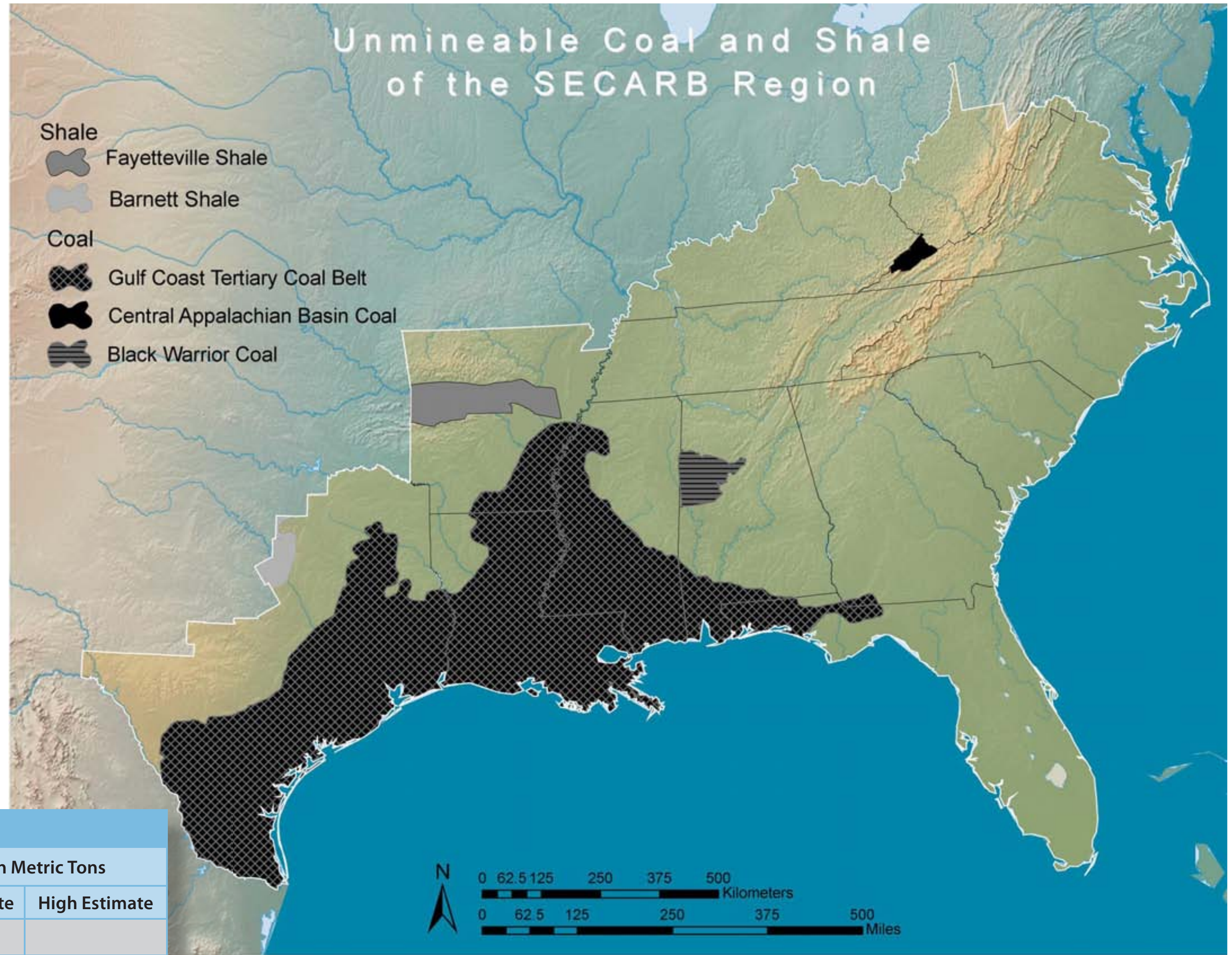
State	Number of Fields		Cumulative Conventional Recovery		Conventional CO_2 Storage Resource		Technically Recoverable Oil from CO_2-EOR	Additional CO_2 Storage Resource*	
	Total	Assessed	Oil Million Bbls	Gas Bcf	Million Metric Tons	Bcf	Million Bbls	Million Metric Tons	Bcf
AL	133	63	622	1,856	344	6,504	410	86	1,640
AR	42	42	1,394	1,415	250	4,728	340	72	1,360
FL	23	8	556	0	109	2,061	180	38	720
LA	964	331	11,847	117,697	6,781	128,153	5,480	1,160	21,920
MS	110	101	1,346	5,300	399	7,549	850	180	3,400
TN	213	213	-	-	-	-	-	-	-
VA	49	49	-	89	10	180	-	-	-
Federal Offshore	1,337	1,001	15,843	176,466	17,754	335,550	5,890**	1,246	23,560
TX***	678	678	12,510	29,373	4,005	75,695	n/a	n/a	n/a
TOTAL	**3,549**	**2,486**	**44,118**	**332,196**	**29,652**	**560,420**	**7,260**	**2,784**	**52,600**

SECARB shares KY and WV with other RCSPs. Data for these States can be found under MGSC and MRCSP.
* Additional storage resource calculated by using 4 Mcf of CO_2 storage per bbl of technically recoverable CO_2-EOR oil.
** CO_2-EOR assessed for offshore shallow water Louisiana fields only.
*** Eastern Texas, TRRC Districts 1–6.

SECARB Coal Areas

Three significant coal basins and two gas shale basins have been assessed within the SECARB region. The first of the coal basins, the Virginia portion of the Central Appalachian Basin, may have the potential to hold from 231 million to 982 million metric tons (255 million to 1,082 million tons) of CO_2. The Black Warrior Basin in Alabama and Mississippi has potential storage resource for 669 million to 1,529 million metric tons (737 million to 1,685 million tons) of CO_2. The third coal basin, the areally extensive Gulf Coast Tertiary Coal Belt, may have the potential to hold from 32 billion to 72 billion metric tons (35 billion to 80 billion tons) of CO_2.

The SECARB partners have examined two gas shale basins in this region to date: the Arkoma (Fayetteville) Shale in the Arkoma Basin of Arkansas and Oklahoma and the Barnett Shale in Texas. The Arkoma Shale is estimated to have a CO_2 storage resource of 14 billion to 20 billion metric tons (16 billion to 22 billion tons). The Barnett Shale is estimated to have a CO_2 storage resource of 19 billion to 27 billion metric tons (21 billion to 30 billion tons). During the SECARB Development Phase Program, the partners will rigorously quantify other coal and shale basins in the region as potential CO_2 storage options.

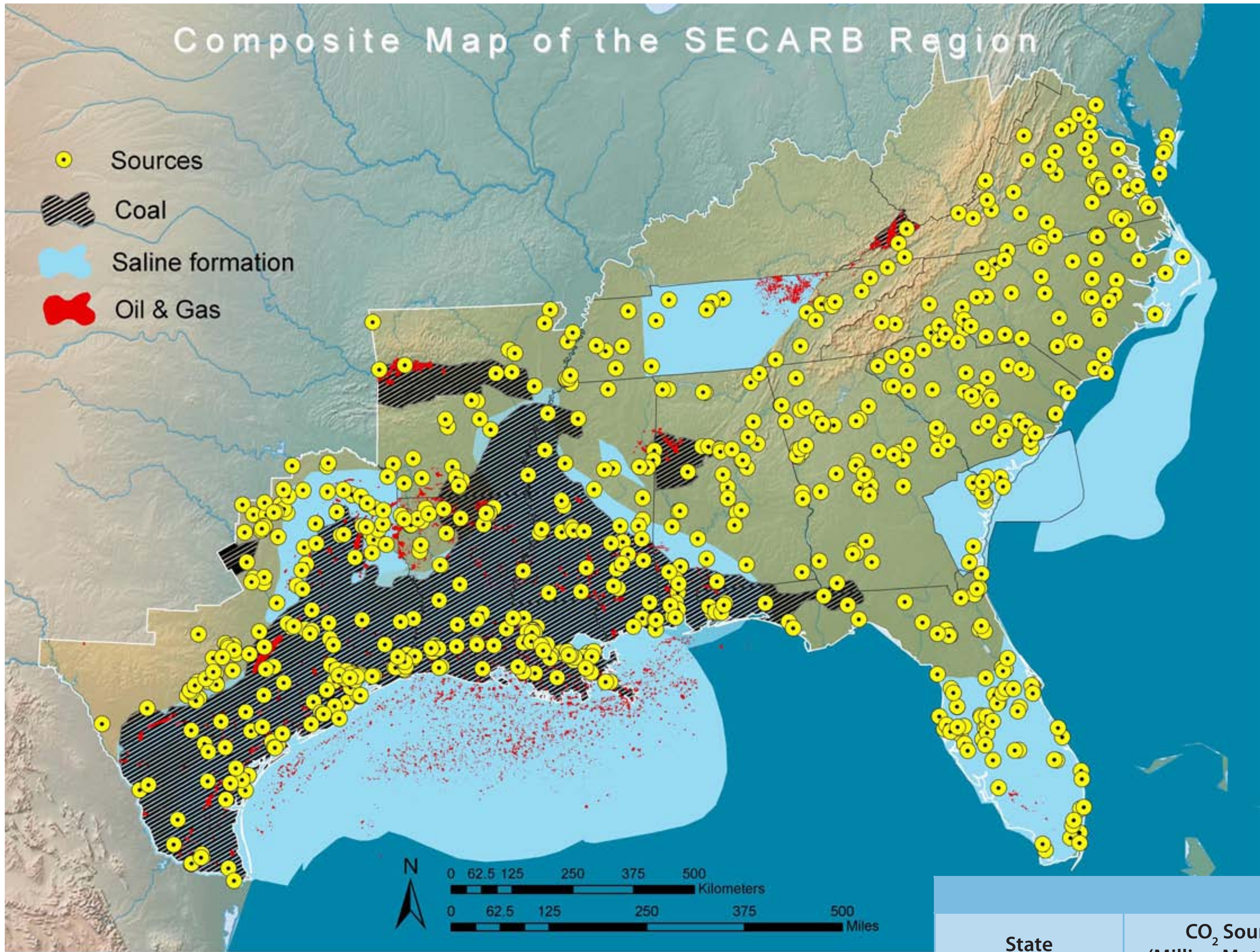


CO_2 Storage Resource for Unmineable Coal Areas and Shale

Basin	State	Status of Development	Area (square miles)	Trillion Cubic Feet (Tcf)		Billion Metric Tons	
				Low Estimate	High Estimate	Low Estimate	High Estimate
COAL							
Central Appalachian	VA	Mature	1,269	4	19	0.2	1.0
Black Warrior	AL	Mature	4,389	13	29	0.7	1.5
Gulf Coast Tertiary Coal Belt	TX*	Undeveloped	71,277	265	606	14.0	32.0
	LA	Undeveloped	40,501	157	358	8.3	19.0
	MS	Undeveloped	28,195	102	234	5.4	12.4
	AR	Undeveloped	7,829	30	69	1.6	3.6
	FL	Undeveloped	6,100	24	55	1.3	2.9
	AL	Undeveloped	5,915	24	55	1.3	2.9
	GA	Undeveloped	501	-	-	-	-
TOTAL COAL			**164,706**	**620**	**1,425**	**33**	**75**
SHALE							
Arkoma (Fayetteville)	AR	Emerging	8,610	266	380	14.1	20.1
Barnett	TX*	Emerging	7,902	356	508	19.0	27.0
TOTAL SHALE			**16,512**	**622**	**888**	**33**	**47**

SECARB shares KY and WV with other RCSPs. Data for these States can be found under MGSC and/or MRCSP.
* Eastern Texas, TRRC Districts 1–6.

Injection operations at the Central Appalachian (left) and the Black Warrior Basin (above) project sites.



Composite Map of CO_2 Sources and Geologic Storage Formations

The distance between stationary source and geologic storage formation is calculated as the shortest straight-line distance from each point. While these results do not give a complete picture of the transportation and infrastructure requirements, it does give a first-order interpretation of the magnitude of the requirements.

The sources in SECARB match up well with the potential storage reservoirs. For example, more than 70 percent of all sources (by volume) in the SECARB region are located within 50 kilometers of a storage site. Approximately 40 percent of the sources are co-located with an appropriate storage site. This especially occurs in the Gulf Coast region where many of the sources overlie saline formations, coalbeds, or both.

The table below identifies how many years' storage is possible, given the current annual emissions and the known CO_2 storage resource.

Drill core and drill chip logging from site characterization at the Mississippi Test Site. (Courtesy of Southern Company and Advanced Resources International)

Estimated Years of Storage

State	CO_2 Sources (Million Metric Tons)	CO_2 Storage Resource (Million Metric Tons)				Number of Years Storage ***
	Total	Oil and Gas	Coal and Shale*	Saline*	Total	
AL	80	344	1,944	12,900	15,188	190
AR	35	250	15,675	4,304	20,229	572
FL	143	109	1,275	16,725	18,109	127
GA	90	-	-	4,909	4,909	55
LA	102	6,781	8,325	139,497	154,603	1,520
MS	34	399	5,400	46,427	52,226	1,546
NC	77	-	-	1,352	1,352	18
SC	40	-	-	1,995	1,995	49
TN	66	-	-	500	500	8
TX**	373	4,005	33,025	205,548	242,578	650
VA	46	10	231	159	400	9
Federal Offshore	N/A	17,754	-	484,996	502,750	N/A
Total	**1,085**	**29,652**	**65,875**	**919,313**	**1,014,840**	**935******

* Low estimates used.
** Eastern Texas, TRRC Districts 1–6.
*** Years of CO_2 storage at the current emission rates (State CO_2 storage resource/State annual emissions).
****Average years storage for whole SECARB area (total CO_2 storage resource/total annual emissions).

SECARB Validation Phase Field Tests

SECARB conducted four field tests for geologic storage projects during the Validation Phase.

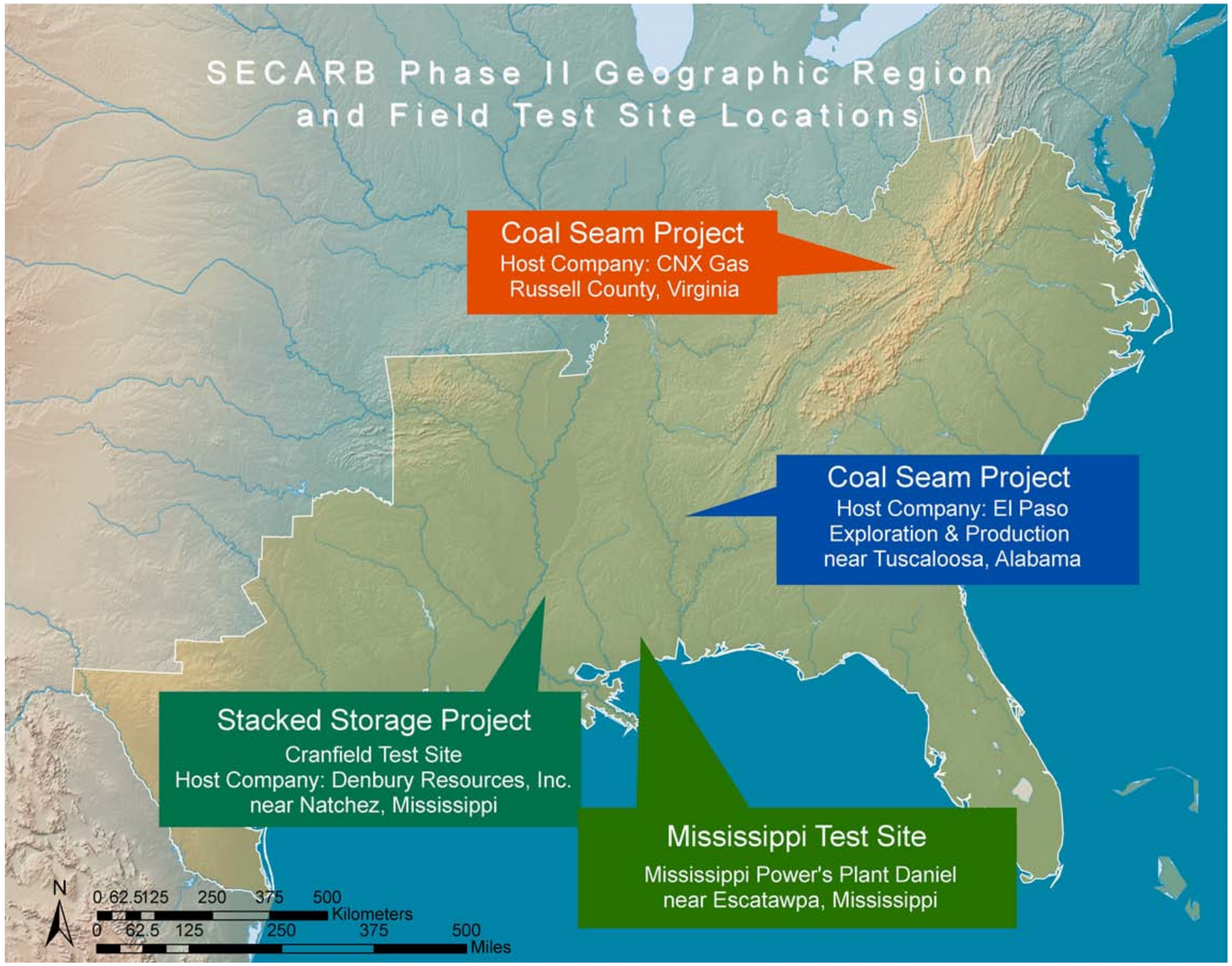
Stacked Storage Pilot Test—Gulf Coast Site

The Gulf Coast Stacked Storage project demonstrates the concept of phased use of subsurface storage volume. This storage approach combines the early use of CO_2 for EOR followed by subsequent injection into associated saline formations. This results in both short- and long-term benefits, as there is the immediate commercial benefit of EOR as a result of the injection of CO_2 (offsetting infrastructure development costs) followed by large-volume, long-term storage of CO_2 in saline-bearing formations. The field test is being conducted in the lower Tuscaloosa Formation in the Cranfield Unit, located in southwestern Mississippi, at a depth of 10,300 feet. The monitoring program includes observing real-time pressure, via wireline readout and satellite uplink, in the injection zone and in the overlying monitoring zone through a dedicated observation well, as well as collecting episodic changes in pressure and saturation in surrounding future producers. Injection rates in the commercial EOR flood are estimated from 90,700 to 453,600 metric tons (100,000 to 500,000 tons) per year of CO_2. The Validation Phase injection is followed by a novel Development Phase large-volume injection into brine bearing formations down dip of the oil ring.

Saline Formation Pilot Test—The Mississippi Test Site

Mississippi Power Company's Plant Daniel, a 2,000-MW facility near the town of Escatawpa in Jackson County, Mississippi, is the site of the saline formation pilot test. The project validates the storage capacity of the "Massive" Sandstone Unit of the lower Tuscaloosa Formation, the target saline formation beneath Plant Daniel. This regionally significant reservoir could hold 6 billion to 74 billion metric tons (6 billion to 81 billion tons) of CO_2, an amount sufficient to store the CO_2 emissions from Plant Daniel and other power plants in the region for decades. Other saline formations present at depths below and above the lower Tuscaloosa "Massive" sandstone could provide considerable additional CO_2 storage resource in the region.

Two new 9,500 foot wells were drilled at the site, allowing the collection of new core, geophysical logs, and seismic data. This new information is being used to confirm the estimated storage resource at the site and is also being incorporated into the regional characterization of CO_2 storage resource. Carbon dioxide injection operations were conducted from October 2–28, 2008.



Drilling rig at Mississippi Test Site. (Courtesy of Southern Company)

Central Appalachian injection well. (Courtesy of SSEB)

Injection Operations at the Mississippi Test Site in Escatawpa, Mississippi.

Satellite uplink providing remote access to data collected at the Cranfield dedicated monitoring well.

Injection operations at the Central Appalachian Coal Seam site in Russell County, Virginia.

Injection operations at the Black Warrior Basin Coal Seam site near Tuscaloosa, Alabama.

Coal Seam Pilot Tests

Central Appalachian Basin

This test validates storage opportunities in the Central Appalachian Basin, a northeast-to-southwest-trending basin encompassing 10,000 square miles in southwestern Virginia, southern West Virginia, and southeastern Kentucky. In January and February 2009, the project team injected 907 metric tons (1,000 tons) of CO_2 into 19 coal seams in the Pocahontas and Lee Formations at depths ranging from 1,044 to 2,276 feet. The project also includes CBM recovery operations to add economic value. The primary project objective is to demonstrate geologic storage in unmineable Appalachian coals as a safe, permanent method to mitigate GHG emissions.

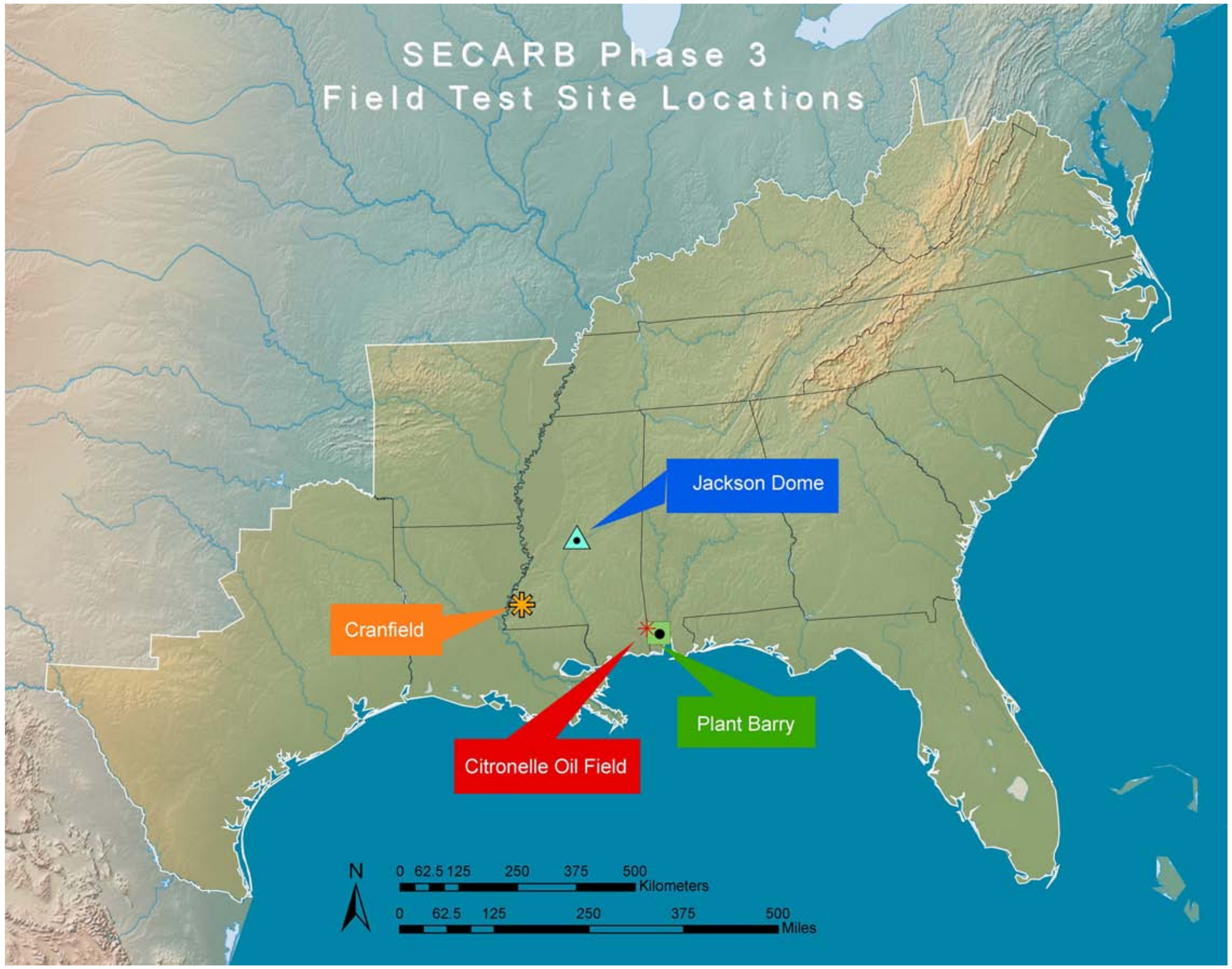
Black Warrior Basin

The principal objectives of the Black Warrior Basin coal seam project are to determine if storage of CO_2 in mature CBM reservoirs is a safe, effective method to mitigate GHG emissions and to determine if sufficient injectivity exists to efficiently drive ECBM recovery. This project uses CO_2 injection testing into Black Warrior Basin coal seams to determine the capability of these seams to adsorb significant volumes of CO_2 for geologic carbon storage and ECBM recovery. An existing CBM well was converted for CO_2 injection, and four wells were drilled to monitor reservoir pressure, gas composition, water quality, and the CO_2 plume. The targeted coal seams are in the Pratt, Mary Lee, and Black Creek Coal groups within the upper Pottsville Formation and range from 940 feet to 1,800 feet in depth and from 1 foot to 6 feet in thickness. Two hundred and seventy-eight (278) tons of CO_2 were injected at the site in Tuscaloosa County, Alabama, in June–August 2010.

SECARB Development Phase Field Tests

Early Test

The Early Test, currently underway in Cranfield, Mississippi, will inject at a rate of 1.5 million metric tons (1.65 million tons) of CO_2 per year for 18 months. In August 2009, the team met a milestone of monitoring an injection of more than 1 million metric tons (1.1 million tons) of CO_2. In November 2009, the SECARB Early Test was recognized by DOE for furthering CCS technology and meeting G-8 goals for the deployment of 20 similar projects by 2010. The Early Test is the fifth project worldwide to reach this CO_2 injection volume and the first in the United States. As of September 2010, the project team has monitored more than 2.5 million metric tons (2.7 million tons) of CO_2 at this site. The SECARB project team is taking advantage of ongoing CO_2-EOR efforts by the field operator, Denbury Resources, Inc. Research is underway in four areas: (1) the High Volume Injection Test area (HiVIT); (2) the Detailed Area of Study (DAS); (3) the Geomechanical Test area; and (4) the near-surface observatory. Following release of a "Finding of No Significant Impact" on March 17, 2009, Development Phase injection started on April 1, 2009, at the HiVIT area and in December 2009 at the DAS.



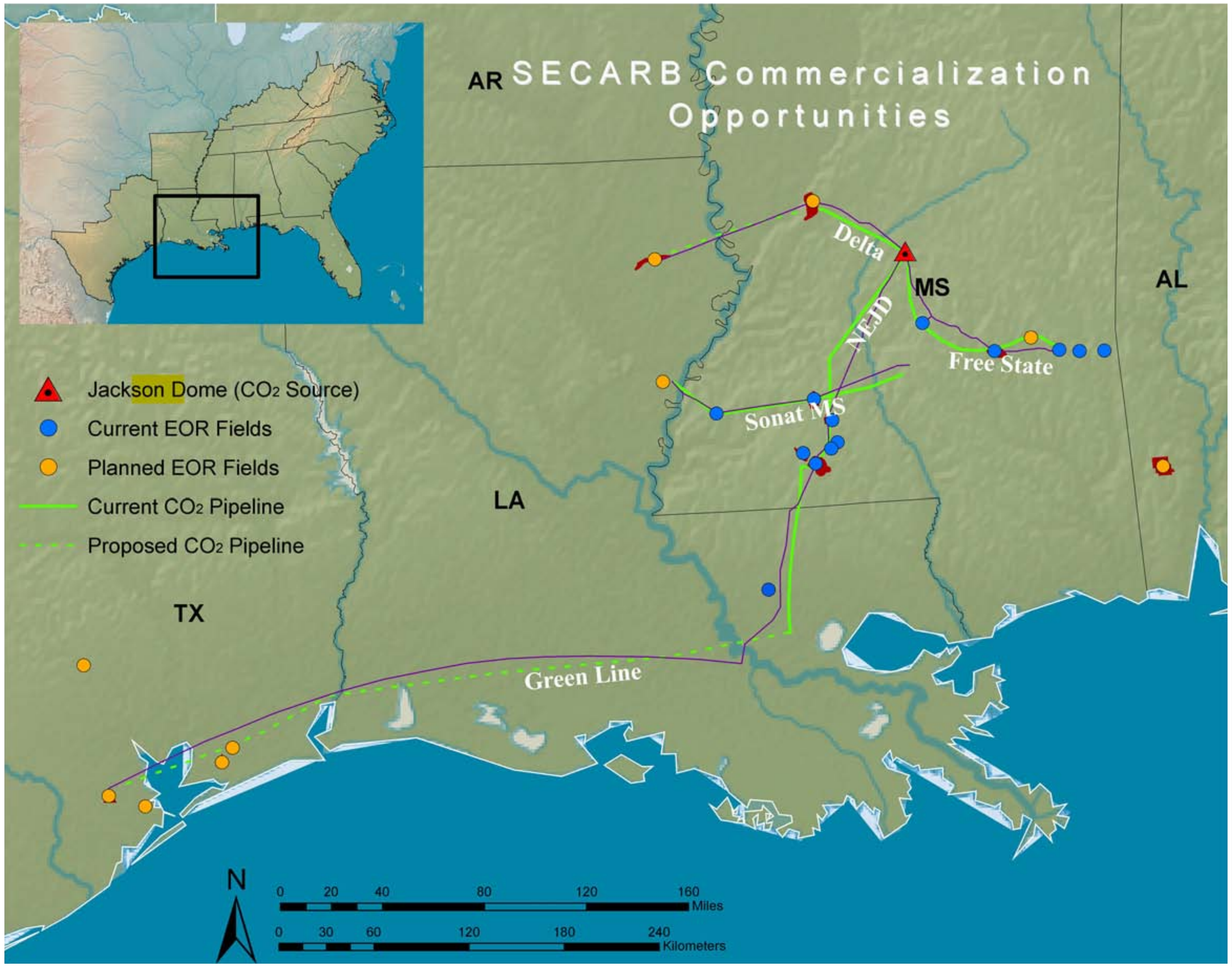
Anthropogenic Test

Information from the Early Test will be applied in Fiscal Year 2011 at the Anthropogenic Test, a fully integrated CO_2 capture, transportation, and geologic storage project. Under separate funding, the CO_2 will be captured at Alabama Power Company's Plant Barry, a coal-fired power generating facility located in Bucks, Alabama. The captured CO_2 will then be transported by pipeline and stored within a saline formation at the nearby Citronelle, Alabama, oil field operated by Denbury Resources, Inc. During the Anthropogenic Test, Denbury will inject approximately 100,000 metric tons (110,00 tons) of CO_2 per year for 3 years. The SECARB team will deploy an extensive MVA program that will commence pre-, during, and post-injection. The Anthropogenic Test is the first RCSP Development Phase large-scale project to utilize anthropogenic, or manmade, CO_2 for geologic storage.

Development Phase Early Test detailed area of study.

Groundbreaking ceremony for the CO_2 capture unit at Plant Barry.

Anthropogenic Test site in Alabama.



The Green Pipeline. (Courtesy of Denbury Resources Inc.)

SECARB Commercialization Opportunities

Early opportunities for commercialization in the Southeast region most likely will be associated with an ability to offset the cost of capturing and storing CO_2. Utilizing CO_2-EOR is the primary candidate for offsetting costs in several SECARB States. Work conducted by SECARB in Gulf Coast formations will assist in expanding CO_2-EOR opportunities. Another candidate is ECBM recovery utilizing CO_2. Field tests conducted by SECARB in Central Appalachia and in the Black Warrior Basin of Alabama will assist in determining the technical and economic feasibility of ECBM.

Within the SECARB region, EOR is in place in Mississippi. Currently, the CO_2 that is used for EOR is coming from the Jackson Dome, a natural source of CO_2 located near Jackson, Mississippi. Denbury Resources operates a pipeline network that transports Jackson Dome CO_2 to oil fields in the Southeast. The Cranfield unit, near Natchez, Mississippi, is one EOR field operated by Denbury, and it is host to a SECARB Validation Phase small-scale injection and a Development Phase large-scale injection in the saline formation down dip of the EOR field.

Denbury Resources is developing and expanding a CO_2 pipeline network from the Jackson Dome to potential EOR sites in Mississippi, Louisiana, Texas Gulf Coast, and Alabama. Denbury also is establishing agreements with sources of CO_2 that can supplement the volumes of CO_2 produced at Jackson Dome. As a result, the Denbury pipeline system has the potential to become the regional backbone of an integrated network for CO_2.

Regional Incentives

Two initiatives in the SECARB region will help advance CCS deployment:

- As part of SECARB Validation Phase field investigation, Virginia Tech, Marshall Miller & Associates, and the Geological Survey of Alabama are evaluating the feasibility of capturing CO_2 from an industrial source and storing it in unmineable coal seams and associated saline formations in Central Appalachia and the Black Warrior Basin.

- As part of SECARB Development Phase field investigation, the Electric Power Research Institute and Southern Company (with operating units in Mississippi, Alabama, Georgia, and Florida) currently are evaluating CO_2 capture and separation technologies. The SECARB team plans to monitor the injection of 100,000 metric tons (110,000 tons) of anthropogenic (power plant) CO_2 from 2011 to 2014.

Integrating CCS into the Community

Outreach and education is a key component of success for all three phases of the SECARB program. During Characterization Phase, an action plan for outreach and education related to small-scale CO_2 storage field tests was developed. This action plan has been carried out in Validation Phase (small-scale demonstrations) and Development Phase (large-scale projects), which includes the SSEB leading the international, national, and regional effort, and the individual field teams leading the site specific public outreach activities. Each field site has hosted an Open House meeting to engage the local community and future CCS workforce. Hundreds of presentations have been delivered and posters displayed since the SECARB Program began in 2003 to share the details of the SECARB projects' definition, design, implementation, operation, and closeout activities with various audiences.

The overall guiding principles of the SECARB outreach and education program are as follows:

- Educating the individuals who will take responsibility for implementing site-specific education and outreach programs.
- Presenting the RCSP and SECARB Programs to various audiences.
- Developing education and outreach action plans.
- Identifying the materials and support needed to implement these plans.

Open House events at the Validation Phase Black Warrior Basin field test site in Alabama (below) and at the Validation Phase Mississippi Test Site in Mississippi (right).

The Development Phase Early Test site in Mississippi (left).

Open House at the Development Phase Anthropogenic Test site in Alabama (left) and the Validation Phase Central Appalachian Coal Seam site in Virginia (above).

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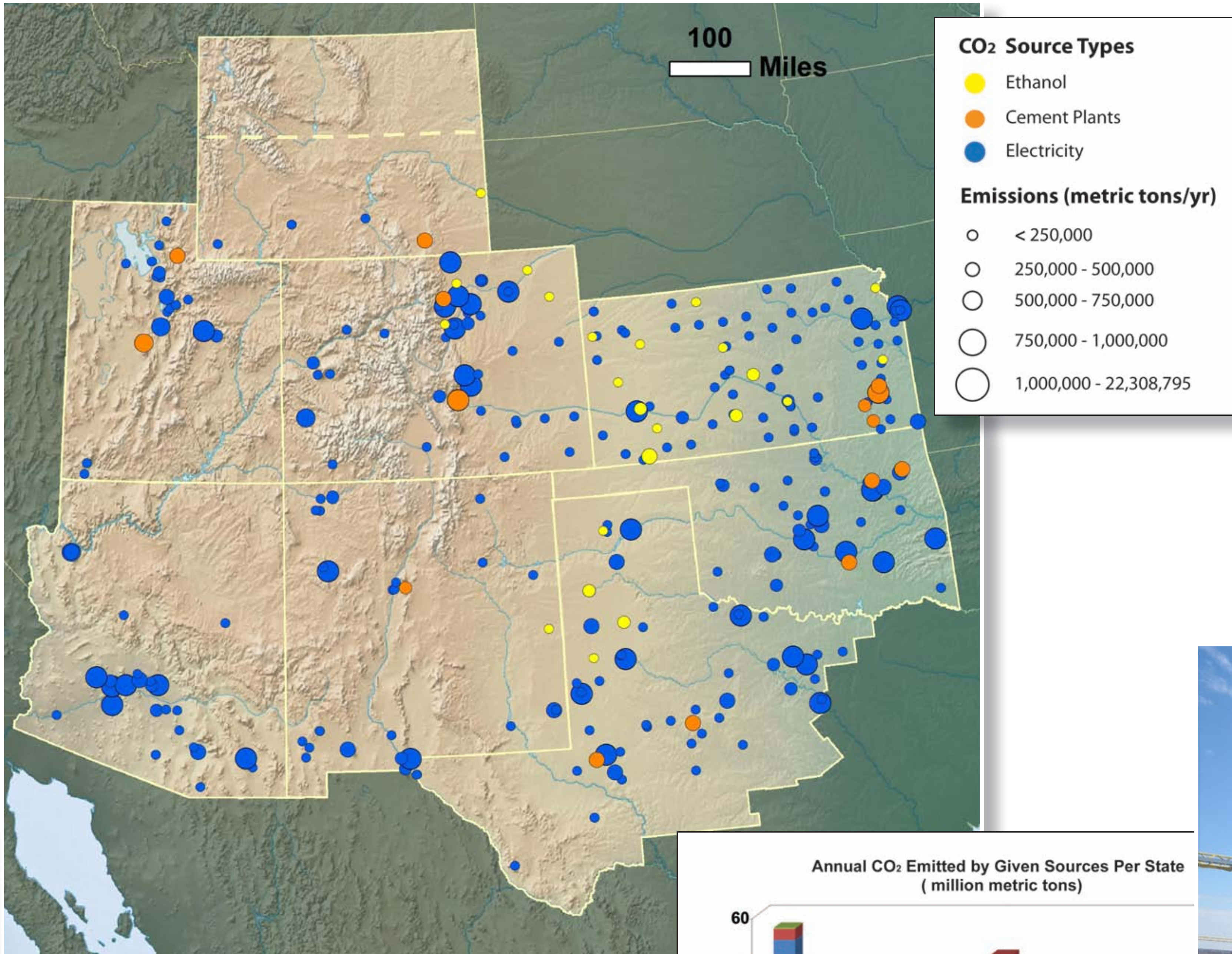
Southwest Regional Partnership on Carbon Sequestration

The Southwest Regional Partnership on Carbon Sequestration (SWP) continues to conduct and analyze several pilot-scale geologic CO_2 storage field tests in depleted oil reservoirs and unmineable coals seams that began in 2006. In 2010, these small- and medium-scale pilot tests will conclude, and SWP is setting the stage for a commercial-scale geologic storage deployment in a deep saline formation. Data and experience resulting from the SWP field tests will aid the development of technologies vital for the efficacy and safety of capture, utilization, and storage of CO_2 from the region's power plants and industrial sources.

The SWP includes a broad cross-section of professionals in geology, engineering, economics, public policy, and public outreach and education. Stakeholders in SWP projects include private industry, non-government organizations, government entities, and most importantly, the general public. Over 70 organizations are represented in the SWP, including electric utilities, oil and gas companies, State governments, universities, non-governmental organizations, and tribal nations. SWP is coordinated by the New Mexico Institute of Mining and Technology, and encompasses New Mexico, Colorado, Kansas, Oklahoma, Utah, and portions of Arizona, Texas, and Wyoming. Field sites for the region are located in New Mexico (San Juan Basin), Utah (Paradox Basin and Uinta Basin areas), and Texas (Permian Basin).

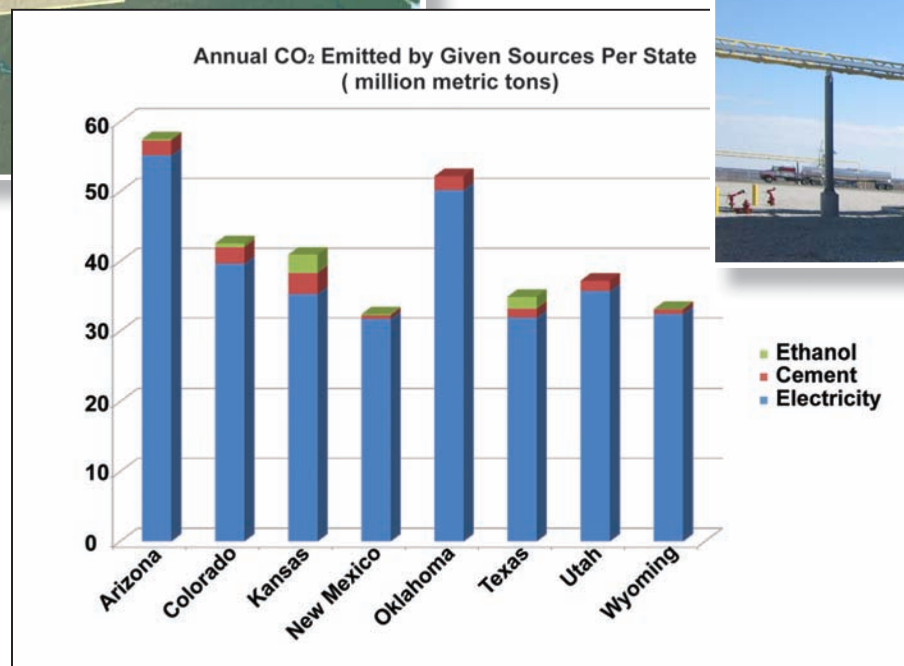


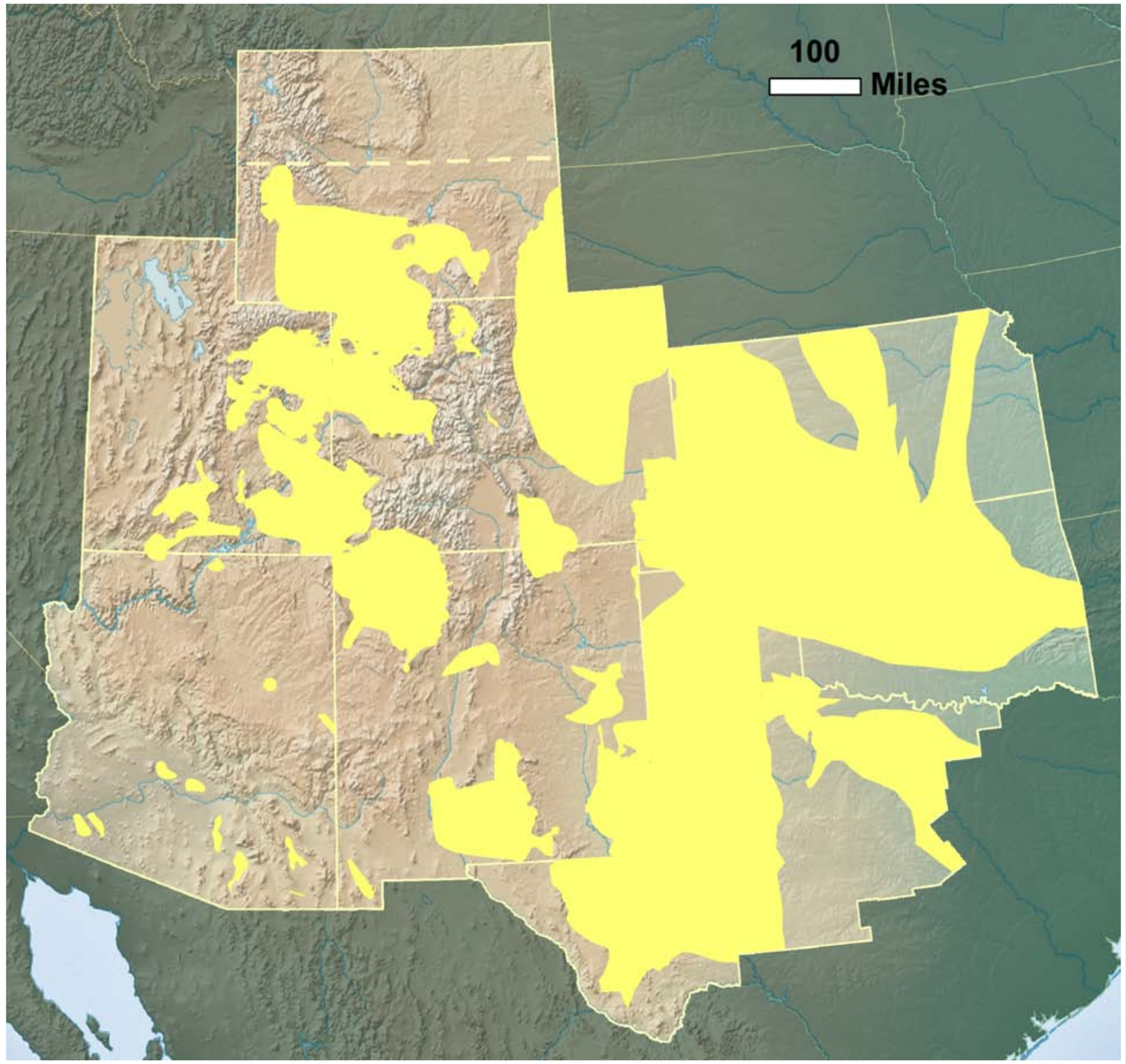
SWP CO_2 Sources

The SWP region possesses abundant resources of oil, natural gas, and coal, and the region's population and energy-production are growing faster than most other areas of the United States. Two major CO_2 pipeline networks transport more than 27 million metric tons (30 million tons) of naturally sourced CO_2 per year from large subsurface reservoirs in southern Colorado and northern New Mexico to petroleum fields in Texas, New Mexico, and Utah. This CO_2 is ultimately re-injected into the subsurface for EOR operations and other industrial uses. The 10 largest coal-fired power plants in the SWP region produce about 125 million metric tons (138 million tons) of CO_2 per year, approaching half of the total emissions in the region. Other stationary sources include natural gas processing plants, refineries, ammonia/fertilizer plants, ethylene and ethanol plants, and cement plants.

Ethanol plant in Kansas.

Over 300 electric power plants serve the Southwest region.

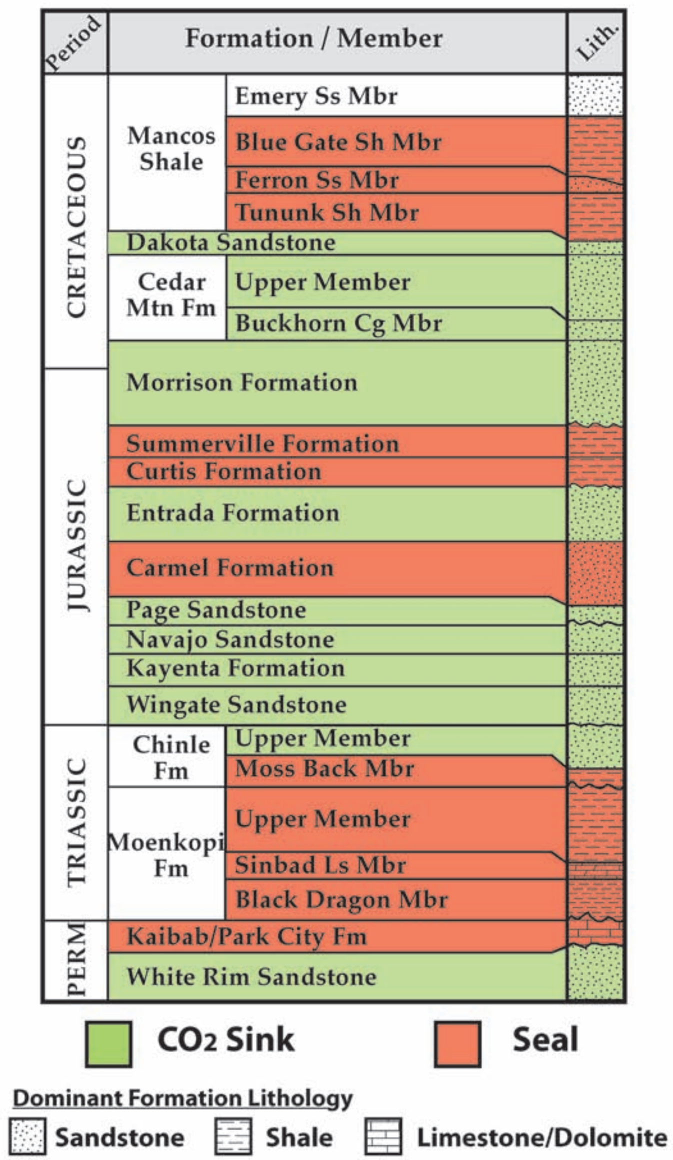




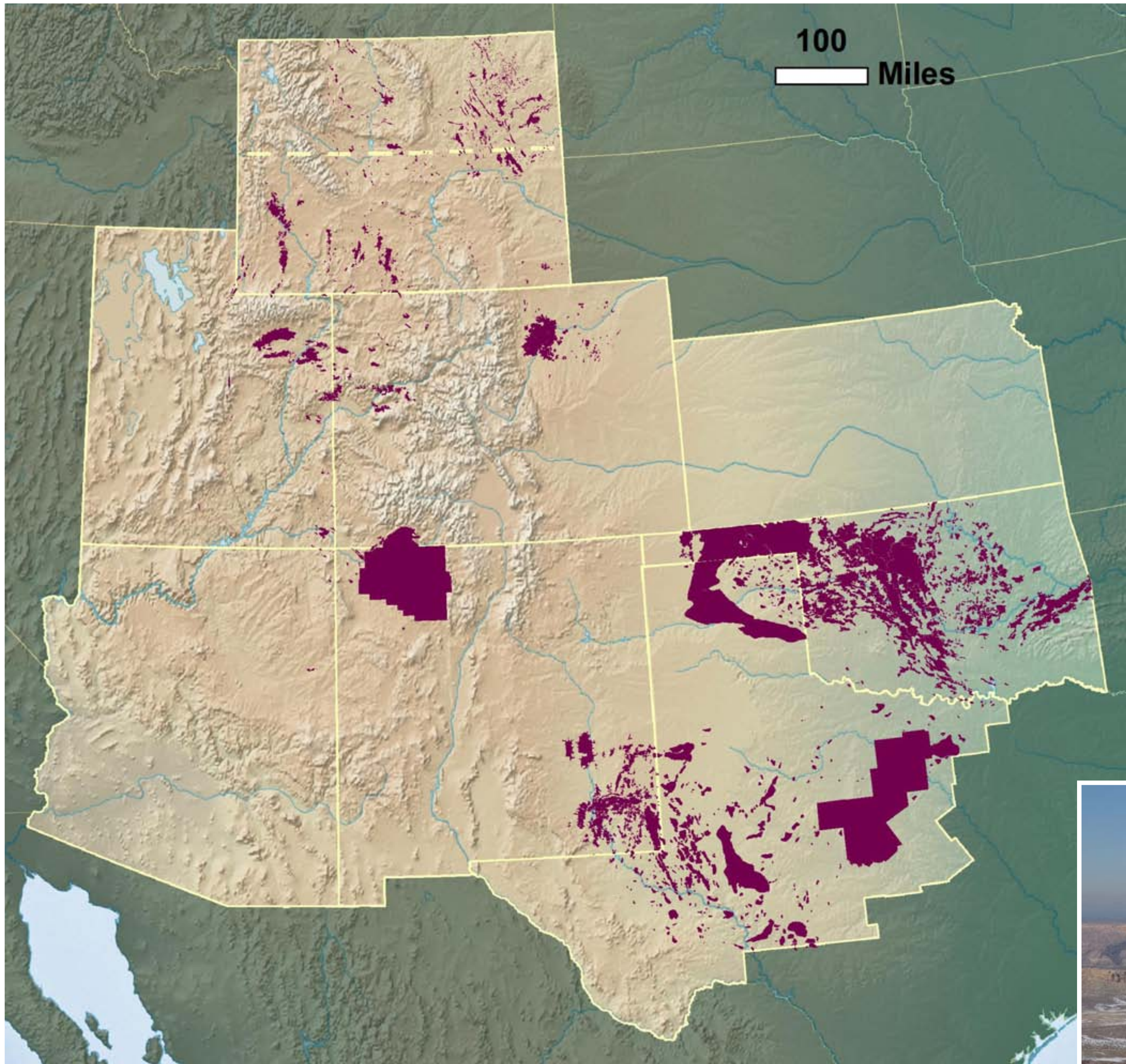
SWP Saline Formations

Within the SWP region, multiple interlayered saline formations with corresponding impermeable seals are common and widespread. These sequences, also called stacked saline formation systems, are considered ideal for the maximization of geologic CO_2 storage capacity and trapping efficacy.

Commercial-scale CO_2 storage will target many of the saline formations present in the SWP region. The sedimentary rock layers forming these stratigraphic sequences typically range from many thousands to tens of thousands of feet thick. In Utah and Colorado alone, two of the sequences forming stacked reservoirs and seal rocks are the Jurassic- and Cretaceous-aged rock sequences, exceeding 2 miles in cumulative thickness. These sections were deposited in the range of 65 to 200 million years ago at a time when extensive coastal dunes covered much of the region, followed by transgressive (rising) inland seas. Deposits of coastal dunes, such as those currently exposed at the surface in areas of southern Utah and Arizona, typically possess reservoirs of excellent (high) porosity and permeability. These in turn are overlain by tidal flat mudstones, evaporite formations, such as salt layers, and marine carbonates. These formations typically exhibit low porosity and permeability, and thus serve as barriers to undesirable CO_2 migration. The Dakota Sandstone, in particular, is a complex mix of marine deposits overlain by many thousands of feet of marine Mancos Shale. In the SWP region, the cumulative CO_2 storage resource of saline formations is estimated to exceed 90 billion metric tons (99.2 billion tons).



Saline Formation CO_2 Storage Resource by State (million metric tons)		
State	Low Storage Resource	High Storage Resource
Arizona	100	1,600
Colorado	30,900	424,300
Kansas	1,200	16,400
New Mexico	32,100	441,600
Oklahoma	5,668	77,931
Texas	639,700	3,818,500
Utah	21,000	288,700
Wyoming	87,400	1,202,200



SWP Oil and Gas Reservoirs

The sedimentary history of the SWP region, combined with its complex tectonic history, resulted in many productive oil and gas reservoirs. Geologic processes created thick stratigraphic sequences predominantly ranging in age from Mississippian (350 million years) to Eocene (35 million years). Much of the region's deposition began in the Mississippian with a shallow sea that deposited organic-rich limestone formations. From the Triassic through the Jurassic, thick sequences of terrestrial sandstones were deposited. An inland sea encroached during the Cretaceous, again depositing thick, organic-rich rocks. As this sea retreated, terrestrial sandstones were deposited and presently function as reservoirs. These reservoir rocks are capped by thick shale, which serve as stratigraphic seals.

Oil and gas production in the SWP region began in the early 1900s and continues today. Currently, oil and gas production remains fairly steady and the region's states rank high for national production (excluding offshore reserves). As these reservoirs are depleted (e.g., Colorado has 40,000 abandoned wells), they become excellent candidates for commercial-scale CO_2 storage.

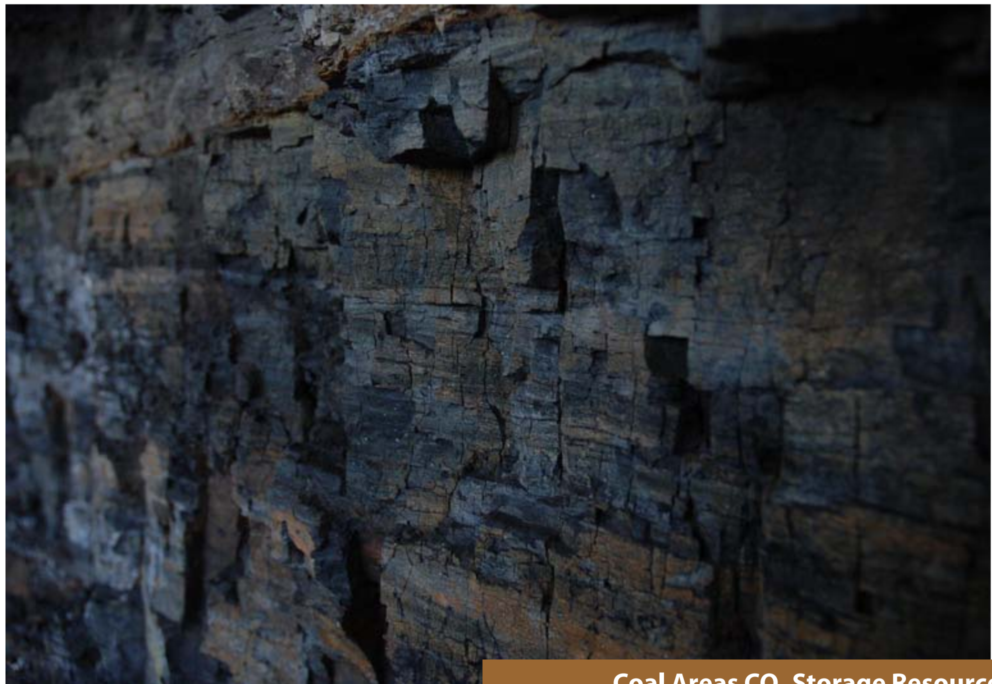
Oil and Gas Reservoir CO_2 Storage Resource by State (million metric tons)

State	CO_2 Storage Resource
Arizona	7
Colorado	1,723
Kansas	1,640
New Mexico	8,246
Oklahoma	10,012
Texas	41,968
Utah	1,405

Pump jack at the Aneth Oil Field, Utah. (Courtesy of Resolute Energy)

SWP Unmineable Coal Areas

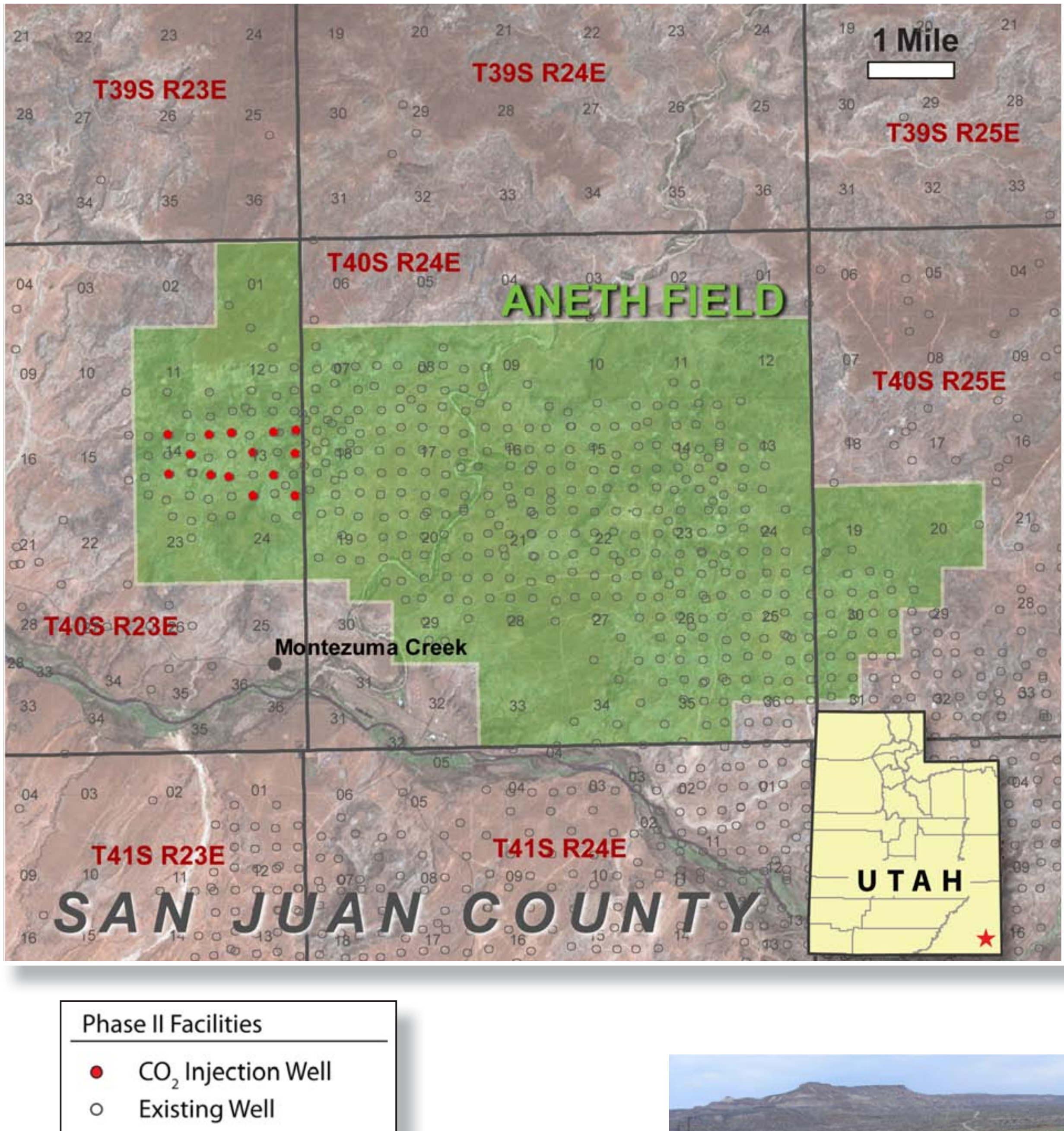
The geologic history of shallow inland seas has produced many significant coal deposits throughout the SWP region. A notable example is the Cretaceous Fruitland Formation, which contains over 209 billion metric tons (230 billion tons) of coal and is the major coal source in the San Juan Basin of New Mexico and Colorado. Unmineable coal seams (coal that is too deep, of poor quality, thin and discontinuous, etc.) are common in the SWP region and potentially yield significant CO_2 storage opportunities.



Many subsurface coal seams are potential storage opportunities.

Coal Areas CO_2 Storage Resource by State (million metric tons)

State	Low Storage Resource	High Storage Resource
Arizona	0.1	0.1
Colorado	489.3	857.3
Kansas	2.1	8.4
New Mexico	75.4	301.8
Oklahoma	1.8	7.4
Utah	30.5	122.1
Wyoming	194.3	777.2



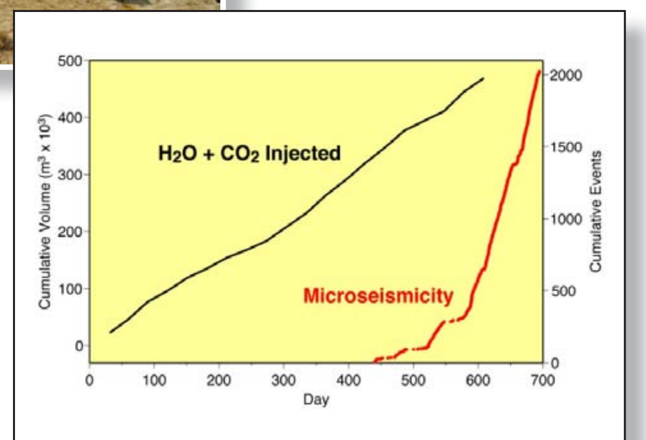
Paradox Basin, Utah: Enhanced Oil Recovery

At the Aneth Oil Field near Bluff, Utah, SWP is completing a CO_2-EOR storage test in an active site managed by Resolute Natural Resources Company and the Navajo Nation Oil and Gas Company. From August 2007 until October 2009, a total of 433,000 metric tons (477,000 tons) of CO_2 was injected into the oil-bearing strata of the Aneth Field over a 2-year period. The primary CO_2 storage targets were the limestones of the Pennsylvanian Desert Creek and overlying Ismay members of the Paradox Formation located in the range of 5,600 to 5,800 feet below the ground surface.

The SWP is continuing to utilize extensive geologic characterization, detailed reservoir models, tracer studies, and geophysical surveys to simulate and monitor the migration of the injected CO_2. In particular, a permanent subsurface seismic array has detected an increase in microseismic energy that appears to be correlated to oil, brine, and CO_2 migration in the oil reservoir. Though the daily microseismic events are too small to be felt at the surface, the specific locations of these events has been invaluable for locating fluid migration pathways, something typically difficult to measure.

Installation of subsurface geophone array at the Aneth Oil Field, Utah.

Injection headers at the Aneth Oil Field, Utah. Each valve controls the injection of CO_2 to an individual well.

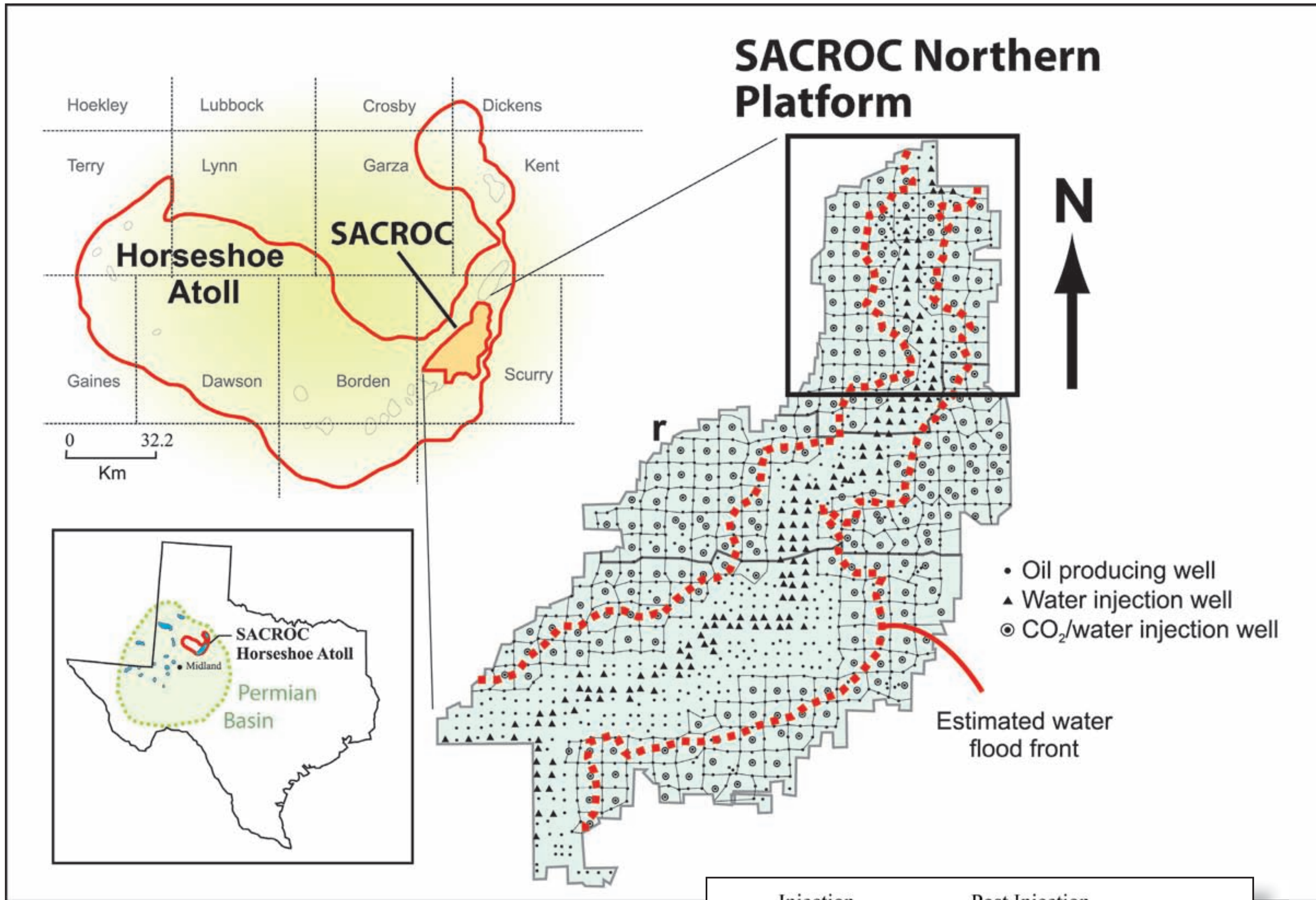


Graph showing correlation between microseismicity and $H_2O + CO_2$ injection at the Aneth Oil Field, Utah.

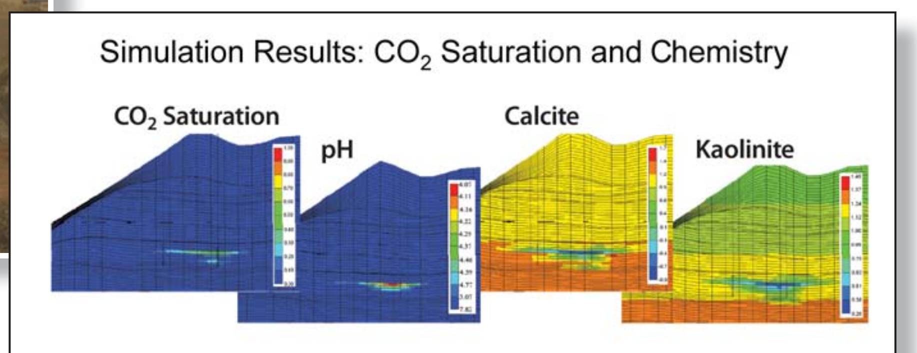
Permian Basin, Texas: Enhanced Oil Recovery and Storage

The SWP is evaluating CO_2-EOR efficiency and CO_2 storage optimization in the SACROC unit of the Permian Basin in Texas, in cooperation with Kinder Morgan CO_2 Company. The total injection rate in the SACROC field exceeds 1,000,000 metric tons (1,100,000 tons) of CO_2 per year. However, the SWP focused on a small area of the field, and its Validation Phase test included comprehensive monitoring and analysis of a small-scale (4 km^2) area surrounding an injection well. Approximately 78,000 metric tons (86,000 tons) of CO_2 was injected in this well during 2009, and injection continued into 2010. Injection targets are the Pennsylvanian-aged, carbonate-rich Cisco and Canyon groups at approximately 6,300 to 7,100 feet below the ground surface.

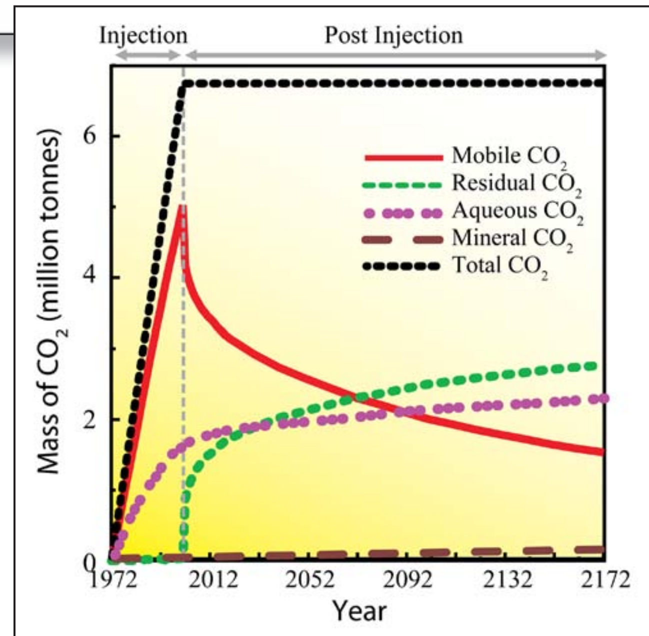
Monitoring efforts continue today, with results evaluated using computational reservoir models that include coupling of multiphase CO_2-groundwater flow with rock deformation and chemical reactions. Model results include estimates of residence times, migration rates, patterns, and CO_2 trapping mechanisms.



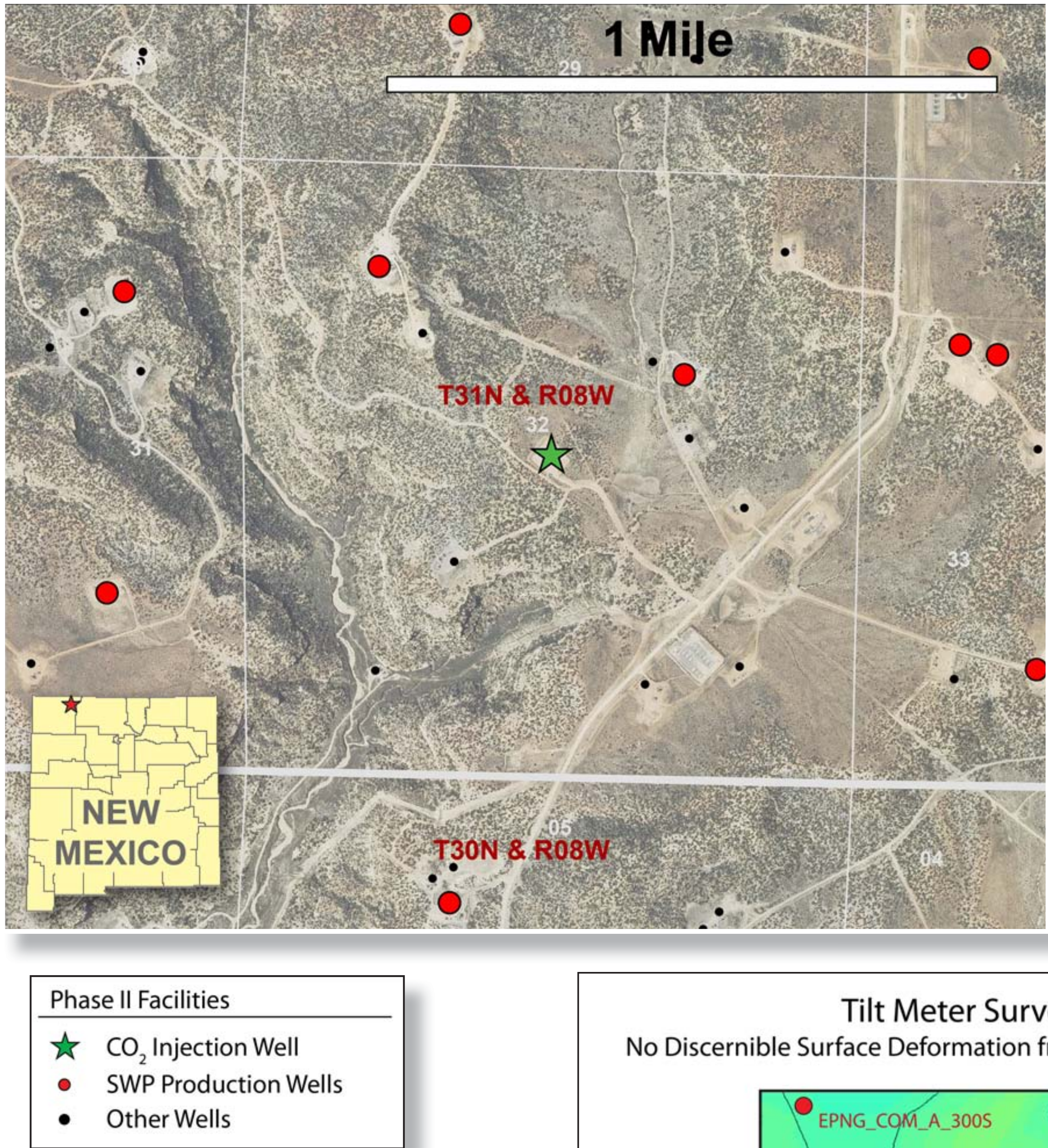
Aerial photo of field operations at SACROC, Texas, including CO_2 injection, EOR, and CO_2 recycling.



Predictive results for simulation of 100,000 metric tons (110,000 tons) of CO_2 injected into the SACROC field. Diagrams show simulated results 2 months after injection.



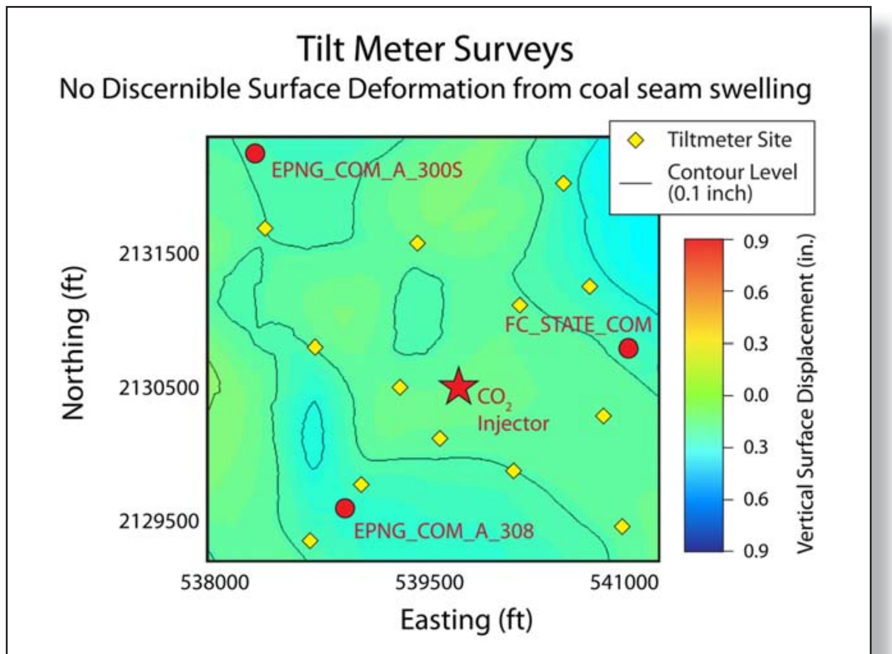
Using known CO_2 injection history from the SACROC field, long-term CO_2 trapping mechanisms were estimated.



San Juan Basin, New Mexico: Enhanced Coalbed Methane

In cooperation with ConocoPhillips, the SWP Validation Phase test in the San Juan Basin of New Mexico helped validate technologies specific to CO_2 injection in deep coal seams and ECBM production. The 1-year injection test began in mid-2008 and targeted the coal-bearing Fruitland Formation at a depth of approximately 3,000 feet. The SWP test goal was to inject 68,000 metric tons (75,000 tons) of CO_2 during the year, but reduced injectivity restricted the ultimate amount to approximately 18,400 metric tons (20,300 tons) of CO_2. However, test results confirm that the San Juan Basin is an excellent target for future CO_2 storage opportunities, especially when considering the large number of nearby power plants, relatively low operating costs, and well-developed natural gas and CO_2 pipeline infrastructure.

SWP developed a suite of monitoring methods tailored specifically for CO_2 storage in subsurface coal seams. Results suggest that coal may swell with the introduction of CO_2, and technology capable of detecting surface and subsurface deformation was critical. While the sensitive instrumentation in and around the CO_2 injection site has detected swelling, the results do not reflect systematic trends.



Tilt meter results indicated no systematic surface deformation after injection.

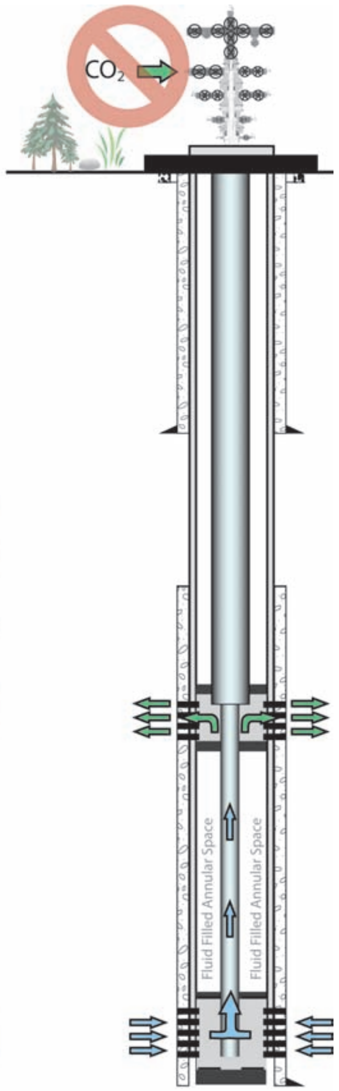
Areal photo of San Juan Basin, New Mexico.

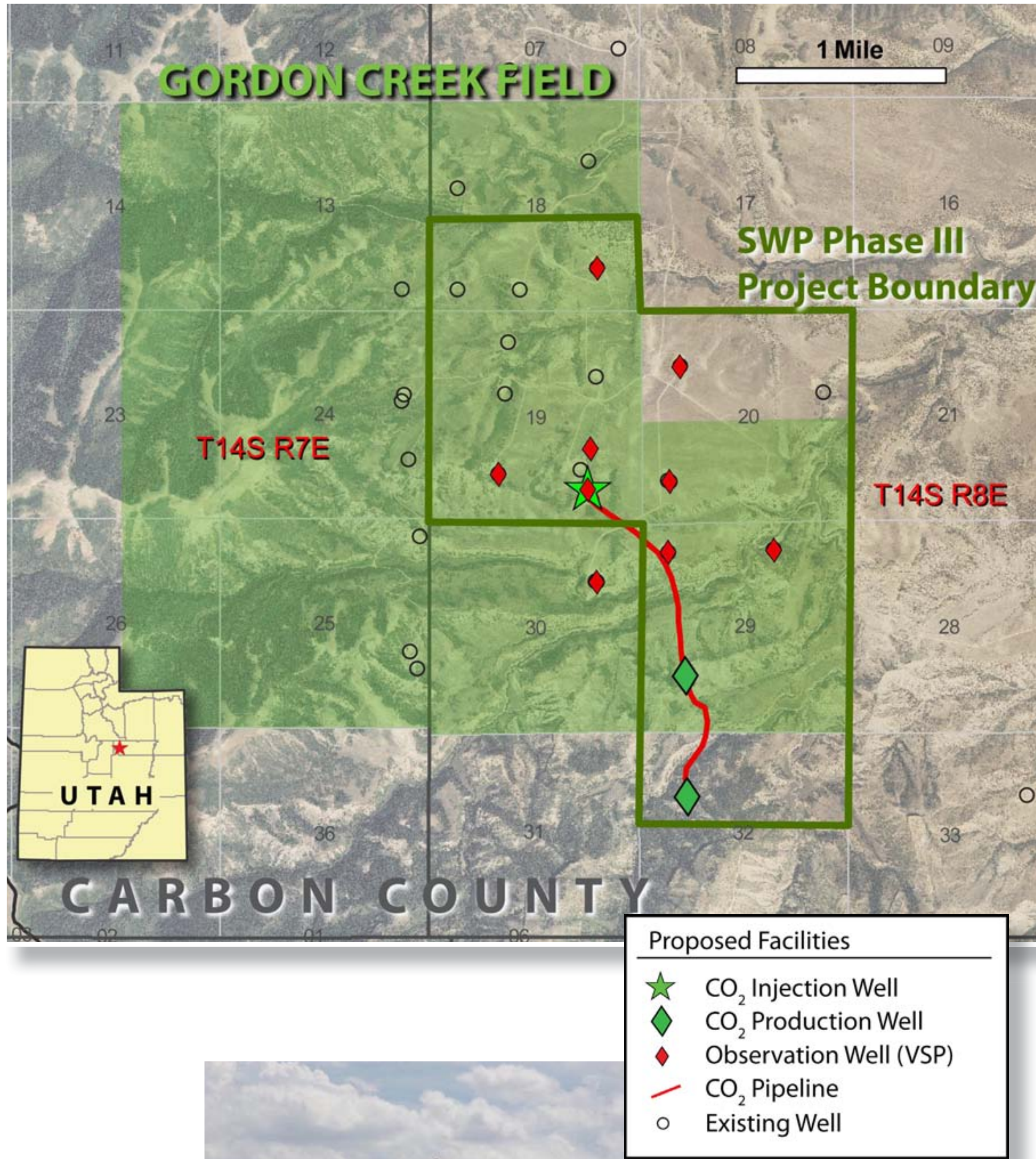
Commercial-Scale Deep Saline Project

For its commercial-scale deep saline project, the SWP will inject commercial-scale amounts of CO_2 into the Navajo Sandstone in a field along the western edge of the Uinta Basin in central Utah. Based on the SWP's extensive experience with previous tests, commercial-scale storage operations favor existing oil/gas fields to: (1) capitalize on existing infrastructure, (2) take advantage of existing regulatory groundwork, and (3) facilitate monitoring networks (e.g., in situ sensors and seismic arrays) in existing wells. Likewise, oil/gas fields often have significantly more site characterization data compiled, facilitating more effective engineering and monitoring methods. Accordingly, the SWP has partnered with Thunderbird Energy Corporation, the operator of the methane-producing Gordon Creek Field, to evaluate many of the geologic formations that are potential storage target reservoirs across the Southwest Region.

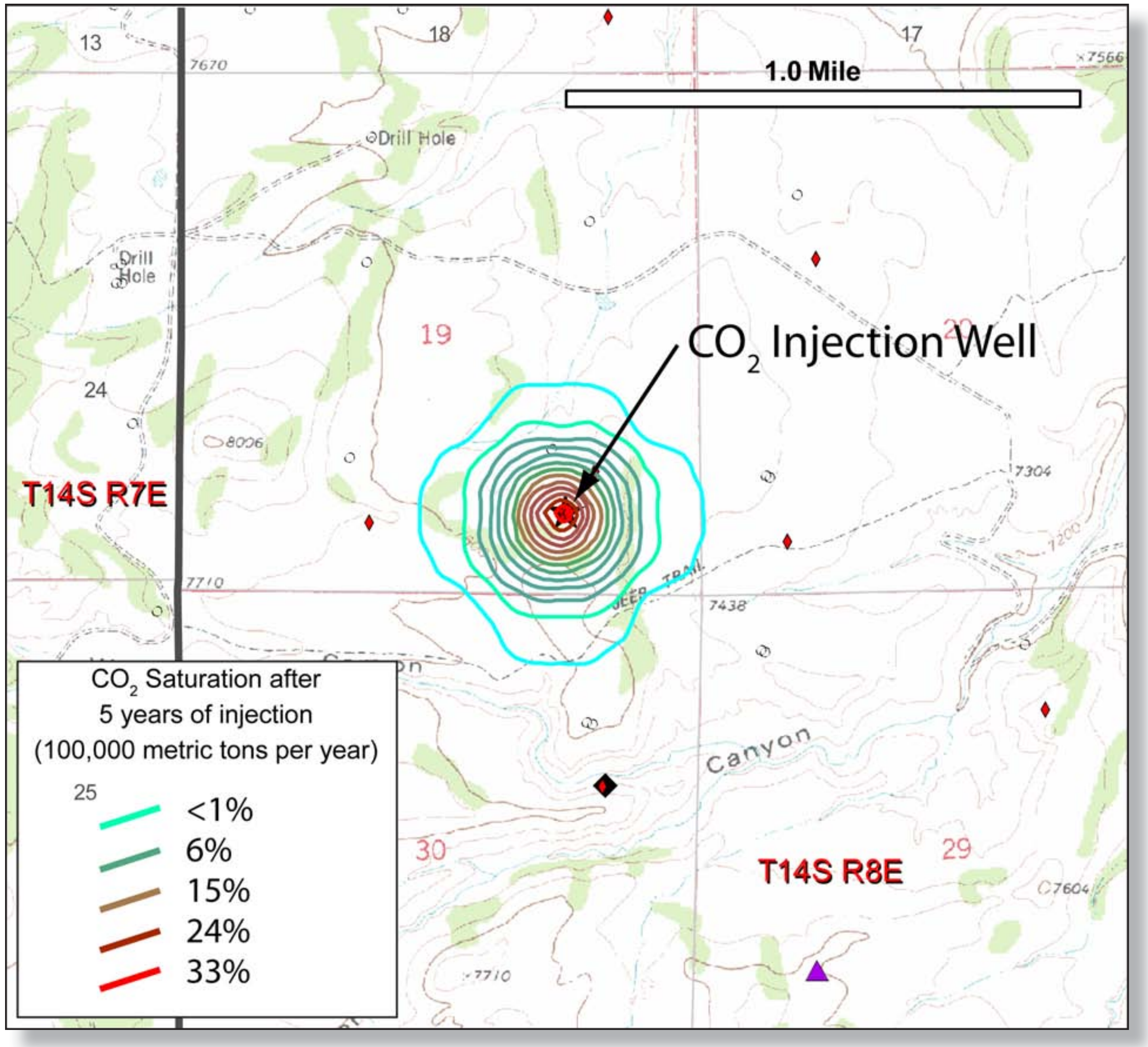
Period	Symb	Formation / Member		Thickness (feet)	Depth (feet)*	Lith.
CRET	Km	Mancos Shale	Emery Ss Mbr		0	
			Blue Gate Sh Mbr	<250	3115	
			Ferron Ss Mbr	10-110	3250	
			Tununk Sh Mbr	200-300	4000	
	Kd	Dakota Sandstone		0-30	4025	
	Kcm	Cedar Mtn Fm	Upper member	150-750	4120	
			Buckhorn Cg Mbr	0-50		
JURASSIC	Jm	Morrison Formation		800±	4460	
	Js	Summerville Formation		120-180	5895	
	Jct	Curtis Formation		140-180	6275	
	Je	Entrada Formation		150-950	6585	
	Jc	Carmel Formation		300-700	7650	
	Jc	Page Sandstone		<70		
	Jgc	Navajo Sandstone		150-300	8400	
		Kayenta Formation		120-200	8750	
		Wingate Sandstone		300-400	8885	
TRIASSIC	Trc	Chinle Fm	Upper member	200-300	9225	
			Moss Back Mbr	20-60		
	Trmt	Moenkopi Fm	Upper member	550-700	9520	
	Trms		Sinbad Ls Mbr	50	10460	
	Trmbd		Black Dragon Mbr	250-350		
PERM	Ppc	Kaibab/Park City Fm		170	10890	
	Pwr	White Rim Sandstone		500-700	11135	

Source of CO_2 CO2 Sink CO2 Seal





View from Gordon Creek.



Simulated CO_2 migration within the Navajo Sandstone in the Gordon Creek Field, assuming 5 years of injection, 100,000 metric tons per year. Maximum migration diameter is approximately 0.5 miles.

Development Phase Geologic Pilots

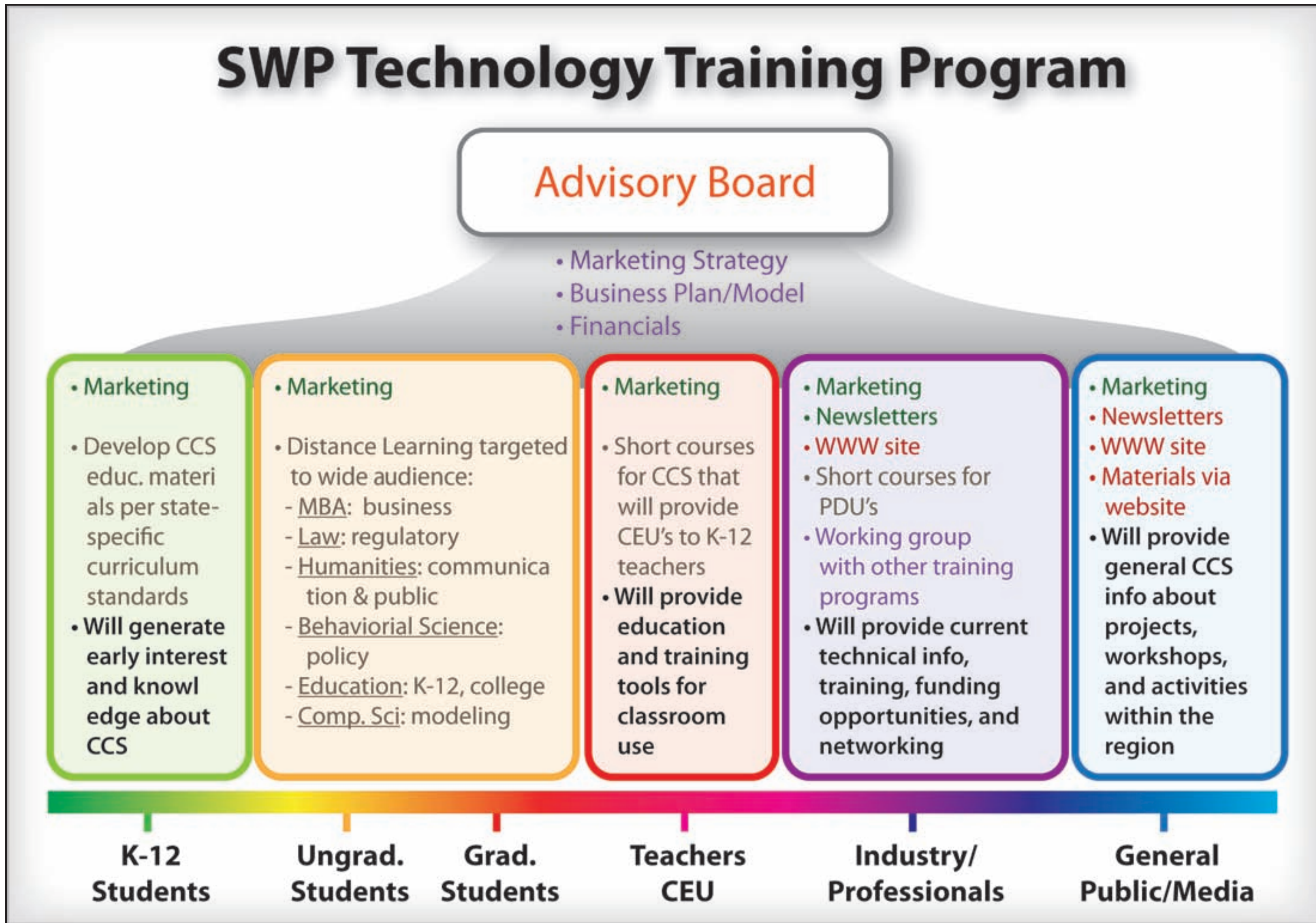
Gordon Creek Field—Commercial-Scale CO_2 Storage

Highlights of the SWP commercial-scale deployment include:

- High porosity and permeability sandstone units exist in most States of the SWP, PCOR, and Big Sky regions.
- Jurassic- and Permian-aged deep saline formations are present in basins throughout the SWP.
- Target formations are the Jurassic Entrada Formation and Navajo Sandstone, which are both porous and permeable eolian units.
- Preliminary research coordinating field study and computer modeling of subsurface flow paths is currently underway.
- Injection of a proposed 908,000 metric tons (1 million tons) per year ensures that the system is evaluated at commercial storage conditions.
- Technical aspects of emphasis include sustained injectivity, capacity, monitoring efficiency, and meaningful risk assessment.
- Modeling of CO_2 plume migration suggests this site will be stable with minimal migration of CO_2 over 5 years.
- This comprehensive evaluation will provide boundary conditions and constraints for application to other future commercial storage sites.

Monitoring Technique(s)	Application
Remote sensing (InSAR, GPS)	Monitor surface deformation.
Air, soil gas tracers (Soil flux, natural and artificial tracers)	Monitor for potential leakage pathway at surface.
Water/brine sampling (isotopes, natural and artificial tracers)	Monitor for CO_2 migration in subsurface formations.
Wellbore measurements (Downhole pressure/temperature, Tiltmeters, Sonic)	Monitoring of subsurface well characteristics.
Logging (porosity, permeability, lithology)	Subsurface engineering and geological characterization.
Geophysics (2-D/-3D/4-D Seismic, VSP)	Monitoring of CO_2 plume migration and injected-related stress.

Above: Areal photo of the Gordon Creek Field, Utah, with marked well positions. At right: Installation of the Gordon Creek Field water disposal pipeline.



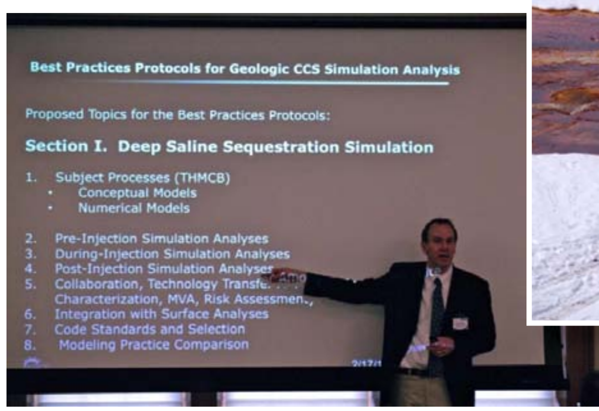
Integrating CCS into the SWP Community

From 2008 to 2010, the SWP partnered with the Research Experience in Carbon Sequestration (RECS) Program to attract graduate students and early career engineers to the CCS field. In 2010, the 10-day program focused primarily on CCS applications using group exercises, field tours, and safety training. This annual event is a groundbreaking step in combating the growing need in the energy industry for a wealth of young engineering talents. RECS participants are given the opportunity to learn from top industry professionals and RECS alumni. For more information on the program, readers are encouraged to access www.recsco2.org.

Other highlights of the SWP Outreach and Education Program include:

- Community Involvement and Outreach Opportunities.
- Town Hall Meetings.
- Student Internships.
- Lab Tours.
- Technology Training Program.

Jason Heath from New Mexico Tech instructing class participants on the use of infrared gas analyzer for the purposes of monitoring surface CO_2 soil gas flux.



International Energy Agency Greenhouse Gas Meeting, Salt Lake City, February 2010.

IEA-GHG field trip to Crystal Geyser, Utah, February 2010.

Southwest Regional Partnership on Carbon Sequestration Contacts

If you have any questions, comments, or would like more information about the SWP, please contact the following individuals:

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Please visit: http://www.southwestcarbonpartnership.org/.

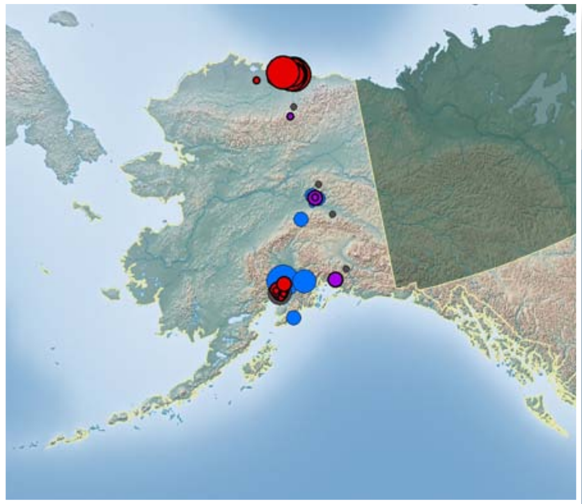
West Coast Regional Carbon Sequestration Partnership

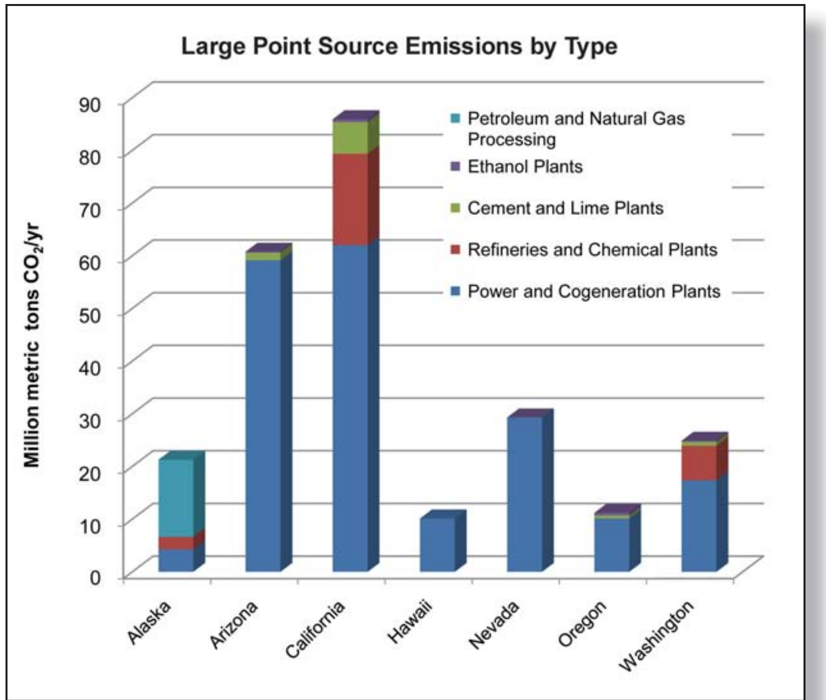
The West Coast region, consisting of the States of Alaska, Arizona, California, Hawaii, Nevada, Oregon, Washington, and the Canadian province of British Columbia, is characterized by a wealth of natural resources, varied ecosystems, complex geology, and a culturally diverse population, which has both a strong entrepreneurial spirit and sense of environmental responsibility. The region has one of North America's broadest mixes of CO_2 sources and opportunities to curb atmospheric CO_2 buildup through carbon storage.

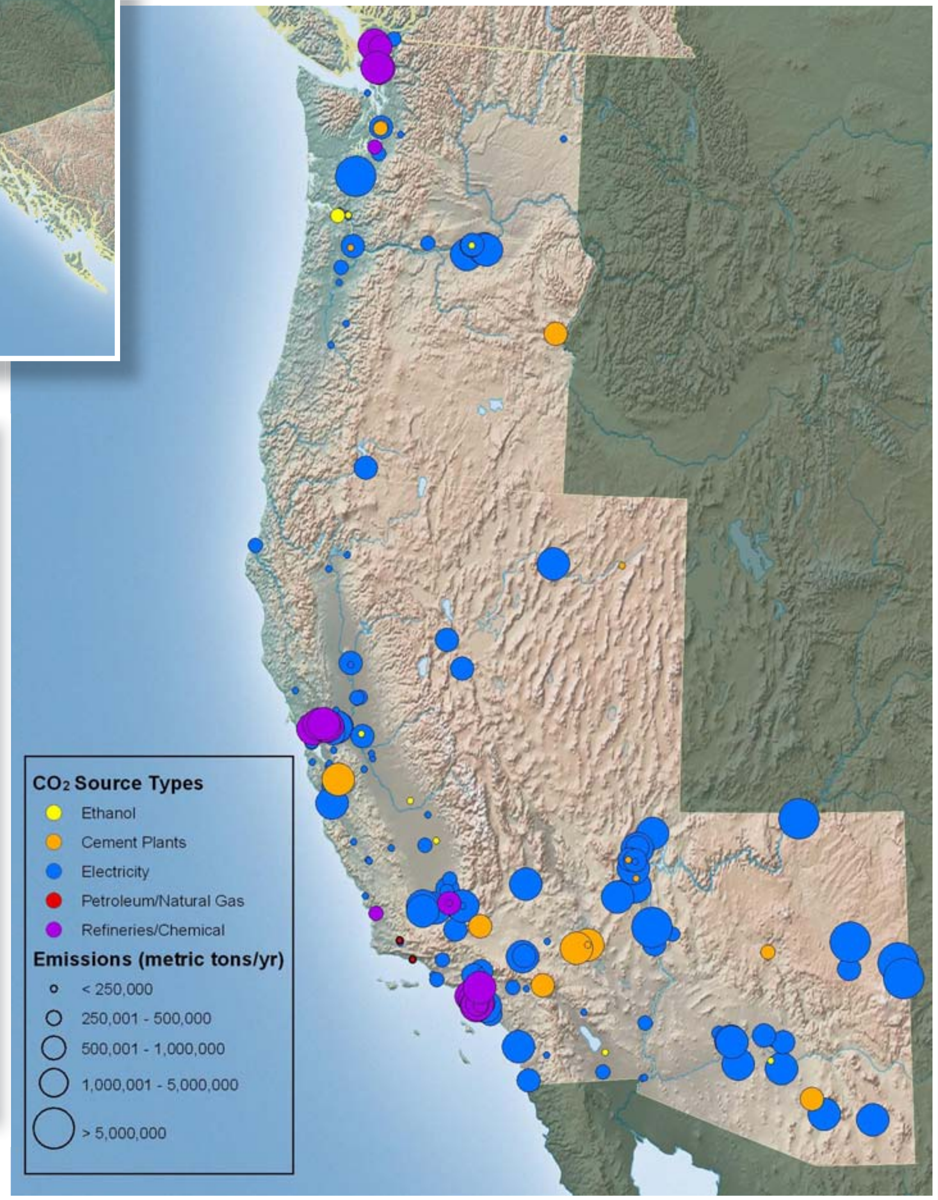
The West Coast Regional Carbon Sequestration Partnership (WESTCARB), led by the California Energy Commission in partnership with Lawrence Berkeley and Lawrence Livermore National Laboratories, includes members from more than 90 public agencies, private companies, and nonprofit organizations. WESTCARB's goals are to characterize regional opportunities for geologic and terrestrial carbon storage; validate the feasibility, safety, and efficacy of some of the best regional opportunities through field tests; and demonstrate geologic storage at a larger scale.

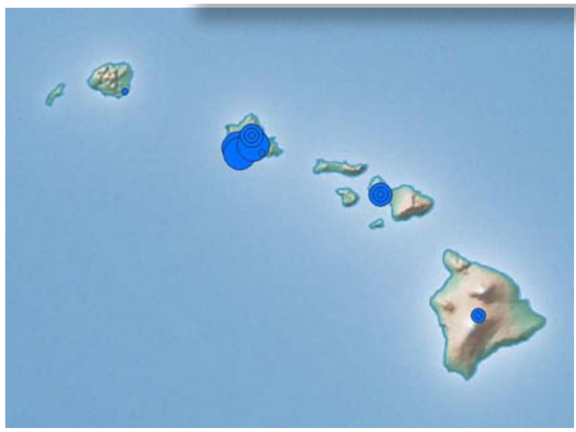
The geology of the WESTCARB region is varied, ranging from the shield volcanoes of Hawaii to tectonic plate margins along the U.S. and Canadian western coastlines, to interior regions featuring mountains and large and small sedimentary basins. WESTCARB geologic characterization studies show excellent carbon storage potential throughout the region. Numerous opportunities for EOR, as well as some for ECBM, offer the potential for geologic storage to be coupled with energy production. In addition, saline formations in broadly distributed sedimentary basins have the potential to store hundreds of years' worth of the region's stationary CO_2 source emissions. Terrestrial storage opportunities rank among the best in North America and may provide a viable approach to offsetting some of the region's substantial transportation-related CO_2 emissions.

WESTCARB has a strong commitment to outreach and education, and it operates in a receptive environment, where policymakers have taken steps to address climate change through enactment of laws, regulations, and initiatives to reduce GHG emissions. WESTCARB members are actively engaged in creating a future where carbon storage can be commercially applied to curb atmospheric CO_2 buildup from fossil fuels, while sustaining healthy economies during the transition to carbon-free energy systems.









WESTCARB CO_2 Sources

Mirroring national trends, electric power plants are the largest CO_2 stationary source type in the WESTCARB region, although the fuel mix used for power generation varies considerably among WESTCARB States. Arizona is home to some of the region's largest coal-fired plants, whereas natural gas combined cycle plants are predominant in California and significant in several other states. Hawaii relies chiefly on oil-fired generation.

Alaska is unique within the WESTCARB region in that oil and natural gas processing dominate CO_2 emissions. Oil refining is also a major emission source in California. Throughout the region, other significant industrial CO_2 sources include cement and lime plants, aluminum smelters, ethanol fermenters, steel mills, and fertilizer plants.

In California, the most populous WESTCARB State, emissions from the transportation sector are especially large. Mobile source emissions constitute a relatively large percentage of total emissions in several other WESTCARB States as well. This underscores the importance of developing terrestrial storage options, as well as deploying geologic storage on traditional and alternative transportation fuel plants to provide offsets of these hard-to-capture emissions. In addition, CO_2 emissions from ethanol and alternative fuel plants have the potential to grow rapidly as the industry expands to meet California's emission performance standards.

Overall, the WESTCARB CO_2 sources database includes information on more than 250 of the largest emitting point sources in the WESTCARB region. Geographic information system tools for analyzing WESTCARB point sources and assessing their proximity to potential regional CO_2 storage locations are available through the WESTCARB Carbon Atlas and through NATCARB.

WESTCARB Saline Formations

Deep sedimentary basins are broadly distributed throughout the WESTCARB Region. Many contain saline formations suitable for CO_2 storage. Research is ongoing to bolster confidence that the high salinity levels of formation waters preclude them as a source for potable water. Researchers also continue to assess sealing formations and to estimate saline formation capacity for storing large volumes of the region's industrially produced CO_2.

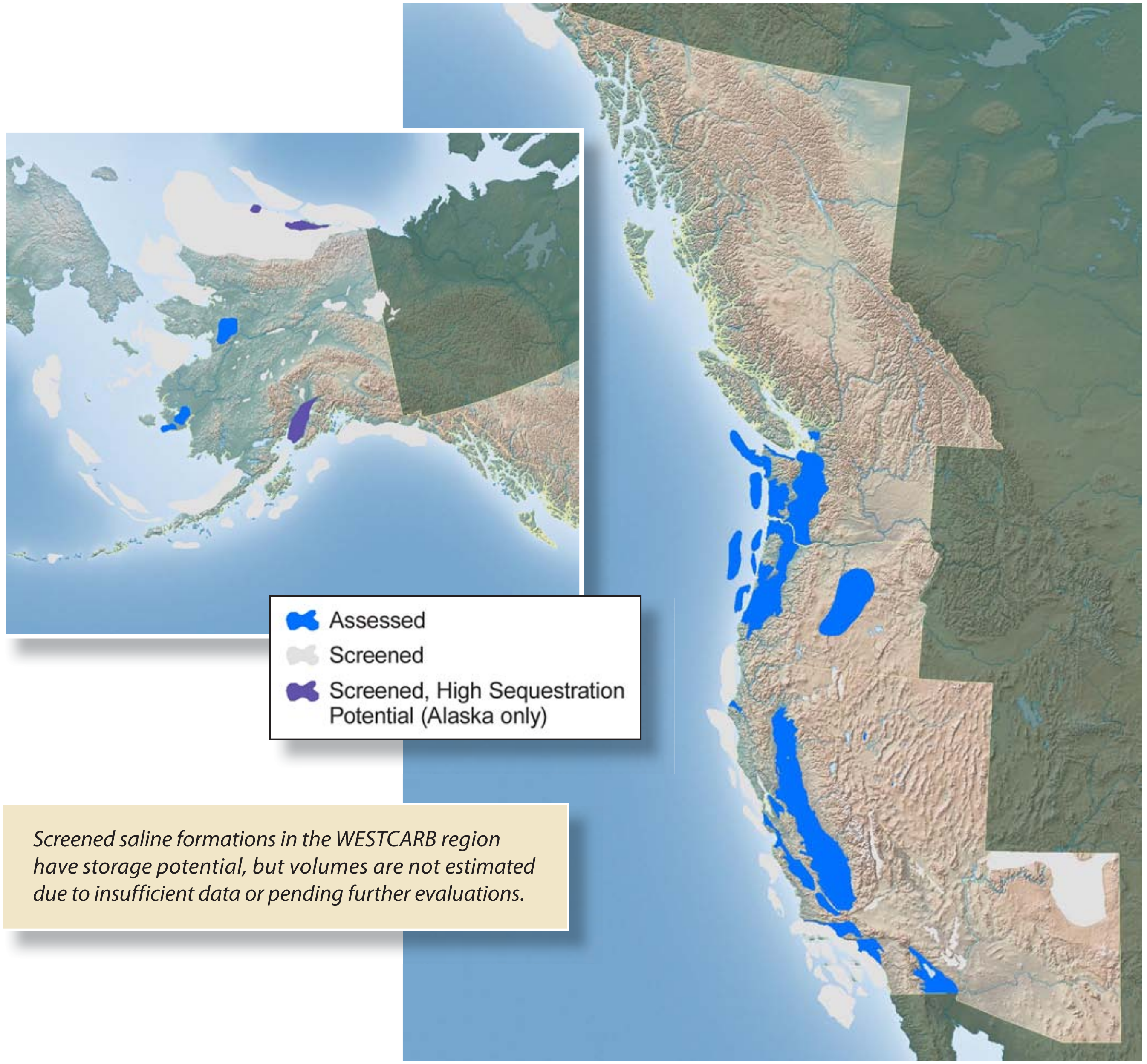
In California, Cenozoic sedimentary basins offer some of the best opportunities for geologic storage. These basins exhibit a wide areal distribution, thick sedimentary sections containing multiple widespread marine sandstones, and thick and laterally persistent marine shale seals. Petrophysical data from oil and gas development support assessments in some basins. California may also be a candidate for CO_2 storage in offshore basins, although the lack of available data has limited the assessment of their CO_2 storage potential to areas where oil and gas exploration has occurred. An ARRA-funded study of the Pliocene and Miocene formations of the Wilmington Graben, directly offshore the Los Angeles and Long Beach Harbor areas, is currently underway. Onshore, WESTCARB ranks the San Joaquin, Sacramento, Ventura, Los Angeles, and Eel River Basins as the most promising basins in California. Researchers estimate the aggregate CO_2 storage resource of the largest onshore basins in the range of 30 billion to 420 billion metric tons (30 billion to 460 billion tons) of CO_2.

In Oregon and Washington, western coastal basins may contain sites suitable for CO_2 storage. These basins contain sandstone and shale sequences up to 10,000 meters (33,000 feet) thick. The largest in terms of potential CO_2 storage resource is Washington's Puget Trough. The total CO_2 storage resource for the sedimentary basins is in the range of 40 billion to 590 billion metric tons (50 billion to 650 billion tons).

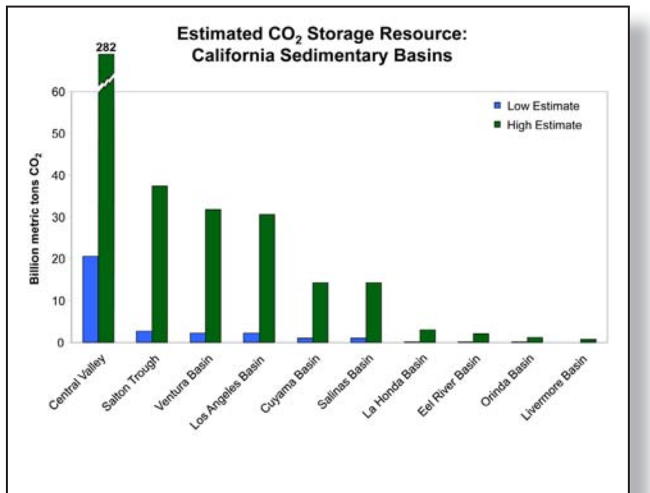
In Arizona, formations underlying the Colorado Plateau region, where most of the State's large coal-fired power plants are located, offer potential storage targets and seals that are laterally extensive and up to hundreds of feet thick. Paleozoic formations and Tertiary basins may also represent storage opportunities and will be included in a new WESTCARB study.

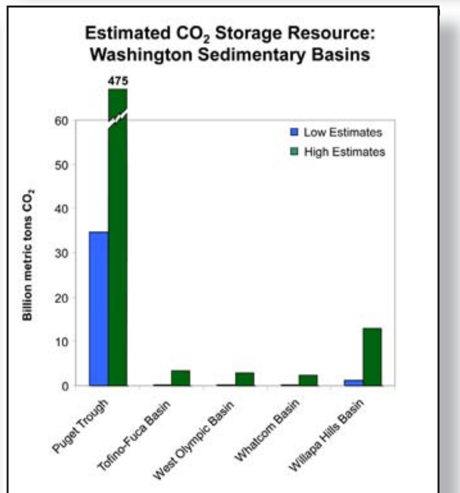
In Alaska, difficulties with site access and harsh working environments place practical limits on characterization and utilization of the CO_2 storage resource. Researchers are focusing on the Cook Inlet Basin and North Slope, where proximity to industrial CO_2 sources and extensive infrastructure, as well as ample characterization data from oil and gas exploration, make CO_2 storage more feasible.

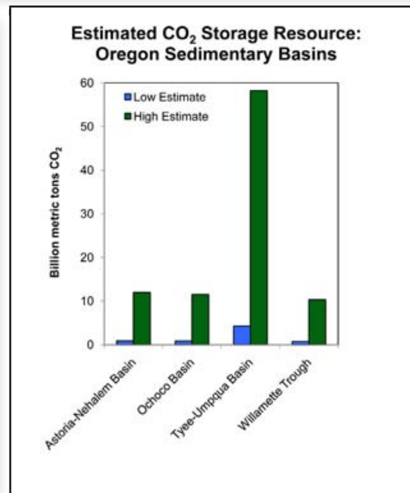
For CO_2 storage in Nevada, Granite Springs Valley in Pershing County, Antelope and Reese River Valleys in Lander County, and Ione Valley in Nye County appear sufficiently large areally and are filled with sediments and volcanic rocks. Site characterization studies are needed to determine if CO_2 storage capacity exists beneath these valleys.

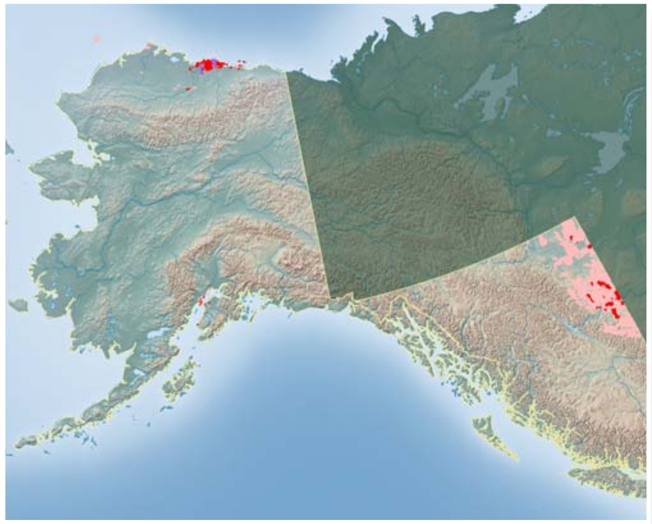


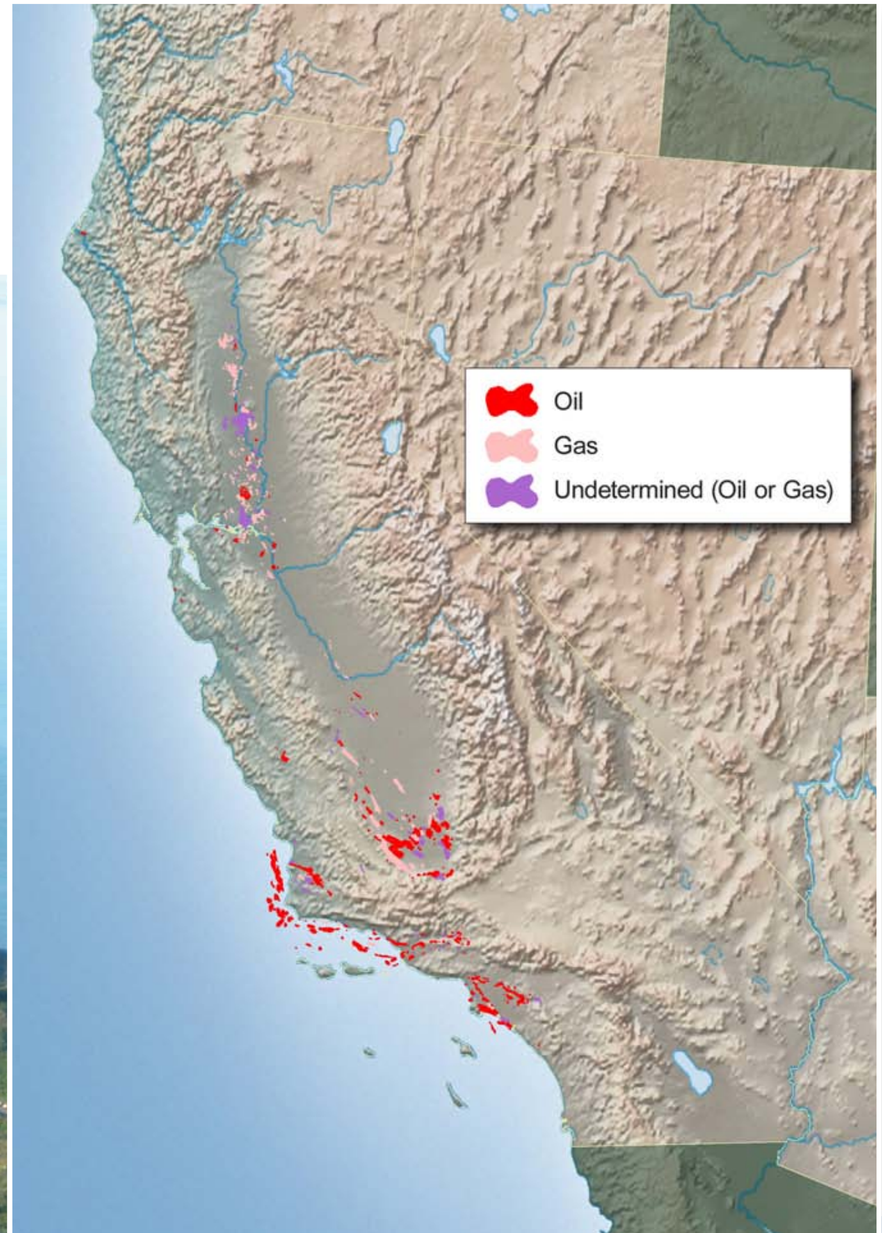
Screened saline formations in the WESTCARB region have storage potential, but volumes are not estimated due to insufficient data or pending further evaluations.











WESTCARB Oil and Gas Reservoirs

In the WESTCARB region, major oil and gas fields represent both storage targets and EOR opportunities—especially in California and Alaska.

In California, most onshore oil reservoirs are found in the southern San Joaquin Basin, Los Angeles Basin, and Ventura Basin. Based on estimates of ultimately recoverable oil reserves, WESTCARB investigators have identified approximately 1.3 billion to 3.4 billion metric tons (1.4 billion to 3.7 billion tons) of CO_2 resource potential.

WESTCARB estimates the CO_2 storage potential in California natural gas reservoirs at 3.0 billion to 5.2 billion metric tons (3.3 billion to 5.7 billion tons). Regionally, the Sacramento Basin has the largest CO_2 storage potential, in the range of 2.0 billion to 4.1 billion metric tons (2.2 billion to 4.5 billion tons). The southern portion of the basin is home to some of California's largest natural gas fields. Now largely depleted, these fields may represent opportunities for CO_2 storage following cessation of commercial natural gas production.

Offshore California, oil and gas accumulations have been found in the Santa Maria, Ventura, and Los Angeles Basins. Reservoirs in highly fractured shales within the Santa Maria and Ventura Basins are not good candidates for CO_2 storage. Estimated CO_2 storage resource for the known developed and undeveloped offshore oil and gas fields within conventional sandstone reservoirs of the Los Angeles and Ventura Basins is 240 million metric tons (265 million tons).

In Alaska, the oil and gas fields on the North Slope are of prime interest because of the large potential for CO_2-EOR, as well as their proximity to some of largest sources of stationary CO_2 emissions in Alaska. The hydrocarbon reservoirs of the Cook Inlet also offer potential for CO_2 storage and EOR given their proximity to industrial CO_2 sources.

Cook Inlet, Southern Kenai Peninsula. (Photo courtesy of Pioneer Natural Resources)

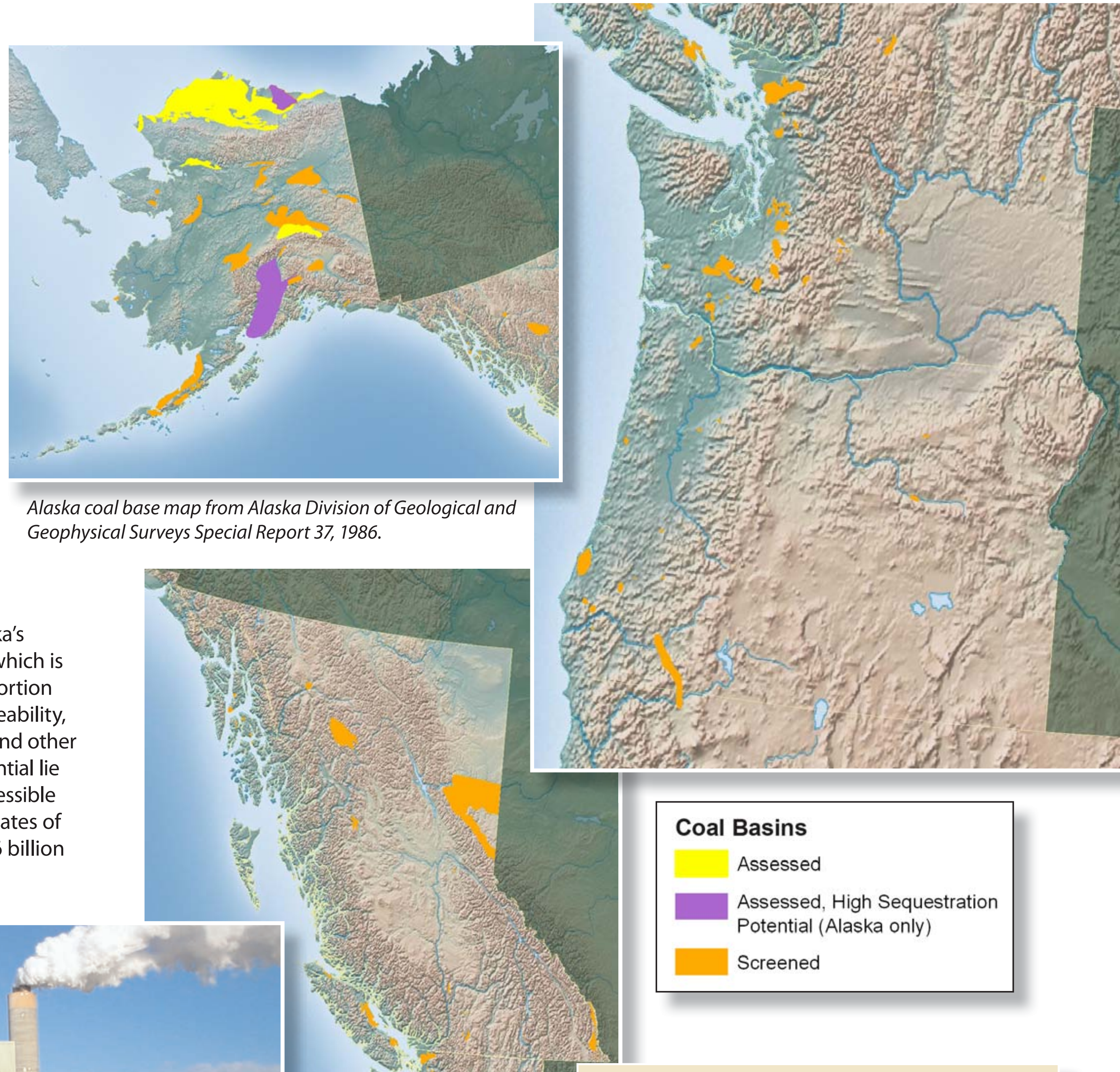
In conjunction with geologic storage, additional production may be achieved in some oil fields through CO_2-EOR, even when secondary recovery methods have already been applied.

WESTCARB Unmineable Coal Areas

Opportunities for geologic CO_2 storage in unmineable coal areas within the WESTCARB region are found predominantly in the Pacific Northwest and Alaska. In the Pacific Northwest, three deep coalbed deposits offer promise: the Bellingham Basin in northwestern Washington; the coals of the upper Puget Sound region, south and east of the Seattle-Tacoma metropolitan area; and small, deep coal deposits in southwestern Oregon.

Coal seams in the Puget Sound region have been previously tested for CBM production. Initial studies show that the subsurface extent of the coal basins represents an area greater than 2,500 km^2 (950 square miles). Initial analysis indicates prospective coal seam reservoir properties of 30 meters (100 feet) coal thickness, a CO_2 sorption capacity of 20 to 24 m^3 (700 to 850 ft^3) CO_2 per ton of coal, and a permeability of approximately 5 millidarcies. The estimated CO_2 storage potential in this area is 1.3 billion metric tons (1.5 billion tons), and the estimated recoverable CBM is 57 billion to 570 billion m^3 (2 to 20 trillion ft^3).

Although coal mining in Alaska has been limited, the State contains major coal deposits that range from shallow to over 2,000 meters (6,500 feet) deep. Alaska's CBM resources are estimated to be approximately 22 trillion m^3 (780 trillion ft^3), which is comparable to the CBM resources in all of the lower 48 states. However, only a portion of this resource is considered favorable for CO_2 storage due to coal quality, permeability, seam geometry, surface access, faulting, permafrost, depositional environment, and other site-specific conditions. The coal seam CO_2 storage opportunities of highest potential lie in unmineable coalbeds in the North Slope and Cook Inlet regions, which are accessible and have coals of suitable thickness, depth, and permeability. Preliminary estimates of geologic CO_2 storage resource in Alaska identify about 24 billion metric tons (26 billion tons) of storage in these deep coal seams.



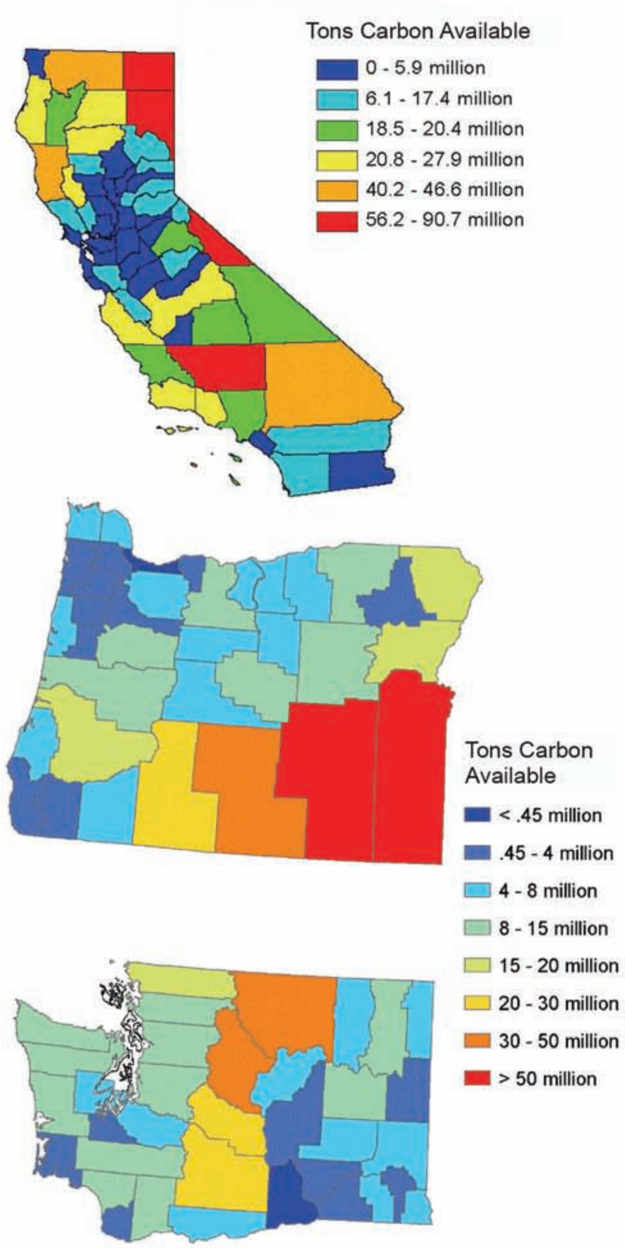
Alaska coal base map from Alaska Division of Geological and Geophysical Surveys Special Report 37, 1986.

Screened coal areas in the WESTCARB region have storage potential, but volumes are not estimated due to insufficient data or pending future evaluations.

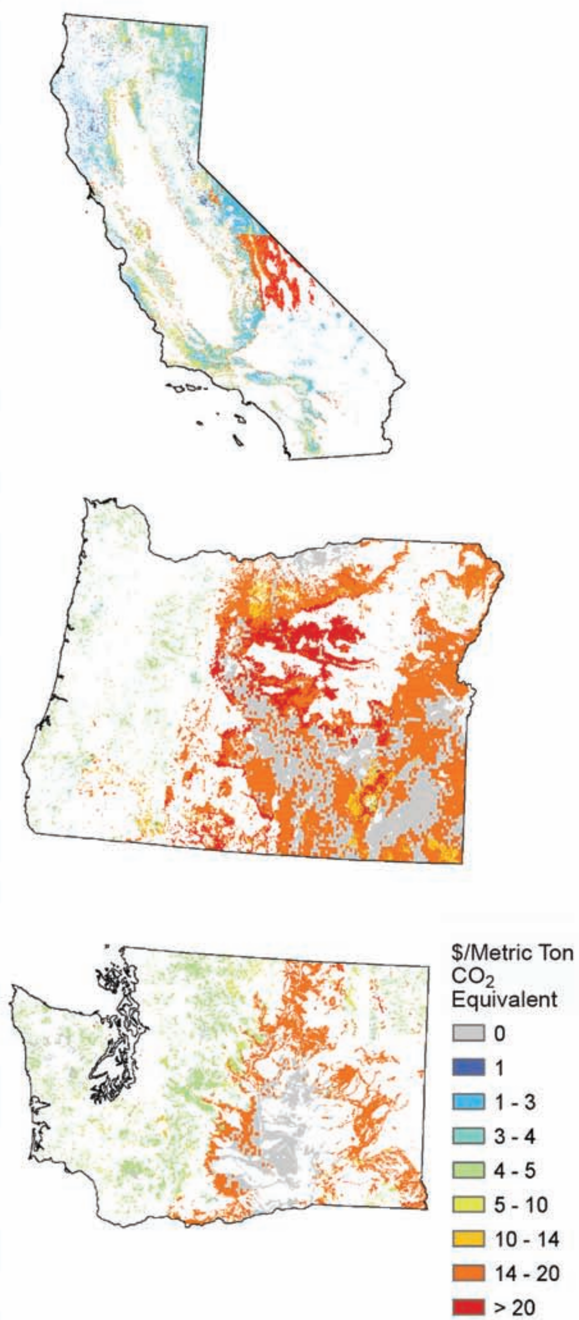
Nanushuk Formation coalbed on the Kukpowruk River, North Slope, Alaska. (Photo courtesy of Gary D. Stricker, USGS)

TransAlta's 1400 MW coal-fired power plant in Centralia, Washington.

Potential Sequestration Through Afforestation After 40 Years



Marginal Cost After 40 Years of Sequestrating Carbon by Afforestation $ Per Metric Ton Carbon



WESTCARB Terrestrial Carbon Storage Opportunities

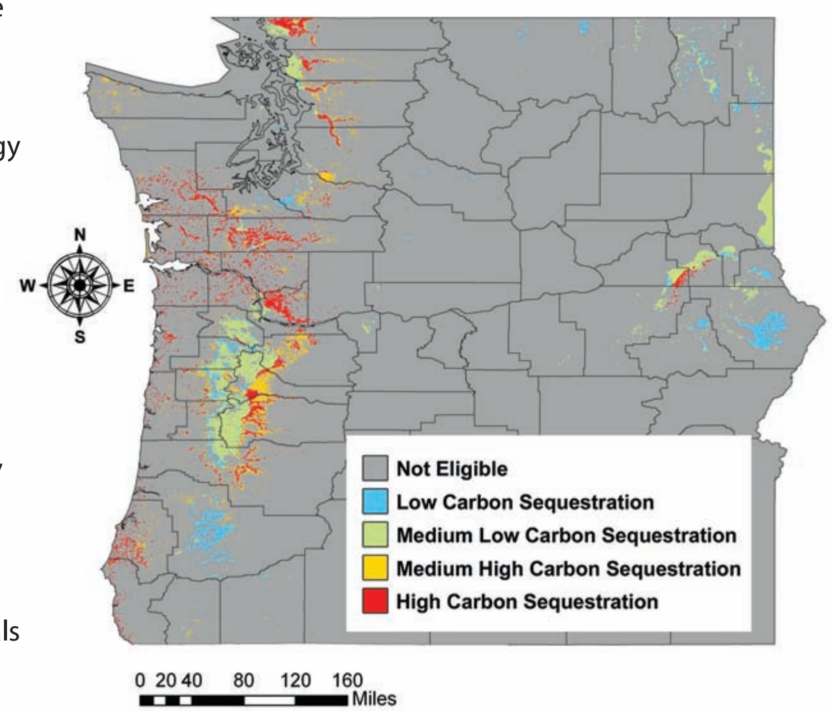
Terrestrial storage opportunities in the WESTCARB region include afforestation (tree planting); changes in forest management to increase carbon stocks; biomass storage in wetlands; beneficial use of biochar; changes in land management and development practices; improved management of forest fuels to reduce the severity of wildfires; and, where practical, the use of removed fuels in biomass energy facilities.

WESTCARB researchers evaluated afforestation of rangelands with native tree species for California, Oregon, and Washington over 20-, 40-, and 80-year time periods. On a dollar per ton of CO_2-equivalent basis, costs are lowest for the longer time spans because the trees have more time in their prime growing years, and the initial costs of land preparation and planting are amortized over a larger quantity of stored carbon. Successful project development entails analysis of the suitability, aggregate area, and geographic distribution of candidate lands; a thorough understanding of total costs; and assessment of the potential variability in sapling survival and tree growth rates.

The potential for riparian afforestation was explored in Arizona, where it could provide numerous ecosystem benefits in addition to carbon storage, such as improved water quality, fish and wildlife habitat, and recreation opportunities. However, several factors, including relatively slow growth rates and the long, thin areal distribution of riparian ecosystems, make implementing such projects in Arizona economically unfeasible on the basis of carbon credits alone.

Researchers also addressed the potential for afforestation with fast-growing hybrid poplar trees, which are able to store large amounts of carbon in a relatively short period and could be harvested as biomass energy crops or as timber. These trees require substantial amounts of water, and the best opportunities may lie in areas with sufficient precipitation, where they could be grown without irrigation. In Oregon and Washington, the estimated area where hybrid poplars could be grown without irrigation (rated as high to medium-high storage potential) totals about 2.5 million acres.

Carbon Sequestration Potential with Hybrid Poplars in Oregon and Washington without Irrigation



WESTCARB Terrestrial Storage Pilot Tests

In Shasta County, California, and Lake County, Oregon, WESTCARB is conducting pilot projects of forest-based carbon storage. Fire-prone forests are treated to restore forest health by removing understory trees, brush, and other fuels that can contribute to catastrophic wildfires and the associated GHG and other atmospheric emissions, as well as causing ecological damage. Where feasible, the removed fuel has been transported to a local biomass power plant, which can offset emissions from electricity that might otherwise be generated by fossil fuel combustion.

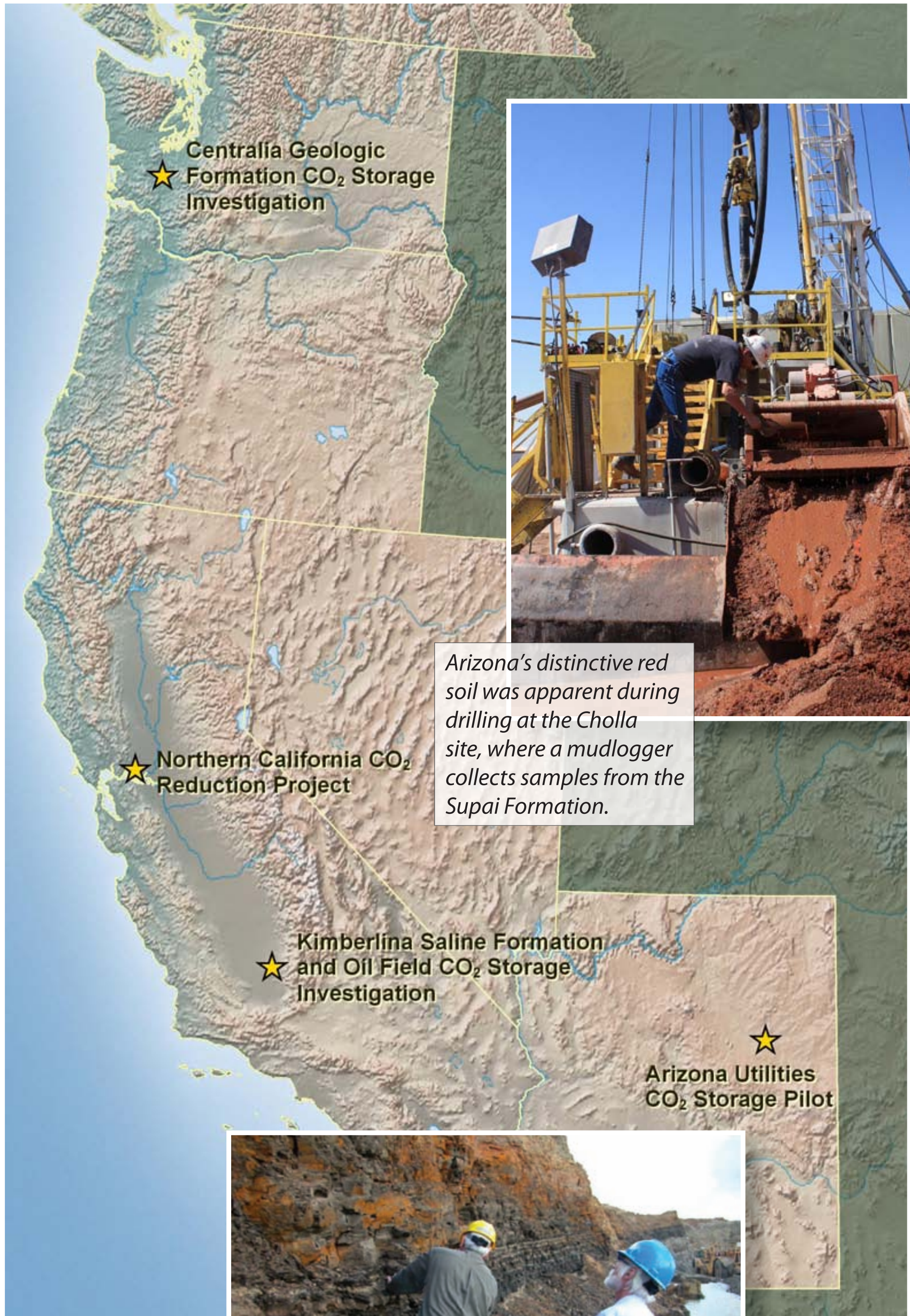
Fieldwork in Shasta County also involves a dozen afforestation projects, where native conifer and oak species are being restored to rangelands and fire-damaged forest lands on plots ranging from 10 to 100 acres each. Data were collected to determine the potential carbon benefits and financial costs of these projects. A conservation-based forest management project involved a nonprofit group and a timber company collaborating to restore and maintain high-quality forest habitats. This project also served as a real-world laboratory for testing aspects of the California Climate Action Registry's Forest Project Protocols, which serve to quantify the net climate benefits of activities that store carbon on forestland.

In the Puget Sound region of Washington State, WESTCARB is assessing the opportunity to develop a performance standard for avoided conversion of forested land to development. Such a standard would encourage projects to cluster residential development, leaving significant amounts of forest land undisturbed. Field measurements will be used to determine the emissions resulting from both dispersed and clustered development practices.

Measuring and monitoring activities form an important component of WESTCARB's terrestrial storage field pilots. Overall objectives are to quantify the effectiveness of storage techniques and gather information on project costs and benefits, as well as the steps involved in applying forest carbon protocols.

Measuring and monitoring activities establish carbon baselines and quantify carbon stored through terrestrial storage projects.

Replanting after a fire can re-establish a forest (left side of fence) and prevent colonization by invasive brush (right side of fence).



Arizona's distinctive red soil was apparent during drilling at the Cholla site, where a mudlogger collects samples from the Supai Formation.

WESTCARB researchers examine coals seams in Washington State.

WESTCARB Geologic Storage Pilot Projects

WESTCARB's pilot-scale geologic projects are designed to characterize and test areas of high CO_2 storage potential in the region. Projects have taken place or are underway in Arizona, California, and Washington.

The Arizona Utilities CO_2 Storage Pilot examines the storage capability of saline formations in the Colorado Plateau in northeastern Arizona, an area with sizeable coal reserves and several large coal-fired plants. In 2009, a characterization well was drilled through sedimentary layers to basement, approximately 3,850 feet deep, next to the ash pond of Arizona Public Service's Cholla Power Plant, near Holbrook. Researchers found highly saline waters and good sealing formations; however, drill stem tests and well logs indicated insufficient permeability in the target formations (Martin and Naco) to support a commercial-size project at this location.

Despite the localized finding of low permeability at the Cholla site, estimates of the overall CO_2 storage potential in the Colorado Plateau remain high because of the thickness of deep-lying, porous saline formations and the presence of good seals.

WESTCARB and C6 Resources, LLC, conducted a site characterization study of Montezuma Hills of the Sacramento River Delta region, where decades of natural gas exploration, production, and storage in neighboring reservoirs provided a starting point for collecting data on the local saline formation geology. The project team developed a geologic model based on available well log and seismic data. The team then used the model to simulate the injection of 5,440 metric tons (6,000 tons) of CO_2 into a saline formation. Results suggest that the area is an excellent candidate for CO_2 storage.

For a site in the San Joaquin Valley near Bakersfield, WESTCARB researchers created a 3-D geologic model based on surrounding well logs, and used modeling programs to simulate the injection of 900,000 metric tons (1 million tons) of CO_2 into a saline formation over a 4-year period. Results show that 20 years after injection ceases, the CO_2 is virtually immobilized within the pore spaces of the target Vedder formation.

In Washington, WESTCARB's targeted study of CO_2 storage potential in deep coal seams and saline formations of the Centralia-Chehalis Basin estimated up to 345 million metric tons (380 million tons) storage resource. This would be sufficient for 22 to 86 years of emissions from the nearby TransAlta coal-fired power plant at 50 percent capture.

Drill rig beside the ash pond of the Cholla Power Plant in Arizona.

WESTCARB Development Phase CO_2 Storage Project

WESTCARB is evaluating opportunities for CO_2 storage with its partners in preparation for a Development Phase CO_2 storage field project. The saline formations in the large sedimentary basins of the WESTCARB region are of prime interest; however, sites in the region's oil and natural gas fields are also under investigation where a business case may favor early commercialization opportunities.

One area of interest is California's Central Valley, which offers geologic features favorable to CO_2 storage: thick, extensive, porous saline rock formations overlain by impermeable layers of shale. Among possible locations are two sites where WESTCARB has conducted preliminary site characterization studies.

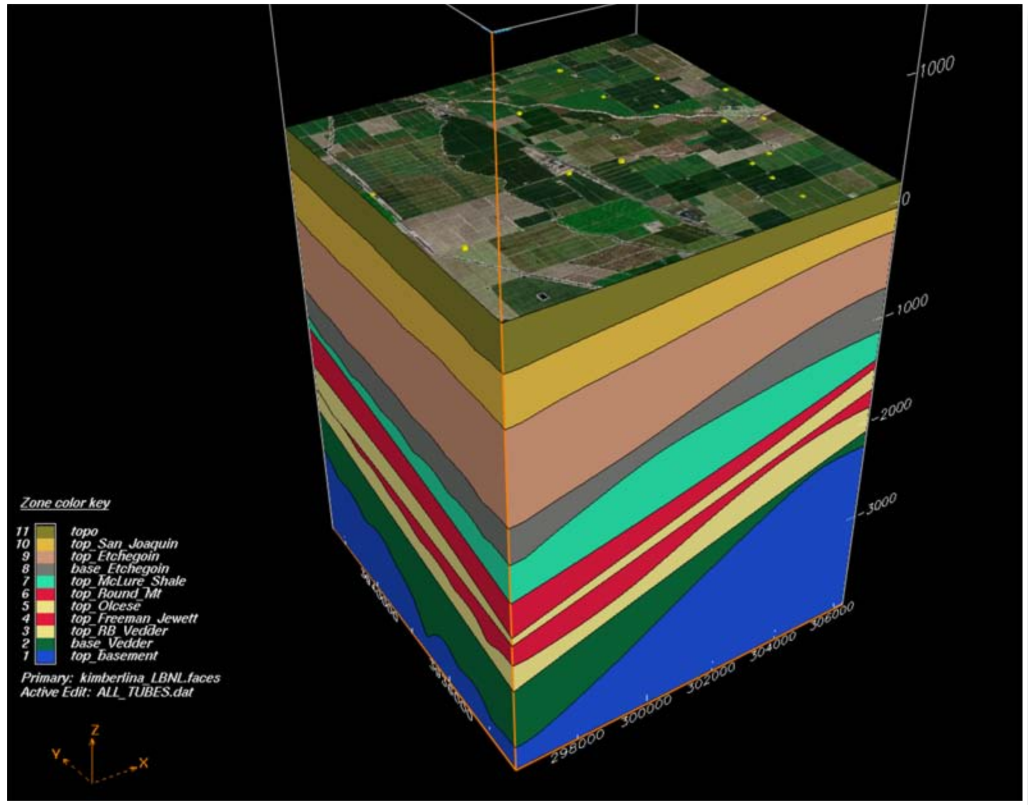
The Kimberlina site, located about 20 miles north of Bakersfield, California, is home to Clean Energy Systems' oxy-combustion pilot plant, which was funded in part by DOE and the California Energy Commission. WESTCARB prepared a static geomodel of the formations underlying the site based on available data from wells in the vicinity. The target formation is the Vedder Sandstone, which appears to be regionally continuous at a depth of about 2,400 meters (8,000 feet). At the site, the Vedder is a braided stream unit with a thickness of about 150 meters (500 feet). Thick shale units provide good overlying seals.

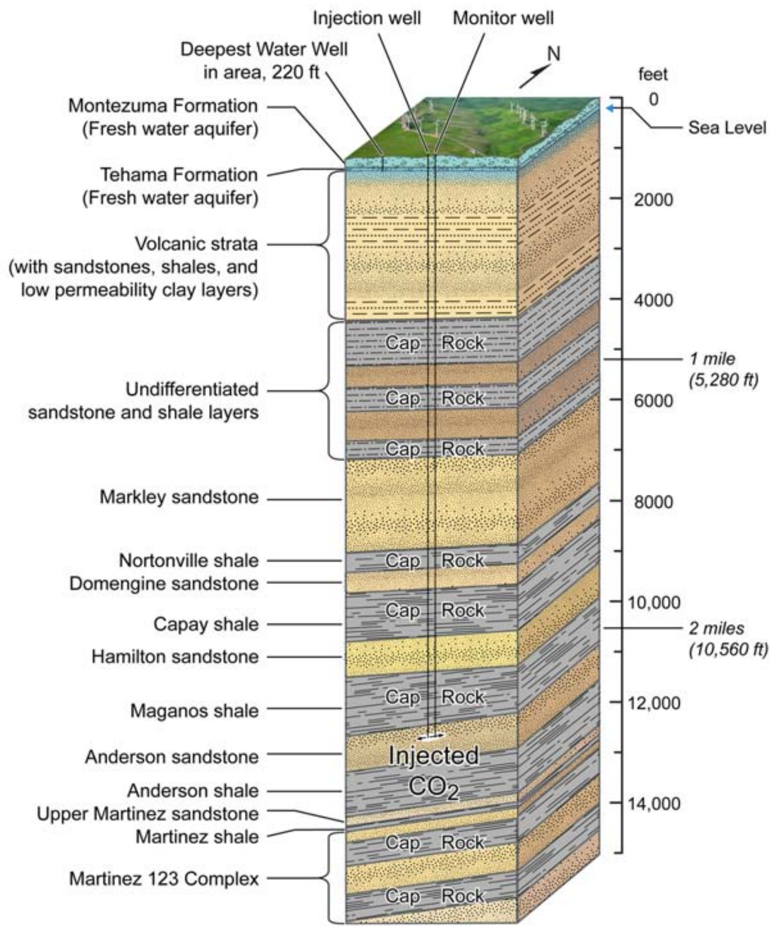
A second site under evaluation is the Montezuma Hills of Solano County in the southwestern Sacramento Valley. Target formations are thick sandstones, such as the Anderson Formation at approximately 3,350 meters (11,000 feet) in depth, which are overlain by numerous shale sequences.

During the project, WESTCARB researchers will employ multiple monitoring technologies, including newly developed instruments to provide baseline data and to monitor the injected CO_2 underground. Results will be compared with computer simulations of the behavior of the injected CO_2, allowing for validation and refinement of modeling techniques. Researchers will continue to monitor the site after the conclusion of injection operations as part of the environmental stewardship phase of the project.

The technical information and experience gained from the large-scale project will allow researchers to better quantify the storage potential of saline formations and help West Coast policymakers and the public understand the role that geologic storage can play in achieving GHG emissions reductions.

At right: Initial geomodel developed by Lawrence Livermore National Laboratory for the formations underlying the Kimberlina site.





At left: Stratigraphic column developed by Lawrence Berkeley National Laboratory showing the formations underlying the Montezuma Hills site.

(Photo courtesy of Wendi Liles, The Keystone Center)

Integrating CCS into the WESTCARB Community

WESTCARB's outreach and education program promotes communication among the research community, policymakers, the public, media, tribal and non-governmental organizations, and industry. WESTCARB is committed to sharing information and gaining feedback from stakeholders on the diverse aspects of technology and project development for both terrestrial and geologic carbon storage. In addition to maintaining a website, WESTCARB hosts meetings in communities where pilot projects are proposed and has held its annual public meetings in Alaska, Arizona, California, Oregon, and Washington to encourage regional participation. WESTCARB has arranged tours of project sites to give stakeholders a firsthand look at field operations and has supported The Keystone Center's teacher trainings on climate change, wherein teachers learn about carbon storage, as well as examining the broader implications of climate change.

WESTCARB works with other organizations to provide information on geologic carbon storage in the western region. The Natural Resources Defense Council and the Environmental Defense Fund (EDF)—joined recently by WESTCARB as a co-sponsor—have held public workshops in Sacramento and Los Angeles, California. California State University Bakersfield, with WESTCARB participation, hosted well-attended public education workshop focused on CCS and EOR opportunities in the San Joaquin Valley.

A WESTCARB partner, the Western Shasta Resource Conservation District, has an ongoing program to educate northern California landowners about terrestrial carbon storage. District personnel meet with individuals and conservation groups, feature informational activities at environmental festivals, and have helped engage participants in WESTCARB's reforestation pilot projects.

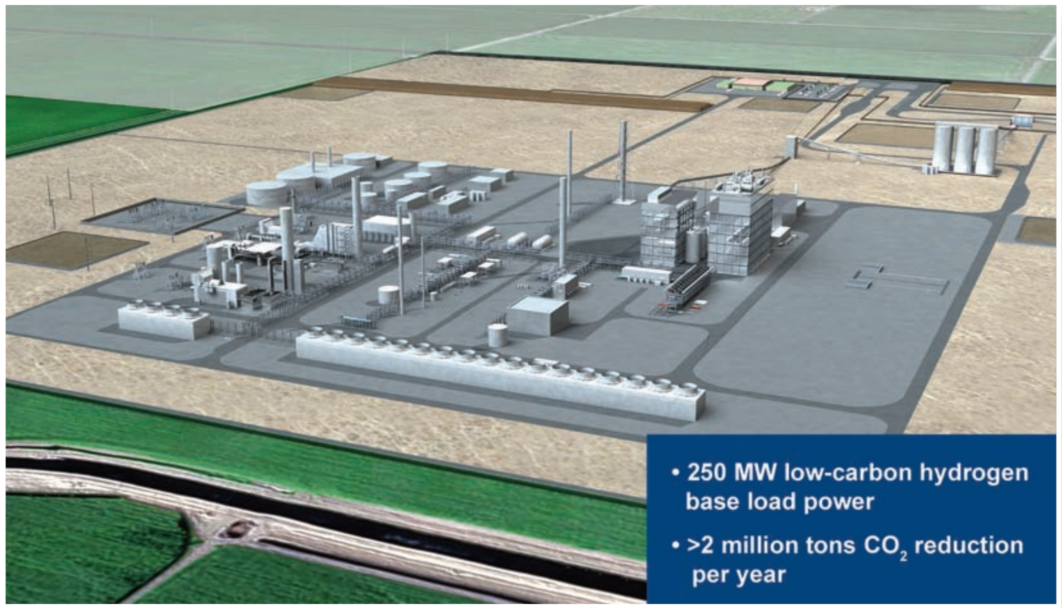
In the policy realm, WESTCARB researchers co-authored the 2008 *Geologic Carbon Sequestration Strategies for California: Report to the Legislature* in response to legislative action (AB 1925) and are currently serving as technical advisors to the California Carbon Capture and Storage Review Panel, which was convened by State agencies to draw up recommendations for CCS regulation. WESTCARB has also organized several CCS workshops for the California Energy Commission's biennial *Integrated Energy Policy Report*, an important guidance document for the State.

Commercialization Activities in the WESTCARB Region

A strong commitment to mitigating climate change is evidenced within the WESTCARB region. Several WESTCARB States have legislated mandatory GHG emission reductions, and most are active in various climate change initiatives and efforts to spur clean energy development. As the Western region strives to meet emission targets in the coming years, commercial deployment of geologic and terrestrial carbon storage stands to become increasingly important.

With this outlook in mind, WESTCARB has sited its geologic field projects in areas suitable for commercial deployment of CCS, giving consideration to the storage capacity of geologic formations; their proximity to major CO_2 sources; and possible economic co-benefits, such as EOR or ECBM production.

For example, WESTCARB has studied the potential for CO_2 storage in the depleting oil and natural gas fields in California's Central Valley. Enhanced oil recovery with steamflooding is already being deployed in some oilfields in the southern part of the valley, and even greater recovery may be realized through CO_2 injection. A DOE study of CO_2-EOR in California suggests that technically recoverable reserves exceed 0.3 million m^3 (5.6 bbl). Currently, large volumes of CO_2 are not available locally; however, Hydrogen Energy California has filed permit applications to build an IGCC plant with CO_2 capture in Kern County, California, with plans to sell the CO_2 for EOR in nearby oilfields.



Artist's rendering of Hydrogen Energy California's proposed IGCC plant with CO_2 capture in Kern County, California.

The saline formations of California's Central Valley, as well as those of Washington's Puget Sound, were also studied by WESTCARB. Their high storage potential and proximity to major stationary sources of CO_2 could make them a valuable resource in the region's GHG reduction efforts. A further WESTCARB study assessed ECBM potential in the Pacific Coal region of Washington, where a nearby coal-fired power plant could provide a source of CO_2.

In California, where natural gas combined cycle (NGCC) power plants factor predominantly in the generation mix, WESTCARB is conducting a technical and economic viability assessment of retrofitting the State's existing NGCC fleet or designing new NGCC facilities with CO_2 capture capabilities.

Some areas of the West Coast afford significant potential for terrestrial carbon storage, and WESTCARB has been working with stakeholders in Oregon and California to apply and test protocols for terrestrial carbon storage projects. Research into the costs and carbon storage rates associated with afforestation, forest conservation, and forest fuels reduction to prevent catastrophic wildfires helps to lay the groundwork for acceptance of these types of projects in carbon offset markets.

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CO_2 Stationary Source Emission Estimation Methodologies Summary

Appendix A

Prepared for

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Sequestration Program

Prepared by

Capture and Transportation Working Group
of the DOE Regional Carbon Sequestration Partnerships

June 2010

Contents

Introduction

The following summarizes the calculations, emissions factors, and databases employed by the Regional Carbon Sequestration Partnerships (RCSPs) with respect to carbon dioxide (CO_2) stationary source emissions estimation methods. Tables of information are used to summarize the methodology. The CO_2 stationary sources include power plants, ethanol plants, petroleum and natural gas processing facilities, cement and lime plants, agricultural processing facilities, industrial facilities, iron and steel production facilities, and fertilizer producing facilities. Estimation methods include databases and emissions factors. Each table lists the databases and emissions factors utilized for the particular CO_2 source type. Not all databases or emissions factors were used by all of the RCSPs. The legend following each table contains the definitions of equation variables.

The documents used to identify each CO_2 stationary source, as well as the practical quantitative method (i.e., emission factors, continuous emissions-monitoring results, emission estimate equations, etc.) used to estimate CO_2 emissions from that source, are listed in the "CO_2 Emissions Methodology References" section of this report. These documents are organized by the reference numbers shown after the main text of each entry. The data sources to determine specific plant capacities, production outputs, or fuel usage data are listed by RCSP in the "Data References by Partnership and Industry" section of this report.

Approach

The approach to determine these methodologies was to identify significant CO_2 emission sources within each region, and then assess the availability of CO_2 emission data or to apply an estimate of the CO_2 emissions based upon sound scientific and engineering principles. In each RCSP, the emissions were grouped by emission source and a methodology was established for each emission source category; then the methodology was utilized to estimate the CO_2 emissions from each emission source category. To summarize these efforts, nine tables containing CO_2 emission estimation methodology and equations for the major CO_2 stationary source industries outlined in the third version of the *Carbon Sequestration Atlas of the United States and Canada (Atlas III)* were created. During the Characterization Phase (Phase I), each RCSP was responsible for developing greenhouse gas (GHG) emission inventories and stationary source surveys within their respective partnership boundary area. More than 4,365 stationary sources have been documented for the seven RCSPs.

Stationary sources fall under one of the nine industry types outlined in Atlas III. Table A-1 identifies the variety of stationary sources falling under any given industry type as identified in *Atlas III*.

Table A-1. CO_2 Stationary Sources by Industry Category

Industry type	CO_2 Stationary Sources Included
Electric Generating Plants	• Coal-, Oil-, and Natural Gas-Fired Power Plants • Limited Municipal Solid Waste
Ethanol Production Plants	• Ethanol Plants, Regardless of Feedstock Type
Agricultural Processing Facilities	• Sugar Production
Natural Gas Processing Facilities	• Natural Gas Processing Facilities
Industrial Facilities	• Aluminum Production Facilities • Soda Ash Production Facilities • Glass Manufacturing Facilities • Automobile Manufacturing Facilities • Compressor Stations • Iron Ore Processing Facilities • Paper and Pulp Mills
Iron and Steel Facilities	• Iron and Steel Producing Facilities
Cement and Lime Plants	• Lime Production Facilities • Cement Plants
Refineries and Chemical Facilities	• Petroleum Refinery Processing • Ethylene Production Facilities • Ethylene Oxide Production • Hydrogen Production Facilities
Fertilizer Production	• Ammonia Production

CO_2 Estimation Methodology

For any stationary source within a given industry type, the RCSPs employed CO_2 emissions estimate methodologies that are based on the most readily available representative data for that particular industry type within the respective partnership area. CO_2 emissions data provided by databases (for example, eGRID, IEA GHG, or NATCARB) were the first choice for all of the RCSPs, both for identifying major CO_2 stationary sources and for providing reliable emission estimations. Databases are considered to contain reliable and accurate data obtained from direct emissions measurements via continuous emissions monitoring (CEM) systems. One drawback of formal databases can be the delay between data collection and publication, but this does not present a significant problem for the RCSPs as the dates of information are clear. When databases were not available, stationary source facility production or fuel usage were coupled with CO_2 emissions factors to estimate annual CO_2 emissions from the production or fuel usage data. Emissions factors, fuel usage data, and facility production data were obtained from various databases, websites, and publications. Stationary source spatial location data (latitude and longitude) were determined from a variety of sources. Some databases (eGRID) contain latitude and longitude information for each stationary source. Where spatial location information was not available through an emissions database, other spatial location methods were utilized. These include the use of mapping tools (Google Earth, TerraServer, and USGS Digital Orthophoto Imagery) equipped with geospatially defined data, along with web-based databases (Travelpost) containing latitude and longitude information for various U.S. locations.

Table 1. Methodology for Estimating CO_2 Emissions from Electric Generating Plants

Methodology	Description
Database	The most current data were used where available. Actual emissions data were obtained from various databases even if not all sources had the same vintage data. These include: • EPA Clean Air Markets Division Facility Emissions Data (2010), where the average of the most recent five years of available data were selected and aggregated to the plant level, and the lowest values dropped to reduce the impacts of startup and maintenance anomalies.[1] • EPA eGRID Database (2004, 2008).[2] • EPA Acid Rain Program Emission Report for 2005 (2006).[3] • Commission for Environmental Cooperation Website (U.S. Plants).[4] • Commission for Environmental Cooperation Website (Canadian Plants) (2002).[5] • Website for Canadian Sources;[6] new plant data from EIA Table ES3; New and Planned U.S. Electric Generating Units by Operating Company, Plant and Month, 2007-2008.[7] • U.S. DOE – EIA Power Plant Database.[8]
Emissions Factors	Data were analyzed based on the IPCC (2006) GHGs methodology using fuel consumption, a fuel-specific carbon coefficient, and the fuel-related fraction of carbon oxidized, similar to the following equation.[9] CO_2 emissions were also calculated via combustion based on fuel type and usage data provided by the Transfer Technology Network (TTN) Database:[10] $M_{CO_2} = \frac{3.664 F_t C_{\%} D_F}{2000}$ (if liquid or gaseous fuel) $M_{CO_2} = 3.664 C_{\%} F_t$ (if solid fuel)
	For new natural gas-fired plants plants without CO_2 data, annual emissions were estimated by calculating megawatt hours from the plant capacity and 50% annual production for natural gas combined cycle or 20% for natural gas simple cycle. 1,100 lb of CO_2 per MWh was approximated based on examination of natural gas plants in the eGRID data to estimate emissions at new plants.[2] $M_{CO_2} = \frac{1100P}{2000}$

Legend:
$C_{\%}$ = Carbon in the fuel (weight fraction; i.e., % ÷ 100) (Found in Appendix B of this report)
D_F = Fuel density (lb per gallon if liquid; lb per million scf if gas)
F_t = Fuel usage rate (depends on fuel type) (gallons per year if liquid; million scf per year if gas; tons per year if solid)
M_{CO2} = Total CO_2 emissions (tons per year)
P = Annual plant generation (MWh)

Notes: The Emissions & Generation Resource Integrated Database (eGRID) is a comprehensive inventory of environmental attributes of electric power systems and has been the most widely used source for gathering CO_2 stationary source emissions by the partnerships. The eGRID provides annual CO_2 emissions data reported from the Environmental Tracking System (Continuous Emissions Monitoring), rather than emissions factors based solely on production or heat input. In addition to emissions data, eGRID also provides facilities' latitude, longitude, primary fuel, annual heat input, and annual power generation.

Table 2. Methodology for Estimating CO_2 Emissions from Ethanol Plants

Methodology	Description
Database	Where available, actual emissions data were obtained from various databases. The most current data were used, even if not all sources had the same vintage data. These include: • e-GRID Spreadsheets[2] • NATCARB's Ethanol Plant Excel Worksheet (2006 data).[11] • Data cited from the Renewable Fuels Association [12,13] and contact with ethanol plant operators within certain partnership areas.
Emissions Factors	Process-related emissions:[14,15,16,17,18] $M_{CO_2} = \frac{\Sigma(E_{g,f}\theta_{E,f})}{2000}$ Combustion emissions using natural gas:[14,16,19,20] $M_{CO_2} = \frac{44E_g\left(\frac{39{,}000\ BTU}{gal}\right)\left(\frac{lbmol}{359\ ft^3}\right)}{2000\left(\frac{1000\ BTU}{ft^3}\right)}$ Combustion emissions using coal:[6,12] $M_{CO_2} = \frac{0.039E_g\theta_{coal}}{2000}$
	CO_2 emissions based on fermentation (2.88 ktonne CO_2 per million gal. ethanol). Emissions factor converted to a lb CO_2 per gallon ethanol produced:[12,21] $M_{CO_2} = \frac{6.34E_{g,f}}{2000}$

Legend:
θ_{coal} = CO_2 emissions factor for coal combustion (lb CO_2 per million Btu)
$\theta_{E,f}$ = CO_2 emissions factor for ethanol production by feedstock (lb CO_2 per gal ethanol): corn = 6.31 lb CO_2 per gal ethanol (MGSC), 6.6 lb CO_2 per gal ethanol (PCOR), and 6.624 lb CO_2 per gal ethanol (WESTCARB); corn/wheat = 6.15 lb CO_2 per gal ethanol and beverage waste = 5.05 lb CO_2 per gal ethanol (MGSC)
E_g = Ethanol production (gal ethanol/year)
$E_{g,f}$ = Ethanol production by feedstock (i.e. corn, corn and/or wheat, beverage waste) (gal per year)
M_{CO2} = Total CO_2 emissions (tons per year)

Table 3. Methodology for Estimating CO_2 Emissions from Agricultural Processing Facilities

Methodology	Description
Emissions Factors	For facilities where fuel usage is known (obtained from EPA TTN Database):[1,2,6,22] $M_{CO_2} = \frac{3.664 F_t C_{\%} D_F}{2000}$ (if liquid or gaseous fuel) $M_{CO_2} = 3.664 C_{\%} F_t$ (if solid fuel) Sugar production CO_2 emissions from the calcination of limestone-dolomite:[1,2,22] $M_{CO_2} = 0.785 E_{Lime}$

Legend:

$C_{\%}$ = Carbon in the fuel (weight fraction) (Found in Appendix B of this report)
D_F = Fuel density (lb per gallon if liquid; lb per million scf if gas)
E_{Lime} = Lime production rate (tons per year)
F_t = Fuel usage rate (depends on fuel type) (gallons per year if liquid; million scf per year if gas; tons per year if solid)
M_{CO2} = Total CO_2 emissions (tons per year)

Table 4. Methodology for Estimating CO_2 Emissions from Natural Gas Processing Facilities

Methodology	Description
Emissions Factors	Petroleum or natural gas processing facilities CO_2 emissions based on fuel usage data and energy content:[23] $M_{CO_2} = \beta F_t \theta_{fuel}$
	Natural gas processing emissions based on production (20% CO_2 content):[7] $M_{CO_2} = 4{,}238 F_{CH_4}$
	Natural gas sweetening process emissions based on fuel combustion needed to provide heat to regenerate the amine sorbent:[1,6,22] $M_{CO_2} = \frac{44.01\, F_{CH_4}}{2000\left(\frac{379\, ft^3}{lbmol}\right)}$
	Emissions based upon recovery from natural gas with a 4% average inlet gas CO_2 concentration and 1% average outlet gas CO_2 concentration:[24,25] $M_{CO_2} = 608 E_{NG}$

Legend:

θ_{fuel} = CO_2 emissions factor based on heat input rate (tons CO_2 per million BTU)
E_{NG} = Natural gas processing rate (million scf per day)
F_{CH4} = Natural gas usage rate (standard cubic feet per year)
F_t = Fuel usage rate (depends on fuel type) (kgal per year = liquid; million scf per year = gas; tons per year = solid)
M_{CO2} = Total CO_2 emissions (tons per year)
β = Heat content of fuel used (million BTU per million scf [gas]; million BTU per ton [solid]; million BTU per kgal [liquid])

Table 5. Methodology for Estimating CO_2 Emissions from Industrial Facilities

Methodology	Description
Emissions Factors	Aluminum production emissions:[26, 27, 28, 29] $M_{CO_2} = E_A\theta_{A1, A2}$ Emissions from aluminum production (based on EPA AP-42 emissions factors):[30] $M_{CO_2} = \frac{3{,}080E_A}{2000}$ Soda ash production combustion emissions were determined from fuel use data obtained from the U.S. EPA's NEI (1999) Database. Fuel use data were used with a default emissions factor for specific fuels to convert fuel consumed to metric tons of CO_2 produced.[31, 32] $M_{CO_2} = F_t\theta_f$ Soda ash production emissions were based on stoichiometric relationship between trona ($Na_3HCO_3(CO_3)_2{\cdot}2H_2O$) and soda ash ($Na_2CO_3$):[31,32,33] $M_{CO_2} = 0.09737\ E_T$ (based on Trona production) $M_{CO_2} = 0.1383\ E_{SA}$ (based on Soda ash production)
	Glass container manufacturing emissions:[34] $M_{CO_2} = 160.16\ E_g$ Flat glass manufacturing emissions:[34] $M_{CO_2} = 180.69\ E_g$ Pressed and brown glass manufacturing emissions:[34] $M_{CO_2} = 112.93\ E_g$ Compressor station emissions based on heat input of natural gas:[30] $M_{CO_2} = \frac{8760\,\beta_{NG}\,(110\,F_{NG})}{2000}$ Compressor station emissions based on NO_X emissions (when heat input is not available):[30] $M_{CO_2} = \frac{110\,C_{NO_x}}{\theta_{NO_x}}$ Autos manufacturing emissions:[35, 36] $M_{CO_2} = \frac{8760\ F_L(110\,\beta_{NG} + 146\,\beta_{diesel} + 214\,\beta_{coal})}{2000}$
	Paper production and combustion emissions based on fuel burned:[1,6,22] $M_{CO_2} = \frac{3.664\,F_t C_{\%} D_F}{2000}$ (if liquid or gaseous fuel) $M_{CO_2} = 3.664\,C_{\%}F_t$ (if solid fuel) Iron ore processing emissions:[30] $M_{CO_2} = 0.0155\,E_{Fe}$

Legend:

$\theta_{A1,A2}$ = CO_2 emissions factor for aluminum production based on the reduction technology implemented (Prebaked (A1) = 1.6 tons CO_2 per ton Al; Søderberg (A2) = 1.7 tons CO_2 per ton Al)
θ_f = CO_2 emissions factor for fuel usage based on fuel type (tons CO_2 per ton fuel = solid; tons CO_2 per gallon fuel = liquid)
θ_{NOx} = NO_X emissions factor based on heat input (lb NO_X per million Btu)
$C_{\%}$ = Carbon in fuel (weight fraction) (Found in Appendix B of this report)
C_{NOx} = NO_X emissions rate (tons per year)
D_F = Fuel density (lb per gallon = liquid; lb per million scf = gas)
E_A = Aluminum production rate (tons per year)
E_C = Clinker manufacture production (tons per year)
E_{Fe} = Iron ore production (tons pellet per year)
E_g = Glass manufacturing production (tons per day)
E_{SA} = Soda ash production rate (tons per year)
E_T = Trona production rate (tons per year)
F_L = Autos manufacturing loading factor (use 0.8 when data not available)
F_{NG} = Compressor loading factor (use 0.6 when data not available)
F_t = Fuel usage rate (depends on fuel type) (gallons per year = liquid; million scf per year = gas; tons per year = solid)
M_{CO2} = Total CO_2 emissions (tons per year)
β_{coal} = Maximum coal heat input rate (million Btu per hr)
β_{diesel} = Maximum diesel fuel heat input rate (million Btu per hr)
β_{NG} = Maximum NG heat input rate (million Btu per hr)

Table 6. Methodology for Estimating CO_2 Emissions from Iron and Steel Facilities

Methodology	Description
Emissions Factors	Emissions from iron and steel manufacturing: [37, 38, 39] $M_{CO_2} = 3.3E_\varepsilon + 0.02(3.667E_{pig}) + 0.004(3.667E_{SS}) + \theta_{EAF}E_{EAF}$
	Iron and steel production emissions factors: [40] General steel production: $M_{CO_2} = 1.27\,E_S$ Use of an electric arc furnace: $M_{CO_2} = E_{EAF}\,\theta_{EAF}$

Legend:

θ_{EAF} = CO_2 emissions factors for electric arc furnace
(MGSC: 0.0044 tons CO_2 per ton EAF steel; SECARB: 0.14 tons CO_2 per ton EAF steel)
E_{EAF} = EAF steel production rate (tons per year)
E_{pig} = Pig iron production rate (tons per year)
E_S = Steel production rate (tons per year)
E_{SS} = Scrap steel consumption rate (tons per year)
E_ε = Coke usage (tons per year)
M_{CO2} = Total CO_2 emissions (tons per year)

Table 7. Methodology for Estimating CO_2 Emissions from Cement and Lime Plants

Methodology	Description
Database	Where available, CO_2 emissions taken from NATCARB Cement Database (2006).[24] Lime plants identified by USGS Mineral Industry Surveys. [41]
Emissions Factors	Process related emissions based on clinker production and estimated generation of cement kiln dust (CKD):[39, 42] $M_{CO_2} = (1 + C_{Dust})\,E_C\,\theta_C$ Combustion related emissions based on clinker production:[39, 42, 43] $M_{CO_2} = 0.463\,E_C$ Emissions from lime production:[39, 43, 44] $M_{CO_2} = 0.75\,E_{QL} + 0.87\,E_{DL}$
	Process emissions:[47] $M_{CO_2} = (1 + C_{Dust})\,E_C\,\theta_C$ Combustion emissions based on clinker production:[43,46,46b] $M_{CO_2} = 0.575\,E_C$ Lime (clinker) production emissions (from lime production reaction stoichiometry): $M_{CO_2} = 0.785\,E_C$
	Lime production combustion emissions:[23,32] $M_{CO_2} = \beta F_t \theta_{fuel}$ Lime production process emissions:[23,32] $M_{CO_2} = 0.75\,RE_{Lime}$
	CO_2 emissions from cement plants were generated based on cement produced, clinker content, amount of raw materials used and CO_2 emitted from combustion.[48] $M_{CO_2} = 0.9\,E_{CP}$

Legend:

θ_C = CO_2 emissions factor for clinker production
(MGSC: 0.507 ton CO_2 per tonne clinker; PCOR: 0.536 ton CO_2 per ton clinker)
θ_{fuel} = CO_2 emissions factor based on heat input rate (tons CO_2 per million BTU)
C_{Dust} = Fraction of cement kiln dust (Assume 2% if no other data is available)
E_C = Clinker production rate (tons per year)
E_{CP} = Cement production rate (tons per year)
E_{DL} = Dolomite lime production rate (tons per year)
E_{Lime} = Lime production rate (tons per year)
E_{QL} = Quicklime production rate (tons per year)
F_t = Fuel usage rate (depends on fuel type) (kgal per year = liquid; million scf per year = gas; tons per year = solid)
M_{CO2} = Total CO_2 emissions (tons per year)
R = content of CaO in lime produced (EPA estimates 0.95 for high calcium lime)
β = Heat content of fuel used
(million BTU per million scf [gas]; million BTU per ton [solid]; million BTU per kgal [liquid])

Table 8. Methodology for Estimating CO_2 Emissions from Refineries and Chemical Facilities

Methodology	Description
Emissions Factors	Refinery processing emissions based on plant production :[49] $M_{CO_2} = E_P\theta_P$
	The combustion CO_2 emission rate was estimated for each fuel within each Petroleum Administration for Defense District (PADD) by multiplying the fuel usage rate (unit volume per yr) for each PADD with the CO_2 emission coefficient (lb CO_2 per unit volume). The total CO_2 emission rate was determined by summing the CO_2 emission rates for all fuels. An emissions factor (tons CO_2 per barrel per calendar day) was then calculated for each of the PADDs by dividing the total CO_2 emission rate for the district by the refining capacity (barrels per calendar day) for the district. States in the PCOR Partnership region are represented in PADDs 2 and 4. The CO_2 emissions factors for PADDs 2 and 4 were estimated in 2008 to be 11.00 and 11.84 tons CO_2 per barrel per calendar day, respectively. (Note: These values must be recalculated each year when new refinery statistics are issued.) As an example, calculation of an emissions factor for a refinery in North Dakota, an emissions factor of 11.00 tons CO_2 per barrel per calendar day of the major product was used to calculate the total combustion-related emissions as follows: [1, 6, 20, 22] $M_{CO_2} = 11E_P$
	Refinery emissions rate: [40] $M_{CO_2} = E_P\theta_P$ Ethylene production emissions: [40] $M_{CO_2} = 2.43\,E_{et}$ Ethylene oxide production emissions: [40] $M_{CO_2} = 0.51E_O$
	An estimated emissions factor based on plant capacity was generated and emissions are estimated as follows:[50] $M_{CO_2} = 0.025(0.9\,E_P)$ CO_2 emissions for hydrogen (H_2) production were based on steam methane reforming (SMR) in which a hydrocarbon and water vapor are used to create H_2 and CO_2 as a byproduct governed by the following reaction: $CH_4 + 2H_2O = CO_2 + 4H_2$ This reaction implies that 0.25 volumes of CO_2 are produced per volume of H_2. Thus, emissions from hydrogen production are calculated as follows: [50,51] $M_{CO_2} = \dfrac{44.01(0.25\,E_H)}{2000\left(\dfrac{379\,ft^3}{lbmol}\right)}$

Legend:

θ_P = CO_2 emissions factor for petroleum refinery production (MGSC: 11.44 tons CO_2 per year per barrel per day petroleum; SECARB: 9.9 tons CO_2 per year per barrel per day of petroleum processed)

$C_{\%}$ = Carbon in fuel (weigh fraction) (Found in Appendix B of this report)

D_F = Fuel density (lb per gallon = liquid; lb per million scf = gas)

E_{et} = Ethylene production (tons per year)

E_H = H_2 production (scf per year)

E_O = Ethylene oxide production rate (tons per year)

E_P = Petroleum plant production rate (barrels per day)

F_{CH4} = Natural gas usage rate (standard cubic feet per year)

F_t = Fuel usage rate (depends on fuel type) (gallons per year = liquid; million scf per year = gas; tons per year = solid)

M_{CO2} = Total CO_2 emissions (tons per year)

Table 9. Methodology for Estimating CO_2 Emissions from Fertilizer Production

Methodology	Description
Emissions Factors	Ammonia production emissions:[39,52] $M_{CO_2} = E_{NH_3}(\theta_{NH_3} + \theta_{fuel})$
	Ammonia production emissions:[52,53] $M_{CO_2} = E_{NH_3}\theta_{NH_3}$

Legend:

E_{NH3} = Ammonia production (tons NH_3 per year)
θ_{NH3} = CO_2 process emissions factor for ammonia production (PCOR: 1.15 tons CO_2 per ton NH_3; MGSC: 1.2 tons CO_2 per ton NH_3; SECARB: 1.13 tons CO_2 per ton NH_3)
θ_{fuel} = CO_2 combustion emissions factor (0.5 tons CO_2 per ton NH_3)
M_{CO2} = Total CO_2 emissions (tons per year)

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Appendix B

Carbon Fraction of Various Fuels Used for Combustion

Fuel	%C, as received	Basic Fuel Units
Eastern Bituminous Coal[1]	72.7	tons
Subbituminous Coal[1]	50.6	tons
Lignite[1]	36.4	tons
Natural Gas[2]	74.9	million ft^3
Fuel Oil[3]	86.7	1000 gal
Municipal Solid Waste[4]	38.0	tons
Propane[2]	81.7	1000 gal
Biomass (wood and wood wastes)[4]	21.5	tons
Residual Oil[3]	86.9	1000 gal
Coke (derived from coal)[5]	86.0	tons
Gasoline[6]	85.5	1000 gal

Notes:

1. EERC Ultimate Analysis (Eastern Bituminous is a Pittsburgh No. 8 Seam, Powder River Basin subbituminous coal is a Cordero Rojo, and lignite is a Fort Union Lignite).
2. Direct Calculations (Natural Gas is CH_4 and Propane is $CH_3CH_2CH_3$).
3. www.ec.gc.ca/energ/fuels/reports/cnslt_rpts/fqp/tables1_e.htm.
4. www.trmiles.com/alkali/fulesc3.html.
5. www.rexresearch.com/coal/4chap/4chap.htm.
6. http://www.woodgas.com/proximat.htm.

Summary of the Methodology for Development of Geologic Storage Estimates for Carbon Dioxide

Appendix B

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Contents

Executive Summary

The U.S. Department of Energy's Regional Carbon Sequestration Partnerships (RCSPs) were charged with providing a high-level, quantitative estimate of carbon dioxide (CO_2) storage resource available in subsurface environments of their regions. Environments considered for CO_2 storage were categorized into five major geologic systems: oil and gas reservoirs, saline formations, unmineable coal areas, shale, and basalt formations. Where possible, CO_2 storage resource estimates have been quantified for oil and gas reservoirs, saline formations, and unmineable coal areas in the third edition of the *Carbon Sequestration Atlas of the United States and Canada* (*Atlas III*). Shale and basalt formations are presented as future opportunities and are not assessed.

The methodology employed by the RCSPs is based on volumetric methods for estimating subsurface volumes. Subsurface storage volume estimates depend on geologic properties and storage efficiency. Storage efficiency for this methodology was determined using Monte Carlo sampling, which includes efficiency terms to define the pore volume that is amenable to geologic storage and displacement terms to define the pore volume immediately surrounding a single CO_2 injector well.

Methodologies used in *Atlas III* are intended to produce high-level, regional- and national- scale CO_2 resource estimates of potential geologic storage in the United States and Canada. At this scale, the estimates of CO_2 geologic storage have a high degree of uncertainty. Because of this uncertainty, estimates from *Atlas III* are not intended to be used as a substitute for site-specific characterization and assessment. As CO_2 storage sites move through the site characterization process, additional site-specific data is collected and analyzed, reducing uncertainty. Incorporation of this site-specific data allows for the refinement of CO_2 storage resource estimates and development of CO_2 storage capacities by future potential commercial project developers.

1. Introduction

Estimates of carbon dioxide (CO_2) geologic storage potential are required to assess the potential contribution of carbon capture and storage (CCS) technologies towards the reduction of CO_2 emissions. Governments and industries worldwide rely on CO_2 storage estimates for broad energy-related government policy and business decisions. Dependable CO_2 storage estimates are necessary to ensure successful deployment of CCS technologies (Bachu et al., 2007; Bradshaw et al., 2007). Several groups worldwide are conducting initiatives for assessing CO_2 geologic storage potential (Bachu et al., 2007; Bennion and Bachu, 2008; Birkholzer and Zhou, 2009; Birkholzer et al., 2009; Bradshaw et al., 2007; Brennan et al., 2010; Burruss et al., 2009; CEF, 2010; CO2CRC, 2008; CSLF, 2010; DOE-NETL, 2006, 2008, 2010b; Economides and Ehlig-Economides, 2009; Gorecki et al., 2009a; Gorecki et al., 2009b; Gorecki et al., 2009c; GSQ, 2010; IEA, 2009; Koide et al., 1992; Kopp et al., 2009a, b; Leetaru et al., 2009; Szulczewski and Juanes, 2009; van de Meer, 1992, 1993, 1995; van de Meer and van Wees, 2006; van de Meer and Egberts, 2008; van de Meer and Yavuz, 2009; van der Meer and Egberts, 2008; Xie and Economides, 2009; Zhou et al., 2008).

The Department of Energy (DOE), in collaboration with the Regional Carbon Sequestration Partnerships (RCSPs), developed the methodology described herein for estimating CO_2 geologic storage potential in the *Carbon Sequestration Atlas of the United States and Canada* (*Atlas III*) (DOE-NETL, 2010a) (DOE-NETL, 2006, 2008, 2010b). The following provides a summary of CO_2 storage resource definitions, the procedure used to estimate CO_2 storage resource, and details on CO_2 storage efficiency in resource estimates in *Atlas III*.

2. Purpose of CO_2 Storage Methodology

This methodology is intended for external users, such as the RCSPs, future project developers, and governmental entities, to produce high-level CO_2 storage resource estimates of potential geologic storage formations in the United States and Canada at the regional and national scale. Three types of CO_2 storage formations were evaluated—oil/gas reservoirs, saline formations, and unmineable coal areas. Oil/gas reservoirs were assessed at the field level, while saline formations and unmineable coal areas were assessed at the basin level. The CO_2 storage potential evaluated using this methodology is intended to be distributed in *Atlas III* (DOE-NETL, 2010b) and online by the National Carbon Sequestration Database and Geographic Information System (NATCARB) (DOE-NETL, 2010c). It is expected that this methodology will be refined in the future, incorporating results of the RCSP's Development Phase projects conducted from 2008 to 2018. DOE expects to update carbon dioxide storage estimates every 2 years in subsequent versions of the *Carbon Sequestration Atlas of the United States and Canada*.

Because this methodology is intended to produce high-level, regional- and national-scale CO_2 resource estimates of potential geologic storage in the United States and Canada, the estimates of CO_2 geologic storage have a high degree of uncertainty. One reason for this uncertainty is the lack of wells penetrating the potential storage formation, resulting in undefined rock properties and heterogeneity of the formation. Because of this uncertainty, CO_2 storage resource estimates are not intended to be used as a substitute for site-specific characterization and assessment. As CO_2 storage sites move through the site characterization process, additional site-specific data is collected and analyzed, reducing uncertainty. This data includes, but is not limited to, site-specific lithology, porosity, and permeability. Incorporation of this site-specific data allows for the refinement of CO_2 storage resource estimates and development of CO_2 storage capacities by future potential commercial project developers.

This methodology is based on volumetric methods for estimating subsurface volumes, in situ fluid distributions, and fluid displacement processes (Calhoun Jr., 1982). These volumetric methods are widely and routinely applied in petroleum, groundwater, underground natural gas storage, underground injection control (UIC) disposal, and CO_2 storage estimations (Bachu, 2008; Bachu et al., 2007; Calhoun Jr., 1982; Frailey et al., 2006; Lake, 1989). Subsurface storage volume estimates depend on geologic properties (area, thickness, and porosity of formations) and storage efficiency (the fraction of the accessible pore volume that will be occupied by the injected liquid or gas). Storage efficiency for this methodology was determined using Monte Carlo sampling, which includes efficiency terms to define the pore volume that is amenable to geologic storage and displacement terms to define the pore volume immediately surrounding a single CO_2 injector well.

3. Definitions of CO_2 Geologic Storage Estimates

Definitions of CO_2 geologic storage terms vary from one organization to the next. Therefore, the following is a summary of CO_2 geologic storage terms used in *Atlas III*.

3.1. CO_2 Storage Resource Estimates

Carbon dioxide storage resource estimates represent the fraction of pore volume of sedimentary rocks available for CO_2 storage and accessible to injected CO_2. Storage resource estimates are screened by criteria including, but not limited to: (1) isolation from shallow potable groundwater,[1] other strata, soils, and the atmosphere; (2) gravity segregation; (3) maximum allowed injection pressure imposed by regulatory agencies to avoid fracturing at the injection well and fracture propagation; (4) caprock or seal capillary entry pressure; and (5) displacement efficiency (Bachu, 2008).

Carbon dioxide storage resource estimates consider only physical trapping of CO_2. Economic or regulatory constraints are not considered in storage resource assessments. Chemical trapping mechanisms such as CO_2 brine dissolution and precipitation or mineralization effects are also not taken into account when calculating saline formation CO_2 storage resource estimates. The dissolution of injected CO_2 into brine and carbonate mineral formation reactions is complex process that is dependent on the temperature, pressure, and brine composition within a formation, as well as the effectiveness of the contact between free phase CO_2, the formation brine and, subsequently, the minerals in the formation strata (Bachu et al., 2007). As described in section 3.3, CO_2 storage resource estimates are based upon the assumption that in situ mobile fluids will either be displaced by the injected CO_2 into distant parts of the same formation or neighboring formations, or managed by means of fluid production, treatment, and disposal.

3.2. CO_2 Storage Capacity Estimates

Carbon dioxide storage capacity estimates represent the geologic storage potential when current economic and regulatory considerations are included. For the development of specific commercial-scale geologic storage sites, economic and regulatory constraints must be considered to determine the portion of the CO_2 storage resource estimate that is available under various development scenarios (Bachu, 2008). Under the most favorable economic and regulatory scenarios, 100 percent of the estimated CO_2 geologic storage resource would be considered CO_2 storage capacity. A methodology for calculating CO_2 storage capacity estimates is not provided since they require a higher level of analysis than regional- and national-scale CO_2 storage resource estimates. Furthermore, specific sites may not be representative of the formation as a whole, and extrapolation of this methodology to specific sites may overestimate capacity.

Examples of economic considerations involved with CO_2 storage include: (1) CO_2 injection rate and pressure, (2) the number of wells drilled into the formation, (3) types of wells (horizontal versus vertical), (4) the number of injection zones completed in each well, (5) operating expenses, (6) management of in situ formation fluids (Zhou et al., 2008), (7) injection site proximity to a CO_2 source (Lucier and Zoback, 2008), and (8) combination with enhanced oil recovery or enhanced gas recovery activities.

Examples of regulatory considerations include: (1) protection of potable water; (2) well spacing requirements, (3) maximum injection rates, (4) prescribed completion methods (cased vs. open-hole), (5) proximity to existing wells, (6) treatment of in situ fluids, and (7) surface usage considerations (Wilson et al., 2003). Many of these considerations are addressed through the EPA UIC Program's Class VI well final rule, which defines specific requirements for CO_2 injection projects. Additional regulatory considerations may exist at the State and Provincial levels. Due to the varied nature of regulatory regimes for potential CO_2 storage reservoirs, CO_2 storage capacity estimates require site-specific assessments.

3.3. Boundary Conditions

Defining boundary conditions is necessary for any type of subsurface assessment. Two systems, open and closed, can be used to define the boundaries for potential CO_2 storage reservoirs. Open systems are permeable fluid-filled reservoirs where in situ fluids are displaced away from the injection location into other parts of the formation or into neighboring formations (Birkholzer and Zhou, 2009; Gorecki et al., 2009b; IEA, 2009;

[1] Potable waters, for the purposes of this assessment, represent waters protected by the Safe Drinking Water Act (SDWA), which are defined as waters with less than 10,000 parts per million (ppm) total dissolved solids (TDS).U.S. Environmental Protection Agency (EPA), 2010. Safe Drinking Water Act, Office of Ground Water & Drinking Water, http://www.epa.gov/safewater/sdwa.

Nicot, 2008; Zhou et al., 2008). Subsequently, the primary constraints on the percentage of pore space that can be filled with CO_2 in open systems are due to displacement efficiencies, rather than pressure increases, although there will often be a need to define a maximum bottom-hole injection pressure to reduce risks associated with injection (Gorecki et al., 2009b; IEA, 2009; Zhou et al., 2008). Displacement of fluids from reservoirs has been examined in recent studies, which focus on potential effects of fluid migration to other subsurface geologic formations (Birkholzer and Zhou, 2009; Birkholzer et al., 2009; Leetaru et al., 2009; Nicot, 2008; Zhou et al., 2008).

Closed systems are fluid-filled reservoirs where in situ fluid movement is restricted within the formation by means of impermeable barriers (Birkholzer and Zhou, 2009; Gorecki et al., 2009b; IEA, 2009; Nicot, 2008; Zhou et al., 2008). Storage volume in closed systems is constrained by the compressibility of the formation's native fluid and rock matrix (van de Meer, 1992, 1993, 1995; van de Meer and Egberts, 2008; van de Meer and Yavuz, 2009; van der Meer and Egberts, 2008). In addition, the CO_2 injection pressure cannot exceed the maximum allowable pressure of the formation because over-pressurization may damage natural formation seals (Burruss et al., 2009; Gorecki et al., 2009b; Zhou et al., 2008). The very low compressibility of formation fluids and rocks limit the capacity of closed systems to a very small percentage of total pore volume (Gorecki et al., 2009b; Xie and Economides, 2009; Zhou et al., 2008). Closed systems may be transformed into open systems by means of managing, treating, and disposing of in situ fluids in accordance with current technical, regulatory, and economic guidelines (Birkholzer and Zhou, 2009; Gorecki et al., 2009b; IEA, 2009; Nicot, 2008; Zhou et al., 2008).

As defined in Section 3.1, storage resource estimates for *Atlas III* are based on open systems in which in situ fluids will either be displaced from the injection zone or managed. Accordingly, CO_2 storage resource estimates provide an upper boundary for CO_2 storage. Realization of the full CO_2 storage resource estimate as a capacity estimate will rely on how site-specific geology, economics, and regulations restrict the management of in situ fluids.

4. Methodology for CO_2 Storage Resource Estimate Calculation

Two different approaches are typically used to estimate subsurface injection volumes—static and dynamic (Calhoun Jr., 1982). Static methods used to estimate CO_2 storage potential are based on volumetric and compressibility-based models (Bachu, 2008; Bachu et al., 2007; Bradshaw et al., 2007; Burruss et al., 2009; 2008; Gorecki et al., 2009b; IEA, 2009; Kopp et al., 2009a, b; Szulczewski and Juanes, 2009; van de Meer, 1995; van de Meer and Egberts, 2008; van de Meer and Yavuz, 2009; van der Meer and Egberts, 2008). Volumetric methods are applied when it is generally assumed that the formation is open and that formation fluids are displaced from the formation or managed via production. Compressibility-based methods can be applied at the site-specific scale if it is demonstrated that the system is closed. Meaningful dynamic simulations typically cannot be done before site-specific data is collected and field-measured CO_2 injection rates or well testing have been completed. The methodology used in *Atlas III* is based on the volumetric approach for estimating CO_2 storage resource potential in oil and gas reservoirs, saline formations, and unmineable coal areas.

4.1. Oil and Gas Reservoir CO_2 Storage Resource Estimates

This methodology defines CO_2 storage resource estimates on a volumetric basis or production basis for oil and gas reservoirs that have hosted natural accumulations of oil and gas and could be used to store CO_2. No distinction is made in this assessment for the maturity of the reservoir. Because oil and gas reservoirs can be productive across a wide variety of depths, no minimum or maximum depth criteria were used for CO_2 storage resource estimates. Oil and gas reservoirs with a water TDS concentration of 10,000 ppm and higher were included, unless specifically noted and justified.

Storage volume methodology for oil and gas reservoirs was based on quantifying the volume of oil and gas that has or could be produced, and assuming that it could be replaced by an equivalent volume of CO_2. With this method, both oil/gas and CO_2 volumes are calculated at initial formation pressure or a pressure that is considered a maximum CO_2 storage pressure. However, there is not always a one-to-one relationship between the oil and gas volume footprint and a trap footprint for holding hydrocarbons (Nicot and Hovorka, 2009). Two main methods were used in *Atlas III* to estimate the CO_2 storage resource for oil and gas reservoirs: (1) a volumetrics-based CO_2 storage resource estimate and (2) a production-based CO_2 storage resource estimate. The method used by each RSCP was based on available data. The two methods have storage efficiency factors built into their respective equations and, therefore, CO_2 storage resource estimates are proposed as a single value for oil and gas reservoirs. Production-based CO_2 storage resource estimates are generally preferred over volumetrics-based CO_2 storage resource estimates because production data contains detailed information collected from the formation. If no production data is available, then volumetrics-based CO_2 storage resource estimates may be applied.

In the oil and gas industry, hydrocarbon recovery related attributes are calculated and applied with respect to the original oil or gas in place (at surface conditions, e.g. stock tank barrels of oil) regardless of the maturity of the oil or gas field development. Likewise, for estimating CO_2 storage resource in oil and gas reservoirs, CO_2 storage efficiency was developed as a function of the original hydrocarbon in place.

The volumetrics-based CO_2 storage resource estimate is based off the standard industry method to calculate original oil-in-place (OOIP) (Calhoun Jr., 1982; Lake, 1989). The general form of the volumetric equation to calculate the CO_2 storage resource mass estimate (G_{CO2}) for geologic storage in oil and gas reservoirs is as follows:

$$G_{CO2} = A\, h_n\, \phi_e\, (1-S_{wi})B\, \rho_{CO2std}\, E_{oil/gas} \tag{1}$$

The product of the area (A), net thickness (hn), average effective porosity (ϕe), original hydrocarbon saturation (1-initial water saturation, expressed as a fraction [S_{wi}]), and the initial oil (or gas) formation volume factor (B) yield the OOIP (or OGIP). The storage efficiency factor ($E_{oil/gas}$) is derived from local CO_2 EOR experience or reservoir simulation as standard volume of CO_2 per volume of OOIP. (In oilfield terms, the CO_2 EOR oil recovery factor and the CO_2 net utilization is equal to the storage efficiency factor.) The standard CO_2 density (ρ_{co2std}) converts standard CO_2 volume to mass. Because of previous extensive experience in estimating volumetrics of formations, each RCSP supplies regional, play, or formation-specific efficiency values. Table 1 summarizes the terms shown in eq 1.

Table 1. Oil and Gas Reservoir CO_2 Storage Resource Estimates

Parameter	Units*	Description
G_{CO2}	M	Mass estimate of oil and gas reservoir CO_2 storage resource.
A	L^2	Area that defines the oil or gas reservoir that is being assessed for CO_2 storage.
h_n	L	Net oil and gas column height in the reservoir.
ϕ_e	L^3/L^3	Average effective porosity in volume defined by the net thickness.
S_{wi}	L^3/L^3	Average initial water saturation within the total area (A) and net thickness (h_n).
B	L^3/L^3	Fluid formation volume factor; converts standard oil or gas volume to subsurface volume (at reservoir pressure and temperature), e.g. stock tank volume of oil per reservoir volume of oil.
ρ_{CO2std}	M/L^3	Standard density of CO_2 evaluated at standard pressure and temperature
$E_{oil/gas}$	L^3/L^3	CO_2 storage efficiency factor, the volume of CO_2 stored in and oil or gas reservoir per unit volume of original oil or gas in place (OOIP or OGIP).

* L is length; M is mass.

A production-based CO_2 storage resource estimate is possible if acceptable records are available on volumes of oil and gas produced. Produced water is not considered in the estimates, nor is injected water (waterflooding), although these volumes may be useful in site-specific calculations (Bachu et al., 2007). In cases where a field has not reached a mature stage, it is beneficial to apply decline curve analysis to better approximate the estimated ultimate recovery, which represents the expected volume of produced oil and gas (Calhoun Jr., 1982; Lake, 1989).

It is necessary to apply an appropriate reservoir volume factor (B) to convert surface oil and gas volumes (reported as production) to subsurface volumes (including correction of solution gas volumes if gas production in an oil reservoir is included). No area, column height, porosity, residual water saturation, or estimation of the fraction of OOIP accessible to CO_2 is required because production reflects these reservoir characteristics. If information is available, it is possible to apply efficiency to production data to convert them to CO_2 storage volumes; otherwise, replacement of produced oil and gas by CO_2 on a volume-for-volume basis (at reservoir pressure and temperature) may be acceptable.

4.2. Saline Formation CO_2 Storage Resource Estimates

Saline formations are composed of water-saturated porous rock and capped by one or more regionally extensive low-permeability rock formations. A saline formation assessed for CO_2 storage is defined as a porous and permeable body of rock containing water with TDS greater than 10,000 ppm. A saline formation can include more than one named geologic stratigraphic unit or be defined as only a part of a stratigraphic unit. Mechanisms for CO_2 storage in saline formations include structural trapping, hydrodynamic trapping, residual trapping, dissolution, and mineralization (Bachu et al., 2007; Kopp et al., 2009b; Xie and Economides, 2009). Structural, hydrodynamic, and residual trapping are initially the dominant trapping mechanisms and are the focus of this methodology.

Saline formations assessed for storage are restricted to those meeting basic criteria including:(1) adequate pressure and temperature conditions in the saline formation to keep the CO_2 liquid or supercritical; (2) presence of a suitable seal system, such as a caprock, to limit vertical flow of the CO_2 to the surface; and (3) a combination of hydrogeologic conditions to isolate the CO_2 within the saline formation.

The storage of CO_2 in saline formations is limited to sedimentary basins with vertical flow barriers and depths exceeding 800 meters. Sedimentary basins include porous and permeable sandstone and carbonate rocks. The 800-meter cutoff is an arbitrary attempt to select a depth that reflects pressure and temperature that yields high-density liquid or supercritical CO_2. All sedimentary rocks included in the saline formation CO_2 storage resource estimate must have seal systems consisting of low-permeability sealing rocks, such as shales, anhydrites, and other evaporates; however, the thickness of these sealing systems is not considered in this methodology. For increasing confidence in a storage resource estimates, other criteria including seal effectiveness (e.g., salinity and pressure above and below the seal system), minimum permeability, minimum threshold capillary pressure, and fracture propagation pressure of a seal system should be considered.

The volumetric equation to calculate the CO_2 storage resource mass estimate (G_{CO2}) for geologic storage in saline formations is:

$$G_{CO2} = A_t \, h_g \, \phi_{tot} \, \rho E_{saline} \tag{2}$$

The total area (A_t), gross formation thickness (h_g), and total porosity (ϕ_{tot}) terms account for the total bulk volume of pore space available. The CO_2 density (ρ) converts the reservoir volume of CO_2 to mass. Rather than using an irreducible water saturation parameter explicitly, the storage efficiency factor (E_{saline}) reflects the fraction of the total pore volume that will be occupied by the injected CO_2. As described in section 5.1., E_{saline} factors range between 0.40 and 5.5 percent over the 10th to 90th percent probability range. Table 2 summarizes the terms shown in eq 2.

Table 2: Saline Formation CO_2 Storage Resource Estimating

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.

4.3. Unmineable Coal Area CO_2 Storage Resource Estimates

Only coal areas containing water with TDS greater than 10,000 ppm merited evaluation for potential CO_2 storage (EPA, 1991). Where water quality data are scarce or unavailable, analogy to other geologic basins was used to estimate the minimum depth criteria. The maximum depth was arbitrarily selected for each basin to account for practicalities of CO_2 storage by sorption in coal. Depending on the geothermal and geo-pressure gradients in a formation, gaseous CO_2 adsorption may only be possible down to depths of about 3,000 ft (900 m) (Ryan and Littke, 2005). At greater depths and depending on coal rank, supercritical CO_2 may enter the solid coal and change its properties, which swells the coal matrix and causes injectivity problems (Metz et al., 2005). Cleat closure induced by increasing effective stress will further decrease permeability to such an extent that coalbed methane cannot be produced below 5,000 ft (1,500 m) (Bachu et al., 2007). Currently, this is defined as the maximum depth limit for potential CO_2 storage in coal (Metz et al., 2005). Beyond this limit, CO_2 storage is limited by the compression costs, which escalate below 11,000 ft (3,300 m) (van de Meer, 1993).

Within the depth intervals selected for a particular basin, a determination was made as to which coals are unmineable by today's state-of-the-art standards of technology. Although advancements in mining technology and changes in the value of the commodity may enable some of the coal areas that are currently deemed unmineable to be mineable in the future, it is beyond the scope of this effort to forecast long-term developments and their impact. Only coals deemed unmineable are included in this CO_2 storage resource estimate.

The following is the volumetric equation to calculate the CO_2 storage resource mass estimate (G_{CO2}) for geologic storage in unmineable coal areas:

$$G_{CO2} = A\, h_g\, C_{s,max}\, \rho_{CO2std}\, E_{coal} \tag{3}$$

The total area (A) and gross area thickness (h_g) terms account for the total bulk volume containing the coal(s) to be assessed. $C_{s,max}$ is the maximum volume of CO_2 at standard conditions that can be sorbed per volume of coal (e.g., the Langmuir isotherm volume constant), and is assumed to be on an in situ or "as is" basis. (A conversion from mass or dry-ash-free volume basis may be necessary.) A component within the calculation of E_{coal}, includes the degree of saturation achievable for an in situ coal compared with the theoretical maximum predicted by the CO_2 Langmuir isotherm (section 5.2). The CO_2 density (ρ_{co2std}) converts the standard CO_2 volume in the Langmuir term (C) to mass. The storage efficiency factor (E_{coal}) reflects the fraction of the total bulk coal volume that will store the injected CO_2. As in section 5.2., E_{coal} factors range between 21 and 48 percent at the 10^{th} to 90^{th} percent probability range. Table 3 summarizes the terms shown in eq 3.

Table 3: *Unmineable Coal Area CO_2 Storage Resource Estimating*

Parameter	Units*	Description
G_{CO2}	M	Mass estimate of CO_2 resource of one or more coal beds.
A	L^2	Geographical area that outlines the coal basin or region for CO_2 storage calculation.
h_g	L	Gross thickness of coal area(s) for which CO_2 storage is assessed within the basin or region defined by A.
$C_{s,max}$	L^3/L^3	Adsorbed maximum standard CO_2 volume per unit of in situ coal volume (Langmuir or alternative); assumes 100% CO_2 saturated coal conditions; if on dry-ash-free (daf) basis, conversion should be made.
ρ_{CO2std}	M/L^3	Standard density of CO_2.
E_{coal}	L^3/L^3	CO_2 storage efficiency factor that reflects a fraction of the total coal bulk volume that is contacted by CO_2.

* L is length; M is mass.

The maximum CO_2 sorption capacity of coal at saturation ($C_{s,max}$), which depends on the coal characteristics and, to a certain extent, on temperature, can be reported on per unit-of-coal-mass basis ($n_{s,max}$). Conversion into per unit-volume basis ($C_{s,max}$) requires the knowledge of coal bulk density ($\rho_{c,dry}$) as well as moisture and/or ash content, depending on the reporting format (such as dry, ash free). The average density of sorbed CO_2 in coal under saturated conditions is described by eq 4:

$$C_{s,max} = n_{s,max}\, \rho_{c,dry}\, (1 - f_{a,dry}) \tag{4}$$

where $f_{a,dry}$ is the ash weight fraction of the dry coal bulk density ($\rho_{c,dry}$). For consistency with the distinction between the micropore sorption and hydrodynamic trapping due to fracture porosity, the coal bulk density should be measured as inclusive of micropore volume (e.g., mercury density of coal) (Gan et al., 1972). However, the helium density of coal, which is the most readily available data, is a good approximation as long as the micropore volume is accounted for in the fracture porosity (Huang et al., 1995).

The in situ fraction of CO_2 (C_s) that is stored per unit of coal under reservoir conditions, as opposed to under ideal (maximum) pressure conditions, depends on reservoir pressure after injection, moisture content, and the amount of gas in place (Clarkson and Bustin, 2000). However, the pressure effect can be approximated by a standard (e.g., Langmuir) isotherm equation. For lower rank coals, care should be taken to perform laboratory testing under reservoir conditions because chemical heterogeneity increases the difference in accessible micropore volumes between wet and dry coals observed at low pressure (low surface coverage) (Prinz and Littke, 2005). If data are available, different isotherms for different coal ranks are used. If no CO_2 isotherm is available, isotherms from similar rank coals in analog basins can be used, such as the isotherm data plotted in Figure 1 (Botnen et al., 2009; Bromhal et al., 2005; Busch et al., 2003; Chikatamarla et al., 2004; Clarkson and Bustin, 1999; Day et al., 2008a; Durucan and Q., 2009; Fitzgerald et al., 2005; Fitzgerald et al., 2006; Goodman et al., 2007; Harpalani and Mitra, 2010; Harpalani et al., 2006; Jessen et al., 2008; Ozdemir and Schroeder, 2009; Pini et al., 2010; 2008; Reeves et al., 2005; Romanov and Soong, 2008; Ross et al., 2009; Siemons and Busch, 2007).

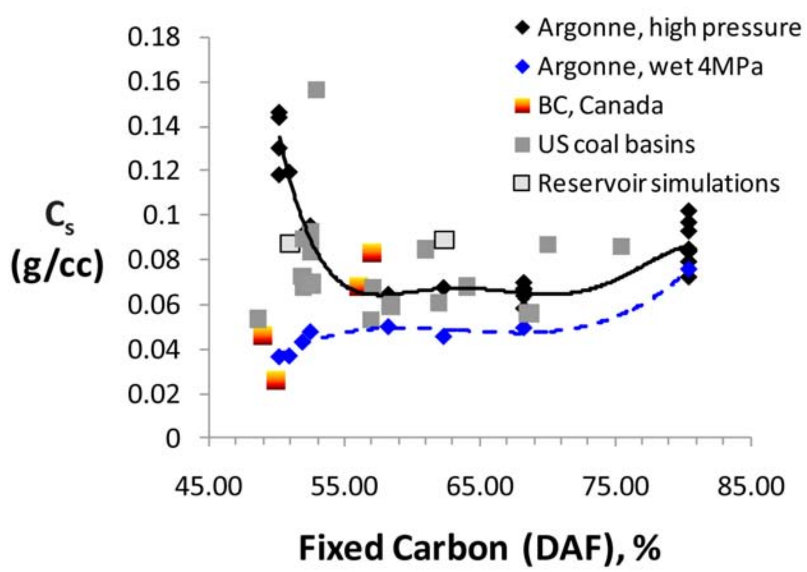

Figure 1. Average CO_2 Sorption (expressed in g/cc) vs. Coal Rank (expressed as percent fixed carbon on a dry and ash free basis (daf)). Red and gray solid squares represent experimental data for Canadian and North American coals, respectively. Black and blue solid diamonds represent experimental data for Argonne premium coals at saturation (high pressure) and at low pressure (4 MPa wet), respectively. Gray solid squares with black outline represent data for two reservoir simulations. (Botnen et al., 2009; Bromhal et al., 2005; Busch et al., 2003; Chikatamarla et al., 2004; Clarkson and Bustin, 1999; Day et al., 2008a; Durucan and Q., 2009; Fitzgerald et al., 2005; Fitzgerald et al., 2006; Goodman et al., 2007; Harpalani and Mitra, 2010; Harpalani et al., 2006; Jessen et al., 2008; Ozdemir and Schroeder, 2009; Reeves et al., 2005; Romanov and Soong, 2008; Ross et al., 2009; Siemons and Busch, 2007).

5. CO_2 Storage Efficiency for Resource Estimates

Carbon dioxide storage efficiency gauges the fraction of accessible pore volume that will be occupied by the injected CO_2. In open systems, the fraction of accessible pore volume is estimated by geologic terms (area, thickness, and porosity) and displacement terms (areal, vertical, gravity, and microscopic displacement) (Lake, 1989). Monte Carlo sampling techniques, as described in Sections 5.1 and 5.2, were used to estimate efficiency factors for CO_2 storage resource estimates for both saline formations and unmineable coal areas over the P_{10}, P_{50}, and P_{90} percent probability range. Efficiency in this methodology is comprised of statistical properties of geologic and displacement parameters.

5.1. Storage Efficiency of Saline Formations

For saline formations, the CO_2 storage efficiency factor is a function of geologic parameters, such as area ($E_{An/At}$), gross thickness ($E_{hn/hg}$), and total porosity ($E_{\phi e/\phi tot}$), that reflect the percentage of volume amenable to CO_2 sequestration and displacement efficiency components, such as areal (E_A), vertical (E_L), gravity (E_g), and microsocopic (E_d), that reflect different physical barriers that inhibit CO_2 from contacting 100 percent of the pore volume of a given basin or region (Bachu et al., 2007; Doughty and Pruess, 2004; Koide et al., 1992; Shafeen et al., 2004; van de Meer, 1992). Equation 5 describes the individual parameters required to estimate the CO_2 storage efficiency factor for saline formations:

$$E_{saline} = E_{An/At}\, E_{hn/hg}\, E_{\phi e/\phi tot}\, E_A\, E_L\, E_g\, E_d \quad (5)$$

The net-to-total area $E_{An/At}$ ratio is the fraction of the total basin or region area that is suitable for CO_2 storage. The net-to-gross thickness $E_{hn/hg}$ ratio is the fraction of the total geologic unit that meets minimum porosity and permeability requirements for injection. The effective-to-total porosity $E_{\phi e/\phi tot}$ ratio is the fraction of total interconnected porosity (Table 4).

The areal displacement (E_A) efficiency is the fraction of planar area surrounding the injection well that CO_2 can contact. This term is influenced by areal geologic heterogeneity, such as faults or permeability, and by CO_2 mobility (Lake, 1989). The vertical (geologic layering) displacement (E_L) efficiency is the fraction of vertical cross section or thickness with the volume defined by the area (A) that can be contacted by the CO_2 plume from a single well, which can be affected by the aquifer dip and by CO_2 buoyancy (Lake, 1989). This term is influenced by variations in porosity and permeability between sub-layers in the same geologic unit. If one zone has higher permeability than other zones, the CO_2 will fill this zone quickly and leave the other zones with less or no CO_2. The gravity displacement (E_g) efficiency is the fraction of net thickness that is contacted by CO_2 as a consequence of the density and mobility difference between CO_2 and in situ water. In other words, 1-E_g is the portion of the net thickness not contacted by CO_2 because the CO_2 rises within the geologic unit. The microscopic displacement (E_d) efficiency is the fraction of water-filled pore volume that can be replaced by CO_2 (Lake, 1989). This term is directly related to irreducible water saturation in the presence of CO_2. For the areal, vertical, and gravity displacement terms, it is assumed that CO_2 fully displaces all in situ fluids. Since 100 percent displacement of fluid is neither theoretically nor technically feasible, the microscopic displacement term identifies the fraction of pore space unavailable due to immobile in situ fluids (Figures 2 and 3). The displacement terms are shown schematically in Figures 2 and 3 and compiled into Table 4.

Efficiency estimates using Monte Carlo sampling are based on statistical properties, such as mean values, standard deviation, ranges, and distributions, that describe geologic and displacement parameters. Little information is known regarding the statistical characteristics of saline formations because geologic parameters and formations are not well characterized (Bachu et al., 2007; Burruss et al., 2009; 2006, 2008, 2010b; Doughty and Pruess, 2004; Gorecki et al., 2009a; Gorecki et al., 2009b; Gorecki et al., 2009c; IEA, 2009). Recently, the International

Table 4: *Parameters for Saline Formation Efficiency*

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)

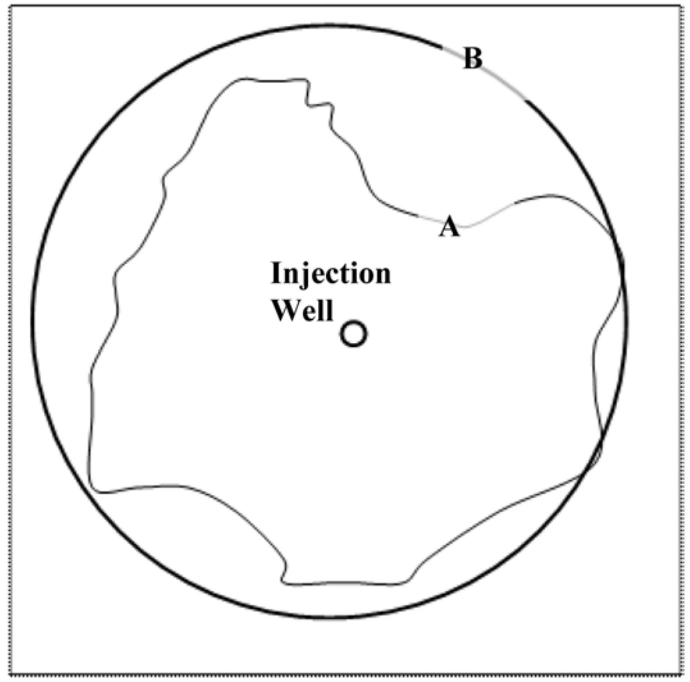

Figure 2: Top-view of injection well and plume area. The area within the irregular shape inside the circle is the areal view of the 3-dimensional CO_2 plume (A). The area inside the larger circle (B) is the accessible pore volume for areal displacement. The areal displacement term, E_A = net area contacted by CO_2 (A) / Total area (B).

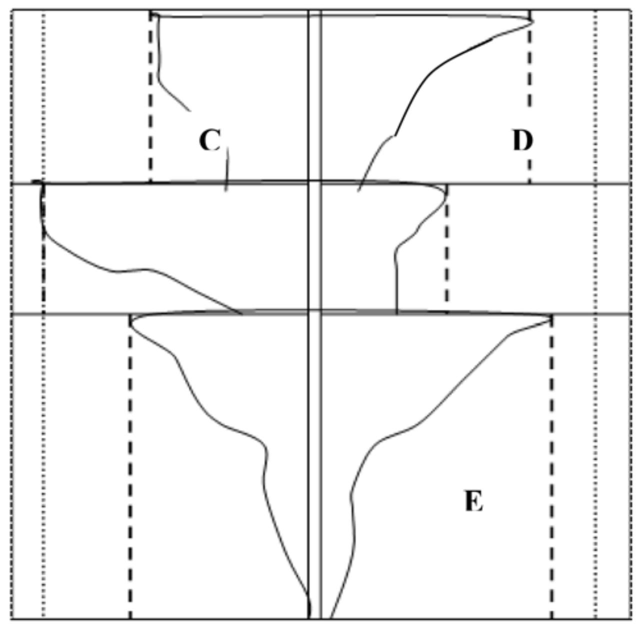

Figure 3: Side view of injection well and plume area. The outer vertical dotted lines are defined by the outer areal circle (Depicted by B in Figure 2). The "plume" area enclosed within each interval that is bound by vertical dashed lines represents the numerator of the E_L term (area enclosed within C); the denominator is the entire space outlined by the dotted line (area enclosed within D). Within the area bound by the dashed lines, the lower portion is not contacted due to gravity (area depicted by E) and is removed by the E_g term. The E_d term then defines the CO_2 displacement efficiency in the plume region.

Energy Agency (IEA [2009]) and Kopp et al. (2009a,b) used field data from oil and gas reservoirs and numerical simulations employing relative-permeability data for CO_2-brine systems measured in the laboratory (Bennion and Bachu, 2008) to predict appropriate ranges for geologic and displacement parameters for saline formations as a function of lithology. A similar report is also available from Gorecki et al. (2009a; 2009b; 2009c). It was assumed that saline formations do not differ fundamentally from oil and gas reservoirs (IEA, 2009; Kopp et al., 2009a). Table 4 includes values reported by IEA (2009) of the P_{10} and P_{90} ranges of geologic and displacement parameters for clastics, dolomite, and limestone lithologies for saline formations.[2] The P_{10} notation reflects that there is a 10 percent probability that the value is less than the P_{10} value, and the P_{90} notation reflects that there is a 90 percent probability that the value is less than the P_{90} value. Because of the difficulty in separating the E_A, E_L, and E_g displacement terms shown in eq 5 in a heterogeneous scenario, these terms were combined by IEA (2009) into a single volumetric displacement term, E_V.

In this methodology, efficiency, as estimated by Monte Carlo sampling, for saline formations was based directly on the P_{10} and P_{90} ranges for net-to-gross thickness $E_{hn/hg}$, effective-to-total porosity $E_{\phi e/\phi tot}$, volumetric displacement (E_V), and microsocopic displacement (E_d) as reported by IEA (2009) (Table 4). Because no documented data for the area $E_{An/At}$ term are available, it was assumed that CO_2 will occupy between 20 and 80 percent of the formation for the purposes of these simulations (DOE-NETL, 2006, 2008).The equation, parameters, symbols, ranges, and description used to calculate efficiency for saline formations are summarized by eq 6 and Table 4.

$$E_{saline} = E_{An/At}\, E_{hn/hg}\, E_{\phi e/\phi tot}\, E_V\, E_d \qquad (6)$$

The area $E_{An/At}$, thickness $E_{hn/hg}$, and porosity $E_{\phi e/\phi tot}$ terms gauge the percentage of volume that is amenable to CO_2 sequestration. The volumetric displacement term (E_V) corrects for the effective CO_2 plume shape. The microscopic displacement term (E_d) corrects for the accessible pore volume available to CO_2.

Efficiency (E_{saline}) was estimated from the individual terms in eq 6 by Monte Carlo sampling. Each individual term in eq 6 is given by a fraction, p. Various parametric distribution functions, such as normal, uniform, and lognormal, could be used to represent the distributions of the p's. Currently, there is not enough data available to support assigning a specific distribution function to each of the individual terms in eq 6 at the regional and national scale. Since the p's are fractions, they are constrained to the range between 0 and 1. Thus, the most appropriate distribution functions will be those that are constrained to the range between 0 and 1.
Two distribution functions meeting this criterion and considered in this work are the beta distribution and the log-odds normal distribution. While both distributions are appropriate, the log-odds normal distribution, also known as the logistics-normal distribution (Aitchison and Shen, 1980), was chosen because of its ability to directly integrate the P_{10} and P_{90} ranges of geologic and displacement parameters provided by IEA (2009) as presented in Table 4. It was assumed that the individual efficiency terms in eq 6 could all be represented using a log-odds normal distribution at the regional and national scale. From the limited data available (IEA, 2009), all parameters were assumed to be independent since no correlation was found between the parameters. However, parameters may be linked at the site-specific scale.

The log-odds normal distribution transforms a fraction, p, by eq 7 and assumes that the transformed variable can be normally distributed.

$$X = \ln\left(\frac{p}{1-p}\right) \qquad (7)$$

The distribution is so named because the p/(1–p) term in eq 7 is the "odds" for a fraction or probability p; therefore, ln[p/(1–p)] is the "log odds." The use of this distribution is referred to as the log odds method when applied with Monte Carlo sampling (Devore, 2004). The transformed variable, X, is then normally distributed and sampled with Monte Carlo techniques. Then, the X value is transformed back to the corresponding p value by eq 8, which is the inversion of eq 7:

$$p = \frac{1}{1+e^{-X}} \qquad (8)$$

Since the relationship between eqs 7 and 8 is monotonic, X_{10} and X_{90} ranges of geologic and displacement parameters provided by IEA (2009) can be computed directly from P_{10} and P_{90} ranges, respectively, using eq 7.

The log odds approach thus transforms p values of a range into corresponding X values of a range. This allows the mean and standard deviation of X to be determined from the X_{10} and X_{90} values. The mean and standard deviation of X fully specify its normal distribution, and these moments are then used as input parameters into the Monte Carlo sampling tools. The P_{10} and P_{90} values of the ranges presented in Table 4 were converted to X_{10} and X_{90} values by eq 7 and are shown in Table 5.

Table 5: X_{10} and X_{90} Values Converted from P_{10} and P_{90} Values from Equation 7

X_{10} and X_{90} Values Converted from P_{10} and P_{90} Values						
	Clastics		Dolomite		Limestone	
	X_{10}	X_{90}	X_{10}	X_{90}	X_{10}	X_{90}
$E_{An/At}$	-1.4	1.4	-1.4	1.4	-1.4	1.4
$E_{hn/hg}$	-1.32	1.15	-1.59	0.75	-1.90	0.49
$E_{\phi e/\phi tot}$	0.58	1.21	0.12	0.90	0.58	1.10
E_V	-1.66	-0.45	-1.05	-0.28	-0.71	0.28
E_d	-0.62	1.15	0.28	0.58	-0.99	-0.32

2 Ranges of geologic and displacement parameters for clastics, dolomite, and limestone lithologies for saline formations were used directly from Table 11 found in the IEA (2009) report.

The mean (μ_x) and standard deviation (σ_x) are calculated from the X_{10} and X_{90} values using standard relationships between the percentiles and moments of a normal distribution

$$\sigma_x = \frac{(X_{90} - X_{10})}{(Z_{90} - Z_{10})} \tag{9}$$

$$\mu_x = X_{10} - \sigma_x Z_{10} \tag{10}$$

where Z_p is the P^th^ percentile value of the standard normal distribution. In this case, Z_{10} equals -1.28 and Z_{90} equals 1.28. Note that the standard deviation is computed first using eq 9, and this value is then used to compute the mean in eq 10. The values of the moments for X computed using eq 9 and 10 are shown in Table 6.

Table 6: μ_x and σ_x Values Calculated from X_{10} and X_{90} Values from Equations 9 and 10

μ_x and σ_x Values Calculated from X_{10} and X_{90} Values						
	Clastics		Dolomite		Limestone	
	μ_x	σ_x	μ_x	σ_x	μ_x	σ_x
$E_{An/At}$	0	1.1	0	1.1	0	1.1
$E_{hn/hg}$	-0.09	0.97	-0.42	0.91	-0.71	0.93
$E_{\phi e/\phi tot}$	0.89	0.25	0.51	0.30	0.84	0.20
E_v	-1.05	0.47	-0.66	0.30	-0.21	0.39
E_d	0.27	0.69	0.43	0.11	-0.66	0.26

Monte Carlo sampling, using the commercial program GoldSim, was run using the mean (μ_x) and standard deviation (σ_x) values tabulated in Table 6 as input parameters. The respective X values are sampled using normal distributions with a sample size of 5,000 iterations for each. The corresponding values of p are computed using eq 8, and the individual p values are multiplied together to determine the storage efficiency factor E as shown in eq 11:

$$E = p(E_{An/At})\, p(E_{hn/hg})\, p(E_{\varphi e/\sigma tot})\, p(E_v)\, p(E_d) \tag{11}$$

or equivalently,

$$E = \left(\frac{1}{1+e^{-X(E_{An/At})}}\right)\left(\frac{1}{1+e^{-X(E_{hn/hg})}}\right)\left(\frac{1}{1+e^{-X(E_{\varphi e/\sigma tot})}}\right)\left(\frac{1}{1+e^{-X(E_v)}}\right)\left(\frac{1}{1+e^{-X(E_d)}}\right)$$

A value of E is thus obtained for each of the 5,000 simulations, and the overall percentiles for the computed E are then estimated. Ranking from smallest to largest, the 500^th^ result corresponds to P_{10}, the 2,500^th^ result corresponds to P_{50}, and the 4,500^th^ result corresponds to P_{90}. These results are shown in Table 7.

Table 7: Saline Formation Efficiency Factors For Geologic and Displacement Terms

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%

The overall efficiency for saline formations ranges from 0.40 to 5.5 percent for the three different lithologies over the 10 and 90 percent probability range, respectively. These efficiency factors are based on documented ranges derived from oil and gas reservoirs and numerical simulations (IEA, 2009). With previous versions of the *Carbon Sequestration Atlas of the United States and Canada*, geologic and displacement parameters were not based on documented ranges (DOE-NETL, 2006, 2008). These saline formation efficiency factors ranged between 1 and 4 percent over the P_{15} and P_{85} percent probability range (DOE-NETL, 2006, 2008). When undocumented ranges for saline formations for previous editions of the Atlas (DOE-NETL, 2006, 2008) were applied using the log odds method described here, the P_{10}, P_{50}, and P_{90} percent probability ranges were 0.51 percent, 2.0 percent, and 5.5 percent, respectively. While the two sets of input ranges generate similar overall efficiency factors for saline formations, the efficiency factors reported here are based on documented P_{10} and P_{90} ranges of geologic and displacement parameters for clastics, dolomite, and limestone lithologies and appropriate distribution functions, log-odds normal in this case, that are constrained to the range between 0 and 1 whereas previous efficiencies were not.

In the case where net-to-total area $E_{An/At}$, net-to-gross thickness $E_{hn/hg}$, and effective-to-total porosity $E_{\phi e/\phi tot}$ are known for a region or basin, the geologic efficiency values can be used directly in eq 6. In this instance, only the displacement efficiency factor is needed, which ranges between 7.4 and 26 percent over the 10 and 90 percent probability range (Table 8).

Overall, CO_2 storage resource estimates for saline formations are calculated from volumetric parameters (eq 2) and efficiency factors (eq 6) over the P_{10}, P_{50}, and P_{90} percent probability range (Tables 7 and 8).

$$G_{CO2} = A_t\, h_g\, \phi_{tot}\, \rho E_{saline} \tag{2}$$

$$P_{10} \quad E_{saline} = E_{An/At}\, E_{hn/hg}\, E_{\phi e/\phi tot}\, E_v\, E_d \tag{6}$$

$$P_{50} \quad E_{saline} = E_{An/At}\, E_{hn/hg}\, E_{\phi e/\phi tot}\, E_v\, E_d$$

$$P_{90} \quad E_{saline} = E_{An/At}\, E_{hn/h}g\, E_{\phi e/\phi tot}\, E_v\, E_d$$

Table 8: Saline Formation Efficiency Factors for Displacement Terms

Saline Formation Efficiency Factors for Displacement Terms $E_{saline}{}^{*} = E_v E_d$			
Lithology	**P_{10}**	**P_{50}**	**P_{90}**
Clastics	7.4%	14%	24%
Dolomite	16%	21%	26%
Limestone	10%	15%	21%

*$E_{An/At}$, $E_{hn/hg}$, and $E_{\phi e/\phi tot}$ values are known directly

Table 9. Parameters for Unmineable Coal Area Efficiency

Term	Symbol	P_{10}/P_{90} Values	Description
Geologic terms used to define the entire basin or region pore volume			
Net-to-Total Area	$E_{An/At}$	0.6/0.8	Fraction of total basin or region area that has bulk coal present.
Net-to-Gross Thickness	$E_{hn/hg}$	0.75/0.90	Fraction of coal area thickness that has adsorptive capability.
Displacement terms used to define the pore volume immediately surrounding a single well CO_2 injector			
Areal Displacement Efficiency	E_A	0.7/0.95	Fraction of the immediate area surrounding an injection well that can be contacted by CO_2.
Vertical Displacement Efficiency	E_L	0.8/0.95	Fraction of the vertical cross section (thickness), with the volume defined by the area (A) that can be contacted by a single well.
Gravity	Eg	0.9/1.0*	Fraction of the net thickness that is contacted by CO_2 as a consequence of the density difference between CO_2 and the in situ water in the cleats.
Microscopic Displacement Efficiency	E_d	0.75/0.95	Reflects the degree of saturation achievable for in situ coal compared with the theoretical maximum predicted by the CO_2 Langmuir Isotherm.

*0.999999999999999 used due to inability to divide by zero when using log odds method.

P_{10} and P_{90} serve as nominal lower and upper bounds that demark a plausible range of efficiency factors, defined in a consistent probabilistic manner. If the 10th and 90th percentile values of the individual terms are properly specified for the targeted application, such as geologic storage, and the distributions for each term are independent and reasonably represented by the log-odds normal assumption, then the computed 10th and 90th percentile values for efficiency factors are properly estimated. However, because these limits are based on a combination of data with varying quality and expert judgment, the P_{10} and P_{90} limits should be interpreted as general, rather than strictly mathematical, limits. That is, with reasonable 10th and 90th percentile limits chosen for each factor, the results provide reasonable 10th and 90th percentile limits for efficiency factors.

5.2. Efficiency of Unmineable Coal Areas

For coal areas, the CO_2 storage efficiency factor is a function of geologic parameters, such as area ($E_{An/At}$) and thickness ($E_{hn/hg}$), which reflect the percentage of volume that is amenable to CO_2 geologic storage and displacement efficiency components, such as areal (E_A), vertical (E_L), gravity (E_g), and microsocopic (E_d), which reflect the portion of a basin's or region's coal bulk volume that CO_2 is expected to contact (Bachu et al., 2007; Doughty and Pruess, 2004; Koide et al., 1992; Shafeen et al., 2004; van de Meer, 1992). The effective-to-total porosity term is not applicable in coal areas. Equation 12 describes CO_2 storage efficiency for coal areas:

$$E_{coal} = E_{An/At}\, E_{hn/hg}\, E_A\, E_L\, E_g\, E_d \qquad (12)$$

The area ($E_{An/At}$) and thickness ($E_{hn/hg}$) terms gauge the portion of a basin's volume that coal is present. The volumetric displacement terms (E_A, E_L, and E_g) identify the portion of the in situ coal volume that CO_2 is accessible. The microscopic displacement term (E_d) identifies the degree of CO_2 saturation (with respect to the maximum predicted by the Langmuir isotherm) within the CO_2-accessible.

The net-to-total area $E_{An/At}$ ratio is the fraction of total basin or region area that has bulk coal present. This term accounts for known or suspected locations that are within a basin or region outline where a coal area may be discontinuous. In the Illinois Basin, for example, there are subregions within the basin where sand channels have incised and replaced coal (DOE-NETL, 2008). The net-to-gross thickness $E_{hn/hg}$ ratio is the fraction of total coal area thickness that has adsorptive capability. The areal displacement (E_A) efficiency is the fraction of the immediate area surrounding an injection well that can be contacted by CO_2. This term is influenced by areal geologic heterogeneity such as faults and permeability anisotropy. The vertical displacement (E_L) efficiency is the fraction of the vertical cross section or thickness, with the volume defined by the area (A) that can be contacted by CO_2 from a single well. This term is influenced by variations in the cleat system within the coal. If one zone has higher permeability than other zones, the CO_2 will fill it quickly and leave the other zones with less or no CO_2. The gravity displacement (E_g) efficiency is the fraction of the net thickness that is contacted by CO_2 as a consequence of the density difference between CO_2 and in situ water in the cleats. In other words, 1-E_g is the portion of the net thickness not contacted by CO_2 because the CO_2 rises within the coal area. The microscopic displacement (E_d) efficiency reflects the degree of saturation achievable for in situ coal compared with the theoretical maximum predicted by the CO_2 Langmuir Isotherm.

Because there is no documented database describing the statistical properties of coal areas, Monte Carlo simulations of storage efficiency for coal areas are based tentatively on coalbed methane production and computer modeling observations (DOE-NETL, 2006, 2008). In comparison with efficiency terms for saline formations, coal area efficiency terms for area and thickness are increased because most coal basins are better defined than saline formations. Displacement efficiency terms for coal are also much higher than similar terms for porous media found in saline formations due to the adsorptive nature of coal. The gravity displacement term will likely be insignificant since coal areas are typically thinner than saline formations. Although it is known that coal swells in the presence of CO_2 and causes a reduction in permeability, coal swelling is not included in the efficiency equation at this time (Day et al., 2008b; Xie and Economides, 2009). The equation, parameters, symbols, ranges, and description used to calculate the storage efficiency factor for coal areas are summarized by eq 12 and Table 9.

Efficiency factors for coal areas were determined by using the log odds method when applied with Monte Carlo sampling by eqs 7–11 as described in the Section 5.1 (Devore, 2004). The overall storage efficiency factor for coal areas ranges from 21 to 48 percent over the 10 and 90 percent probability range (Table 10). In the case where net-to-total area $E_{An/At}$ and net-to-gross thickness $E_{hn/hg}$ are known for an unmineable coal area, the geologic efficiency values can be used directly in eq 12. In this instance, only the displacement efficiency factor is needed, which ranges between 39 and 77 percent over the 10 and 90 percent probability range (Table 11).

Overall, CO_2 storage resource estimates for unmineable coal areas are calculated from volumetric parameters (eq 3) and efficiency factors (eq 12) over the P_{10}, P_{50}, and P_{90} percent probability range (Tables 10 and 11).

Table 10: Coal Area Efficiency Factors

Coal Area Efficiency Factors $E_{coal} = E_{An/At}\, E_{hn/hg}\, E_A\, E_L\, E_g\, E_d$		
P_{10}	P_{50}	P_{90}
21%	37%	48%

Table 11: Coal Area Efficiency Factors for Displacement Terms

Coal Area Efficiency Factors for Displacement Terms $E_{coal}{}^{*} = E_A\, E_L\, E_g\, E_d$		
P_{10}	P_{50}	P_{90}
39%	64%	77%

*$E_{An/At}$ and $E_{hn/hg}$ values known directly

$$G_{CO2} = A\, h_g\, C_{s,max}\, \rho_{CO2std}\, E_{coal} \qquad (3)$$

$$P_{10} \quad E_{coal} = E_{An/At}\, E_{hn/hg}\, E_A\, E_L\, E_g\, E_d \qquad (12)$$

$$P_{50} \quad E_{coal} = E_{An/At}\, E_{hn/hg}\, E_A\, E_L\, E_g\, E_d$$

$$P_{90} \quad E_{coal} = E_{An/At}\, E_{hn/hg}\, E_A\, E_L\, E_g\, E_d$$

P_{10} and P_{90} serve as nominal lower and upper bounds that demark a plausible range of efficiency factors, defined in a consistent probabilistic manner. If the 10^{th} and 90^{th} percentile values of the individual terms are properly specified for the targeted application, such as geologic storage, and the distributions for each term are independent and reasonably represented by the log-odds normal assumption, then the computed 10^{th} and 90^{th} percentile values for efficiency factors are properly estimated. However, because these limits are based on a combination of data with varying quality and expert judgment, the P_{10} and P_{90} limits should be interpreted as general, rather than strictly mathematical, limits. That is, with reasonable 10^{th} and 90^{th} percentile limits chosen for each factor, the results provide reasonable 10^{th} and 90^{th} percentile limits for efficiency factors.

6. Summary and Conclusions

A summary of the methodology for estimating CO_2 storage resource potential for geologic CO_2 storage in *Atlas III* is presented. The RCSPs used this methodology for determining CO_2 storage resource estimates for three types of geologic formations: oil/gas reservoirs, saline formations, and unmineable coal areas. These CO_2 storage resource estimates are based on physically accessible CO_2 storage pore volume in formations and on the assumption that the storage reservoirs are open systems in which the in situ fluids will either be displaced from the injection zone or managed. Economic and regulatory constraints are not considered; hence site-specific assessments should not be performed using this methodology. Carbon dioxide storage resource estimates are intended for use by external users, such as RCSPs, future project developers, and governmental entities, for high-level assessments of potential CO_2 storage reservoirs in the United States and Canada at the regional and national scale.

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CO_2 Stationary Source and Geologic Storage Resource Estimates by State/Province

Appendix C

Prepared for

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Sequestration Program

Prepared by

DOE Regional Carbon Sequestration Partnerships and
the National Carbon Sequestration Database and Geographic Information System

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CO_2 Stationary Source Emission Estimates by State/Province

The table ("Identified Stationary CO_2 Sources") displays CO_2 stationary source data by state/province which were obtained from the RCSPs and compiled by NATCARB. As described on page 25, a total of more than 4,507 stationary sources with total annual emissions exceeding 3,400 million metric tons (3,748 million tons) of CO_2 have been documented by the RCSPs.

Information on the methods used in estimating CO_2 stationary source emissions can be found in the "CO_2 Stationary Source Emission Estimation Methodologies Summary" in Appendix A. Emissions data specific to each RCSP can be found within each RCSP section of *Atlas III*.

The States/provinces with the largest CO_2 stationary source emissions include Texas, Alberta, Indiana, Ohio, Florida, Pennsylvania, Illinois, Louisiana, West Virginia, and Missouri. The 343 stationary sources identified in Texas are estimated to emit 373 million metric tons per year (411 million tons per year) of CO_2. The 305 stationary sources identified in Alberta are estimated to emit 208 million metric tons per year (229 million tons per year). The 92 stationary sources identified in Indiana are estimated to emit 155 million metric tons per year (171 million tons per year).

Identified Stationary CO_2 Sources

State/Province	CO_2 Emissions Million Metric Ton Per Year	Number of Sources
Alabama	80	59
Alaska	20	49
Alberta	208	305
Arizona	55	50
Arkansas	35	30
British Columbia	15	53
California	84	182
Colorado	52	56
Connecticut	10	63
Delaware	6	16
District of Columbia	0	5
Florida	143	108
Georgia	90	64
Hawaii	10	45
Idaho	2	18
Illinois	122	138
Indiana	155	92
Iowa	55	63
Kansas	48	102
Kentucky	93	48
Louisiana	102	133
Maine	5	106
Manitoba	4	12
Maryland	37	21
Massachusetts	25	137
Michigan	84	45
Minnesota	59	103
Mississippi	34	49
Missouri	98	126
Montana	28	78
Nebraska	31	35
Nevada	27	16
New Brunswick	6	7
New Hampshire	8	66
New Jersey	35	123
New Mexico	35	32
New York	77	386
Newfoundland & Labrador	4	7
North Carolina	77	55
North Dakota	42	31
Northwest Territories	0	2
Nova Scotia	11	7
Ohio	149	51
Oklahoma	57	45
Ontario	50	48
Oregon	11	22
Pennsylvania	142	76
Quebec	14	32
Rhode Island	2	18
Saskatchewan	42	35
South Carolina	40	48
South Dakota	21	53
Tennessee	66	29
Texas	373	343
Utah	43	27
Vermont	0	73
Virginia	46	56
Washington	21	35
West Virginia	99	26
Wisconsin	77	219
Wyoming	59	101
Offshore	46	47
TOTAL	3,467	4,507

Total CO_2 Storage Resource Estimates by State/Province

The table ("Total CO_2 Storage Resource") displays the total CO_2 storage resource estimates by state/province which were obtained from the RCSPs and compiled by NATCARB. The total CO_2 storage resource is the sum of saline formation, oil and gas reservoir, and unmineable coal area CO_2 storage resource estimates. The current total CO_2 storage resource identified by the RCSPs is approximately 1,850 to 20,470 billion metric tons (2,040 to 22,570 billion tons).

Information on the methods used in estimating CO_2 storage resource can be found in the "Methodology for Development of Geologic Storage Estimates for Carbon Dioxide" in Appendix B. Please note CO_2 geologic storage information in *Atlas III* was developed to provide a high level overview of CO_2 geologic storage potential across the United States and parts of Canada. Carbon dioxide resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCS project developers a starting point for further investigation of the extent to which geologic CO_2 storage is feasible. This information is not intended as a substitute for site-specific characterization, assessment and testing. Please refer to page 14 of *Atlas III* for additional information on this level of assessment.

*Total CO_2 Storage Resource**

State/Province	Million Metric Tons		Million Tons	
	Low Estimate	High Estimate	Low Estimate	High Estimate
Alabama	14,020	166,320	15,454	183,336
Alaska	8,980	20,530	9,899	22,630
Alberta	46,080	50,170	50,795	55,303
Arizona	130	1,590	143	1,753
Arkansas	6,150	63,260	6,779	69,732
British Columbia	1,600	2,130	1,764	2,348
California	33,510	416,930	36,938	459,587
Colorado	32,960	426,800	36,332	470,466
Connecticut	0	0	0	0
Delaware	20	80	22	88
District of Columbia	0	0	0	0
Florida	17,120	219,850	18,872	242,343
Georgia	520	23,260	573	25,640
Hawaii				
Idaho	50	720	55	794
Illinois	10,040	118,290	11,067	130,392
Indiana	14,480	85,650	15,961	94,413
Iowa	10	160	11	176
Kansas	2,780	18,000	3,064	19,842
Kentucky	1,530	9,750	1,687	10,748
Louisiana	168,270	2,083,280	185,486	2,296,423
Maine				
Manitoba	1,050	1,050	1,157	1,157
Maryland	860	5,050	948	5,567
Massachusetts	0	0	0	0
Michigan	15,390	59,260	16,965	65,323
Minnesota				
Mississippi	51,460	637,970	56,725	703,242
Missouri	20	320	22	353
Montana	123,630	1,656,640	136,279	1,826,133
Nebraska	22,890	76,870	25,232	84,735
Nevada	0	0	0	0
New Brunswick				
New Hampshire				
New Jersey	0	0	0	0
New Mexico	39,550	449,300	43,596	495,268
New York	2,620	7,740	2,888	8,532
Newfoundland & Labrador				
North Carolina	1,320	18,170	1,455	20,029
North Dakota	108,230	125,080	119,303	137,877
Northwest Territories				
Nova Scotia				
Ohio	14,140	26,110	15,587	28,781
Oklahoma	8,120	8,130	8,951	8,962
Ontario	10	20	11	22
Oregon	7,080	97,390	7,804	107,354
Pennsylvania	10,100	30,920	11,133	34,083
Quebec	0	0	0	0
Rhode Island	0	0	0	0
Saskatchewan	7,900	15,740	8,708	17,350
South Carolina	200	9,660	220	10,648
South Dakota	17,580	156,180	19,379	172,159
Tennessee	490	6,650	540	7,330
Texas	393,490	4,662,190	433,748	5,139,185
Utah	22,180	289,960	24,449	319,626
Vermont	0	0	0	0
Virginia	330	1,240	364	1,367
Washington	29,930	411,570	32,992	453,678
West Virginia	6,630	20,260	7,308	22,333
Wisconsin	0	0	0	0
Wyoming	101,590	1,216,640	111,984	1,341,116
Offshore	509,220	6,776,230	561,319	7,469,515
TOTAL	1,854,260	20,473,110	2,043,972	22,567,741

* States/Provinces with a "zero" value represent estimates of minimal CO_2 storage resource, while states/provinces with a blank represent areas that have not yet be assessed by the RCSPs.

CO_2 Storage Resource Estimates for Oil and Gas Reservoirs by State/Province

The table ("CO_2 Storage Resource Estimates for Oil and Gas Reservoirs") displays oil and gas reservoir CO_2 storage resource estimates by state/province. As described on page 28, the RCSPs have documented the location of more than 142 billion metric tons (156 billion tons) of CO_2 storage potential in oil and gas reservoirs distributed over 29 States and 4 provinces. In the table, States/provinces with a "zero" value represent estimates of minimal oil and gas reservoir CO_2 storage resource while States/provinces with a blank represent areas that have not yet been assessed by the RCSPs. Carbon dioxide storage resource data for oil and gas reservoirs specific to each RCSP can be found within each RCSP section of *Atlas III*. Additional details can be obtained from the NATCARB website (http://www.natcarb.org/).

Areas with the largest oil and gas reservoir storage potential identified include Texas, offshore, Louisiana, Alberta, Ohio, Oklahoma, New Mexico, Saskatchewan, North Dakota, and California. These CO_2 storage resources are significant, with an estimated 120 years of storage available in Texas oil and gas reservoirs at Texas's current emission rate. Oklahoma's oil and gas reservoirs are estimated to have CO_2 storage resource for more than 140 years of emissions from the state.

Please note CO_2 geologic storage information in *Atlas III* was developed to provide a high level overview of CO_2 geologic storage potential across the United States and parts of Canada. Carbon dioxide resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCS project developers a starting point for further investigation of the extent to which geologic CO_2 storage is feasible. This information is not intended as a substitute for site-specific characterization, assessment and testing. Please refer to page 14 of *Atlas III* for additional information on this level of assessment.

*CO_2 Storage Resource Estimates for Oil & Gas Reservoirs by State/Province**

State/Province	Million Metric Tons	Million Tons
Alabama	350	386
Alaska		
Alberta	10,090	11,122
Arizona	10	11
Arkansas	260	287
British Columbia	10	11
California	3,440	3,792
Colorado	1,610	1,775
Connecticut		
Delaware		
District of Columbia		
Florida	130	143
Georgia		
Hawaii		
Idaho		
Illinois	100	110
Indiana	20	22
Iowa		
Kansas	1,590	1,753
Kentucky	50	55
Louisiana	10,610	11,696
Maine		
Manitoba	740	816
Maryland		
Massachusetts		
Michigan	770	849
Minnesota		
Mississippi	560	617
Missouri	0	0
Montana	2,600	2,866
Nebraska	30	33
Nevada		
New Brunswick		
New Hampshire		
New Jersey		
New Mexico	7,350	8,102
New York	920	1,014
Newfoundland & Labrador		
North Carolina		
North Dakota	4,410	4,861
Northwest Territories		
Nova Scotia		
Ohio	10,060	11,089
Oklahoma	8,120	8,951
Ontario		
Oregon		
Pennsylvania	2,970	3,274
Quebec		
Rhode Island		
Saskatchewan	6,920	7,628
South Carolina		
South Dakota	190	209
Tennessee	0	0
Texas	46,200	50,927
Utah	1,160	1,279
Vermont		
Virginia	60	66
Washington		
West Virginia	1,830	2,017
Wisconsin		
Wyoming	2,300	2,535
Offshore	16,790	18,508
TOTAL	142,250	156,804

* States/Provinces with a "zero" value represent estimates of minimal CO_2 storage resource, while states/provinces with a blank represent areas that have not yet be assessed by the RCSPs.

CO_2 Storage Resource Estimates for Unmineable Coal Areas by State/Province

The table ("CO_2 Storage Resource Estimates for Unmineable Coal Areas") displays unmineable coal area CO_2 storage resource estimates by state/province. As described on page 29, the RCSPs have documented the location of more than 59 to 117 billion metric tons (65 to 128 billion tons) of CO_2 geologic storage potential in unmineable coal areas distributed over 29 States and 1 province. In the table, States/provinces with a zero represent estimates of minimal unmineable coal area CO_2 storage resource while States/provinces with a blank represent areas that have not yet be assessed by the RCSPs. Unmineable coal area CO_2 storage resource data specific to each RCSP can be found within each RCSP section of *Atlas III*. Additional details can be obtained from the NATCARB website (http://www.natcarb.org/).

Areas with the largest unmineable coal area CO_2 storage resource identified include Texas, Alaska, Louisiana, Mississippi, Wyoming, Alabama, Arkansas, offshore, Illinois, and Florida. An estimated 35 to 85 years of CO_2 storage resource is available in Texas unmineable coal areas for Texas's current emission rate. Alaska's unmineable coal areas alone are estimated to have CO_2 storage resource for 24 to 55 years worth of emissions from the state.

Please note CO_2 geologic storage information in *Atlas III* was developed to provide a high level overview of CO_2 geologic storage potential across the United States and parts of Canada. Carbon dioxide resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCS project developers a starting point for further investigation of the extent to which geologic CO_2 storage is feasible. This information is not intended as a substitute for site-specific characterization, assessment and testing. Please refer to page 14 of *Atlas III* for additional information on this level of assessment.

*CO_2 Storage Resource Estimates for Unmineable Coal Areas by State/Province**

State/Province	Million Metric Tons		Million Tons	
	Low Estimate	High Estimate	Low Estimate	High Estimate
Alabama	1,910	4,340	2,105	4,784
Alaska	8,980	20,530	9,899	22,630
Alberta	840	840	926	926
Arizona	0	0	0	0
Arkansas	1,570	3,580	1,731	3,946
British Columbia				
California				
Colorado	490	860	540	948
Connecticut				
Delaware				
District of Columbia				
Florida	1,240	2,810	1,367	3,097
Georgia	30	60	33	66
Hawaii				
Idaho				
Illinois	1,450	2,860	1,598	3,153
Indiana	90	190	99	209
Iowa	0	10	0	11
Kansas	0	10	0	11
Kentucky	130	250	143	276
Louisiana	8,300	18,910	9,149	20,845
Maine				
Manitoba				
Maryland				
Massachusetts				
Michigan				
Minnesota				
Mississippi	5,450	12,470	6,008	13,746
Missouri	0	10	0	11
Montana	320	320	353	353
Nebraska	0	0	0	0
Nevada				
New Brunswick				
New Hampshire				
New Jersey				
New Mexico	80	300	88	331
New York				
Newfoundland & Labrador				
North Carolina				
North Dakota	600	600	661	661
Northwest Territories				
Nova Scotia				
Ohio	110	150	121	165
Oklahoma	0	10	0	11
Ontario				
Oregon				
Pennsylvania	230	330	254	364
Quebec				
Rhode Island				
Saskatchewan				
South Carolina				
South Dakota				
Tennessee	0	0	0	0
Texas	13,890	31,740	15,311	34,987
Utah	30	120	33	132
Vermont				
Virginia	190	790	209	871
Washington	0	0	0	0
West Virginia	320	500	353	551
Wisconsin				
Wyoming	11,860	12,140	13,073	13,382
Offshore	1,350	3,080	1,488	3,395
TOTAL	59,460	117,810	65,543	129,863

* States/Provinces with a "zero" value represent estimates of minimal CO_2 storage resource, while states/provinces with a blank represent areas that have not yet be assessed by the RCSPs.

Saline Formation Storage Resource Estimates by State/Province

The table ("CO_2 Storage Resource Estimates for Saline Formations by State/Province") displays saline formation CO_2 storage resource estimates by state/province. As described on page 27, the RCSPs have documented the location of saline formations with an estimated storage potential from approximately 1,650 to more than 20,200 billion metric tons (from 1,820 to more than 22,260 billion tons). In the table, States/provinces with a zero represent estimates of saline formation CO_2 storage resource while States/provinces with a blank represent areas that have not yet be assessed by the RCSPs. Saline formation CO_2 storage resource data specific to each RCSP can be found within each RCSP section of *Atlas III*. Additional details can be obtained from the NATCARB website (http://www.natcarb.org/).

Areas with the largest saline formation CO_2 storage resource identified include offshore, Texas, Louisiana, Montana, Wyoming, Mississippi, New Mexico, Colorado, California, and Washington. At Texas's current emission rate, there is an estimated 890 to 12,290 years of CO_2 storage resource available in Texas saline formations.

Please note CO_2 geologic storage information in *Atlas III* was developed to provide a high level overview of CO_2 geologic storage potential across the United States and parts of Canada. Carbon dioxide resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCS project developers a starting point for further investigation of the extent to which geologic CO_2 storage is feasible. This information is not intended as a substitute for site-specific characterization, assessment and testing. Please refer to page 14 of *Atlas III* for additional information on this level of assessment.

*CO_2 Storage Resource Estimates for Saline Formations by State/Province**

State/Province	Million Metric Tons		Million Tons	
	Low Estimate	High Estimate	Low Estimate	High Estimate
Alabama	11,760	161,630	12,963	178,167
Alaska				
Alberta	35,150	39,240	38,746	43,255
Arizona	120	1,580	132	1,742
Arkansas	4,320	59,420	4,762	65,499
British Columbia	1,590	2,120	1,753	2,337
California	30,070	413,490	33,147	455,795
Colorado	30,860	424,330	34,017	467,744
Connecticut	0	0	0	0
Delaware	20	80	22	88
District of Columbia	0	0	0	0
Florida	15,750	216,910	17,361	239,102
Georgia	490	23,200	540	25,574
Hawaii				
Idaho	50	720	55	794
Illinois	8,490	115,330	9,359	127,130
Indiana	14,370	85,440	15,840	94,181
Iowa	10	150	11	165
Kansas	1,190	16,400	1,312	18,078
Kentucky	1,350	9,450	1,488	10,417
Louisiana	149,360	2,053,760	164,641	2,263,883
Maine				
Manitoba	310	310	342	342
Maryland	860	5,050	948	5,567
Massachusetts	0	0	0	0
Michigan	14,620	58,490	16,116	64,474
Minnesota				
Mississippi	45,450	624,940	50,100	688,878
Missouri	20	310	22	342
Montana	120,710	1,653,720	133,060	1,822,914
Nebraska	22,860	76,840	25,199	84,702
Nevada	0	0	0	0
New Brunswick				
New Hampshire				
New Jersey	0	0	0	0
New Mexico	32,120	441,650	35,406	486,836
New York	1,700	6,820	1,874	7,518
Newfoundland & Labrador				
North Carolina	1,320	18,170	1,455	20,029
North Dakota	103,220	120,070	113,781	132,355
Northwest Territories				
Nova Scotia				
Ohio	3,970	15,900	4,376	17,527
Oklahoma	0	0	0	0
Ontario	10	20	11	22
Oregon	7,080	97,390	7,804	107,354
Pennsylvania	6,900	27,620	7,606	30,446
Quebec	0	0	0	0
Rhode Island	0	0	0	0
Saskatchewan	980	8,820	1,080	9,722
South Carolina	200	9,660	220	10,648
South Dakota	17,390	155,990	19,169	171,950
Tennessee	490	6,650	540	7,330
Texas	333,400	4,584,250	367,511	5,053,271
Utah	20,990	288,680	23,138	318,215
Vermont	0	0	0	0
Virginia	80	390	88	430
Washington	29,930	411,570	32,992	453,678
West Virginia	4,480	17,930	4,938	19,764
Wisconsin	0	0	0	0
Wyoming	87,430	1,202,200	96,375	1,325,199
Offshore	491,080	6,756,360	541,323	7,447,612
TOTAL	1,652,550	20,213,050	1,821,625	22,281,074

* States/Provinces with a "zero" value represent estimates of minimal CO_2 storage resource, while states/provinces with a blank represent areas that have not yet be assessed by the RCSPs.

CO_2 Stationary Source Emissions and CO_2 Storage Resource Estimates Summary by State/Province

This table ("CO_2 Emissions and Geologic Storage Resource Summary") is a compilation of all data provided in this Appendix. State/Provinces with the "zero" represents estimates of the minimal CO_2 storage resource while States/Provinces with a blank represent areas that have not yet been accessed by the RCSPs.

Please note CO_2 geologic storage information in *Atlas III* was developed to provide a high level overview of CO_2 geologic storage potential across the United States and parts of Canada. Carbon dioxide resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCS project developers a starting point for further investigation of the extent to which geologic CO_2 storage is feasible. This information is not intended as a substitute for site-specific characterization, assessment and testing. Please refer to page 14 of *Atlas III* for additional information on this level of assessment.

CO_2 Emissions			Oil and Gas Reservoir Storage Resource	Unmineable Coal Areas Storage Resource		Saline Formation Storage Resource		Total Storage Resource	
			Million Metric Tons	Million Metric Tons		Million Metric Tons		Million Metric Tons	
State/ Province	Million Metric Ton/ Year	No. Sources		Low Estimate	High Estimate	Low Estimate	High Estimate	Low Estimate	High Estimate
Alabama	80	59	350	1,910	4,340	11,760	161,630	14,020	166,320
Alaska	20	49		8,980	20,530			8,980	20,530
Alberta	208	305	10,090	840	840	35,150	39,240	46,080	50,170
Arizona	55	50	10	0	0	120	1,580	130	1,590
Arkansas	35	30	260	1,570	3,580	4,320	59,420	6,150	63,260
British Columbia	15	53	10			1,590	2,120	1,600	2,130
California	84	182	3,440			30,070	413,490	33,510	416,930
Colorado	52	56	1,610	490	860	30,860	424,330	32,960	426,800
Connecticut	10	63				0	0	0	0
Delaware	6	16				20	80	20	80
District of Columbia	0	5				0	0	0	0
Florida	143	108	130	1,240	2,810	15,750	216,910	17,120	219,850
Georgia	90	64		30	60	490	23,200	520	23,260
Hawaii	10	45							
Idaho	2	18				50	720	50	720
Illinois	122	138	100	1,450	2,860	8,490	115,330	10,040	118,290
Indiana	155	92	20	90	190	14,370	85,440	14,480	85,650
Iowa	55	63		0	10	10	150	10	160
Kansas	48	102	1,590	0	10	1,190	16,400	2,780	18,000
Kentucky	93	48	50	130	250	1,350	9,450	1,530	9,750
Louisiana	102	133	10,610	8,300	18,910	149,360	2,053,760	168,270	2,083,280
Maine	5	106							
Manitoba	4	12	740			310	310	1,050	1,050
Maryland	37	21				860	5,050	860	5,050
Massachusetts	25	137				0	0	0	0
Michigan	84	45	770			14,620	58,490	15,390	59,260
Minnesota	59	103							
Mississippi	34	49	560	5,450	12,470	45,450	624,940	51,460	637,970
Missouri	98	126	0	0	10	20	310	20	320
Montana	28	78	2,600	320	320	120,710	1,653,720	123,630	1,656,640
Nebraska	31	35	30	0	0	22,860	76,840	22,890	76,870
Nevada	27	16				0	0	0	0
New Brunswick	6	7							
New Hampshire	8	66							
New Jersey	35	123				0	0	0	0
New Mexico	35	32	7,350	80	300	32,120	441,650	39,550	449,300
New York	77	386	920			1,700	6,820	2,620	7,740
Newfoundland & Labrador	4	7							
North Carolina	77	55				1,320	18,170	1,320	18,170
North Dakota	42	31	4,410	600	600	103,220	120,070	108,230	125,080
Northwest Territories	0	2							
Nova Scotia	11	7							
Ohio	149	51	10,060	110	150	3,970	15,900	14,140	26,110
Oklahoma	57	45	8,120	0	10	0	0	8,120	8,130
Ontario	50	48				10	20	10	20
Oregon	11	22				7,080	97,390	7,080	97,390
Pennsylvania	142	76	2,970	230	330	6,900	27,620	10,100	30,920
Quebec	14	32				0	0	0	0
Rhode Island	2	18				0	0	0	0
Saskatchewan	42	35	6,920			980	8,820	7,900	15,740
South Carolina	40	48				200	9,660	200	9,660
South Dakota	21	53	190			17,390	155,990	17,580	156,180
Tennessee	66	29	0	0	0	490	6,650	490	6,650
Texas	373	343	46,200	13,890	31,740	333,400	4,584,250	393,490	4,662,190
Utah	43	27	1,160	30	120	20,990	288,680	22,180	289,960
Vermont	0	73				0	0	0	0
Virginia	46	56	60	190	790	80	390	330	1,240
Washington	21	35		0	0	29,930	411,570	29,930	411,570
West Virginia	99	26	1,830	320	500	4,480	17,930	6,630	20,260
Wisconsin	77	219				0	0	0	0
Wyoming	59	101	2,300	11,860	12,140	87,430	1,202,200	101,590	1,216,640
Offshore	46	47	16,790	1,350	3,080	491,080	6,756,360	509,220	6,776,230
TOTAL	3,467	4,507	142,250	59,460	117,810	1,652,550	20,213,050	1,854,260	20,473,110

* States/Provinces with a "zero" value represent estimates of minimal CO_2 storage resource, while states/provinces with a blank represent areas that have not yet be assessed by the RCSPs.

Acronyms and Abbreviations

Acronym/Abbreviation	Definition
AEO	Annual Energy Outlook
ARRA	American Recovery and Reinvestment Act of 2009
BLM	Bureau of Land Management
BOEMRE	Bureau of Ocean Energy Management, Regulation, and Enforcement
BOR	Bureau of Reclamation
BPM	Best Practices Manual
BSCSP	Big Sky Carbon Sequestration Partnership
BTU	British Thermal Unit
CBM	Coalbed Methane
CCPI	Clean Coal Power Initiative
CCS	Carbon Capture and Storage
CH_4	Methane
CO_2	Carbon Dioxide
CO_2-EOR	Carbon Dioxide-Enhanced Oil Recovery
CSLF	Carbon Sequestration Leadership Forum
$CaCO_3$	Calcium Carbonate
$CaMg(CO_3)_2$	Dolomite
DAS	Detailed Area of Study
DOA	U.S. Department of Agriculture
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of Interior
DOJ	U.S. Department of Justice
DOT	U.S. Department of Transportation
DSS	Decision Support System
DU	Ducks Unlimited Inc.
ECBM	Enhanced Coalbed Methane
EGR	Enhanced Gas Recovery
EIA	Energy Information Administration
EOR	Enhanced Oil Recovery
EPA	U.S. Environmental Protection Agency
EPCA	Energy Policy and Conservation of Act of 2005
FE	DOE's Office of Fossil Energy
FERC	Federal Energy Regulatory Commission
FOA	Funding Opportunity Announcement
FWS	U.S. Fish and Wildlife Service
GHG	Greenhouse Gas
GIS	Geographic Information System
GWPC	Ground Water Protection Council
HFC	Hydrofluorocarbon
HiVIT	High Volume Injection Test
IEA GHG	IEA Greenhouse Gas R&D Programme
IGCC	Integrated Gasification Combined Cycle
IOGCC	Interstate Oil and Gas Compact Commission
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
MGSC	Midwest Geological Sequestration Consortium
Mt	Metric Tons
MMt	Million Metric Tons
MRCSP	Midwest Regional Carbon Sequestration Partnership
MVA	Monitoring, Verification, and Accounting
N_2O	Nitrogen Oxide
NACAP	North American Carbon Atlas Partnership
NAEWG	North American Energy Working Group
NARUC	National Association of Regulatory Utility Commissioners
NATCARB	National Carbon Sequestration Database and Geographic Information System
NCCI	National Carbon Cyberinfrastructure
NETL	National Energy Technology Laboratory
NGCC	Natural Gas Combined Cycle
NO_x	Nitrogen Oxide
NPS	National Park Service
OCS	Outer Continental Shelf
OCSLA	Outer Continental Shelf Lands Act
OGIP	Original Gas in Place
OOIP	Original Oil in Place
PCOR	Plains CO_2 Reduction Partnership
PFC	Perfluorocarbon
PPB	Prairie Public Broadcasting
ppm	Parts Per Million
PRB	Powder River Basin
R&D	Research and Development
RCSP	Regional Carbon Sequestration Partnership(s)
RECS	Research Experience in Carbon Sequestration
RST	Reservoir Saturation Tool
scf	Standard Cubic Feet
SDWA	Safe Drinking Water Act
SECARB	Southeast Carbon Sequestration Partnership
SSEB	Southern States Energy Board
STB	Surface Transportation Board
STEP	Sequestration Training Education Program
SWP	Southwest Regional Partnership on Carbon Sequestration
Tcf	Trillion Cubic Feet
TOC	Total Organic Content
TDS	Total Dissolved Solids
UIC	Underground Injection Control
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
UNFCCC	United Nations Framework Convention on Climate Change
VSP	Vertical Seismic Profile
WESTCARB	West Coast Regional Carbon Sequestration Partnership

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